ROAD SALT CAPTURE AND MITIGATION THROUGH THE INTEGRATION OF BIOCHAR WITH ROADSIDE LANDSCAPE DRAINAGE SYSTEMS


by

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(Under the Direction of Jon Calabria)



ABSTRACT

This thesis investigates biochar's potential to mitigate the negative impacts of road salt on roadside soils through stormwater runoff and formulates recommendations for integrating biochar into road shoulder drainage systems. Road salt, primarily sodium chloride (NaCl), is widely used for deicing, but it negatively impacts ecosystems, particularly by polluting water sources. Wood-derived biochar, produced at high temperatures, is recommended for its ability to improve soil properties, including increasing water retention, reducing compaction, and enhancing nutrient availability. This thesis recommends a beginning application rate of 3-4% by weight, amended into the root zone of salt-tolerant vegetation, such as native warm-season grasses and halophytes. This research suggests that roadside enhancements with biochar, executed by a case-by-case approach, can offer sustainable solutions for managing road salt pollution. This thesis highlights the need for further research, particularly regarding the long-term monitoring of biochar and the development of sustainable biomass for biochar production.



Keywords: biochar, chloride, deicing, road salt, stormwater, runoff

MITIGATING THE NEGATIVE EFFECTS OF ROAD SALT USING BIOCHAR IN ROADSIDE SOILS

by

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## DEDICATION

This thesis is dedicated to my partner, Elizabeth, who has consistently supported my pursuit of a landscape architecture degree and instilled more confidence in me than I could ever imagine. I am proud of the path we've paved together so far and excited for the journey that lies ahead. I would also like to dedicate this thesis to my parents and my sister for supporting my dreams and showing me unwavering love every step of the way.

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# CHAPTER 1

# INTRODUCTION

The United States has over 164,000 miles of highways in the National Highway System that form the backbone of vehicular transportation in the United States, while individuals over the age of 16 averaged 2.44 driving trips daily in 2022 (Office of Highway Policy Information 2011; Steinbach and Tefft 2023). To keep these systems moving, federal and state transportation departments work to provide safe and efficient driving conditions for the U.S. population. Road safety is a challenge when winter weather prevents drivers from getting where they are going without risking their safety on slick and icy roads. The most common solution to address unsafe winter road conditions is to treat them with road salt.

Since the early 20th century, the United States has used granular sodium chloride ($NaCl$) to deice roadways for safer travel. After the significant expansion of the highway system in World War II, the use of road salt began to increase, and the DOT ensured motorists in the U.S. had access to reliable roadways and could expect ice-free “bare pavements” shortly after winter storms. The DOT’s mandate of maintaining bare pavement roads required continuous snow plowing during storm events and 400-1200 pounds of salt per lane mile (Wenta and Sorsa 2020). Today, road salt and other chloride-based deicing products remain the most common method due to inexpensive and abundant access by most state and federal transportation departments.

According to the Transportation Research Board, the United States spends approximately $2.3 billion annually to manage winter weather's effects on highways (2013). In addition, chloride-based deicers' environmental and corrosive impacts cost the United States about $5 billion (Transportation Research Board, National Academies of Sciences, and Medicine 2013). Part of the northeast region of the United States, which is near coastal areas of the Atlantic Ocean and wraps around the Great Lakes, is referred to as the Salt Belt because of the increased usage of road salt compared to the greater United States. Consequently, infrastructure and vehicles in the Salt Belt have shorter lifespans because of chloride's corrosive properties (Houska 2007). The dispersal of road salt significantly impacts roadside vegetation and soils, wildlife, surface water runoff, and aquatic biota and even contributes to the contamination of fresh drinking water (Strifling 2018). In addition to winter maintenance costs, the environmental and corrosion costs of winter maintenance materials in the United States are estimated at least $5 billion annually (Casey et al. 2014).

Stormwater runoff is water from rain and melting snow (meltwater) that flows over land and does not soak into the ground. This runoff can pick up constituents on the ground's surface and carry them into streams, lakes, and groundwater. Stormwater runoff contains various constituents, including metals, nutrients, and polycyclic aromatic hydrocarbons (PAHs), but chloride-based road salts are one of the most water-soluble components of highway stormwater runoff. Road salt is carried much further into the environment than other constituents. While most other constituents remain suspended solids when carried by stormwater, the ionic bond between the sodium ($Na^+$) and chloride ($Cl^-$) of road salt breaks. The chloride and sodium molecules are dispersed throughout the water, causing $Na^+$ and $Cl^-$ to move freely within the solution (Beck 2020). As stormwater traverses its path toward a water body, it infiltrates the soil. Soils are natural filters, and as stormwater infiltrates, the soil captures the suspended constituents in the water. Soils have varying compositions and textures, which affect infiltration. For example, soils with high clay and organic content are most at risk for decreased permeability and aeration due to salt (Casey et al. 2014). Suggesting that sandy soils, which have higher permeability, might be more suitable for road shoulders in areas with heavy road salt use so runoff can infiltrate and filter through the soil. Some of the constituents in runoff are nutrients that plants absorb, and some are organic and inorganic substances (Masoner et al. 2019) that integrate into the soil and become humus. This process is necessary to maintain healthy aquatic ecosystems. If left uncontrolled, it may create dead zones in aquatic ecosystems that cause organisms in the water to migrate or die (Carmichael and Boyer 2016). A higher bulk density in soil generally means the soil is more compact and has less pore space, leading to reduced infiltration. Water infiltration is less likely to occur on roadsides because pollutant-heavy road runoff that builds up on the surface of the soil causes the soil to be less porous and increases its bulk density (Cooper, Mayer, and Faulkner 2014). Therefore, highway constituent-loaded stormwater runoff may find a longer path to surface water systems like streams or lakes. Chloride can reside in surface soils and infiltrate slowly over two and a half to five months, depending on conditions (Robinson, Hasenmueller, and Chambers 2017). Research findings on a restored urban stream in Maryland suggest that groundwater may be a long-term reservoir for accumulating road salts and will continue accumulating more if chloride leaching of roadside and agricultural soils is unaddressed (Cooper, Mayer, and Faulkner 2014).

Although there are alternatives to road salt for deicing procedures, none are as available, affordable, and accessible as sodium chloride (Casey et al. 2014). The United States already possesses well-established infrastructure and standard operating procedures for extracting, distributing, and applying road salt, streamlining its implementation as a deicing method. Minnesota already operates approximately 800 snowplows to service 12,000 miles of road, according to Minnesota's Department of Transportation (2018). There is a need to investigate alternative methods and interventions to mitigate road salt distribution effects on the environment and offer a more sustainable approach to winter road maintenance.

To try to change modern deicing methods on a large scale, one would need to address the more prominent economic factors of the current salt market. Rock salt held the largest share of the salt market in 2023, attributing most of its demand to road applications, which are expected to continue growing at a rate of 1.8% through 2032 (Fortune Business Insights 2023). The world salt market supports various roles, such as production workers, logistics personnel, sales representatives, and administrative staff, which would all be negatively impacted by a shift from salt use. In the United States alone, highway deicing represents about 43% of the total salt consumed (U.S. Geological Survey 2020). Changing the salt market would be much bigger than just changing the systems of the United States, it would require shifting the global salt market, affecting international trade, production, and consumption patterns.

Various strategies are implemented to reduce the amount of salt necessary to treat highways, such as brining (Salminen, Nystén, and Tuominen 2011), intelligent snowplows and spreaders that disperse salt according to road temperatures (Transportation Research Board, National Academies of Sciences, and Medicine 2013), proper training and education for snowplow operators (Fortin and Dindorf 2012), and innovative design strategies to decrease the need for salt for deicing (Fortin and Simonson 2023). Alternatively, there are reactive mitigation strategies to address stormwater management strategies. Researchers have conducted more intensive interventions such as reverse osmosis (Fitch, Craver, and Smith 2006), "enhanced roadside drainage systems" (Trenouth, Gharabaghi, and Farghaly 2018), and distilling ponds (Hayes et al. 1996). However, many of these options are not accessible or affordable for most government transportation organizations and municipalities across the United States. A relatively new low-impact development intervention, biochar amendment in roadside soils, has properties such as cost-effective production, long-term benefits, low maintenance, and versatility that could be more accessible and affordable than other options.

Research in recent years has shown that biochar is a promising soil amendment for roadside drainage design that offers several benefits for mitigating road salt impacts and managing stormwater runoff (Imhoff and Nakhli 2017; Kim et al. 2021). Biochar is "a carbon-containing material prepared through thermal treatment of biomass in a limited supply of oxygen and used for an array of applications including waste management, climate change mitigation, soil fertility improvement, bio-energy production, and contaminant remediation" (Abhishek et al. 2023). The carbon structure, large surface area, and high pore structure of biochar have made it a worthy candidate in numerous studies that target stormwater management issues and salt-affected soil remediation. A study conducted under the management of the Transportation Research Board by Imhoff et al. concluded that biochar amended into roadside soils increased the effective saturated hydraulic conductivity of the soils with low initial hydraulic conductivity and infiltration (2021). They also found that in field experiments, hydraulic conductivity increased by 31% in sandy loam soils and 9177% in silt loam soils (2021). The performance of biochar for stormwater infiltration varied based on the type of biomass used to create the product. Biomass is defined as “any material from a biological source” (U.S. Biochar Initiative 2023). This includes crop residues, non-commercial wood and wood waste, manure, solid waste, non-food energy crops, construction scraps, yard trimmings, methane digester residues, and grasses.

Biochar has also been observed capturing constituents in highway stormwater runoff. Research done by the University of North Carolina at Charlotte found, in several studies, that soil columns amended with biochar increased the capture of common highway stormwater runoff contaminants more effectively than the soil-only column (Rice-Boayue et al. 2023). However, the effectiveness of removing specific types of contaminants varied between biochar derived from different types of biomasses. The study by Rice-Boayue et al. suggests an ideal type of biomass for creating biochar that may be ideal for mitigating chloride (Rice-Boayue et al. 2023). Wang et al. reviewed and synthesized multiple studies on biochar's ability to reduce salinity in salt-affected soils without altering the soil's pH. The research found that biochar "has a strong adsorption capacity which enables it to effectively adsorb and immobilize soil salts on its surface or within its pores" (Wang et al. 2024), helping to reduce the salt concentration below the soil surface, allowing more favorable conditions for plant growth. Biochar can also enhance the root vigor of plants in salt-affected soils when used as an amendment under certain conditions, improving plant growth (Saifullah et al. 2018).

The Federal Highway Administration (FWHA) and the Department of Transportation (DOT) have existing BMPs (best management practices) that they implement to address excessive stormwater runoff and minimize impacts from roadway constituents that stormwater carries into receiving waters. These state and federal organizations also contain referenced standards for constructing and implementing roadsides, most often adhering to the guidelines set forth by the American Association of State Highway and Transportation Officials (AASHTO). The U.S. DOT is "committed to using all of its authorities to substantially reduce greenhouse gas emissions and transportation-related pollution” (U.S. Department of Transportation 2024). Researchers can contribute to these goals by implementing strategic and intelligent systems to produce and use biochar as a soil amendment in roadside soils, thereby achieving carbon sequestration, renewable energy generation, and biomass waste management (Roberts et al.

2009). Additionally, biochar amendment is estimated to be more cost-effective than an array of other BMPs for stormwater management (Imhoff and Nakhli 2017; Imhoff et al. 2021). Biochar-amended roadside soils may have the capacity to contribute to AASHTO design goals of accommodating excessive stormwater runoff and protecting roadside soils from excessive erosion (AASHTO 2011). Biochar can help vegetation establish healthy and vigorous root systems in roadside areas where it otherwise could not be due to the effects of contaminated stormwater runoff and the salinization of roadside soils by road salts (Ouedraogo, Yuzhu Fu, and Yunus 2023; Lee et al. 2022).

Roadside vegetation selection also plays a role in the effectiveness of biochar and contributes greatly to optimizing stormwater management, pollution control, and aesthetics of the public right of way. Establishing roadside vegetation is crucial to ensure a stable and safe road shoulder and drainage design that prevents excessive erosion. Research shows that increasing native species and biodiversity on roadsides creates a more resilient and adaptable design (Armstrong et al. 2017). Choosing plants like native warm-season grasses and other native flowering perennials leads to more biodiversity and visual interest and increased roadside stability. Additionally, implementing halophytes, plants adapted to thrive in saline environments can contribute to the desalinization of roadside soils and the reduction of chloride concentrations through chloride uptake and storage (Bazihizina et al. 2024; Shabala and Mackay 2011). Ultimately, the implementation of biochar as an amendment in roadside soils must consider all factors that contribute to its effectiveness for stormwater management and road salt mitigation, including informed plant selection and strategic planting design, while also considering social and economic aspects that facilitate the process of implementation and ongoing management.

This thesis explored the existing research on integrating biochar into roadside soils through a multi-method approach, utilizing a comprehensive review of relevant literature and an in-depth analysis of field studies, lab experiments, and pilot-scale projects. By examining a diverse range of research methods, this study aims to provide a comprehensive understanding of biochar's potential to mitigate the negative effects of road salts on the environment. Additionally, this thesis develops recommendations for government agencies to implement biochar in roadside soils to improve stormwater management and address road salt pollution. The goal of this research was to design an environment where native roadside vegetation may survive, and stormwater can be filtered and infiltrated more efficiently to reduce harmful chloride concentrations that are polluting surface and ground waters. Furthermore, this research identified planting design strategies and potential species that may assist in the effectiveness of biochar as a roadside amendment.

This thesis identifies roadside interventions for typical highway cross-sections with vegetated shoulders. Therefore, the primary focus of this research is on priority 2-lane and 4-lane state and interstate highway systems with vegetated shoulders in salt belt states of the United States. This research does not attempt to change walled highways or roadway drainage pathways that lead to public sewer systems. Rather, it enhances existing infrastructures through biochar amendment and planting design.

To formulate recommendations, this study investigated the following questions:

1) What are the ecological and economic implications of using biochar for road salt mitigation compared to existing strategies?
2) What biochar properties best mitigate road salt and enhance stormwater management, and which feedstock types promote these properties?

3) How can biochar be integrated into current roadside design and management practices to maximize its effectiveness and sustainability?

The recommendations developed are design guidelines for integrating biochar into standard roadside design with guidance from standards set by AASHTO, FHWA, and other government agencies. Additionally, sustainable practices for the procurement and integration of biochar for the use of road construction will be explored, and suggestions for ongoing monitoring and maintenance will be made.

# CHAPTER 2

# LITERATURE REVIEW

This literature review explores the environmental challenges of road salt and biochar's potential as a sustainable solution. It details the widespread use of sodium chloride (NaCl) for deicing in North America and its negative impacts on ecosystems, such as affecting freshwater species, polluting drinking water, and reducing soil permeability (Casey et al. 2014). The chapter discusses how chloride runoff from stormwater leads to elevated levels in urban streams, surpassing safety guidelines for aquatic life. The affordability and effectiveness of NaCl pose challenges to finding replacements. The chapter then transitions to an in-depth examination of biochar, a promising sustainable soil amendment for mitigating road salt impacts and managing stormwater runoff. This review considers other aspects of the roadside landscape, such as vegetation species and planting design, that contribute to the effectiveness and attractiveness of roadside stormwater management interventions and may even facilitate greater benefits with the support of biochar amendments. The chapter concludes by discussing the logistics, sustainability, and maintenance of biochar application in roadside soils, emphasizing the need for a comprehensive approach to ensure long-term effectiveness and environmental benefits.

## 2.1 INTRODUCTION TO ROAD SALT

Over the past few decades, the United States has seen a steady increase in the use of chloride roadway deicers for winter road maintenance. Chloride-based salts, most prominently sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$), are the most common road-freezing depressants (Transportation Research Board, National Academies of Sciences, and Medicine 2013). Rock salt is formed when water evaporates and salts that are dissolved in the water form crystals. Salt deposits can be found near the sea in salt pans where seawater has evaporated or in salt mines where ancient seas or oceans once were. In the entire world market in 2010 the United States had the second-highest production and reserves of salt in the world (Feldman 2011). In the United States, the states of New York and Ohio contain some of the largest producers and distributors of rock salt (Fortune Business Insights 2023). In 2023, the salt consumption market in the U.S. was dominated by salt used for de-icing measures (Fortune Business Insights 2023). The harvesting and production of salt, especially for de-icing purposes, may have reduced in total over time due to innovative solutions to reducing salt consumption, but the market is not showing a trending reduction in demand because NaCl is still the most affordable de-icing material available in most applications (Kelting and Laxon 2010).

Chloride is the negatively charged ion that is the main component of many different types of salt. The term chloride refers to a molecular compound containing a chlorine ion, a negatively charged chlorine atom. Sodium Chloride (NaCl) consists of Na cations and Cl anions at a 1:1 ratio. Commercially produced NaCl can be formed into crystals of various size ranges; it can be fine granular powder, compressed pellets, or blocks (Feldman 2011). Salt is soluble in polar solvents, such as water.

Standard recommendations for salt used for road deicing in the United States have been specified by the American Association of State Highway Transportation Officials and the American Society of Testing and Materials (AASHTO 2003; American Society of Testing Materials 2020). Rock salt recommended for road deicing measures is typically designated by type and grade. Type refers to the original source of the rock salt and whether it is a type that is appropriate for pavement deicing measures. Type 1 salt is most regularly used for deicing procedures. Gradation of rock salt refers to the particle size distribution or the range of particle sizes present in a sample of rock salt. There are two common grades that are classified by ASTM: standard and special grading. Standard-grade rock salt is most often used in the United States, especially for road deicing (Minsk et al. 2006).

When road salt interacts with water or ice within a specific temperature range, its physical properties change (Fortin and Dindorf 2012). According to Beck et. al, water ($H_2O$) consists of hydrogen and oxygen, with oxygen accounting for approximately nine-tenths of the molecule's mass (2020). Water remains in a liquid state between 0 °C and 100 °C and solidifies into ice when the temperature drops below 0 °C. Regardless of its state, $H_2O$ exhibits polarity. This means that part of the molecule, specifically the oxygen atom, is negatively charged due to the high density of electrons, and the hydrogen atoms are positively charged. The addition of salt to $H_2O$ lowers the freezing point of the solution. This interaction takes place because NaCl is an ionic compound. Ionic bonds are formed when one atom donates an electron to another. In the case of NaCl, sodium (Na) gives an electron to chloride (Cl) and creates a highly electronegative bond. When NaCl is introduced to water, electropositive sodium is attracted to the electronegative oxygen of water, while the electronegative chlorine of NaCl is attracted to the electropositive hydrogen of water. These attractions set up a competing push-and-pull effect, straining the ionic and covalent bonds within the solution. However, $H_2O$ has a stronger covalent bond and pulls apart the NaCl molecules, creating separated $Na^+$ and $Cl^-$ ions that move freely within the water (Beck 2020). Consequently, the salt is fully dissolved, creating brine, which is distinct from saltwater due to its higher concentration. The saltwater solution created by the ice and salt drains from the road into adjacent stormwater systems such as roadside vegetated strips, swales, or drainage pipes, leaving the road ice-free and increasing traction for vehicles using the road.

There are two main strategies for the application of road salt to roadway pavements. These consist of anti-icing (proactive and preventative) strategies and deicing (reactive) strategies. Anti-icing is the action of applying freezing-point depressants onto highway pavements at the start of winter storms or prior to the beginning of precipitation with the goal of inhibiting the development of bonds between snow, ice, and the pavement. Application is often continued at intervals throughout a storm to maintain a safe surface (Minsk et al. 2006). On the other hand, deicing commonly takes place after plowing the roads when snow has accumulated over an inch in depth. This usually requires greater quantities of salt to be distributed along the roadways to break up packed snow and reach the pavements. This action works to weaken the bond between the snow, ice, and the pavement surface enough to allow for it to be plowed off the roadway (Fortin and Dindorf 2012).

Rock salt and NaCl brine solutions are the most affordable and accessible roadway anti-icing or deicing products. However, NaCl isn't recommended for use on pavements in every case because it is ineffective when pavement temperatures are below -12° Celsius (National Research Council 1991). When pavement temperatures drop below NaCl's eutectic point, municipalities often switch to sanding for traction or a calcium chloride ($CaCl_2$) mixture, which has a higher tolerance to freezing but is more costly (Minsk et al. 2006). The theoretical amount of road salt needed to deice roadways is usually higher than the actual amount necessary to be effective. Indirect interactions, such as when salt and melted ice create a brine solution that drains across the road or when vehicular traffic carries and disperses the salt mixture down the road, spreading it to untreated roadway areas, can reduce the amount of road salt dispersal needed if strategically dispersed to benefit from these factors (Fortin and Dindorf 2012; Feldman 2011).

To ensure the effectiveness of road salt, municipalities must consider other factors that diminish the quality of road salt. The threats to the quality of road salt often arise in the transport and storage of the product because of its exposure to humidity and other elements that can change its physical attributes, creating less than ideal consistencies for the most efficient dispersal for deicing procedures. Precautionary and often mandatory storage procedures for road salt can avoid many of the negative effects that can take place while road salt is in storage. Highway agencies ideally will store road salt on impervious pads, in leakproof shelters such as special loading barns or silos that allow gravity loading (National Research Council 1991).

NaCl tends to clump or "cake" when exposed to high enough humidity levels. Caking occurs when individual salt crystals adsorb enough moisture in storage to form brine on the surface of salt crystals. When humidity drops again to a lower percentage, evaporation of adsorbed water causes recrystallization, which often results in strong bonds between crystals, causing bridging of salt crystals and caking (Feldman 2011). To combat this, additives are often combined with road salt supplies that counteract the effects of humidity.

Additives added to road salt vary based on the manufacturer and serve a variety of purposes. The most common additive that is found in road salt for anti-caking purposes is iron-cyanide compounds (Transportation Research Board, National Academies of Sciences, and Medicine 2013). Novotny et al. expand on the impacts of anti-caking additives, "these complex cyanide compounds can degrade in snowmelt and /or receiving waters and become toxic free cyanide (1999). The quantity of cyanide, although small (approximately 0.01% by dry weight in salt), can be viewed as a water quality problem in waterbodies receiving large flows of salt-induced snowmelt runoff without sufficient dilution" Novotny et al. (1999). Additionally, manufacturers will often blend deicing and anti-icing materials with phosphates, amines, and organic matter from biomass (OMB) to inhibit the corrosive properties of chloride to preserve infrastructure longer (Transportation Research Board, National Academies of Sciences, and Medicine 2013). In some cases, the use of road salt for highway management has caused collisions by inviting wildlife onto the road who are attracted by the taste of NaCl and other salt-based products. Researchers have conducted studies in which additives were put into road salts and repellents were sprayed on roadsides to limit vehicle collisions with wildlife (Casey et al. 2014). However, researchers in Canada suggest that it is pools of salty water on the roadside that form during storm events have been found to be the most significant attractor for wildlife to roads (Mathieu et al. 2007). Mathieu et al. imply that addressing the management of stormwater to avoid pooling could influence a reduction of wildlife-vehicle collisions. They also suggest that removing or managing visually obstructing roadside vegetation may influence a reduction in wildlife-vehicle collisions.

The application of road salts to highways in the United States has many benefits for the safety and efficiency of its drivers. In summary, the practices of salting roads, despite the benefits, come with major impacts and long-term damage to a variety of environmental and socio-economic factors.

## 2.2 IMPACTS OF ROAD SALT

Dispersal of chloride into the environment cannot solely be attributed to the spreading of salts for roadway safety management. Other factors, such as the storage and transport of road salts (Casey et al. 2014), wastewater effluent (Kyser, Section, and Doucette 2018), and agricultural practices (Lee et al. 2022), have significant impacts on the salinization of freshwater and soils in the natural environment. While studies that concern other sources of excess chloride in the natural environment have been explored for the analysis of chloride's interactions and impacts, the research undertaken in this thesis aims to expand the understanding of chloride and other environmental constituents entering ecosystems at unsustainable rates due to the application of road salts. These influxes of salts in the environment have expansive implications, adversely affecting fundamental natural processes on the planet. Addressing these challenges is crucial for the resilience of humanity and the natural environment.

Pollution attributed to road salts begins as soon as its components leave the roadway. Stormwater runoff is a large contributor to the movement of road salts and other roadway constituents (Masoner et al. 2019). The hydrologic cycle involves various processes that contribute to the journey of water before it returns to water bodies. It begins when water evaporates from oceans, lakes, and rivers and leaves behind things such as salts, minerals, and pollutants in the water bodies, transporting just $H_2O$. The water then condenses into clouds and eventually precipitates as rain or snow back onto the Earth's surface. Once on the surface, hydrogen bonding of water causes it to form into pools or streams as it follows the path of least resistance influenced by gravity towards the lowest point. While water traverses the land, it picks up various constituents, sediments, and biota that often become suspended in the solution. These suspended particles can often be referred to as total suspended solids (TSS). TSS is an important water quality parameter for assessing water solutions' quality from drainage paths, streams, lakes, or oceans (Clary et al. 2020). TSS is a generic term that contains various forms of constituents that may behave differently from each other when water is introduced. Trenouth et al. explain how "road runoff in seasonally cold climates frequently carries within it a substantial physicochemical pollutant burden containing not only the aforementioned total suspended sediments (TSS) and [polycyclic aromatic hydrocarbons] PAHs, but road salt (NaCl), nutrients such as total phosphorus and total Kjeldahl nitrogen, petroleum hydrocarbons and heavy metals, including Cr, Co, Cu, Ni, Zn and Pb, amongst others" (2018). Despite a few of these suspended solids in stormwater carrying necessary nutrients to maintain healthy water bodies and soil, like phosphorus and nitrogen, the problem that often arises is an excessive number of organic constituents that are more than the natural environment can handle. Clary et al. state that an excess of phosphorus in aquatic environments can result in deprivation of oxygen for some organisms, despite phosphorus being beneficial for the growth of aquatic plants and algae (2020).

While road salt is primarily applied during winter to manage snow and ice on the roads, the largest environmental impacts observed from road salts occur during snowmelt events in spring (Driscoll, Shelley, and Strecker 1990). The impacts of the "first flush" event are greater than other winter storm events in most cases because of what Vladimir et al. describe as "enrichment" (1999). Enrichment is a chemical process occurring in the snowpack whereby, during repeated freezing and melting, ions are rejected from the crystalline lattice (snowflake structure) of snow and become available for wash off during the first stage of snowmelt" (Novotny et al. 1999: Ch 1 Pg 4). As there are ongoing winter maintenance snowplowing procedures, snow is piled along the sides of highways and stored there until snowmelt occurs. The snow becomes densely packed from the weight of more snow or freeze and thaw cycles. As road salts melt the ice and snow piles, meltwater runs off into adjacent snow piles. Through this process, roadside snow piles accumulate additional constituents suspended in the meltwater as it re-freezes into roadside snow piles, thus increasing the concentration of dissolved metals in snowmelt (Bäckström et al. 2004). Many of these pollutants remain on the roadside throughout winter until there is a significant temperature change and "first flush" snowmelt event. For this reason, meltwater is considered stormwater water in the context of this thesis.

Road salts often wash into nearby water bodies as a nonpoint source of pollution. The Priority Substances List Assessment Report performed by Environment Canada says, "All chloride ions that enter the soil and groundwater can ultimately be expected to reach surface water; it may take from a few years to several decades or more for steady-state groundwater concentrations to be reached." (2001: 1). Environment Canada is specifically concerned about the impacts of road salts on watercourses that drain urbanized areas as well as streams, wetlands, or lakes that drain major roadways. These types of water bodies have been found to have high levels of chloride far into the months following winter road salt application, well into summer (Cooper, Mayer, and Faulkner 2014), (Corsi et al. 2015), (Kaushal et al. 2005). This suggests that chloride ions are being stored in soils, groundwater, and surface waters, moving slowly and releasing further into the environment throughout the year. These processes often cause salinity levels to remain over freshwater threshold concentrations stated by the EPA for extended periods, posing a threat to aquatic and terrestrial biota as well as drinking water resources in groundwater (Jackson and Jobbágy 2005). The Minnesota Pollution Control Agency found that 50 waterbodies in the state exceed the water quality standards, and an additional 75 water bodies have chloride levels that are nearing the standard (Minnesota Pollution Control Agency 2023). Large concentrations of chloride and its facilitation of excess nutrients and metals in waterbodies can cause an array of issues for aquatic life and humans.

There are two levels of toxicity that coincide with chloride that affects aquatic organisms: acute and chronic toxicity. Acute toxic effects are associated with relatively elevated chloride concentrations and infer a more lethal environment for various species (Carmichael and Boyer 2016). Chronic toxicity occurs at lower concentrations and often has more indirect consequences, such as changes in the population or community structure of aquatic organisms (Baraza and Hasenmueller 2021) and disruption of the structure of aquatic food webs (Environment Canada and Health Canada 2001). Furthermore, heavily contaminated water is denser and sinks to the bottom of lakes and slow-moving streams, preventing seasonal water mixing. This creates anaerobic environments in which bottom-dwelling organisms cannot survive in (Environment Canada and Health Canada 2001). The aquatic conditions listed above have multiple negative side effects, including harmful algae blooms that can be toxic and lethal to humans and pets (Carmichael and Boyer 2016) and have to potential to provide less competition for invasive species by altering the reproductive tendencies of certain native species (Hintz and Relyea 2017).

The application of road salts also comes with negative economic impacts. MassDOT suggests that salinity changes to water supplies are a threat to cranberry marshes and maple syrup production in the state (Massachusetts Department of Transportation 2022). In a review of the effects and costs of road-deicing in Adirondack Park in New York, the authors estimated a potential 1% decline in ecosystem services provided by lakes and rivers and a 5% decline in ecosystem services provided by forested areas within 100 feet of roadways (Kelting and Laxon 2010). Based on model simulations, this could result in economic impacts of approximately $2,320 per lane mile, adding up to a cost of $37 million per year when estimated ecosystem service costs are applied to the 16,100 lane miles maintained by Massachusetts DOT (Massachusetts Department of Transportation 2022).

Reducing the toxicity of stormwater runoff containing road salts to avoid acute and, ideally, chronic toxicity in waterbodies connected to highway runoff water paths is the main goal of the research in this thesis. Researchers explored the factors that contribute to a growing and diverse problem identified as Freshwater Salinization Syndrome (FSS) (Kaushal et al. 2023). FSS refers to increases in salinity, alkalinity, ionic strength, major ions, hardness, pH, and temperature reported across a wide range of freshwaters around the world. FSS is a unique diagnosis that varies between regions and watersheds. However, FSS is characterized by a set of associated consequences or environmental symptoms that these areas share. The salinization of freshwater is just one of the symptoms of FSS, which involves a range of other changes attributed to fluctuations or causes of increased salinity, such as chemical changes in soils and changes in vegetation (Kaushal et al. 2023). Observing the impacts of road salt on the environment as a system with a range of contributing factors on a case-by-case basis is important to consider when developing mitigation strategies for road salts entering the environment. Different DOT standard practices, urban environments, and ecosystems are all factors that contribute to the salinization of freshwater and soils across the United States.

## 2.3 EXISTING SALT INFRASTRUCTURE AND MANAGEMENT PRACTICES

There are no federal regulations on road salt's direct application and distribution. However, the EPA does support state initiatives to mitigate environmental impacts caused by road salt through best management practices. The BMPs include setting application rates that reflect specific site characteristics, such as pavement temperature, traffic frequency and speed, and proximity to surface waters. The largest contributor to federal power over deicing procedures lies in The Clean Water Act. The Clean Water Act, however, still only targets point-source pollution discharges into surface waters and does not account for non-point water pollution and groundwater pollution, the two largest threats presented by chloride in road salt and roadway stormwater runoff (Cooper, Mayer, and Faulkner 2014).

### 2.3.1 Dispersal of Snow and Ice Materials

Most municipalities within the Salt Belt in the United States classify their roadways through a priority system for winter road maintenance practices. High-priority roadways in these states are commonly applied to the most highly traveled roadways in each state and are determined by average traffic loads and average speed of roadways (North Carolina Department of Transportation 2017; New York State Department of Transportation 2012; Rubin et al. 2022; Wisconsin Department of Transportation 2012; Massachusetts Department of Transportation 2022). Most of these roadways are interstate highways, including most four-lane and major two-lane roads.

Road salt application to the roadway is the most direct way that road salt is dispersed into the environment. The transportation and stockpiling of road salt at storage facilities is also a large indirect contributor to the rising amount of chloride in the natural environment when left unmanaged. "Unwanted releases of snow and ice control materials from storage facilities have contributed to road salts being placed on the Priority Substances List under the Canadian Environmental Protection Act (CEPA) (3)" (Transportation Research Board, National Academies of Sciences, and Medicine 2007: 13). Basic storage procedures include storing solid chemicals inside to prevent runoff of salts and caking, structures should be constructed on an impermeable pad and should have stormwater runoff management systems to contain or redirect contaminated runoff. However, some municipalities still have facilities without these preventative infrastructures. Unmanaged storage has been linked to complaints by homeowners of contaminated wells in Montana and Maine (Casey et al. 2014; Rubin et al. 2022). Other indirect paths of snow and ice control materials into the natural environment include dry salt that becomes powdered and is resuspended in the air by high-speed traffic and transported by wind. Additionally, liquified road salt is splashed, sprayed, or plowed to the roadside, significantly decreasing the survivability rate of roadside vegetation (Brown, Gorres, and Sawyer 2011).

### 2.3.2 Salt Spreading Procedures

Most municipalities encourage anti-icing as part of their snow and ice prevention on public roadways. While this often involves brining, it also includes the application of pre-wetted salt to the roadways. Pre-wetted salt differs from brine in that it is not dissolved into a liquid. Rather, the surface of salt granules is moistened to prevent salt loss from granules bouncing off the road during the application, saving up to 30% of the salt applied to the roadways (Rubin et al. 2022). The Maine Department of Transportation (MDOT), as well as various other DOTs (Massachusetts Department of Transportation 2022), have been reducing the number of brine applications because of the dependency on extremely accurate weather forecasts, special application equipment and infrastructure, lack of understanding by the general public, and additional labor and resources that are utilized before winter weather events (Rubin et al. 2022). While brine is often the most affordable product to purchase, the resources and attention required for the most effective application of brine may not be worth it for some municipalities. Pre-wetted salt also has initial investment costs for equipment needed for spreading; however, it has been shown to be more effective for anti-icing and contributes to a reduction in road salt dispersal into the environment by containing more road salt on road surfaces. MassDOT, for example, “plans to evaluate the feasibility, effectiveness, and potential impacts of using pretreated salt (salt with liquid deicer already applied) in key locations, especially in areas where space is limited for brine storage” (Massachusetts Department of

Transportation 2022: 24). According to MassDOT, pretreated salt avoids or minimizes the need for liquid storage as well as the added equipment such as saddle tanks to prewet salt at the time of application. However, data provided by material suppliers indicate that the liquids used to pretreat salt are often agricultural byproducts such as beet juice. The organic-based liquids can have a relatively high biological and chemical oxygen demand (BOD and COD) and nutrient content and thus, the sensitivity of downstream receiving waters to low dissolved oxygen issues must be considered" (Massachusetts Department of Transportation 2022: 24).

### 2.3.3 Existing Design Strategies for Road Salt Management

Fortin and Simonson have expressed in their article *Designing a Low Salt Future* in Roads & Bridges Magazine that reduction of the need for salt application through innovative and strategic design is the best way to reduce excess chloride into the environment (2023). Fortin and Simonson suggest in their article that maximizing pavement exposure to the sun to increase surface temperatures can significantly reduce the need for salt applications. Additionally, intentional meltwater control routes can reduce the amount of ice on roadways by preventing the re-freezing of meltwater as it crosses pavement surfaces (23-24). Despite advancements in snow and ice control technologies, road salts are still a major threat to the natural environment, and the increasing salinity of soils and freshwater must be addressed.

The primary focus of this research is on priority 2-lane and 4-lane state and interstate highway systems in salt belt states of the United States with vegetated shoulders. This research does not attempt to change walled highways or roadway drainage pathways that lead to public sewer systems. Rather, it enhances existing infrastructures through biochar amendment and planting design. In some cases, the urban roadside and road median design are created to manage stormwater through green infrastructure. Green infrastructure, such as stormwater retention boulevards or tree wells that treat runoff, should be considered as an existing management strategy for stormwater pollution reduction. Existing research indicates urban streams tend to have the highest chloride concentrations found in surface waters (U.S. Geological Survey 2009; Corsi et al. 2015) and that there is a correlation between the amount of impervious surface in a lake's watershed and the concentrations of chloride seen in the lake (Novotny, Murphy, and Stefan 2007). Efforts to reduce the application of road salt are necessary to contribute to a greater reduction of chloride pollution. In addition, the urban landscape and a handful of existing stormwater treatment infrastructures along roadsides can benefit from the amendment of biochar into the soils that are filtering stormwater runoff.

## 2.4 BIOCHAR

Chloride occurs naturally in the environment and is found in most freshwater sources. The increasing concentration of chloride in our freshwater sources is of the highest concern because of the negative impacts that come with it. Therefore, this research aims to explore opportunities to reduce the amount of chloride and other harmful constituents in road salts entering our water resources, and it aims to slow the trend of increased chloride in surface and groundwater. The first surface road salts encounter after leaving the paved roadway is usually soil. High concentrations of salts in soils can mobilize potentially toxic heavy metals, including lead, cadmium, and mercury, which are known to accumulate in terrestrial and aquatic food webs (Norrström and Jacks 1998; Bäckström et al. 2004; Schuler and Relyea 2018). Excess salts can also promote nitrate leaching (Green, Machin, and Cresser 2008; Kaushal et al. 2023), directly impacting water quality. In addition, sodium ions disperse clay particles within roadside soils, which blocks pore spaces and limits water infiltration (Frenkel, Goertzen, and Rhoades 1978;

Qadir and Schubert 2002). This decreases hydraulic conductivity and often leads to increased surface runoff, erosion, and anaerobic soils, making it difficult for roadside vegetation to survive and decreasing opportunity for treatment of roadway stormwater runoff before it reaches paths that will take it to surface waters.

While the infiltration of road salts into soils sounds counterintuitive to mitigation efforts, this research aims to slow, treat, and capture salt-laden stormwater runoff as close as possible to the source of the pollution, which in this case is the roadway. To facilitate these goals, the improvement of roadside soils must accomplish three tasks: promote infiltration and retention of stormwater runoff, promote survivability of native roadside vegetation, and capture dissolved road salts and other pollutants. Recent research has shown that biochar has the potential to accomplish all three of these goals if strategically incorporated into roadside soils.

Biochar is a carbon-rich material derived from the decomposition of biomass in the presence of heat. It is considered a "sustainable and environmentally friendly method for soil fertilization, a source of energy production, and a biofilter for stormwater treatment"(Ouedraogo, Yuzhu Fu, and Yunus 2023: 7). Biochar is most often produced through pyrolysis, burning biomass in low-oxygen or no-oxygen environments. This method ensures that the biomass is converted into stable carbon rather than ash. The resulting composition of the material produced from this process depends on the composition of the biomass used to create the biochar (Ouedraogo, Yuzhu Fu, and Yunus 2023). Although all biochar produced is composed of carbon in high quantity, hydrogen, nitrogen, and oxygen, the physical characteristics of biochar vary depending on the organic material it is derived from and the pyrolysis process used to create it. Biochar, in general, will appear black or dark gray and resemble charcoal. However, its texture and porosity differ depending on its production. Biochar can be powdery, granular, or in large chunks like hardwood mulch. All biochar is highly porous with a large surface area; however, as with the other characteristics, the pores differ depending on the biomass and production process (Rice-Boayue et al. 2023). Biochar can also be "activated" by treating the carbonaceous material with various chemicals, steam, and high temperatures to create a more porous and higher surface area biochar product (Leng et al. 2021). Biochar's manipulatable unique properties and structure offer excellent water treatment, soil enrichment, and carbon sequestration potential (Yaashikaa et al. 2020).

### 2.4.1 Stormwater Runoff Infiltration and Retention

High concentrations of Na in soil have been associated with higher concentrations of metals in groundwater (Jamshidi, Goodarzi, and Razmara 2020). This has been attributed to dissolved constituents in stormwater runoff, especially NaCl (Cooper, Mayer, and Faulkner 2014). When dissolved solids in stormwater infiltrate roadside soils, the cation exchange capacity of the soil is altered. Cation exchange capacity (CEC) is a measure of the soil's ability to hold and exchange cations (positively charged ions). The CEC of soil is changed when sodium ions (cations) from road salt replace other essential cations like calcium, magnesium, and potassium on soil particles. This reduces soil permeability because sodium ions cause soil particles to disperse and cause soil to lose structure. Additionally, dissolved metals and smaller suspended particles can clog smaller pores in soils, forcing water to infiltrate through larger pores. This leads to increased runoff and erosion and reduced structural integrity because of changes to soil electrical conductivity caused by road salts (Shannon et al. 2020).

While any exposure of road salts to the natural environment is detrimental to natural processes, constricting the distance chloride can move in stormwater has the most positive outcomes for the mitigation of chloride from road salts into the natural environment. The top layers of soil on earth act as a natural filter, absorbing and trapping constituents. Encouraging the infiltration of stormwater with the integration of biochar into roadside soils can heighten the filtration of stormwater as it percolates down through the soil (Minnesota Department of Transportation 2020). Infiltration of stormwater into the soil can recharge groundwater supplies. This process helps dilute constituents in the water by mixing stormwater with the existing groundwater, which typically has lower concentrations of constituents. The dilution effect, if stormwater is effectively filtered through the soil, reduces the overall concentration of pollutants that eventually reach surface waters (Fanelli, Prestegaard, and Palmer 2017). Increasing water retention and structural integrity of roadside soils can help decrease high concentrations of chloride and other constituents in surface and groundwater and decrease erosion and high velocities of water. Most importantly, increasing water residence time and soil water retention provides more opportunities for biochar and vegetation to filter stormwater runoff. Although some research suggests that the infiltration of highway runoff and green infrastructure may exacerbate the increasing pollution of groundwater drinking sources (Burgis et al. 2020), biochar amendment proves to be a potential strategy to mitigate these effects while promoting the infiltration and retention of stormwater runoff. Furthermore, biochar's CEC benefits may decrease with higher pyrolysis temperatures, but porosity increases (Rice-Boayue et al. 2023).

Due to its porous structure, biochar has been found to help lengthen water residency time in soils. The length of time road salt stays in surface soils before leaching into waterways depends on the time of soil water residence, soil characteristics, and hydrologic flow paths (Snodgrass et al. 2017; Shannon et al. 2020). "Retention in soils is an important factor in the delay between road salt application and the arrival of Na and Cl in shallow groundwater streams"(Robinson, Hasenmueller, and Chambers 2017: 84). Robinson et. al found that salt retention depended on soil type along roadway transects and that salt can slowly release over two and a half to five months following salt application (2017). While road salts being stored in roadside soils can be beneficial for reducing long-term concentrated exposure of road salts to freshwater resources, first-flush or flooding events can temporarily increase Na and Cl in large concentrations since stormwater runoff can transport much of the salts stored in soils to groundwater or surface waters (Granato 1996).

In lab and field experiments, Imhoff and Nakhli demonstrated that amending biochar into roadside soils can enhance stormwater retention and reduce stormwater runoff and peak flow rate (2017). One field test performed by Imhoff and Nakhli in a roadway filter strip along a four-lane divided highway in Delaware showed that the biochar amendment increased the ability of tilled roadway soil to reduce stormwater runoff volume and peak flow rate by ~50% (2017). Additionally, the study compared the area needed to treat 1 acre of impervious surface for grass strips and biochar-amended soils. They found that biochar-amended soils only need 0.12 acres to treat stormwater runoff with approximately 83% removal of unwanted nutrients and sediments. In contrast, grass buffers needed 3.7 acres for the same treatment results, showing that "biochar-amended soils are possible in many roadway applications where grass buffers are not" (Imhoff and Nakhli 2017: 41). When Lee et. al tested biochar's ability to manage soil salts and water, they found that the initial application of biochar exacerbates the salinization of soils, however, after several irrigation-evaporation cycles they found the biochar enhanced movement of salts through intensified top accumulation by evaporation (2022). This resulted in the ability to remove the top two cm of soil, which contained high concentrations of salt, effectively de-salinizing the soil. Biochar was also found to counteract soil cracking by alleviating soil compaction (Lee et al. 2022).

### 2.4.2 Roadside Vegetation

Promoting plant growth and establishing native roadside vegetation is essential to the primary goals of remediating salt-affected soils caused by road salt application. The use of biochar as an amendment not only helps sequester carbon from the production of biochar, but its use in soil amendments is an effective strategy for $CO_2$ removal from the atmosphere by promoting plant growth (Kumar et al. 2022; Lehmann et al. 2021; Yaashikaa et al. 2020). Salt negatively impacts plants in two ways: High concentrations of salts in the soil make it harder for roots to extract water, and high concentrations of salts within the plant can be toxic. While salts on the outside of the roots have an immediate effect on cell growth and plant metabolism, toxic concentrations of salt inside the plant accumulate and affect plant function over time (Munns and Tester 2008). To mitigate these adverse effects of salt on plant health and soil structure, incorporating biochar into soil amendments offers a promising solution.

Biochar's ability to reduce stress on plants when amended into soils was attributed to its sorptive properties, as shown in a study performed by Thomas et al. exploring biochar's salt mitigation effects on two herbaceous plant species (2013). Mitigation of the impacts of plant stress was achieved through biochar by either reducing plants' exposure to stress agents (heavy metals and organic pollutants) or ameliorating their stress response. One of the contributors to stress in roadside vegetation is drought due to effects caused by road salt, which limits infiltration and water retention of soils (Shannon et al. 2020). Pine forest waste biochar was found to significantly increase vegetation survival rate when tested for drought tolerance in alkaline loamy sand soil. In a study by Artiola et al., bermudagrass in soils with 2% and 4% (mass content) application rates of biochar was found to survive at 50% and 100%, respectively, during water stress tests, while non-biochar amended soils had a 0% survival rate of bermudagrass (2012).

Promoting native perennial roadside vegetation has been found to be a more effective strategy in efforts to establish roadside vegetation. Brown et al. explored a variety of salt-tolerant grasses in Rhode Island to replace traditional mowed turfgrasses on highway roadsides (2011). They found that salt-tolerant grasses showed no improvement in survival over the grass varieties already in use. Suggesting that salt is not the primary cause of vegetation failure. However, they did find that perennial vegetation cover on test plots amended with biosolids remained above 50% throughout the two-year study period and beyond. Furthermore, Brown et al. found that the seed mix used by Rhode Island DOT did not persist on the roadside but rather was replaced by native or naturalized species (2011). The use of native and naturalized roadside vegetation is important to maintain native ecosystems and to provide maximum benefit to native flora and fauna where possible. In fact, the Surface Transportation and Uniform Relocation Assistance Act of 1987 mandates that at least one-quarter of one percent of the funds spent on landscaping projects on the federal-aid highway system be used to plant native wildflowers and grasses (United States Congress 1987). Additionally, AASHTO guidelines recommend that the "continuous effort in developing vegetation and improving soil conservation methods should be actively promoted to provide assurance that the best methods of preventing erosion are being used" (AASHTO 2007: 10.2.1.3).

The effectiveness of biochar in removing pollutants from soil and promoting the growth of roadside vegetation is affected by the soil type in which it is amended and the biomass used to produce the biochar. Liu et al. explored the application of biochar in remediating salt-affected soils and suggested that "biochar amendments could show better performance in promoting plant growth in salt-affected soils more than the all-soil types" (Liu et al. 2023: 10). Recommending using biochar types with high cation-exchange capacity (CEC), high porosity and surface area, and an alkaline pH to neutralize acidic soils. High CEC is generally considered beneficial for K, Mg, and Ca cycling, which is beneficial for vegetative growth (He et al. 2021). One positive response found in a meta-analysis concerning the effects biochar amendment had on plant growth was a 29.3% increase in plant yield in any case of biochar properties or soil conditions (Liu et al. 2023). This suggests that, in most cases, the addition of biochar to salt-affected soils will yield positive results. However, the potential negative effects of biochar in salt-affected soils need to be considered. The uncertainties and potential environmental risks, if not properly executed, warrant further study and evaluation. The potential for biochar to exacerbate salt in soils and groundwater depends on a complex interaction of factors. Research by Wang et al. indicated that biochar produced from manure feedstock has the potential to exacerbate salinity in soils rather than remediate it because of the initial high salt content in the feedstock (Wang et al. 2024). Therefore, careful selection of feedstock, consideration of initial soil conditions, and understanding the long-term behavior of biochar in the soil are essential to avoid unintended consequences.

Other impacts of road salt on vegetation arise when salt becomes airborne and drifts to adjacent vegetation, landing on leaves and impacting chemical balances or photosynthesis processes. Salt becomes airborne when high-speed traffic re-suspends material after it dries to powder on the roadway (2011). The use of native and naturalized roadside vegetation is important to maintain native ecosystems and to provide maximum benefit to native flora and fauna where possible. Additionally, salt may be sprayed off the roadway during application or splashed from the roadway by traffic (Casey et al. 2014). These issues cannot be addressed through the use of biochar but can be addressed through strategies such as brining or prewetting salt crystals prior to contact with the road (Minnesota Department of Transportation 2020). The presence of large vegetation adjacent to the road has an important influence on the airborne pollutants that escape from a highway site. Trees and shrubs can trap airborne pollutants and retain them on the leaf surfaces until precipitation washes the deposits off onto the ground (Driscoll, Shelley, and Strecker 1990). So even though any contact of roadway constituents and road salt with plants is negative for plant health, there are positive benefits to maintaining and promoting the survivability of roadside vegetation when considering the benefits of mitigating constituents attributed to highway activities.

**2.4.3 Mitigation of Road Salts and Other Pollutants**

Ultimately, the goal of this research is to explore strategies that state DOTs can implement to mitigate the impacts of road salts on the natural environment. Biochar has offered the most promising solution by showing in multiple studies its potential to filter stormwater, capture heavy metals, increase water retention capacity in soils, sequester carbon, and increase infiltration (Rice-Boayue et al. 2023; Murtaza et al. 2021; Razzaghi, Obour, and Arthur 2020; Liu et al. 2023). Biochar has been found to have an effect on the retention and fate of other pollutants in stormwater as well. Stormwater can carry up to 600 pollutants, mainly from vehicle-related sources (Eriksson et al. 2007). A handful of studies have been performed by various researchers over time to examine biochar's ability to capture some of these pollutants. Biochar's structure greatly influences its ability to remove suspended solids. One study found an average of 89% of suspended solids through adsorption (Ouedraogo, Yuzhu Fu, and Yunus 2023). Nitrogen is a major component to plant growth but can build to excessive levels on roadsides. It has been found to be retained in biochar very effectively with biochar that is produced at lower temperatures (less than 600 °C) (Minnesota Pollution Control Agency 2024). One study observed an 86% improvement in total nitrogen removal and at least a 68% improvement in nitrate removal in biochar-amended biofilters compared to unamended ones from stormwater (Ulrich, Loehnert, and Higgins 2017). Biochar has also been found to contribute to metal retention from stormwater due to its physiochemical properties (Cruz et al. 2023). The large surface area and porous structure of biochar provide numerous sites for metal adsorption. Metal retention is executed through various mechanisms including biochar's negative surface charge attracting positively charged metal ions, cation exchange of biochar cations (like Ca and Mg) for metal cations present in stormwater, and complexation with organic matter (Huber et al. 2016). Additions of other organic amendments, like compost, may improve metal retention because of complexation. This has been found to be particularly effective for copper(Huber et al. 2016). Other heavy metals found to be captured by biochar under various conditions were Lead (Pb), Zinc (Zn), Cadmium (Cd), Arsenic (As), and Nickel (Ni) (Kumar et al. 2023). Additionally, biochar can capture various organic constituents including, PAHs (Reddy), trichloroethylene (TCE, a degreasing solvent) (Kumar et al. 2023), pharmaceuticals (including drugs and antibiotics)(Kumar et al. 2023), agrochemicals (including pesticides, insecticides, and fertilizers) (Murtaza et al. 2021), dyes (Kumar et al. 2023). While biochar has been shown to be effective at the capture and adsorption of many suspended stormwater vehicle-related contaminants, its ability to capture and store dissolved constituents through electrostatic interactions may not be effective for chloride capture.

When road salt dissolves in water, it is separated on an ionic level. This results in $Na^+$ and $Cl^-$ ions freely moving in the water solution. Biochar has shown promising results in vegetation and soil studies because its negatively charged surface can adsorb positively charged sodium ions (Na+) (Thomas et al. 2013; Saifullah et al. 2018). Additionally, biochar can exchange sodium ions with other cations like calcium, magnesium, and potassium present on its surface (Wang et al. 2024; Lee et al. 2022). Chloride (Cl-) is the negatively charged ion that is the main component of many different types of salt. The term chloride refers to a molecular compound containing a chlorine ion, a negatively charged chlorine atom. Soil treatment using biochar works far beyond the purpose of just mitigating road salts and has been found to be effective in multiple stormwater treatment applications (Minnesota Pollution Control Agency 2021). Therefore, tests for chloride in soil are often lumped into testing for an array of constituents in soils using specific conductance (Smith and Granato 1999). There is no extensive research into the capture of Cl- in soil using biochar specifically. However, the existing research into the positive remediating effects of biochar in saline soils is strong. The increase of roadside vegetation and the opportunities biochar presents for more dilution of saline stormwater runoff are huge components of the alleviation of chloride in freshwater systems (Kumar et al. 2022; AASHTO 2007: 10.2.2.2). Ongoing research must further explore biochar's capacity to adsorb Cl- to its surface and retain Cl- until removal is possible. Furthermore, research into biochar's contribution to roadside vegetation may have the capacity to absorb Cl- and hold it for extended downstream mitigation. Ongoing research at Loyola University in Chicago, Illinois, is showing promising results of the utilization of biochar in bioswales for chloride retention and capture, as well as research from Stockholm University in Sweden that explores wetland plants' capacity to decrease chloride concentrations in water (Michaels et al. 2024; Schück and Greger 2022).

## 2.5 APPLICATION OF BIOCHAR IN ROADSIDE SOILS

AASHTO is a standard-setting body for highway design and construction across the United States. The AASHTO Materials Standards provide detailed specifications for roadside soils, particularly soil classification and aggregate mixtures for highway construction purposes (AASHTO M 145), compaction requirements, material properties (gradation, plasticity, and strength), and erosion control measures. The properties of these specifications that biochar can affect are bulk density (BD) and Cation Exchange Capacity (CEC). BD affects soil compaction, root penetration, and water movement. ASSHTO recommends a BD range of 1.2 to 1.6 grams per cubic centimeter ($g/cm^3$)(AASHTO 2021). A low bulk density is correlated with a high porosity and implies an increase in water holding efficiency and a decrease in erosion (He et al. 2021). AASHTO recommends a CEC of 10 to 20 centimoles of charge per kilogram of soil (cmol/kg) (AASHTO 2021). This range typically allows soil to retain essential nutrients like calcium, magnesium, and potassium. Yuan et al. found through a meta-analysis that biochar significantly increased CEC in salt-affected soils by 21.1%, slightly higher than its CEC increase in non-salt-affected soils (20%) (2023). This implies that biochar may be even more effective for increasing CEC in salt-affected soils than in non-salt-affected soils. The balance between optimizing the function of biochar amendments and adhering to construction and safety standards for roadside soils is crucial to this research. With the addition of biochar to roadside soils, we must address the physical properties that change in the soil as well, such as stability.

AASHTO standards require a “clear zone” in most highway designs. A clear zone, formally a Clear Recovery Zone (CRZ), is a term used to designate “the unobstructed, traversable area provided beyond the edge of the traveled way for the recovery of errant vehicles” (AASHTO 2018: Sect 4.6.1). The CRZ requires highly compacted soil for stability and stormwater management purposes. AASHTO recommends a 95% compaction rate, as determined by a Modified Proctor Test. This compaction is necessary to maintain the structural integrity of the roadside. However, it also leads to an impermeable surface in the CRZ, which is intensified by the addition of constituents carried by stormwater, especially road salts, which clog soil pores and further contribute to excessive stormwater runoff (Rice-Boayue et al. 2023). While proper drainage of roadways, especially high-speed highways, is a priority for the safety of drivers, State highway agencies are also encouraged by the EPA and the National Pollution Discharge Elimination Permit (NPDES) to infiltrate most stormwater runoff from highways into roadside soils (United States Congress 1972; Goenaga et al. 2023). Therefore, a goal for treating road salts and other constituents in stormwater runoff using biochar amendments is to find a balance between water retention, infiltration, and stability. This can be achieved by using biochar to increase the porosity and water retention of soil (Das et al. 2023; Goenaga et al. 2023; Imhoff et al. 2021). A soil with high porosity but low water retention may allow rapid infiltration but not retain enough water for plant growth (Das et al. 2023). Conversely, soil with high water retention but low hydraulic conductivity can easily become waterlogged and lead to potential excess runoff (Imhoff et al. 2021). What is important to note is that the impact biochar has on hydraulic conductivity in soils is complex and depends on factors such as soil type, biochar type, and compaction. Generally, biochar tends to increase hydraulic conductivity in fine-textured soils but may decrease it in coarse-textured soils like sand (Minnesota Pollution Control Agency 2024).

The addition of biochar to roadside soils poses further interventions than just biochar amendments in order to accomplish the goal of mitigating road salts from entering the natural environment. Das et al. performed column testing to examine whether the amendment of sand or expanded shale, clay, and slate aggregates (ESCS) could “increase infiltration despite compaction and if either of these amendments”, in addition to biochar, “provide other intended functions during extreme hydrological conditions, such as high-intensity rainfall and drought" (Das et al. 2023: 7). They found that ESCS-amended soil doubled the infiltration capacity and enhanced water retention in soil by 58%. In addition, ESCS provided additional benefits, such as higher pollutant removal capacity than sand. With 21% more metal content removal than the sand media filter. The large aggregate size of ESCS and its ability to withstand compaction offered more positive potentials for the effectiveness of biochar in roadside soils while maintaining the safety recommendations of the CRZ (Das et al. 2023). Additionally, in another study, fine and coarse aggregates were preferred amendments in soils where the density needed to be increased, and coarse aggregate amendment strategies produced the best balance between field compaction, hydraulic conductivity, and expected sinkage (Goenaga et al. 2023). Goenaga et al.'s study also found no significant effect in reducing relative compaction from 90-95% to 80-85%; rather, they found the influence of soaked soils to contribute the most to tire sinkage and the highest risk of a run-off-road crash (2023). They concluded that "when the surface is soaked, the potential for an increase in sinkage is proportional to the soil's clay content" (Goenaga et al. 2023: 9). These findings support the need for an individual approach to identify existing soil conditions when considering the amendment of biochar into roadside soils.

Recommended application rates of biochar in roadsides require further research on a case-by-case basis because of the extensive possible interactions that can take place between roadway stormwater runoff and the different types of biochar and soils in which they are tested. Imhoff et al. found positive results with a 4% (mass content) application rate when observing water retention in roadside soils with biochar (2017). Rosetti et al. found in column experiments that amending biochar 30% by volume may be suitable for roadside soils in typical storm events when evaluating effluent total dissolved nitrogen (TDN) concentrations with the goal of promoting infiltration, nitrogen removal, water retention, and re-vegetation of roadsides post-construction (2023).

Side slopes on roadsides are a determinant factor in the management of stormwater runoff, effective erosion control, maintenance costs, and the safety of drivers. Side slopes are defined as "the inclined surfaces adjacent to the traveled way of a road. These slopes are designed to manage water runoff, prevent erosion, and stabilize the road structure. They can be categorized as either embankments (raised slopes) or cuts (lowered slopes)" (Federal Highway Administration 2023). AASHTO defines road shoulders as "the portion of the roadway contiguous to the traveled way that accommodates stopped vehicles, emergency use, and provides lateral support of the subbase, base, and pavement. Shoulders may be paved (with concrete or asphalt) or unpaved (with aggregate or soil)" (AASHTO 2011: Chapt 7).

Slope and soil data are used in combination to approximate the stability of a slope's erosion potential (AASHTO 2018: 4.8.4). AASHTO recommends a slope of 6-8 percent for turf shoulders, stressing that turf shoulders are subject to buildup that may inhibit proper drainage of the traveled way if adequate cross slope is not provided (AASHTO 2018: 4.4.3-4.4.4). It is noted that drivers are often wary of stabilized or steep shoulders, especially on high-volume highways. Stabilization of shoulders and providing refuge space for vehicles during emergency situations are two factors that can lead to safer outcomes. Biochar has also been found to reduce erosion in some cases. Jien and Wang studied soil losses and erosion rates in biochar-amended and unamended soils in a simulated field condition experiment (2013). They found that the lowest soil losses occurred in the biochar-amended soils, and the erosion rate significantly decreased as biochar application increased. Their results indicate that biochar has a high potential for reducing erosion and improving soil structure (Jien and Wang 2013). Biochar achieves resistance to erosion by promoting the formation of stable soil aggregates, binding soil particles together, and increasing their resistance to erosion (He et al. 2021). The binding action is attributed to the physical structure of biochar as well as its chemical properties, acting as a nucleus for aggregate formation (Kim et al. 2021). Increased aggregation creates a more stable soil that is less susceptible to being dislodged and erosion.

The more infiltration a design can promote without water logging soil is ideal. This is more achievable with flatter side slopes to increase water residency time on the surface. The Federal Lands Highway Administration (FLHA) indicates that side slopes of 1V:10H (10%) are desirable along roadways over 45 mph (2018). The FLHA Project Development and Design Manual (PDDM) says to "design slopes to be as flat as is reasonable. Cut and fill slope design is a compromise between aesthetics, safety, stability, and economics. Generally, low cuts and fills are economical to construct on relatively flat slopes and will enhance aesthetics, safety, and maintenance"(2018: 9.5.2.3.1). However, other factors, such as weather conditions, safety standards, and site restrictions demand a balance between multiple requirements. In severe winter climates, AASHTO prefers channel side slopes of 1V:5H or 1V:6H to reduce snowdrifts (AASHTO 2018: 4.8.2). One recommended strategy to pursue slope flattening is benching. Benching is a method of breaking and controlling sheet flow on long, steep slopes through strategized grading (AASHTO 2007: 3.5.2.2). Ultimately, stormwater that does not have the ability to infiltrate will reach drainage channels. Drainage channels, which are open channels usually parallel to the roadway, function to collect surface runoff from the roadway. Drainage channels are designed, built, and maintained in consideration of the roadside environment. This involves factors such as soil types, average precipitation frequency and amount, and other environmental factors. The primary function of drainage channels is to convey stormwater to designated outlet points. However, drainage channels also present an opportunity to promote infiltration and stormwater treatment enhanced with biochar. This is more difficult to achieve on roadside drainage channels with abrupt slope changes. Concentrating biochar application on shoulders is preferred because it is the first area that stormwater interacts with after leaving the road and generally contains the flattest section of the roadside, which is more provides more opportunity for infiltration. Still, for drainage channels with gradual slope changes, there is an opportunity for the integration of biochar and native vegetation to be established in side slope and bioswale soils.

## 2.6 LOGISTICS, SUSTAINABILITY, AND MAINTENANCE

Biochar has become an attractive material to treat stormwater because of characteristics that it shares with other similar soil amendments and stormwater filtration solutions, such as activated carbon, sand, or biofilters (Das et al. 2023; Cruz et al. 2023; Flanagan et al. 2019). In addition to test results that indicate better performance for contaminants removal from stormwater than other materials, biochar has also been considered to have the highest probability for a sustainable solution for stormwater management (Ouedraogo, Yuzhu Fu, and Yunus 2023; Yuan et al. 2023). “The wide applicability of biochar and the economic management of waste circumvent take-make-waste approach, which enables re-incorporation of valuable waste into the agricultural systems, thereby promoting a circular economy, achieving net zero emission goals in the future by several nations, and principally playing a key role in sustainable development around the globe” (Kumar et al. 2023: 3). Often, biochar is approached with a Triple Bottom Line framework by researchers (Rice-Boayue et al. 2023). This framework expands on traditional reporting frameworks and considers social, environmental, and economic factors to identify the long-term impacts of our actions on society and the environment. This framework influences many recommendations for biochar use, including its production, transportation, application, and maintenance.

### 2.6.1 Logistics and Sustainability

One of the largest concerns with pursuing biochar as an amendment to roadside soils is the production and transportation of the material. Additionally, where to sustainably source the biomass from which the biochar is made. Two dilemmas present themselves when planning logistics and sustainability of the utilization of biochar in design. One of the sustainable frameworks of biochar is its ability to sequester carbon (Yaashikaa et al. 2020). It would be contradictory to release any significant amount of carbon emissions in the production and transportation of biochar and counterintuitive to the motives of this research, which is to increase the resilience of human and natural environments (Lehmann et al. 2021). Secondly, the procurement of biomass to produce biochar must be done in a sustainable manner as well.

Biomass is

Biomass must be harvested without causing deforestation, habitat destruction, or soil degradation. Additionally, unsustainable biomass collection could negate the benefits of biochar by releasing more carbon than sequestered (Lehmann et al. 2021). Common strategies to strive for sustainable biomass collection include using agricultural residues or forestry byproducts, which otherwise produce more greenhouse gas emissions from waste decomposition, and procuring biomass locally to support local economies and reduce travel distance (Sohi et al. 2009).

In order to achieve climate change mitigation benefits and be financially viable as a system, the use of local biomass to make biochar may be the best option for municipalities

(Roberts et al. 2009) The primary costs of biochar production are the feedstock collection and pyrolysis. The pyrolyzer, specifically, "consumes large amounts of energy and requires more skilled work force as compared to other stages"(Homagain et al. 2016). This leads to a large initial investment for the pyrolyzer as well as operating costs, accounting for 36% of the life-cycle cost in a study focused on wood-derived biochar in Northwestern Ontario, Canada (Homagain et al. 2016) The feedstock transport, biochar transport, and biochar application have smaller contributions to the overall cost. However, transportation distance can significantly affect the costs, suggesting biochar systems are most economically viable as distributed systems with low transportation requirements. After testing agricultural residues (corn stover), yard waste, and switchgrass, Roberts et al. concluded that of the three, waste biomass streams like yard waste are the best candidates for biomass collection and production of biochar (2009). Feedstocks with high lignin content (such as wood residues) have shown higher stability, an increase of moisture retention and nutrient capacity, and higher total carbon content when pyrolyzed at high temperatures (>500 °C) than other biochar feedstocks with non-lignin-derived materials (Dai et al. 2020; Zhang et al. 2022; Ulrich, Loehnert, and Higgins 2017). Economically, yard waste could offset costs by collection of yard waste tipping fees, while minimally altering current municipal practices and routines. Additionally, the collection of woody biomass yard waste for biochar production can stimulate the local economy, maintain net positive energy, and reduce GHG emissions by reducing travel distance (Franco and Page-Dumroese 2023; Roberts et al. 2009).

There are a handful of biochar production plants within the US. Each state has one to five biochar production facilities, with the exception of California, which has 15 locations identified by the US Biochar Initiative (US Biochar Initiative 2024). Therefore, many locations across the

US where biochar can be integrated into road construction need access to biochar material with significant transportation costs. We also need to take into consideration that each production facility may not have the type of biochar ideal for roadside soils. Creating a circular economy for the production and utilization of biochar is crucial to building a sustainable process for utilizing biochar along roadsides. Yaashikaa et al. discuss sustainable models for biochar production and suggest that "small-scale production systems can be connected with other systems creating closed system models so that waste from one process can be utilized as an input for the other with high social, economic and ecological outcomes in circular economy" (2020: 11).

An example of a closed system model is municipal workers collecting woody yard waste, like limbs, from private residences and public spaces. The waste biomass is then chipped or shredded with a woodchipper and pyrolyzed using a mobile biochar unit, like CharBoss (Rocky Mountain Research Station 2020), on-site or in a central location. Then, the product is transported directly to job sites for amendment into soil or storage facilities with weather-resistant storage. The application of biochar is then followed by soil testing and data collection to analyze performance and refine application techniques and schedules. Furthermore, a municipality may consider integrating renewable energy, like solar, to power production units. They may also seek local partnerships to collaborate with universities, research institutions, and private companies to improve application and production methods. Stockholm, Sweden is one of the best examples of cities that have enacted similar production strategies and city initiatives while striving for a carbon-neutral city. It is expected to bring in a revenue of 854,000 Euros once the program is fully complete and operational (Franco and Page-Dumroese 2023).

### 2.6.2 Stability of Biochar

The long-term stability of biochar is crucial to its ongoing function in roadside soils. "It is generally agreed that biochar increases aggregate stability and macroaggregate formation in soils" (Rice-Boayue et al. 2023: 74). The stability of biochar is the longevity and resistance to the decomposition of biochar in the ecosystem where it decays slowly and withstands biotic and abiotic degradation. Longer stability of biochar in soil means more carbon sequestration over time as well as longer intervals between maintenance or reapplication of biochar. Biochar has been shown to remain stable for a very long time period in soil (~1000 years) (Kumar et al. 2023). This is attributed to biochar's recalcitrance, which means its resistance to decomposition (Kumar et al. 2022). Biomass type does influence biochar recalcitrance. Biochar that has an aromatic structure has high resistance to microbial decomposition (Lehmann et al. 2021). While generally stable and resistant to decomposition, biochar's biomass feedstock, pyrolysis temperature, and soil conditions affect the longevity of biochar's integrity over time.

Over extended periods, biochar undergoes transformations in the soil, which influences its impact. Biochar physically breaks down during freeze-thaw cycles, wetting-drying cycles, and abrasion by soil particles. However, even when biochar is broken down, biochar particles can maintain their chemical stability and continue to contribute to soil health (Sohi et al. 2009). Biochar can also experience slow oxidation in the soil over long periods of time and experience different interactions with soil organisms depending on the conditions (He et al. 2021). Long-term monitoring and studies are necessary to further understand its stability in soils over long periods.

### 2.6.3 Maintenance

Since the stability of 80% of the carbon in biochar has been found to persist for up to 1000 years, it is difficult to determine the length of time that biochar amendments in roadside soils remain effective for stormwater filtration and pollutant capture (Roberts et al. 2009). Researchers have found that over time, dependent on the environmental conditions in which biochar is, the pores of biochar can become clogged with small particles and reduce the porosity and filtration of the product. Factors such as compaction, inappropriate biochar application, and pretreatment of biochar can impact performance if not carefully controlled (Ouedraogo, Yuzhu Fu, and Yunus 2023; Rice-Boayue et al. 2023; Leng et al. 2021). Maintenance of biochar amendments in roadside soils must include monitoring of functions through frequent stormwater runoff and soil testing. Although there has yet to be long-term monitoring of biochar amendments in roadside soils, research suggests that reapplication of biochar to roadsides is likely on the order of years rather than months or weeks (Minnesota Pollution Control Agency 2024). One study suggests scraping the top two centimeters of soil from the surface to address the observed capillary action of salts seemingly exacerbated by biochar (Lee et al. 2022). Capillary action is the process where water moves through the pores in the soil, similar to how water climbs up a paper towel. When soil contains salt, the water carries those salts with it, rising to the surface and leaving behind salty residue as it evaporates. The addition of biochar can help to create a plant-friendly salinity in the lower soil profile. Still, the top layer has the potential to accumulate salts and decrease the permeability of soil surfaces if not managed (Lee et al. 2022).

The US Biochar Initiative has some recommendations for single vs. repeated applications of biochar in agriculture, which can be used as a guide when approaching the creation of a maintenance regime for biochar amended into roadside soils. Because of biochar's stability and resistance to decomposition, single applications can provide beneficial effects over many seasons. So annual application is likely not necessary in most applications. Repeated or incremental applications can be made in most agricultural applications. However, roadside maintenance plans do not have many existing practices in which biochar can be efficiently distributed in tandem with existing practices. Rather, in perennial vegetative systems, like roadsides, applying biochar during planting ensures incorporation into the soil profile and within the root zone. For existing plantings, a municipality may decide to carry out repeated surface applications as decided based on close monitoring. However, it is best to mix with compost or fertilizer to reduce the risk of losing biochar (United States Biochar Initiative 2024).

Applying biochar as an amendment to soils rather than a top dressing ensures that the biochar is within the root zone, fostering healthier and more resilient vegetation. Roadside vegetation plays a key role in the performance and effectiveness of biochar amendments. Biochar contains many benefits that can be enhanced by innovative roadside planting design and vegetation species selection. A detailed and informed plan for the establishment of roadside vegetation is crucial to the effectiveness and resiliency of biochar amendments in roadside soils.

## 2.7 ROADSIDE VEGETATION

The establishment of roadside vegetation is a priority in almost every road construction project. This is crucial to maintain the structural integrity of the roadway and to prevent excessive erosion. It is generally preferable to allow for the natural reestablishment of vegetation after construction is complete (AASHTO 2007: Section 3.5.2.1). Maximizing natural regeneration is a viable option, but it is often not enough to fully revegetate a roadside environment. Passive revegetation from nearby native seed banks can be employed, but it is often not enough to fully revegetate a roadside environment (Armstrong et al. 2017). Additionally, the survival of species will decrease in harsher roadside environments like the targeted sites with high salinity and pollutant concentrations that suggested biochar application is intended for.

Biochar offers benefits for plant growth, such as enhanced soil structure, water retention, and mitigation of salt stress (Liu et al. 2023; Thomas et al. 2013). These are all factors that can increase the survivability of roadside vegetation (Dai et al. 2020). However, the amendment of biochar doesn't protect plants from salt spray and road salts are likely to cause germination inhibition, even in species that exhibit some salt tolerance as mature plants, making it a difficult process to establish new vegetation in areas of high road salt application (Brown, Gorres, and Sawyer 2011).

The establishment of roadside vegetation is usually carried out in phases by government roadway construction contractors. Phasing offers the opportunity for immediate erosion control while less expensive routes to establish vegetation are pursued, like seeding. This process usually begins with the establishment of annual ryegrass, which germinates quickly and provides rapid cover in the first growing season (Gover, Johnson, and Kuhns 2011). Ryegrass is considered a good option for temporary control while other long-term species are established. Establishing a weed-resistant environment is essential for the long-term success of roadside vegetation (Armstrong et al. 2017). It is common to have a cover crop such as ryegrass (*Lolium multiflorum*) or winter wheat (*Triticum aestivum*) for immediate stabilization (Gover, Johnson, and Kuhns 2011).

When choosing species to plant on the roadside it is crucial to gather specific site information. Addressing limiting factors like soil quality, drainage, and weed control is a huge factor in the success of vegetation. Native plants are preferred for roadside revegetation due to their ecological benefits and adaptability. Native vegetation also tends to be more resilient to harsh, salty conditions, even when compared to non-native highly salt-tolerant species (Brown, Gorres, and Sawyer 2011). The FHWA recommends "coordinating with botanist or specialist in the restoration of vegetation to select plant species and application rates of grasses and other plant seed that is native to or compatible with the area" when choosing species and processes for roadside vegetation establishment (Federal Lands Highway Administration 2018: Chapter 9). The plant selection process should always consider site-specific conditions, local adaptation, genetic diversity, and project objectives.

A promising option in most regions for roadside soils is native warm-season grasses (NWSG)(Gover, Johnson, and Kuhns 2011). NWSG are highly adaptable and grow most actively in summer months, establishing deep root systems that increase their resilience over winter months. Artiola et al. found that warm-season grasses can perform better in soils with extreme pH conditions with the addition of pine forest waste biochar because of their salinity tolerance (2012). NWSG have a slower establishment period than other roadside species options (three to four seasons) and requires intermediate-term species. NWSG has a clumping tendency and spreads through natural annual seed dispersal rather than rhizomatic spread like many grass species. It is important to consider FWHA and AASHTO recommendations for approaching each roadside vegetation project with a site-specific approach that can focus on species selection to optimize ecological, social, and economic function.

When choosing roadside species that meet the project objective to capture and mitigate road salt, it is essential to choose salt-tolerant species that will thrive. Halophytes are a type of species specifically adapted to thrive in saline environments, making them ideal for mitigating the adverse effects of road salts. Many halophytes act as hyperaccumulators, absorbing and storing significant quantities of salt ions ($Na+$ and $Cl-$) in their tissues (Hasanuzzaman et al.

2014). This effectively removes salt from the soil, reducing its concentration and mitigating effects on other plants and organisms (Armstrong et al. 2017; Brown, Gorres, and Sawyer 2011). Some halophytes possess mechanisms that prevent excessive salt uptake to minimize the impact on their physiological processes (Shabala and Mackay 2011). While this doesn't contribute to salt removal from the soil, it allows certain halophytes to survive and thrive in saline environments, contributing to increased vegetation cover, reduced erosion, and conditions more suitable for establishments of other species. Along with the benefits of phytoremediation and salt concentration reduction, there are challenges with halophytes that must be considered.

Seasonal variability of halophytes greatly changes the effectiveness of the species in roadside design. Most halophytes, just as most roadside vegetation, are dormant in the winter, when salt application is highest, limiting their effectiveness in capturing road salt in runoff (Hasanuzzaman et al. 2014). Some studies indicate biochar can hold road salts and chloride over winter until the growing season for halophytes to remediate the soils (Thomas et al. 2013). However, it should be noted that soil temperatures and other conditions can affect these processes. Often, halophytes don't have the opportunity to germinate early enough in the growing season to catch the increased salt concentrations in spring during snowmelt and first flush (Clary et al. 2020). Another consideration for the use of halophytes for the mitigation of roadside soils is the maintenance of plant matter, especially when phytoremediation is an objective. Halophytes only have the ability to store chloride and salts, so removal of halophyte vegetation is required seasonally if re-release of road salts back into the environment is to be avoided when halophyte species die back in winter. Unfortunately, harvesting and re-use of halophytes for the production of biochar is not ideal since the chloride and salts in the plant tissue remain in the biochar throughout production until released during biochar breakdown in soil amendments, exacerbating the concentrations of salts in the soil (Lee et al. 2018). However, halophytes can still be highly advantageous species to include in roadside planting design for road salt mitigation and soil conditioning to encourage increased growth opportunities for other species. "Salt excreter halophytes", such as Seaside Goldenrod and American Sea Rocket, uptake salt but do not store it. Rather, the salt is excreted onto their leaves to be dispersed by rain or wind. Excreters do not contribute much to the remediation of soils but can produce salt-hardy root systems and decrease salt concentrations in the soil (Renshaw 2021). The integration of halophytes into the species matrix of a roadside vegetation mix can be beneficial to the remediation of salt-affected soils and increase the performance of other surrounding species.

# CHAPTER 3

# METHODS

The objectives of this research were to identify what feedstock type and production strategy produces biochar that enhances stormwater management and road salt mitigation. Additionally, this research identifies an effective and sustainable biochar application procedure for roadsides. This thesis uses literature analysis to support design recommendations by exploring the existing research on the performance of biochar in roadside soils. Recommendations for government adjacencies to implement biochar in roadside shoulders were developed using the findings of this research and the preceding literature review. The goal of this research is to create an environment where native roadside vegetation persists, and stormwater can be filtered and infiltrated more efficiently to reduce harmful chloride concentrations that are likely polluting surface and ground waters.

## 3.1 DATA COLLECTION

Studies were selected from existing research that included field experiments with biochar in roadside or salinized soils. Some of the studies also performed laboratory experiments to cross-examine their studies using column and microcosm experiments (Imhoff et al. 2019; Imhoff and Nakhli 2017). Properties such as water retention and infiltration were prioritized, as well as studies that tested biochar's interaction with salts and stormwater pollutants like heavy metals. Research into biochar for roadside soils has been explored for stormwater management purposes, as well as research into biochar's use for the remediation of salt-affected soils. Few studies have been performed to identify the benefits of biochar for the purpose of mitigating the effects of road salt on the environment. Therefore, identified properties desired for salt mitigation are analyzed through various studies concerning biochar's effectiveness for those properties. Analysis and data collection of selected studies were performed through a highlighting and tagging process that was followed for each study. This process allows the user to categorize different parts of the literature based on themes and concepts, making it easier to find and reference specific information later. Through this process, patterns can be identified across multiple sources, and trends or gaps in the literature can be identified. Tags included were targeting materials used in the studies and the resulting effects of biochar in those studies compared to the set control factors in each experiment. Tags were chosen with the purpose of guiding the formulation of design recommendations. Included tags were Application Rate / Depth, Constituent Capture, Carbon Sequestration, Longevity, Pores / Surface Area, Pyrolysis Specs, Vegetation Type, and Water Retention. Taguette (n.d.), a free and open-source tool designed for qualitative research, was used for the tagging process. Taguette allows you to import your research materials, highlight and tag specific quotes or sections, and then export the results. With this tool, you can add new tags, select text, and assign tags to organize and analyze data effectively.

The tagged information was systematically evaluated against the findings from the broader literature review. Criteria for evaluation included consistency of recommendations across studies, report outcomes, and applicability to roadside conditions. This analysis enabled the synthesis of findings into design recommendations for biochar application rates and feedstock for biochar for roadside soils that receive runoff containing pollutants and road salts.

### 3.1.1 Limitations

It is acknowledged that the selection of studies may introduce bias and that the findings are limited to data available from the selected studies, which were not all performed under similar field conditions that reflect the same conditions of potential sites where biochar application may be considered. I controlled bias in the selection of these studies by choosing a diverse experimental scale that involves lab, pilot, and field studies. These studies also utilize various soil types and biochar sources, which allowed more informed and specific recommendations, reducing bias towards a particular soil type or biochar product. All the selected sources directly or indirectly acknowledge the importance of studying biochar's effect over time. The periods of monitorization range in these studies from several months to multiple years. Additionally, two studies provided cost-benefit analyses comparing biochar amendment to other BMPs (Imhoff and Nakhli 2017; Imhoff et al. 2021). Future research could expand the dataset to include a broader range of studies and conditions.

## 3.2 LITERATURE ANALYSIS

Studies included lab tests and field studies that examined biochar and its effects on soils. Studies have been chosen with the intention of determining recommendations for the application of biochar to roadside soils including factors such as application rate and depth, processes as to how biochar is amended into the soils (till, no-till, or premixed prior to soil application), and other factors such as biochar feedstock type, pyrolysis processes, and ongoing maintenance. Field experiments are pursued in most studies chosen for analysis since laboratory experiments provide informative suggestions for the application of biochar into soils but cannot simulate the varying stimuli field conditions often include. While lab experiments can provide valuable insights into the fundamental mechanisms and potential benefits of biochar, they often fail to fully capture the complex and dynamic conditions of real-world environments. Keeping in mind factors such as soil type, biochar properties, and pyrolysis conditions contribute to the variability of biochar performance in any application (He et al. 2021).

**Yoo, Kim, and Yoo (2020):**

This research paper explores the potential of biochar as a sustainable soil amendment for urban roadside trees, explicitly addressing the issue of water stress caused by frequent flooding and droughts. A greenhouse experiment using Ginko biloba saplings to investigate how biochar affects soil structure and plant growth under extreme water conditions. Despite this study not directly relating to biochar on roadside soils for constituent capture, it is one of a few studies that explore the behavior of biochar in urban roadside soils and not conducted in the agriculture and forestry sectors. The study highlights the importance of biochar in mitigating soil water stress and its potential to improve the overall health and resilience of urban roadside tree systems.

<u>Biochar Feedstock and Production</u>

Researchers used biochar produced from peanut shells and twigs. The feedstock was pyrolyzed at 200-300°C for 3 hours. Biochar was then sieved through a 2mm screen to homogenize it prior to being mixed with the soil. While this study doesn't specifically use wood-derived biochar, it highlights the positive impacts of biochar on soil structure, particularly under extreme conditions, which are relevant to roadside environments that experience fluctuations in moisture due to weather events and road salt application.

<u>Biochar Application and Amendment Process</u>

Biochar was applied at a rate of 2.5% by weight and mixed with sandy clay loam soils in pots. Researchers used a shovel to mix 0.6 kg of biochar with 25.46 kg of soil, for a total of

26.06 kg in each pot. Gingko saplings were planted in the pots after the soil and biochar were mixed and fertilizer was applied. The study found that biochar, each at a low application rate of 2%, significantly increased macroaggregates in the soil. However, the study also acknowledges that the impact of biochar on bulk density might become more apparent with longer-term experiments and higher application rates. This supports the recommendation to start with a 3-4% application rate in roadside soils, with adjustments based on site-specific conditions and monitoring data.  Soil samples were taken at a depth of 0-15cm for analysis. Specific depths of biochar application were not applicable in this study since biochar was amended with soil prior to filling the pots. However, the samples can be an indication of biochar behavior in this soil type at similar depths.

Monitoring Techniques

Researchers measured soil properties such as bulk density, pH, total nitrogen, and hot-water extractable carbon. Soil microbial activity was measured through CO2 flux measured weekly using the chamber method from Wang et al. (2011). Soil aggregate fractions were separated using a wet-sieving method and analyzed for carbon and nitrogen content. Potential plant growth was monitored by measuring total biomass, leaf number, shoot and root height, and plant carbon and nitrogen content. Researchers used a general linear model and linear regression analysis to analyze data. Researchers emphasized the importance of considering the actual soil water status rather than just relying on potential ranges like the least limiting water range (LLWR). They introduce the "% optimal water condition" as a more informative parameter for assessing soil health and plant growth. This highlights the need for robust monitoring strategies that track both soil moisture levels and plant responses to biochar amendments in roadside applications

Yoo et al. found the improved soil structure, water retention, and nutrient availability provided by biochar can create a more favorable environment for plant growth, even under challenging conditions. Supporting the recommendation to use biochar in conjunction with salt-tolerant vegetation to mitigate road salt impacts.

**Blanco-Canqui et al. (2020):**

This study investigates the long-term effects of biochar application on soil carbon sequestration and overall soil quality in agricultural settings. The study focuses on comparing two types of cropping systems: conventional no-till corn production and dedicated bioenergy crops, specifically switchgrass, and a low-diversity prairie grass mix, with and without biochar amendments. Although the research is focused on agricultural production and the production of bioenergy crops, perennial vegetation used in this study is a potential candidate for recommended roadside plantings. The key finding in this study is that biochar application resulted in a significant increase in soil carbon stocks, exceeding the amount directly added by biochar. The study also found that perennial bio-energy crops, especially the low-diversity grass mix, significantly improved soil physical properties, including aggregate stability, water retention, and plant available water, compared to conventional corn.

<u>Biochar Feedstock and Production</u>

Biochar was derived from mixed wood (Quercus, Ulmus, and Carya spp. woodchips) It was produced using an auger bed gasification process at 600°C. This feedstock demonstrated that this type of biochar led to significant increases in soil carbon concentration after six years. The result reinforces the recommendation of using wood-derived biochar, specifically mixed hardwoods, which are more representative of mixed wood materials that may be used for biochar from the collection of local biomass such as residential tree limb debris.

Biochar Application and Amendment Process

Biochar was applied at a rate of 9.3 Mg/ha on a dry-weight basis. It was then incorporated to a depth of 15 cm by chiseling soil with a plow, followed by disking to turn over and break up the soil surface, a fairly common agriculture process for soil preparation. Plots without biochar received the same treatment. While this study doesn't explicitly compare different application rates, it does suggest that 9.3 Mg/ha was sufficient to show a notable increase in soil carbon stocks, doubling the amount initially added with biochar. This observation, combined with information from the literature review, suggests that biochar benefits may plateau over time at lower rates. This further supports a suggestion of 3-4% by weight as a starting application to determine if more is needed for specific site properties.

Monitoring Techniques

Blanco-Canqui et al. conducted a six-year field study, meticulously measuring changes in soil properties over time. The predominant method was analyzing soil cores that were collected using a truck-mounted hydraulic probe. The cores were 60 cm long and had a 4 cm diameter. Cores were collected in four locations of each plot at interval depths of 0-5 cm, 5-15 cm, 15-30 cm, and 30-60 cm. Cores were then composited by depth level for analysis for each plot. For soil water retention, intact cores were taken from 0-5 cm and 5-10 cm depths and analyzed using low-pressure and high-pressure extraction methods.

Soil property measurements such as bulk density and gravimetric water content also utilized soil core methods for analysis. Researchers oven-dried cores at 105 °C for 24 hours to determine water content. Total carbon and nitrogen were analyzed using the dry combustion method using two different analyzers. Water infiltration was measured using the double-ring infiltrometer method. This consists of driving two rings, 20 cm, and 40 cm diameters, in the soil

10 cm deep into the soil. Water was added to both rings to maintain an equal water level throughout the experiment. Change in water level within the rings was then recorded at various intervals over a 3-hour period. Wet soil aggregate stability was measured using a wet-sieving method. Mean weight diameter (MWD) calculation was used after determining the mass fraction of aggregate in each aggregate size class to determine wet aggregate stability.

The research found that perennial bioenergy crops significantly increased soil carbon concentration and improved soil physical properties such as aggregate stability and water retention, particularly in the topsoil layer. This finding supports the recommendation to incorporate salt-tolerant perennial vegetation, specifically native warm-season grasses like switchgrass, into roadside plantings, as this type of vegetation can contribute to soil health improvement and potentially enhance the effectiveness of biochar amendments in mitigating road salt impacts.

This long-term approach allowed researchers to observe the sustained impact of biochar on soil carbon accumulation and other soil properties. The study underscores the need for long-term monitoring to assess the true effectiveness of biochar amendments, particularly in real-world roadside applications. The research also highlights the importance of tracking various soil properties, such as soil organic carbon concentration, bulk density, aggregate stability, water retention, and plant-available water, to gain a comprehensive understanding of how biochar influences soil health and its ability to mitigate road salt impacts.

**Blanco-Canqui, Creech, and Easterly (2024):**

This study investigates the long-term effects of wood biochar on soil properties and crop yields in a semi-arid environment. Researchers in this study conducted a 5-year field experiment using common crop rotations and various levels of biochar in silt loam soil. It was found that biochar, especially at higher application rates, had significant effects on soil fertility properties, but not consistent effects on soil physical properties. Biochar was shown to improve crop yields in some years but showed a decrease over time. This suggests that although biochar persists in soils potentially for 1000 years or more (Sohi et al. 2009), repeated application over time may be necessary. This research is imperative to consider the long-term maintenance and benefits of biochar in roadside soils as state DOTs formulate highway management plans.

Biochar Feedstock and Production

Biochar was produced by High Plains Biochar LLC in Laramie, Wyoming, from mixed hardwood feedstock (Cottonwood (*Populus deltoides L.*)*,* Pine (*Pinus L.*), Elm (*Ulmus americana L.*), and Ash (*Fraxinus americana L.*) and pyrolyzed at 815 °C. This feedstock used supports my recommendation of using wood-derived biochar, specifically mixed hardwoods, which are more representative of mixed wood materials that may be used for biochar from the collection of local biomass such as residential tree limb debris. Blanco-Canqui et al. suggest that wood biochar's porous structure and large surface area contribute to its ability to enhance soil properties and potentially mitigate road salt impacts

Biochar Application and Amendment Process

Biochar was incorporated in spring at a depth of 15 cm using a disk and the experiment was managed under no-till conditions. The study tested a range of biochar application rates from 3.125 to 25 Mg $ha^{-1}$. While biochar showed some positive effects at lower application rates, the most significant improvements in soil properties and crop yields occurred at the higher rates of 12.5 and 25 Mg $ha^{-1}$. However, the study suggests that biochar benefits may plateau past 12.5 Mg $ha^{-1}$, meaning increasing the application rate beyond this point may not yield proportional improvements. This information is valuable when determining cost-effective application strategies of biochar for roadside soils and further supports starting at lower rates and increasing as determined necessary.

Monitoring Techniques

Bulk soil samples were collected using a hydraulic core sampler with a diameter of 5 cm. Samples were collected at depths of 0-15 cm, 15-30 cm, and 30-60 cm at one, three, and five years throughout the study. Intact soil cores were collected at depths of 0-5 cm and 5-10 cm for analysis of water retention and bulk density. Wet aggregate stability was determined using a wet-sieving method. Water infiltration was measured in the field using a 25 cm diameter single-ring infiltrometer driven 10 cm deep into the soil. Other measurements, such as plant available water, total soil carbon concentration, and soil organic matter concentration, were also determined. Crop yields were harvested using a small plot combine with a grain head and measured based on harvested area adjusted to a 12% moisture content. Statistical data were analyzed using PROC MIXED and PROC STEPWISE in SAS software. Intermittent measurements throughout this study allowed researchers to observe the evolving impacts of biochar and determine that the benefits of biochar in soil may decrease over time. This supports the recommendation for long-term monitoring of biochar application to adjust application over time.

Additional Observations

The study also found that biochar had a greater effect on soil chemical and fertility properties than on physical properties. Increases in soil pH, organic matter, and available phosphorus were observed. The soil improvements indicate that biochar is likely to benefit vegetation on roadsides. The findings also highlight the potential for biochar to support vegetation in challenging environments like roadsides.

**Lee et al. (2022):**

This research conducted field and lab experiments that explored the potential of biochar to alleviate soil salinization. The experiments investigated the mechanisms behind biochar's effects on soil salt and water dynamics. The authors discovered biochar application initially exacerbated salinization of soils because the biochar used had high salt content. The biochar, however, ultimately promotes salt leaching during irrigation and salt removal by causing top accumulation of salts in the top 2 cm of soil, which could be removed mechanically. Furthermore, the study found biochar reduces soil compaction and cracking, contributes to water conservation, and lowers water evaporation. This study was essential to examine for my research to better understand the interactions that biochar may have with salinized roadside soils and to explore the potentials of biochar not just for the mitigation of road salts in stormwater runoff but for the remediation of roadside soils as well.

<u>Biochar Feedstock and Production</u>

The biochar used in this study for both experiments was produced from local cotton stalk through pyrolysis at a maximum temperature of 550 °C.

<u>Biochar Application and Amendment</u>

This study is beneficial because it observes the effects of directly applying biochar to existing soil types in both field and laboratory settings. In the field experiments, biochar was applied at a weight ratio of 5% to the top 20 cm of the soil. With the volume ratio being dependent on the average bulk density of the soil. In the field experiment, biochar was mixed into the soil using rotary tillage.  In laboratory experiments, specific weights of biochar were mixed with air-dried soil sieved through a 2mm mesh at weight ratios of 1%, 5%, and 10%.

Monitoring and Techniques

This study used several techniques to monitor biochar's effects on soil properties and plant growth. Soil samples were collected using a custom-made corer and sectioned at various depths for analysis. Sampled soil columns were sectioned on site every 1cm in the top 3-4 cm and 2-3 cm below. Various parameters were measured including pH, EC, CEC, TC, TN, and salt and nutrient concentrations. Additionally, in infield experiments, cotton plant growth was monitored, including seed emergence, plant height, number of boll-bearing branches, and final net productivity. Results suggest that biochar, by facilitating salt removal and creating a more favorable soil environment, can support the establishment and growth of salt-tolerant vegetation in saline soils. Reflecting similar conditions of many roadsides in salt-belt states.

Additional Observations

Biochar was found to enhance salt leaching and redistribution, causing salt accumulation at the surface of the soil. This finding is important when considering the ongoing management of biochar-amended roadside soils and plant selection. Plants with shallow root growth tendencies may have more difficulty surviving in biochar-amended soils. Researchers also observed that biochar reduced soil compaction and cracking, contributing to water conservation and reducing evaporation, increasing available water content for plants. Lee et al. also highlights that mechanical removal of topsoil layers is a practice already employed by farmers in some regions. This underscores the potential for biochar to enhance existing practices and shows that even in the event of intensive roadside interventions new maintenance machinery may not be needed.

**Imhoff, Culver, and Chiu (2019):**

This research is a study investigating biochar amendments' efficacy in reducing stormwater runoff and pollutant loading from roadway soils, specifically tracking nitrate in stormwater. Field and laboratory experiments were performed to assess the impact of biochar on stormwater infiltration, runoff volume, and water quality. The field study was three years long and showed a significant decrease in peak stormwater flow and runoff volumes with biochar-amended soils throughout the entire three-year period. The study observed reductions in nitrogen in subsurface water as well. However, the primary benefit of biochar was attributed to its ability to decrease stormwater runoff volumes. Lab column studies found positive effects on water retention and drainage rates. This study holds beneficial insights into effective application rates and depths of biochar for roadside soils, as well as feedstock parameters and types that exhibit qualities of biochar interactions that could be effective in mitigating road salts and chloride in stormwater runoff.

Biochar Feedstock and Production

Pinewood biochar pyrolyzed at 550 °C from Soil Reef Biochar was used in this study. Positive results observed in lab column experiments, as well as field experiments, support the recommendation to utilize wood-derived biochar for roadside application.

Biochar Application and Amendment for Field Experiment

Two filter strips were constructed along a state highway in Middletown, DE. One was amended to a depth of 30 cm by tilling a 4% mix, by mass, of biochar and was left unamended as a control, but prepared identically but without biochar incorporation. Both filter strips were stabilized and seeded. Imhoff et al. typically use a 4% biochar amendment by mass for their experiments. A 4% rate consistently demonstrated beneficial effects on soil hydrology and nutrient retention. This observation supports the thesis recommendation of starting with a 3-4% application rate, with adjustments based on site-specific conditions and monitoring data.

Monitoring Techniques for Field Experiment

Runoff volumes were measured in each filter strip using three ISCO 6712C water samplers equipped with ultrasonic sensors. The sensors were installed at outlet ends of collection trenches and monitored changing water levels. Information from time and volume measurements during rain events was used to estimate flow. Volumetric water content was monitored using eight Decagon GS-1 Water Content Sensors connected to data loggers which were placed at 1-15 cm and 15-30 cm deep. Soil temperature and rainfall data were also tracked. Automated water samplers collected surface samples of stormwater as it exited the roadway (influent), entered the filter strip, and ran off each filter strip (effluent). Subsurface water samples were collected from 4-in diameter horizontal perforated pipes installed 30 cm deep on the downgrade edge of each filter strip. These measurements indicated infiltrating water properties. Water quality parameters measured including TSS and various other parameters (pH, EC, $NH_4^+$, $NO_3^-$, $NO_2^-$, P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, Al, TC, TIC, TOC, and TNb). All of the water quality analyses were conducted by the University of Delaware Soil Testing Laboratory. Additionally, stormwater flow modeling simulated both surface and subsurface flow to help understand the processes by which biochar amendment altered stormwater hydrology. The researchers acknowledge the complexity of biochar's interactions with soil processes and the need for further investigation. The use of different soils in supplemental column experiments, including Delaware and Virginia soils, with the same application and biochar product with comparable sampling results further supports the recommendations of using similar biochar types and initial application rates across a variety of soil types for biochar amendment interventions.

Additional Observations

The findings from these experiments consistently demonstrate that biochar amendment leads to a reduction in stormwater runoff, a crucial aspect of mitigating road salt transport. For example, biochar amendment resulted in a significant decrease in peak flow rate and cumulative runoff volume. This effect persisted even after three years of operation, indicating the long-term effectiveness of biochar in enhancing soil infiltration and reducing runoff. Similar findings in column experiments and modeling support these findings and the recommendation to use biochar as a soil amendment in roadside soils to enhance infiltration and minimize the volume of salt-laden runoff reaching water bodies. Despite mixed results between experiments for nutrient cycling, this study still shows the importance of careful monitoring of nutrient dynamics in biochar-amended roadside soils.

**Imhoff and Nakhli (2017); Imhoff et al. (2021); (Imhoff et al. 2019):**

This research was a long-term study funded by Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board. This study investigates the efficacy of biochar as a soil amendment to reduce stormwater runoff and pollutant loading from roadways. This study was conducted at three different scales: lab, pilot, and field experiments. The lab-scale experiments suggested that biochar can significantly improve soil hydraulic properties by increasing water retention and unsaturated hydraulic conductivity in three soil types. Pilot-scale experiments also confirmed these benefits of biochar by showing a reduction in stormwater runoff. The field study experiment, which took place over 74 storm events, revealed that biochar significantly reduced stormwater runoff volume and peak flow rates. This study also discovered that biochar amendments facilitated macropore formation through enhanced aggregation of soils. The study concludes that biochar amendment is a cost-effective and environmentally friendly solution for reducing stormwater runoff and pollution from roadways and reducing the need for new infrastructure by promoting the use of the existing right-of-way.

Biochar Feedstock and Production

The biochar used in the study was from Soil Reef Biochar produced from Southern Yellow Pine feedstock. The biochar is produced via continuous pyrolysis at 550°C for 10 minutes. The biochar was rinsed with deionized water and oven-dried before application. This rinsing process removes hydrophobic coatings on the biochar that could influence soil wettability. This specific biochar consistently showed positive results in both field and laboratory settings, supporting the recommendation to use wood-derived biochar for roadside applications.

Biochar Application Rate and Amendment

The field experiment involved amending biochar to a depth of 30 cm into one of two filter strips. The biochar was applied at a rate of 4% by weight and mixed into the soil through tilling. A separate filter strip was prepared as a control by tilling without biochar addition. Both filter strips were then seeded according to Delaware Department of Transportation requirements. This application rate consistently demonstrated positive effects on soil hydrology and, in certain cases, nutrient retention. This supports the thesis recommendation of a 3-4% starting rate.

Monitoring Techniques

Many of the monitoring techniques in this study reflect processes and devices from the other Imhoff et al. study observed in this thesis. Please refer to that study for specific parameter devices. Saturated hydraulic conductivity was the main parameter of focus for this study. A Guelph tension disk infiltrometer was used to measure saturated hydraulic conductivity in filter strips. With measurements taken at eight points about nine months after tilling and biochar amendment. Stormwater runoff and peak flow rates were monitored for 74 storm events between 2016 and 2017. Soil sampling through cores was collected from both filter strips for the analysis of bulk density and aggregate size. Subsurface water samples were collected from horizontal perforated pipes installed at a depth of 30 cm on the downgradient edge of each filter strip. These samples represent water infiltration quality. The researchers used the DISC software to measure and analyze the effects of biochar on soil hydraulic properties and stormwater runoff.

Additional Observations

Researchers' use of pilot-scale experiments offers a valuable approach for investigating biochar's efficacy under more controlled conditions before implementing large-scale field trials. These experiments, despite being conducted in a laboratory setting, capture the three-dimensional water flow occurring in the field, allowing researchers to gain a better understanding of biochar's impact on stormwater runoff and nutrient dynamics. This supports the thesis recommendation to consider pilot-scale studies as a valuable step in the research and development of biochar-based road salt mitigation strategies.

**Kuoppamäki et al. (2019):**

This research investigates the effectiveness of biochar in mitigating pollution from urban runoff. Researchers conducted a field experiment using large-scale lysimeters, a device used to measure water percolation and composition through the soil, to simulate roadside conditions in southern Finland. Three soil types were tested: peat, sewage sludge-derived compost, and the same compost amended with biochar. The study aimed to determine the impact of soil treatments on nutrients and metal leaching. The study included a 23-month stabilization period followed by simulated stormwater irrigation. Results showed that biochar significantly reduced the leaching of nitrogen and certain metals compared to the other soil types.

Biochar Application and Production

Biochar used in this study was produced from birch tree feedstock using slow pyrolysis at 380-420 °C for 2 hours. Biochar was amended to a depth of 15 cm in two of the three treatments of this study. The biochar was applied at a rate of 3% by volume and mixed with composted sewage sludge and fine sand.  The processes used to amend biochar were not detailed. A separate 5 cm layer of biochar was added below this biochar-compost mixture, resulting in a high concentration of biochar in the top 20 cm of the lysimeter, where most of the root activity and nutrient uptake were expected to occur. The two other treatments consisted of compost without biochar and peat. With peat serving as the baseline comparison.

Monitoring Techniques

This study employed a combination of techniques to assess the impact of biochar amendment on nutrient and metal leaching. For hydrologic monitoring, pressure sensors placed in outflow water tanks recorded the outflow rates of infiltrated water at 10-minute intervals. Sensors at depths of 0.2 m and 1.6 m from the surface continuously monitored soil temperature and moisture. Rainfall and weather data were collected using a micro weather station at 10-minute intervals as well. Water samples were collected from infiltrating water at 2–4-month intervals during the 23-month stabilization period, and samples were taken the two days following artificial stormwater irrigation and once a month later. Grass growing in lysimeters was cut at the end of the growing season, and the aboveground mass was dried and weighed. Parameters measured in water sampling included pH, EC, TP, TN, and total dissolved metal content. Biochar and grass sampling contained similar parameters.

Additional Observations

This study suggested biochar as a potential solution for managing unwanted constituents in urban runoff. Although investigation into the mitigation of road salts is not considered in this study, it is essential to consider the other constituents in stormwater runoff and ensure biochar has the capacity to manage all the contents of highway runoff and help promote infiltration. Furthermore, road salts have been found to increase the mobilization of heavy metals in soils (Bäckström et al. 2004). It is essential to investigate the potential of biochar's efficacy in counteracting this in roadside soils and to identify application strategies in this study that the authors found to be effective. This study found that biochar reduced the leaching of pollutants and improved the retention of heavy metals. This suggests that biochar can help prevent pollutants from migrating into groundwater and surface waters and that biochar may be able to maintain effectiveness in complicated conditions like roadsides. Researchers did acknowledge that biochar’s effectiveness can vary depending on factors such as soil, type, biochar properties, and environmental conditions. Reinforcing recommendations for robust monitoring and tracking long-term impacts of biochar.

**Table 1: Literature Analysis Study Characteristics**

| **Sources** | **Yoo et al. (2020)** | **Blanco-Canqui et al. 2020** |
|---|---|---|
| **Experiment Type / Location** | Lab | Field Study<br>Atlantic, Iowa |
| **Feedstock** | Peanut Shells and Twigs | Mixed Hardwood: Quercus (Oak), Ulmus (Elm), and Carya (Hickory) woodchips |
| **Process/ Temp/ Time** | Pyrolysis / 200-300 °C / 3 Hours | Augur Bed Gasification / 600 °C |
| **Application Rate** | 2.5% w/w | 9.3 Mg/ha (0.48% w/w)<br>(BD assumed as 1.3g/cm³ and a 15 cm amendment depth is used for calculation) |
| **Soil Type** | Sandy Clay Loam | Exira Silty Clay Loam and Marshall Silty Clay Loam |
| **Additional Amendment / Treatments** | Slow-release fertilizer to top 5cm of soil at 1150 kg N ha-1 | **Corn:** Received 224 kg/ha of nitrogen (N) as urea and ammonium nitrate at planting. **Switchgrass and Low-Diversity Grass Plots**: Received 56 kg/ha of N as urea |
| **Application Depth** | Soil-Amended Pots Study focused 0-15 cm | 0-15 cm depth |
| **Study Length** | 130 days | 6 years |

**Table 1: Literature Analysis Study Characteristics (continued)**

| Sources | Blanco-Canqui et al. 2024 | Lee et al. (2022) |
|---|---|---|
| **Experiment Type / Location** | Field Study<br>Sidney, Nebraska | Lab Study<br>Field Study<br>Kashgar oasis,Xinjiang, China |
| **Feedstock** | Mixed Hardwood: Cottonwood (Populus deltoides L.), Pine (Pinus L.), Elm (Ulmus americana L.), and Ash (Fraxinus americana L.) | Cotton stalks |
| **Process/ Temp/ Time** | Pyrolysis / 815 °C<br>(High Plains Biochar LLC) | Pyrolysis / 550 °C |
| **Application Rate** | 3.125 Mg ha-1 (0.16% w/w)<br>6.25 Mg ha-1 (0.32% w/w)<br>12.5 Mg ha-1 (0.64% w/w)<br>25 Mg ha-1 (1.28% w/wt)<br>(BD assumed as 1.3g/cm³ and a 15 cm amendment depth is used for calculation) | **Field Study:** 5% w/w<br>**Lab Study:**<br>Leaching Columns:<br>1%, 5%, 10%, dry w/w<br>Evaporation Columns:<br>5%, 10% dry w/w |
| **Soil Type** | Keith Silt Loam | **Field Study:** 3 sandy loam soils: Mellow soil, medium salinization (MS) soil, high salinization (HS) soil<br>**Lab Study:** Air-dried mellow sandy loam soil |
| **Additional Amendment/ Treatments** | Nitrogen Fertilizer was applied at 84 kg N ha-1 and 168 kg N ha-1 in years 1 and 5 to millet and year 4 to sunflowers. | **Lab Study:** Urea was applied to the top 5 cm of leaching columns to simulate nitrogen fertilization |
| **Application Depth** | 0-15 cm depth | **Field Study:** 20 cm<br>Lab Study: Distributed and mixed evenly with 5 kg of dry soil throughout each column |
| **Study Length** | 5 years | **Field Study:** Mellow soil plot monitored for 2 years, MS and HS plots monitored for 4 months<br>**Lab Studies**: Varying durations for each experiment |

**Table 1: Literature Analysis Study Characteristics (continued)**

| **Sources** | **Imhoff et al. 2019** | **Imhoff and Nakhli (2017); Imhoff et al. (2021); (Imhoff et al. 2019)** |
|---|---|---|
| **Experiment Type / Location** | Lab Study<br>Field Study<br>New Castle County, Delaware | **Lab Study**<br>**Pilot-Scale Study:** Greenhouse<br>**2 Field-Scale Studies**: New Castle County, Delaware and Cecil County, Maryland |
| **Feedstock** | **Field Study:**<br>Southern Yellow Pine<br>**Lab Study:** 3.5-year field-aged biochar from Charlottesville, Virginia | **Lab Study:** 3.5-year field-aged biochar from Charlottesville, Virginia<br>**Pilot and DE Field Study:** Southern Yellow Pine<br>**MD Field Study:** Douglas Fir and Ponderosa Pine Limbs |
| **Process/ Temp/ Time** | **Field Study:**<br>Pyrolysis / 550 °C / 10 min | **Pilot, DE Field Study:** Pyrolysis / 550 °C / 10 min<br>**MD Field Study:** Pyrolysis / 950 °C |
| **Application Rate** | 4% w/w | **Lab Study:** 4% w/w<br>**Pilot and DE Field Study:** 4% w/w<br>**MD Field Study:** 2% and 4% w/w |
| **Soil Type** | **Lab Study:** Variety of textures from Virginia soils<br>**Field Study:** Engineered Roadway Soil in Delaware, Background Sandy Loam | **Lab Study:** Variety of textures from Virginia soils<br>**Field Study:** Engineered Roadway Soil in Delaware,<br>Background Sandy Loam<br>MD Field Study: Silt Loam |
| **Additional Amendment/ Treatments** | **Lab Study:** Compost amended 30% by volume in all columns<br>Calcium Sulfate (CaSO4) was added to all columns to maintain soil structure | **Lab Study:** Compost amended 30% by volume in all columns<br>Calcium Sulfate (CaSO4) was added to all columns to maintain soil structure |
| **Application Depth** | 0-30 cm depth | 0-30 cm depth |
| **Study Length** | 3 years | Pilot Study: 26 months<br>DE Field Study: 1+ Year<br>MD Field Study: 5 months |

**Table 1: Literature Analysis Study Characteristics (continued)**

| Sources | Kuoppamäki et al. (2019) |
|---|---|
| **Experiment Type / Location** | Field Lysimeter Study<br>Lahti, Southern Finland |
| **Feedstock** | Birchwood |
| **Process/ Temp/ Time** | Slow pyrolysis / 380-420 °C / 2 hours |
| **Application Rate** | 5% by volume (0.79% w/w, assuming sand BD is 1.6 g/cm³) |
| **Soil Type** | Media designed to mimic road verges, with layers of gravel, filter sand, crushed stones, and a top layer of growing substrate. |
| **Additional Amendment/ Treatments** | In the Comp+bc treatment, a 15 cm layer of 50/50 composted sewage sludge and sand soil mix, amended with 5% biochar by volume, was placed on top of a 5 cm layer of pure biochar. |
| **Application Depth** | Amendment in top 15 cm of mix<br>Pure biochar in the bottom 5 cm of the mixture |
| **Study Length** | Stabilization Period of 23 months prior to artificial stormwater irrigation.<br>Approx 1 month of simulated stormwater events and post-irrigation monitoring |

**Table 2: Summary of Literature Findings and Observations**

| Sources | Yoo et al. (2020) | Blanco-Canqui et al. (2020) |
|---|---|---|
| **Amendment Strategy** | Shovel Mixing | Chiseling, followed by disking |
| **Vegetation Type Observed** | Ginko biloba saplings | Corn, Switchgrass, and low-diversity grass mix (LDM) |
| **Carbon Sequestration** | N/A | C-Stocks nearly doubled, biochar enhanced accumulation of native soil organic carbon |
| **Water Retention** | Lengthen water retention in biochar-treated soils | + 30% available water in 0-5 cm depth for Switchgrass and LDM compared to corn<br><br>+ 29% available water in 5-10 cm depth for Switchgrass and LDM compared to corn |
| **Constituent Capture** | N/A | N/A |
| **Longevity/ Stability** | The proportion of large macroaggregates was consistently higher in biochar-amended soils. | + 29% MWD in 5-15 cm depth for LDM compared to corn and switchgrass<br><br>+ 23% MWD of water-stable aggregates in 0-5 cm depth for Switchgrass and LDM compared to corn |
| **Notes** | 2.5% amendment was chosen based on a previous study that showed just 2% amendment rates improve macroaggregates<br><br>Plant total Biomass + 369% compared to control. + 491% leaf number compared to control. | Biochar significantly enhances soil carbon sequestration, likely due to the negative priming effect. Switchgrass and LDM have positive impacts on soil physical properties, especially in the top 0-15 cm of depth. Biochar at the applied rate did not significantly affect other soil properties.<br>No significant interaction between biochar and bioenergy crops. |

**Table 2: Summary of Literature Findings and Observations (continued)**

| Sources | Blanco-Canqui et al. 2024 | Lee et al. (2022) |
|---|---|---|
| **Amendment Strategy** | Disking, followed by no-till practices | **Field Study:** Rotary tillage<br>**Lab Study:** Mixed with soil and packed into PVC soil columns |
| **Vegetation Type Observed** | Proso Millet (*Panicum miliaceum L.*), Yellow Field Peas (*Pisum sativum L.*), Winter Wheat (*Triticum aestivum L.*), Sunflower (*Helianthus annuus L.*) | Cotton was sown into biochar-amended mellow soil plot after biochar amendment and again the following year after the top soil was layer scraped. |
| **Carbon Sequestration** | Higher Application Rates(12.5 and 25 MG/ha had increased carbon concentrations (+ 37.2% for 25 MG/ha)<br>More than 50% of added biochar carbon was lost in the first few years. | |
| **Water Retention** | No significant improvement in water infiltration or available water content. Slight increase in year 5 in plots with high amendment rates (12.5 and 25 mg/ha). | **Field Study:** Biochar improved the pore network and facilitated water retention and movement within the soil.<br>**Lab Study:** Columns with 5% and 10% biochar had water-holding capacities of 44.8% and 57.2%, respectively. Compared to 26.4% for the control. |
| **Constituent Capture** | + 10.8% pH for 25 Mg/Ha in year 1<br>+ 7.7% pH for 25 Mg/Ha in year 5<br>+ 18.1% soil organic matter for 25 Mg/Ha<br>+25.9% phosphorus in year 1 for 25 MG/ha, +18.5% phosphorus in year 5 for 25 MG/ha<br>(increases compared to control plots) | Biochar was found to enhance salt movement in soil to create a more favorable soil profile for plant growth (salt leaching from root zone and accumulation on surface).<br>Higher rates of application (5% and 10%) increased downward movement of sulfate.<br>Biochar increased cation adsorption, making essential nutrients like K and Na available for plants |
| **Longevity/ Stability** | | Salinity levels in BC-amended mellow soil remained low over a two-year field study compared to control plots. |
| **Notes** | Found a decline in soil carbon benefits over time. Increased water retention in plots with higher amendment rates suggests the need for higher amendment rates on roadsides. | |

**Table 2: Summary of Literature Findings and Observations (continued)**

| **Sources** | **Imhoff et al.2019** | **Imhoff and Nakhli (2017); Imhoff et al. (2021); (Imhoff et al. 2019)** |
|---|---|---|
| **Amendment Strategy** | **Field Study:**<br>Tilled into the existing soil | **Lab Study:** Packed into columns<br>**Pilot Study:** Soil premixed with biochar<br>**Field Studies:** Tilled into existing soil |
| **Vegetation Type Observed** | Unidentified grass | **Lab Study**: N/A<br>**Pilot Study:** N/A<br>**DE Field Study:** Unidentified grass<br>**MD Field Study:** Grass mix (70/30 tall fescue/annual ryegrass) |
| **Carbon Sequestration** | | |
| **Water Retention** | **Field Study:**<br>Biochar amendment continued to demonstrate significant reductions in peak stormwater flow and cumulative runoff volume three years after construction. | **Lab Study:** +500% for some loamy sand<br>**Pilot Study:** Stormwater infiltration increased dramatically, and saturation decreased<br>**DE Field Study:** +31% KSAT in sandy loam compared to control<br>**MD Field Study:** +9177% KSAT in silt loam compared to control<br>In all studies involving MD Silt Loam soil bulk density decreased. (23% field and 21% lab)- This means improved infiltration. |
| **Constituent Capture** | **Field Study:**<br>Findings suggest biochar amendments may influence nitrogen capture | **Pilot Study:** After 26 months, nitrate removal increased from 42% to 88%<br>**DE Field Study:** -83% nutrient loads from biochar-amended soils. Translates to a reduction in pollution transport. |
| **Longevity/ Stability** | **Lab Study:**<br>Field-aged biochar was used. It was found to leach significantly less compared to fresh biochar | Pilot and Field Studies showed consistent improvement in KSAT and reduction in stormwater runoff in biochar-amended soils throughout the duration of the study |
| **Notes** | Reduced peak flow rates and cumulative runoff volume throughout a 3-year study.<br>Increased soil permeability and altered water retention curve.<br>Significant reductions in phosphorous levels. In field and lab studies. | Biochar amendment costs approximately $34,600 per impervious acre treated, making it more cost-effective than many other BMPs. |

**Table 2: Summary of Literature Findings and Observations (continued)**

| **Sources** | **Kuoppamäki et al. (2019)** |
|---|---|
| **Amendment Strategy** | Mixed into a growing substrate directly<br><br>The pure biochar layer directly beneath |
| **Vegetation Type Observed** | All lysimeters were planted with a mixture of grass seeds typically found on Finnish Roadsides |
| **Carbon Sequestration** | Grasses grown in BC+compost treatments had significantly higher (+588.89%) carbon mass compared to those grown in peat treatment. |
| **Water Retention** | The compost treatments both initially showed higher stormwater retention compared to the peat treatment. |
| **Constituent Capture** | Phosphorus Retention: 99% retained in all treatments<br>Total Nitrogen (TN) Retention: -TN retention in the stabilization period for treatments with compost, BC reduced TN leaching by 44% during stormwater irrigation.<br>Metal Retention: 100% Cr, Pb, and high Cu retained in all treatments. Compost treatments showed significant leaching of Zn, Al, Ni, and Cd throughout the study. BC decreased Al, Cu, Ni, and Zn during the stabilization period. |
| **Longevity/ Stability** | BC retention of metals persisted throughout the study (~2 years). BC could become saturated with pollutants over time. |
| **Notes** | This study suggests the addition of compost with biochar to increase the first storm surge. However, there are concerns about other introduced constituents by the compost.<br>Biochar can improve the capture of certain metals. |

# CHAPTER 4

# RECOMMENDATIONS AND DISCUSSION

This chapter will focus on the application of biochar to reduce road salt's effects on roadside soils. The chapter discusses four key aspects of using biochar in roadside designs: biochar feedstock and production, biochar application rate and depth, vegetation selection and planting design, and monitoring landscape performance. The chapter ends by discussing the benefits and limits of biochar as a sustainable solution. It will also highlight the need for continued research to improve how biochar is used in roadside areas.

## 4.1 RECOMMENDATIONS

Recommendations for the biochar type, biochar application, roadside vegetation strategies, and monitoring strategies are developed from conclusions and strategies that have been consolidated from study research and extensive literature review. These recommendations consider FWHA and AASHTO standards as well as other standards developed by state DOTs and government organizations.

### 4.1.1 Biochar Feedstock Type

Wood-derived biochar produced at a higher temperature (> 500 °C) is recommended as an amendment in roadside soils. Wood-derived feedstocks are recommended for various economic, social, and environmental factors.

- **Wood waste represents a readily available and sustainable feedstock** for biochar production since it is a common by-product of the forestry and wood processing industries as well as a common component of municipal yard waste collections (Zhang et al. 2022; Roberts et al. 2009; Murtaza et al. 2021; US Biochar Initiative 2024).

- **Wood-derived biochar typically has a high carbon content and a stable carbon structure** usually attributed to high lignin content, which makes it resistant to decomposition in the soil (Blanco-Canqui, Creech, and Easterly 2024; Imhoff and Nakhli 2017; Saifullah et al. 2018). The stability of amended biochar is crucial for long-term carbon sequestration, a key environmental benefit of biochar that is necessary to strive for to create sustainable systems. The recalcitrant nature of wood biochar also contributes to its long-term effectiveness in improving soil properties and reducing the need for frequent reapplication (Blanco-Canqui, Creech, and Easterly 2024; Imhoff and Nakhli 2017; Murtaza et al. 2021).
- **Wood-derived biochar typically has favorable physical properties.** Wood biochar possesses a highly porous structure with a large surface area (Imhoff et al. 2021; Ippolito et al. 2014; Blanco-Canqui, Creech, and Easterly 2024; Leng et al. 2021). These properties are particularly beneficial for stormwater management because they enhance water retention, infiltration, and soil aggregation. Water retention is enhanced due to the porous structure of wood biochar being able to hold water (Imhoff and Nakhli 2017). This can lead to reduced runoff volume, promote plant growth, and enhance drought resilience. Infiltration is increased due to macroporosity created by wood biochar, which improves the soil's permeability (Imhoff et al. 2021; Rice-Boayue et al. 2023). Further reducing runoff and promoting replenishment of groundwater resources. Wood biochar can also promote the formation of larger soil aggregates than some other biochar because of its larger particle size (Imhoff et al. 2021; Imhoff and Nakhli 2017). This contributes to better infiltration, aeration, and root growth.

- **Wood biochar has a relatively high CEC.** This allows wood biochar to retain nutrients, such as calcium, magnesium, and potassium, preventing them from leaching out of the soil (Imhoff and Nakhli 2017; Minnesota Pollution Control Agency 2024). This can improve nutrient availability for plants and reduce the need for fertilizers for vegetation growth.
- **The large surface area and chemical structure of wood biochar make it effective at adsorbing pollutants.** Pollutants such as heavy metals, pesticides, and excess nutrients are either trapped in pores of biochar or attracted to the surface of the biochar (Murtaza et al. 2021; Zhang et al. 2022; Yaashikaa et al. 2020; Ouedraogo, Yuzhu Fu, and Yunus 2023)

### 4.1.2 Biochar Application Rate

The use of biochar in roadside soils is an emerging idea that needs extensive research into the application rates and depths that can be effective across all soil types or conditions. Biochar application rates are usually expressed in percentage by weight (% w/w) or metric tons per hectare (Mg ha-1). For percentage by weight across all considered studies, 2% was a lower application rate and it was reported that soil properties like macroaggregate formation and available water content increased (Yoo, Kim, and Yoo 2020). However, Imhoff et al. found that a 4% w/w application rate led to a greater mass of macroaggregates compared to 0% and 2% biochar amendments (Imhoff et al. 2019). Biochar amended at 4% w/w was found across the Imhoff et al. studies for amending roadway soils (Imhoff et al. 2021, 2016; Imhoff et al. 2019; Imhoff and Nakhli 2017). This amendment was applied in the most similar conditions to the scope of this research for this thesis. It effectively reduced 83% of stormwater runoff, as well as a handful of other results above that wood-derived biochar is capable of. In other considered studies application rates were 6.25 Mg $ha^{-1}$(0.32% w/w, assuming bulk density is 1.3 $g/cm^3$) and 12.5 Mg $ha^{-1}$ (0.64% w/w, assuming bulk density is 1.3 $g/cm^3$) when applied to agricultural lands (Blanco-Canqui, Creech, and Easterly 2024). Based on both long-term experiments from which those application rates were identified, the authors suggest biochar benefits may plateau or diminish over time. Suggesting at least >10 Mg ha−1 (0.51% w/w, assuming BD is 1.3 g/cm³ and amendment depth is 15 cm) may be needed to have any significant impact on soil physical properties like bulk density and porosity (Blanco-Canqui, Creech, and Easterly 2024; Blanco-Canqui et al. 2020). Furthermore, Lee et al. utilized a 5% w/w in a field setting and found that it promoted soil macroaggregation, however, it noted that the biochar made the soil "as loose as newly plowed soil", indicating formation of larger soil aggregates, but also bringing concern for road shoulder stability and tire sinkage along with high rates of application (2022: 10). The analysis found that higher tested rates (5% w/w) were effective in capturing nutrients, such as nitrogen and phosphorus, as well as retaining some metals, such as chromium (Cr) and lead (Pb) (Kuoppamäki et al. 2019). Additionally, a 5% w/w rate was found to be effective for increasing the movement of salt in soils to aid desalination and promote plant growth. The Imhoff et al. studies discuss the potential cost-effectiveness of biochar as a stormwater management tool and compare its costs to other best management practices (BMPs). Based on field observations, it was determined a 4% w/w application rate costs about $31,700 per impervious acre treated including the associated costs of construction and design. Highlighting that urban grass buffers may be cheaper but require much larger footprints for effectiveness (Imhoff and Nakhli 2017). Additionally, Imhoff et. al compared biochar amendment to 25 BMPs and found it to be more affordable than 21 of the BMPs. While the benefits of biochar have been found to increase with application rate, scalability, and cost-effectiveness must be considered. **Based on this information, it is recommended to start with a 3-4% by-weight application rate in roadside soils if no information about the site soils in which biochar is being amended is specified.**

All sources consistently emphasize the importance of conducting field testing to determine the optimal biochar application rate for particular sites. This is crucial to account for the complex interactions between biochar, soil, and environmental factors.

A few studies specify general guidance on adjustment for higher application rates. With a higher application rate, the concern about shoulder road stability increases. Consideration of additional amendments, such as expanded shale, clay, and slate aggregates (ESCS) should be explored if shoulder stability is of concern (Das et al. 2023).

- **For coarse-textured soils** (e.g., sandy loam, loamy sand), having a higher application rate may be beneficial to increase water retention and infiltration in these soil types. Since these soils have larger particle sizes and lower water-holding capacities (Imhoff and Nakhli 2017).
- **For soils with low organic matter content**, biochar can most efficiently improve the physical and chemical properties of soils that are deficient in organic matter. Higher application rates can have a more pronounced impact on soil structure, nutrient retention, and microbial activity (Minnesota Pollution Control Agency 2024)
- **For compacted soils,** biochar can help alleviate soil compaction by increasing porosity and soil structure (Minnesota Pollution Control Agency 2024).
- **Soils with low pH (acidic soils)** can achieve higher pH with increased biochar application due to its inherent alkalinity. This is mainly suggested in areas where acidic soils are prevalent (Murtaza et al. 2021; Blanco-Canqui, Creech, and Easterly 2024; Liu et al. 2023)
- **Soils with existing high sodium content** can benefit from increased biochar application rates by making them more conducive to plant growth, adsorbing and exchanging salts, and reducing soil electrical conductivity (EC) (Liu et al. 2023; Saifullah et al. 2018)

Some soil conditions may also call for additional amendments such as ESCS for stabilization purposes to assist biochar structure (Das et al. 2023) or compost to increase initial nutrient availability (Kuoppamäki et al. 2019). The presence of a median can influence how stormwater drains from the road surface. Medians are often designed to prevent water from crossing over to the other side of the road. Which influenced the research approach of focusing on treating one side of the road, assuming replicability on the other side of the road. If water can flow across the median, a more integrated approach to the biochar application might be needed, potentially adjusting distribution on either side. Additionally, this these recommendations do not address biochar application strategies for vegetated medians that function as stormwater drainage systems. The principles of biochar for roadside design can also be applied to medians which are designed to capture and treat runoff before it reaches drainage outlets or surface waters. However, further investigation into application strategies, such as special soil mixtures, and various objectives of median design are necessary to formulate specific recommendations.

### 4.1.3 Biochar Depth

Biochar should be amended into the root zone of the target vegetation. This ensures that biochar can effectively interact with root systems and provide beneficial effects on soil properties, nutrient availability, and water retention. For example, if intended plantings are native warm-season grasses like switchgrass, biochar should be incorporated into the top 12 inches of soil to account for a majority of root mass for that species to have access to the nutrients and water retained in biochar (Fig. 4.1). Soil filtration of runoff should also be considered when deciding the depth of amendment. For example, loamy sand soils may benefit from deeper biochar amendment since plants are more prone to drought in these soil types (Artiola, Rasmussen, and Freitas 2012).

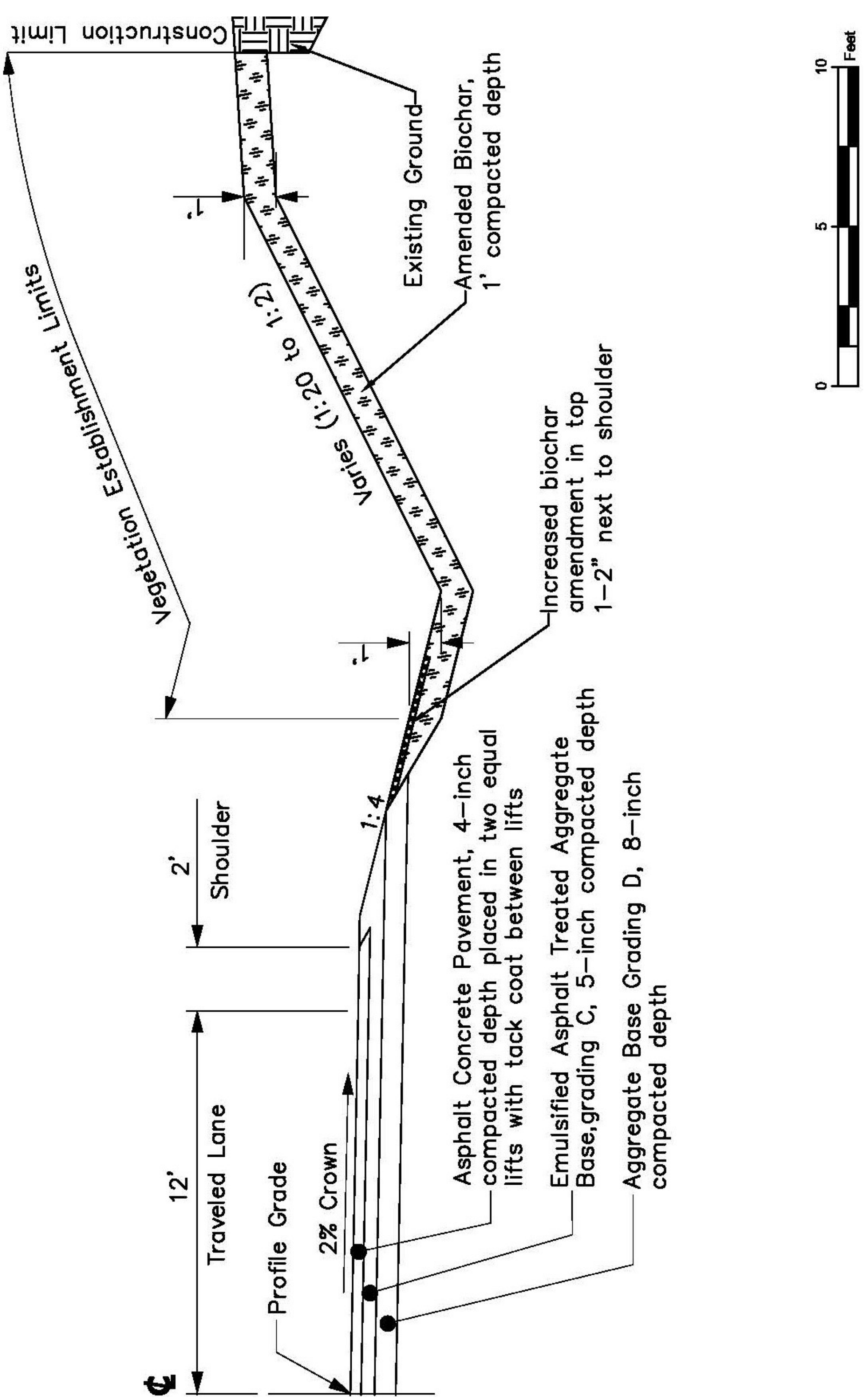


**Figure 4.1 Typical Highway Cross Section with Biochar Amendment**

Tilling biochar into the soil implies amendment depth should be sufficient to allow for proper mixing and incorporation. However, rotary mixing holds the most potential for consistent and balanced biochar application to existing roadsides observed in this research (Lee et al. 2022)

**4.1.4 Topdressing**

Topdressing may also be recommended for maintaining the effectiveness of biochar properties, although not nearly as effective as an amendment. Topdressing could be a viable option for erosion control for stabilizing soil surfaces or for facilitating water infiltration and vegetation establishment. Successful top-dressing applications for agricultural applications have been through a process of reoccurring applications of micronized biochar suspended in water (United States Biochar Initiative 2024). In glasshouse experiments, Thomas et al. found that biochar derived from a lignocellulosic feedstock (American beech (*Fagus grandifolia*) sawdust) could mitigate or even eliminate the negative effects of salt addition on plant performance when applied as a topdressing (Thomas et al. 2013). However, only high application rates (50 t ha-1) showed substantial effects. Topdressing may be very beneficial for the initial establishment of vegetation as a topdressing, but more investigation into existing research tailored to that purpose is required. Topdressing with biochar does present a risk of loss through erosion by wind and water. It should be considered that topdressing with biochar should be incorporated into additional stabilization techniques like hydroseeding or rolled erosion control products (RECPs) to increase contact with the soil surface for maximum benefits. Topdressing could be suitable for established plantings where tilling is not feasible, however, application recommendations and techniques for this are not provided in this research. Topdressing must be implemented responsibly to minimize biochar loss and ensure long-term effectiveness.

### 4.1.5 Vegetation

The establishment of roadside vegetation is crucial to maintain the structural integrity of the roadway and to prevent excessive erosion. The establishment of vegetation can be organized into three main recommended phases: initial establishment, species selection and planting, and long-term management. Phasing the establishment of vegetation reflects natural processes of habitat creation and natural succession, leading to a more resilient and tailored approach to each specific roadside project.

Phase one concerns the initial establishment of vegetation on the roadside. In some cases, allowing the natural regeneration of vegetation on the roadside is a possible route that is cost-effective and is an ecologically sound approach, as it often promotes biodiversity and utilizes locally adapted species. In most cases of new construction or renovation natural regeneration is an insufficient approach. Generally, it is recommended to implement a fast-growing cover crop, like annual ryegrass, to provide immediate erosion control and stabilization. This allows time for the establishment of slower growing, more permanent species that offer greater ecological, structural, and social benefits.

Phase two consists of species selection and implementation of planting design. Native plants are generally preferred for roadside revegetation due to their adaptability to local conditions, ecological benefits, and resilience to harsh environments, including salinity (Brown, Gorres, and Sawyer 2011). Native warm-season grasses (NWSG) are highly recommended for their qualities of adaptability, deep root systems, and resiliency in harsh soil environments (Gover, Johnson, and Kuhns 2011). Additionally, choosing salt-tolerant species like halophytes, which are adapted to saline environments and can facilitate greater chloride retention, should be considered (Hasanuzzaman et al. 2014). Most importantly it is recommended to base species selection on site-specific conditions. A careful inventory of adjacent habitats and plant communities is necessary to achieve a resilient and sustainable roadside landscape. This inventory should inform and inspire the selection of species chosen for implementation. Coordinating with a botanist or a restoration specialist is highly recommended to ensure appropriate species selection that supports project objectives.

Phase three involves a critical step to ensure the success of vegetation establishment and ongoing management to maintain planting design performance. The long-term management and monitoring of roadside vegetation must be baked into the vegetation establishment plan to ensure a successful project. After the establishment of cover crops and the installation of the planting design, the maintenance and observation of species must be evaluated on an individual basis. Ensuring the success of each species selected is necessary to maintain biodiversity and uniformity. For example, one must account for the slower establishment of NWSG. NWSG may require three to four seasons to fully establish, necessitating the use of intermediate species for temporary cover and erosion control. However, maintenance of temporary vegetation is important to ensure the NWSG is not overtaken or hindered by it. On the other hand, halophytes may be considered for annual cutback and removal of plant matter after establishment to prevent the re-release of accumulated salts back into the environment. Continued monitoring of the performance of each plant species is important to address factors such as salt spray or other environmental conditions that are not allowing a species to thrive and may require a species replacement. Additionally, addressing natural succession over time and managing encroachment of adjacent ecotones is necessary to consider in long-term management planning of roadside vegetation. Succession may be invited into planting design or undesired for reasons of roadside performance and motorist safety, so management of tree saplings or other successive species may need to be addressed.

This three-phase approach provides an organized approach to roadside revegetation after roadside disturbance or new construction. These recommendations for establishing roadside vegetation highly emphasize a case-by-case approach and provide guidelines for the execution of a successful biochar amendment project. For further information on establishing roadside vegetation, *Roadside Revegetation: An Integrated Approach to Establishing Native Plants and Pollinator Habitat* by Armstrong et al. (2017) is recommended.

### 4.1.6 Planting Design

Designing a roadside planting plan for the purpose of salt mitigation should retain the objective of slowing and retaining stormwater runoff as much as possible without creating pooling water. This research has determined that interventions such as the amendment of biochar in roadside soils and the utilization of halophytes are two good options for this purpose. Stormwater becomes runoff as soon as it leaves the edge of the roadway. This is the first opportunity to begin treating runoff through roadside interventions. Vegetation immediately adjacent to the road edge should consider clear zone preferences of road design (AASHTO 2011). Additionally, for ease of maintenance, it should be considered to plant vegetation in separate manageable strips. For the first 10 feet of the shoulder, if possible, vegetation should not be a visual impairment for driving, especially considering curves or emergency maneuvers (Federal Lands Highway Administration 2018). It is recommended to establish low-to-medium growing vegetation (1-3 feet or less) along this first strip. This should consist of native flowering plants and halophytes that are hearty, winter-resilient, and salt-tolerating since they get the brunt of the salt exposure and effectively function as the first layer of the filter. Halophytes that may be considered here are Saltmeadow cordgrass (*Spartina patens*), Saltmarsh Sedge (*Carex salina*), and American Sea Rocket (*Cakile edentula*). Native grasses to be considered in this mix are Little Bluestem (*Schizachyrium scoparium*) and Prairie Dropseed *(Sporobolus heterolepis*). Native pollinators could include Prairie Verbena (*Glandularia bipinnatifida*): Butterfly Milkweed (*Asclepias tuberosa*), and Golden Alexander (*Zizia aurea*).

The next strip away from the roadways should consist of medium-height (1-4 feet) meadows and prairie plants. This strip is along the bottom half of the foreslope of the roadside which meets the edge of the swale or final planting strip. This would be an ideal location to plant NWSG for root structure and stability such as Big Bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*, and Switchgrass *(Panicum virgatum*). Mixed in with NWGS is the opportunity to integrate pollinators such as New England Aster (*Symphyotrichum novae-angliae*), Coneflower (*Echinacea purpurea*), and Wild Bergamot (*Monarda fistulosa*). Providing a medium-height strip helps create a smooth visual transition from the roadway and provides an opportunity for a variety of plants to thrive, increasing biodiversity and aesthetics.

The final planting strip consists of a tall meadow (4 feet +) that has perpendicular runoff to the roadway or directs runoff into a swale to be carried to preferred drainage outlets or surface waters. This area consists of the swale bottom and the backslope of the roadside. Plants chosen for this strip should be taller to combat salt spray from the road from leaving the roadside buffer. Additionally, plants in this area should be salt-tolerant and exhibit other beneficial properties such as opportunities for pollinators and habitat for small organisms. It is important to choose species without aggressive roots to avoid damage to the swale function since the primary function of the swale is to convey runoff away from road surfaces and avoid flooding. It is also important to avoid woody vegetation that may cause damage to maintenance vehicles or add unnecessary risk to errant vehicles that leave the roadway. One halophyte to consider is Prairie Cordgrass (*Spartina pectinata*). Additionally, pollinators such as Joe-Pye Weed (*Eutrochium purpureum*), Ironweed (*Vernonia fasciculata*), American Beachgrass (*Ammophila breviligulata*), and Maximilian Sunflower (*Helianthus maximiliani*) should be considered.

The transitional planting of lower vegetation to higher vegetation is just one approach to planting biochar-amended roadside soils for the purpose of road salt mitigation and stormwater treatment. Visual representation of the proposed planting design and its comparison to typical mowed turf roadsides is shown in Figure 4.2 and Figure 4.3. Recommended plants serve as examples in this thesis and may not be suitable for every location or be the optimal mix for native pollinators and local ecosystems. It is necessary to perform a thorough site analysis, and it is recommended to consult a professional, such as a botanist when creating planting mixtures. Additionally, it is crucial to avoid invasive plants, which are identified by the National Invasive Species Information Center (U.S. Department of Agriculture 2024). Some of these plants may be able to be established from seed mixes if spread through strategies such as hydroseeding or with the utilization of erosion control mats. It is recommended to plant and establish potted NWGS and other strong-rooted plants to expedite the establishment and stabilization of soils to prevent erosion.


**Figure 4.2: Typical Mowed Turf Roadside Cross Section**

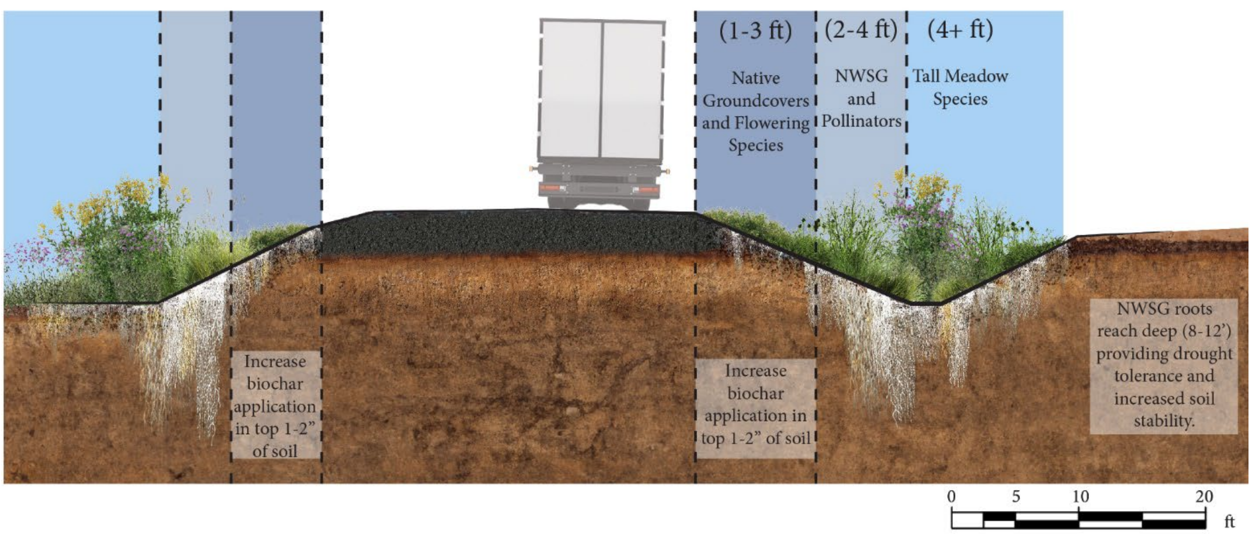


**Figure 4.3: Recommend Roadside Planting Cross Section**

### 4.1.7 Monitoring Landscape Performance

One of the most essential aspects of biochar application for roadside management is tracking and monitoring its effects on stormwater runoff quality to evaluate landscape performance. Other factors, such as soil properties, vegetation establishment and growth habits, and analysis of vehicular statistics such as wildlife collisions or driver mortality rates, should be tracked to identify co-benefits or negative trends that could be attributed to biochar amendments. Because of the variability of biochar's production and its interactions with different soil types, it is highly recommended to perform pilot-scale or field-scale experiments within areas intended for large-scale interventions before full-scale roadside application. Pilot-scale experiments can be used to evaluate the influence of biochar amendments on stormwater runoff and infiltration in a more controlled environment than field studies while still capturing the water flow in the field (Imhoff and Nakhli 2017). For example, researchers constructed four 0.6 x 0.3 x 0.3 m boxes and sunk them into the ground along a highway roadside greenway. Two were filled with sandy loam soil, and two with a mixture of sandy loam and 4% biochar by mass. Researchers then measured water before it entered the greenway, the runoff leaving the greenway, and the water that infiltrated through the greenway. Rhizon pore water samplers were installed in each box at five and 25 cm depths to collect pore water samples (Rhizosphere Research Products 2023). A tension disk infiltrometer was used to measure infiltration rates at two locations for each box, and measurements were taken throughout the wetting/drying cycles. The DISC software, developed by the USDA (U.S. Department of Agriculture 2023), was used to determine water retention and the saturated and unsaturated hydraulic conductivity of soil in each box (Imhoff and Nakhli 2017). The information gathered from this pilot-scale experiment further informed a more extensive field study and helped interpret data collected from the field site, which used the same soil type.

Field-scale experiments evaluate the long-term performance of biochar amendments in real-world applications. Field-scale experiments typically involve fully implementing biochar amendments to a large section of roadside soils and monitoring stormwater runoff volume and quality over an extended period. In the field-scale studies of Imhoff et al., researchers amended biochar at a 4% mass fraction to sandy loam soils in a filter strip along a four-lane divided highway in Delaware. Over two years, stormwater runoff was monitored for 74 storm events (Imhoff and Nakhli 2017). In this experiment, trench drains and perforated piping were installed at the inlet and outlet of each filter strip to collect and measure the quantity and quality of stormwater runoff. The trenches directed the runoff into piping systems equipped with flow meters and automated water samplers. These field study experiments tracked runoff volume and peak flow rates, water retention, and infiltration rates. Additionally, key hydraulic properties of the soil were tracked, including porosity, bulk density, and saturated and unsaturated hydraulic conductivity. Pollutant loads in stormwater runoff that were tracked were nitrate, nutrients, sediments, and dissolved organic carbon. However, no salt or chloride concentrations were tracked in these studies.

Chloride is considered a reliable chemical tracer in environmental studies because it is highly soluble and mobile in water. This makes it helpful in tracking the movement and accumulation of road salt in soil, groundwater, and surface water. In water, chloride is often measured through specific conductance with conductivity meters, which track the overall salinity of water. Several studies have used specific conductance to estimate chloride levels in streams and groundwater. The correlation of specific conductance readings during periodic water sampling throughout storm events with long-term trends enabled researchers in these studies to track high-chloride events and attribute them to increases in road salt applications (Corsi et al. 2015; Granato 1996). Other devices that track chloride levels are multiparameter water quality sondes (YSI n.d.). These can be deployed in stormwater systems to collect continuous data on water quality parameters, including chloride (Baraza and Hasenmueller 2021). Handheld multiparameter instruments are also available for spot-checking parameters on-site (Baraza and Hasenmueller 2021). Road salt application and frequency must also be considered when monitoring stormwater concentrations. Smart snowplow sensors, Road Weather Information Systems (RWIS), and infrared thermometers have helped municipalities optimize road salt application and reduce application rates (Fay et al. 2013).

Monitoring and tracking all parameters of stormwater and soil quality is crucial for a holistic understanding of environmental health and effective management of potential factors affecting desired water and soil quality outcomes. The ongoing and long-term tracking of water quality and soil properties when altering existing infrastructures is crucial for environmental protection and addressing negative trends early on. Thorough monitoring facilitates the optimization of design and increases the performance of sustainable practices over time. Many municipalities need the existing resources to facilitate the tracking of roadside projects and their effects. State DOTs need to form local relationships with research institutions, colleges, and other environmental organizations such as the National Wildlife Foundation and USDA, US Forest Service, The Water Research Foundation, U.S. Environmental Protection Agency, National Science Foundation (NSF), National Fish and Wildlife Foundation (NFWF/USEPA), Department of Energy (DOE), and Transportation Research Board, who have participated in research studies for road salt and roadside stormwater research before (Artiola, Rasmussen, and Freitas 2012; Clary et al. 2020; Imhoff et al. 2016).

## 4.2 DISCUSSION

The existing research evaluated in this thesis supports these recommendations and further expands the potential uses of biochar in a world experiencing changing climates. Biochar is a tool that we can use to adapt by mitigating anthropogenic disturbances to the natural environment, like the dispersal of road salts, as well as a tool that can be utilized to protect natural resources, like freshwater sources, that are vital to the prosperity of humans and the natural environment. The benefit of biochar's carbon sequestration is an additional factor that helps pursue carbon neutrality and slow climate change.

By demonstrating biochar’s effectiveness in mitigating the adverse effects of road salt and other vehicle-related contaminants on the environment, landscape architects and roadside designers are provided with a sustainable solution for maintaining and promoting healthy roadside environments and healthier ecosystems. This research offers practical guidance on improving soil health and resilience in urban and rural roadside projects, leading to better plant establishment and longevity of completed projects, potentially reducing long-term investments in roadside management by state and federal transportation organizations.

While the literature review and recommendations extensively discuss biochar performance variability across different soil types, it is critical to re-emphasize this point in the context of the study’s findings. The limited number of field studies reviewed may not encompass all potential variations in biochar performance due to soil variability. Addressing this reinforces the need for more comprehensive studies in the future to establish clearer guidelines for biochar amendments. A site-specific approach is necessary to optimize biochar performance. Future research should also entail a community-specific approach to address the larger implications of the research such as economic, social, and greater ecological goals of a community. Additionally, future research should explore the implementation of biochar in urban green infrastructure such as boulevards, tree wells, rain gardens, and bioswales with a focus on road salt mitigation and first-flush effects of snowmelt on urban streams and surface waters. Furthermore, biochar produced with a higher temperature of pyrolysis exhibits higher surface area, porous structure, and aromatic components that contribute to stability. However, CEC may decrease with higher pyrolysis temperature, leading to decreased CEC, a necessary property to combat pollutants. (Rice-Boayue et al. 2023). Biochar produced with lower temperatures may be more aligned with project goals in urban soils to maximize CEC. The recommendations in this thesis can guide some decision-making for biochar implementation in various green infrastructure. However, additional research for biochar applications beyond the scope of this research should consider additional resources.

Mitigating the spread of road salt may contribute to reduced infrastructure maintenance by decreasing the opportunity for salt to cause corrosion and decreasing erosion of stabilizing soils. Additionally, biochar amendments in roadside soils can provide valuable services like water filtration, flood control, pollination from increased plant production, and aesthetic appeal of highways for more enjoyable driving experiences and enhanced property values. However, long-term data in biochar research, especially for its use in roadside soils, is limited. Potential negative effects of biochar could be unrecognized since no large-scale implementation of biochar amendments in roadsides has been carried out and analyzed for an extended length of time. Biochar interactions with road salt alternatives, such as organics like beet juice and chemicals like calcium magnesium acetate, have not been studied in this thesis. Research such as the adsorption capacity of biochar for beet juice components and the influence of biochar-amended soils on CMA in runoff should be investigated further. Additional further research for this study includes monitoring the long-term effects of biochar amendment, including its stability, impact on soil health, and ability to mitigate road salt impacts over extended periods. The implementation of this research should also include insights into the pursuit of sustainable practices.

Creating sustainable systems for the procurement of biochar feedstock is essential to the economic feasibility of large-scale implementation of roadside amendments. Future research must focus on developing closed-loop systems that utilize locally available waste biomass and minimize greenhouse gas emissions during production and transportation. With these systems, biochar can be a large proponent in efforts to create climate-neutral cities through carbon sequestration of waste materials and debris. The scalability of biochar amendment strategies also needs to be evaluated further. Assessing the scalability should consider approaches such as field trials, cost-benefit analyses, long-term monitoring, stakeholder engagement, and the development of policies and regulations that support the use of biochar in road construction and maintenance projects.

This research is essential for landscape architects and adjacent professionals to consider as it supports ASLA's Climate Action Plan (2021) by providing tools to achieve climate action goals set for 2040, such as carbon sequestration, providing local economic benefits in the form of measurable ecosystem services (increased habitat), health co-benefits (cleaner fresh water sources), sequestration, and green jobs (debris collection for reuse). Furthermore, this research provides tools to empower communities through local collection and production practices and restore and remediate ecosystems impacted by anthropogenic infrastructure while protecting and promoting biodiversity.

# CHAPTER 5

# CONCLUSION

Use of road salt, primarily sodium chloride (NaCl), is used to ensure road safety during winter weather conditions in the United States. This reliance on road salt, while effective at deicing roadways, leads to significant environmental consequences. Road salt runoff pollutes water sources, decreases soil permeability, and harms native vegetation, posing a threat to both human and ecological health. Significant investment is made in road salt, with an estimated annual cost of $2.3 billion for winter road maintenance and $5 billion for addressing its environmental and corrosive impacts. Despite the availability of alternative de-icing methods, none are as affordable, accessible, and readily implementable as NaCl due to the existing infrastructure and standard operating procedures. The challenge lies in finding a sustainable approach to road salt management that balances road safety with environmental protection.

Biochar, a carbon-rich material derived from the thermal decomposition of biomass, is a viable candidate as an amendment in roadside soil for the remediation of salinized soils and the mitigation of the negative effects of road salt on the environment. Biochar possesses properties that can enhance soil health, improve water infiltration, and reduce stress on plants. This thesis explores existing research on integrating biochar into roadside soils through study analysis and literature reviews to develop recommendations for government agencies. The ultimate goal of this research is to create a roadside environment where native vegetation can thrive, and stormwater can be effectively filtered and infiltrated to reduce harmful chloride concentrations polluting water sources.

It is recommended to use wood-derived biochar produced at higher temperatures (> 500 °C) as an amendment for roadside soils applied at 3-4% mass by weight. Amending biochar into the root zone depth of proposed vegetation, with 12 inches as a suggested starting point. Additional amendment in the top layer of soil (1-2 inches) is also recommended near road edges, which receive the most concentrated runoff. Sources emphasize that site-specific conditions can influence effectiveness, as well as varying biochar feedstock types and biochar production strategies.

For planting design, native warm-season grasses are recommended as suitable vegetation options. Halophytes, plants adapted to thrive in saline environments, are also highly recommended for their ability to adsorb and store salt ions. Planting design should focus on slowing and retaining stormwater runoff without causing flooding or pooling. It is suggested to create separate planting strips along the roadside in consideration of the clear zone preferences and select a diverse mix of plants for increased biodiversity and aesthetics. Additionally, it is strongly recommended to monitor and track water and soil quality parameters to evaluate the effectiveness of biochar amendments and adjust as needed. This can be carried out through collaborating with research institutions and environmental organizations for technical expertise and support in implementing sustainable roadside management plans.

This thesis presents a design intervention for vegetated roadsides that doesn’t require new infrastructure or excessive alteration to existing road construction standards and maintenance procedures. Biochar amendments have the potential to be a sustainable option for municipalities to address pollution and changing climate while also providing the opportunity to stimulate the local economy and reuse material that otherwise would not be utilized (woody yard waste). However, this thesis also highlights variability in the performance of different biochar types across multiple soil types. If a sustainable approach of woody debris reuse for feedstock is pursued, the effects of biochar amendment in roadside soils have a high potential to exhibit variability across applications. Additionally, the large-scale implementation of biochar presents significant logistical challenges in the sourcing of biomass sustainably, the production and transport of biochar without substantial greenhouse gas emissions, and the additional costs associated with production, transportation, and application. Individual cost-benefit analyses can help determine the economic feasibility of biochar in different contexts, further stressing the importance of a case-by-case approach to biochar amendment for roadsides.

### 4.3.1 Limitations

This research synthesizes much of the available studies that could be identified that highlight the effects of road salt on the environment and the potential of biochar as amendments in roadside soils. Only seven field studies were reviewed, which may not represent all possible conditions and variables. The utilized studies emphasize the need to have a site-specific approach and suggest testing multiple factors such as soil properties, existing vegetation, and external factors that may influence results. Because of this, generalizability is limited to recommendations that represent a good starting point for biochar amendments. Studies analyzed were performed over varying lengths of time including a 5-year period. However, biochar has been found to remain stable in soils for long periods of time, and no extensive studies have been performed to evaluate the long-term impacts of biochar application. Furthermore, the different types of wood-derived biochar can have varying effects, and results might not be consistent across different feedstock sources and pyrolysis techniques. Additionally, specific interactions between biochar and road salts need further exploration to understand potential side effects or unrealized benefits of biochar's role in the mitigation and capture of road salts in runoff.

### 4.3.2 Future Research

Suggested future research includes site-specific testing of different biochar types in similar conditions as well as more extensive testing of various soil types with one type of biochar. This information would be able to be cross-analyzed and further inform more specific recommendations for biochar amendment in roadside soils. Additionally, the procurement of feedstock and the production of biochar should be explored through a local lens by individual municipalities and government entities to determine the most sustainable options for implementation that do not exacerbate the release of carbon and accelerate climate change effects. Cost-benefit analyses may also be recommended for communities looking to implement biochar in road construction practices to determine the economic viability and scalability of biochar applications in large-scale roadside projects.

To address these research gaps, a comprehensive field study is proposed. This experiment should be designed to evaluate the performance of mixed woody debris biochar made through different production techniques in different soil environments. This study will include at least three test sites along priority state highways, each representing a distinct soil type (sandy, loamy, and clay) and reflecting levels of road salt contamination levels in runoff reflective of the region. Each site will be divided into plots and tilled with different types of woody debris biochar (local leaf and limb debris feedstock at varying pyrolysis temperatures), leaving one tilled but unamended plot as a control for each site. Test sites will be planted with a mix of native halophytes, pollinators, and NWSG with a height profile of low- medium growing (1-3 ft), medium-growing (3-4 ft), and tall-growing (4ft +) extending outward from the roadside, following recommended planting design in this thesis. Key performance indicators such as soil nutrient levels, water retention, plant growth, and chloride concentrations of surface runoff and effluent from the plot sites will be measured over at least a two-year period. Long-term monitoring is preferred over multiple years to evaluate the long-term stability and effectiveness of biochar amendments in mitigating road salt impacts. Performance measuring can be executed through various techniques discussed in this thesis recommendations such as installing runoff collection systems. Additionally, conducting a pilot-scale experiment before a full-scale field study can help optimize biochar application rates, assess feasibility, and identify potential challenges. This design aims to provide actionable insights into the optimal conditions for biochar application, ensuring its effectiveness across diverse roadside environments for the mitigation of road salt.

In the urban context, including green infrastructure such as vegetated swales and rain gardens, project goals may be different from those of this research. Research shows that biochar produced with a higher temperature of pyrolysis may decrease CEC, a necessary property to combat pollutants (Rice-Boayue et al. 2023). Biochar produced with lower temperatures may be more aligned with project goals in urban soils to maximize CEC. There could be biochar mixtures that leverage the properties of biochar produced at different temperatures while still maintaining the benefits of both biochar types. Further research utilizing biochar for road salt management should explore the benefits of biochar produced at a lower temperature to maximize the absorption of salts.

Further research is crucial to fully realize biochar's potential. Additional studies into optimal biochar types, application methods, and long-term impacts are essential for broader adoption and maximization of ecological, economic, and societal benefits that our roadside can provide. This thesis explores biochar as a sustainable solution for the challenges posed by road salt, supporting healthier roadside environments. By mitigating road salt contamination, biochar can protect water resources, improve soil health, and create more resilient ecosystems. The potential benefits of biochar extend far beyond roadside applications, offering a promising pathway toward carbon sequestration, waste reduction, and a circular economy. Investing in biochar research is an investment in a sustainable and resilient future.

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# APPENDIX

# BIOCHAR APPLICATION GUIDELINES: *MITIGATING ROAD SALT IN THE ENVIRONMENT: SUSTAINABLE RECOMMENDATIONS FOR ROADSIDE BIOCHAR APPLICATION*

# MITIGATING ROAD SALT IN OUR ENVIRONMENT

## SUSTAINABLE RECOMMENDATIONS FOR ROADSIDE BIOCHAR APPLICATION

Collin Madison
University of Georgia
College of Environment + Design
2024

# Table of Contents

## Purpose of This Guide

This guide provides recommendations for incorporating biochar into roadside soils to mitigate the negative environmental impacts of road salt. Road salt runoff poses a significant threat to water quality and ecosystem health. Biochar, as a soil amendment, can enhance soil properties, improve stormwater infiltration, and reduce the transport of road salts into surface and groundwater. This guide, drawing on extensive research and field studies, outlines practical strategies for biochar application, including recommended feedstock type, application rates, and planting designs. By implementing these guidelines, government agencies and municipalities can promote sustainable roadside management practices that protect water resources, enhance soil health, and support the establishment of resilient roadside vegetation.

# Benefits of Biochar in Roadside Soils

### Water Retention

Biochar improves soil structure through its porous structure and large surface area. The porous structure helps with water retention by allowing more room for water in the soil. At the same time, the pores in biochar increase infiltration and allow water to move more easily through the soil and recharge groundwater. Increased porosity of roadside soils reduces stormwater runoff and mitigates the effects of initial storm runoff that contains high concentrations of dissolved road salts and other constituents[1].

### Aggregation

The large surface area of biochar helps aggregation and nutrient retention[2]. Biochar particles act as binding agents for soil particles, leading to the formation of larger, more stable aggregates[3]. Larger soil aggregates can improve soil stability and contribute to aeration. Biochar particles can hold and exchange cations, including essential nutrients. The cations can act as bridges that bind soil particles together[2].

## Biochar

### Plant Health

Biochar helps roadside vegetation through enhancement of soil properties. Factors such as increased retention and porosity contribute to plant available water and root growth[4,5]. Additionally, biochar reduces soil compaction by improving soil structure, increases the soil's cation exchange capacity and increases pH in acidic soils[3].
Biochar holds onto nutrients, preventing them from leaching out of the soil. The increased nutrient availability helps reduce salt stress on plants. Biochar can also adsorb sodium ions (Na+) and exchange them with beneficial cations like calcium, magnesium, and potassium, further reducing harmful effects of sodium on plants[6].

## Large-Scale Benefits

### Carbon Sequestration

The production of biochar converts biomass into a stable form of carbon that resists decomposition. Biomass is any material from a biological source[7]. Plants absorb $CO_2$ from the atmosphere during photosynthesis, storing carbon in their tissues. When plants decompose, the $CO_2$ is eventually released back into the atmosphere. Pyrolysis of the plant biomass into biochar sequesters and stores the captured $CO_2$ for very long time, potentially a century or more[8].

### Sustainability + Resilience

The production of biochar using waste biomass can utilize material that would otherwise decompose and release carbon back into the atmosphere. By diverting waste mass to biochar production, we prevent carbon emissions and create a valuable soil amendment. This approach supports a circular economy and contributes to a net reduction in greenhouse gas emissions if carried out strategically[9].

# Biochar Sourcing

## Feedstock

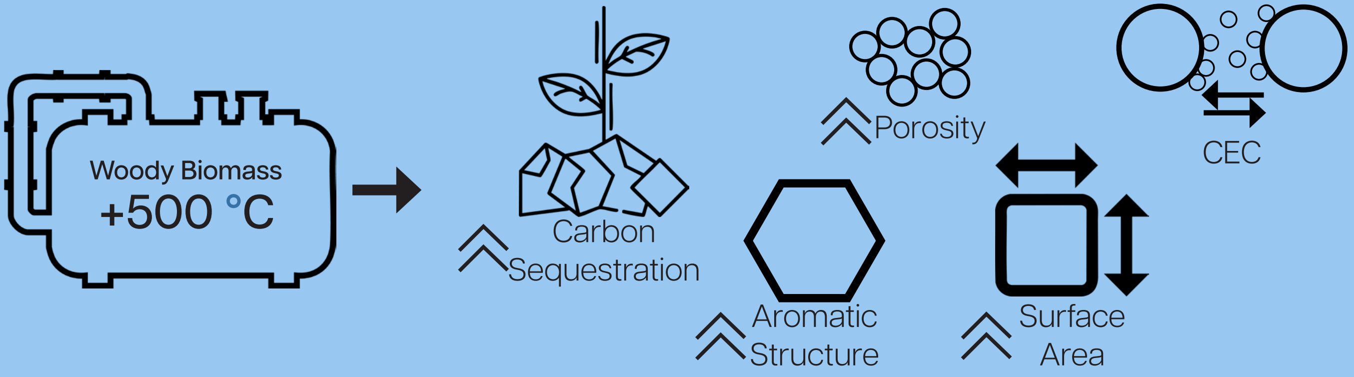
Woody biomass waste generally results in the properties ideal for roadside amendments[9]. Woody biomass means materials like tree limbs, branches and wood chips. Biochar with high lignin content has an aromatic atomic structure, which has been attributed to increased carbon sequestration and stability. Other biochar feedstocks can be used for biochar application if they share similar properties to wood-derived biochar. However, the produced biochar my exhibit different properties and perform differently. For example, feedstocks such as stover and rice husks from agricultural practices have high lignin content, but have fine to medium particle sizes which may contribute less to aggregation and soil stability.

## Biochar pH

Biochar made from wood generally has an alkaline pH[10], which can increase the pH of the soil it is mixed with. However, some tree species or woody shrubs may result in low or very high pH. Mixed woody biomass that is used to create biochar should be logged and used as reference when analyzing biochar product to influence and refine future production cycles.

## Production Properties

High pyrolysis temperature (above 500 °C): Higher pyrolysis temperatures generally result in greater carbonization, more aromatic structures, higher porosity, larger surface area, and benefits of cation exchange capacity (CEC)[14].



# Strategies for Local Production

**Utilize Municipal Woody Waste:** Many municipalities already collect woody yard waster, including tree limbs, branches, and wood chips, making it readily available and sustainable feedstock source.

**Partner with Local Businesses:** Explore collaborations with local businesses that generate woody waste, such as arborists, landscapers, sawmills, and construction companies.

**Engage Community Members:** Encourage community members to contribute to biochar feedstock sourcing by providing designated drop-off locations for yard waste or implement a curbside collection programs.

**Produce Locally:** Small-scale production near collection sites may facilitate a versatile option for production. Mobile production products, such as the CharBoss by AirBurners Inc., offer flexibility and scalability[11]. Mobile production units generally have a lower upfront cost compared to stationary pyrolysis systems which makes them more accessible to smaller municipalities or organizations with limited budgets.

Fig. 1: (AirBurners, 2024)

*AirBurners Power Series* — *AirBurners Roll-Off Firebox* — *AirBurners CharBoss*

## Are There Local Producers?

There are few production facilities who specialize in biochar production on a wholesale level. The United States Biochar Initiative website[12] contains a directory of biochar researchers and production facilities in the US that can be used to locate whats nearest to the project site. While wholesale purchasing a production is a possibility in some locations, it may not always be the most sustainable option.

## Can It Be Sustainable?

Local sourcing and production can present a sustainable option. Reduction of transportation distance can reduce costs and green house gas emissions. Gathering feedstocks from local sources can support local economies[9].
Implementing a distributed biochar production system with multiple small-scale units located near feedstock sources may be a solution.

# Site Identification

The purpose of this guide is to provide recommendations for the mitigation of road salt using biochar amendments in roadside soils. To define the priority site of a project area, whether it be a state, county, or localized effort, a handful of factors, such as application frequency, stormwater runoff drainage routes, and site properties should be considered. Two-lane and four-lane highways are often designated as high-priority travel roads in DOT snow control plans and tend to have the highest rate of road salt application. High-priority roadways in rural and suburban areas often have vegetated roadsides that can benefit from biochar amendment and are less likely to have complex drainage systems that lead directly to public sewers.

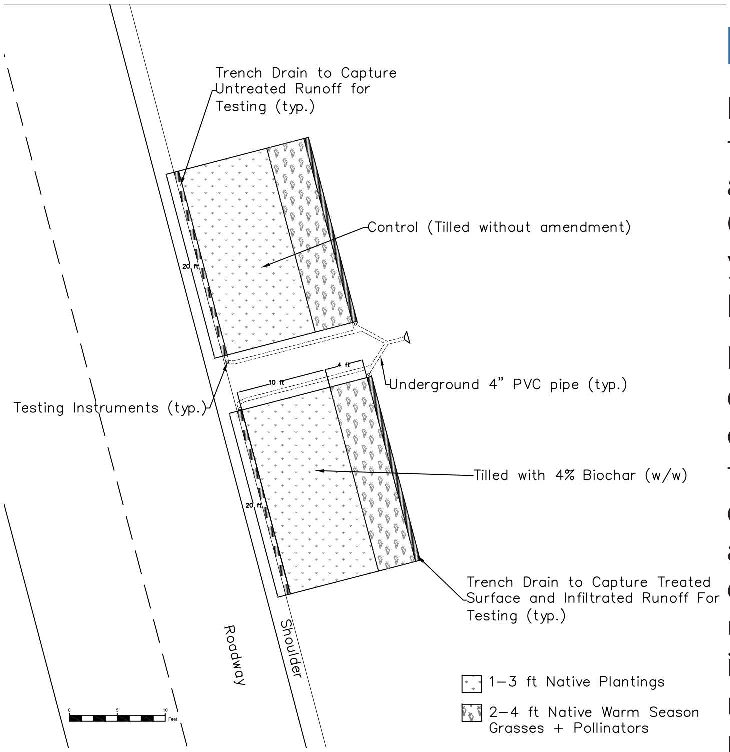
## Site Assessment

Site assessment is crucial before starting a project to ensure informed decision- making and successful outcomes. These are some important factors to consider during a site assessment:

- Soil properties
- Watershed analysis and drainage patterns
- Vegetation analysis
- Weather trends
- Local winter maintenance plan
- Roadside regulations and standards
- Site accessibility, risk factors
- Environmental sensitivity
- Potential for community engagement

Fig. 2: (Vidacycle, 2023)

*Testing for Infiltration Rates*




*Field Experiment Example*

## Field-Scale Experiments

Field-scale experiments are a crucial step in the research and development of biochar amendments for road salt mitigation strategies. Conducting pilot scale experiments at or near your chosen site of interest is crucial to the process of constructing a sustainable system.

Field-scale experiments provide a cost-effective and controlled environment for optimizing biochar application rates, assessing feasibility and identifying challenges, evaluating environmental impacts, refining designs and management strategies, and building confidence among stakeholders. This approach ultimately leads to more informed and effective implementation of biochar on a larger scale, maximizing its potential to create healthier and more sustainable roadside environments.

# Incorporation With Roadside Soil

## Methods

**Tilling-** This method involves mechanically mixing biochar into the soil using equipment like tillers or plows. Tilling is commonly used in agricultural settings and is often appropriate for roadside soils.

**Rotary Mixing-** For new road construction projects, rotary mixers can effectively incorporate biochar and is used during new construction or when significant soil disturbance is acceptable.

**Top Dressing-** This method involves spreading biochar on the soil surface without incorporation. While less effective than amending, topdressing can be useful for stabilizing soil surfaces, facilitating water infiltration, and promoting vegetation establishment.

# Incorporation Depth

### Amendment Rate

It is recommended to begin with an amendment rate of 3-4% wieght by mass (w/w) and to adjust from that point[14].

### Top Layer

Regardless of other factors, incorporating biochar into the very top layer of soil (1-2 inches) is highly recommended to reduce soil cracking and promote infiltration.

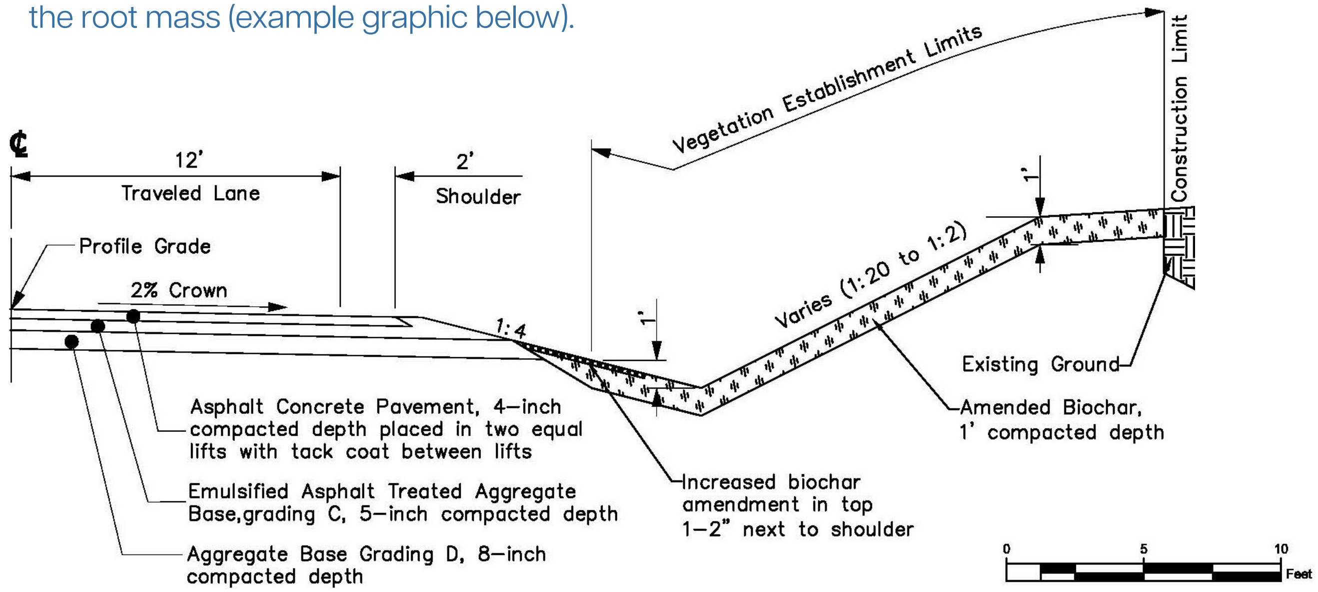

Fig. 3: (CENUSA Bioenergy, 2013)

*Biochar-amended Soil*

### Root Zone

Biochar should be incorporated into the root zone of the proposed vegetation. This ensures that biochar can effectively interact with root systems and provide beneficial effects on soil properties, nutrient availability, and water retention.

For example, if the intended plantings are native warm-season grasses like switchgrass, biochar should be incorporated into the top 12 inches of soil to account for a majority of the root mass (example graphic below).




*Typical Highway Cross Section with Biochar Amendment*

## Planting Design

Biochar amendments can enhance roadside vegetation[6]. However, innovative planting design boosts biochar effects by improving soil infiltration and nutrient uptake, which helps filter runoff[13]. Selecting native or naturalized plants, increasing biodiversity, and creating pollinator habitats aid in road salt mitigation and support larger sustainability goals.

Fig. 4: (Creampuff 2023)

*A Roadside Planted with Native Plants*

## The Case For Natives

Native grasses and perennials provide numerous advantages over turf grasses for roadside planting. Particularly when considering the challenging conditions presented by road salt application and stormwater runoff.

**Less Maintenance:** Although some turf species are native, wild grasses and perennials generally require less maintenance and exhibit greater resilience to environmental stressors, like road salt. Turf grasses often require frequent mowing, fertilization, and pesticide application to thrive on roadsides.

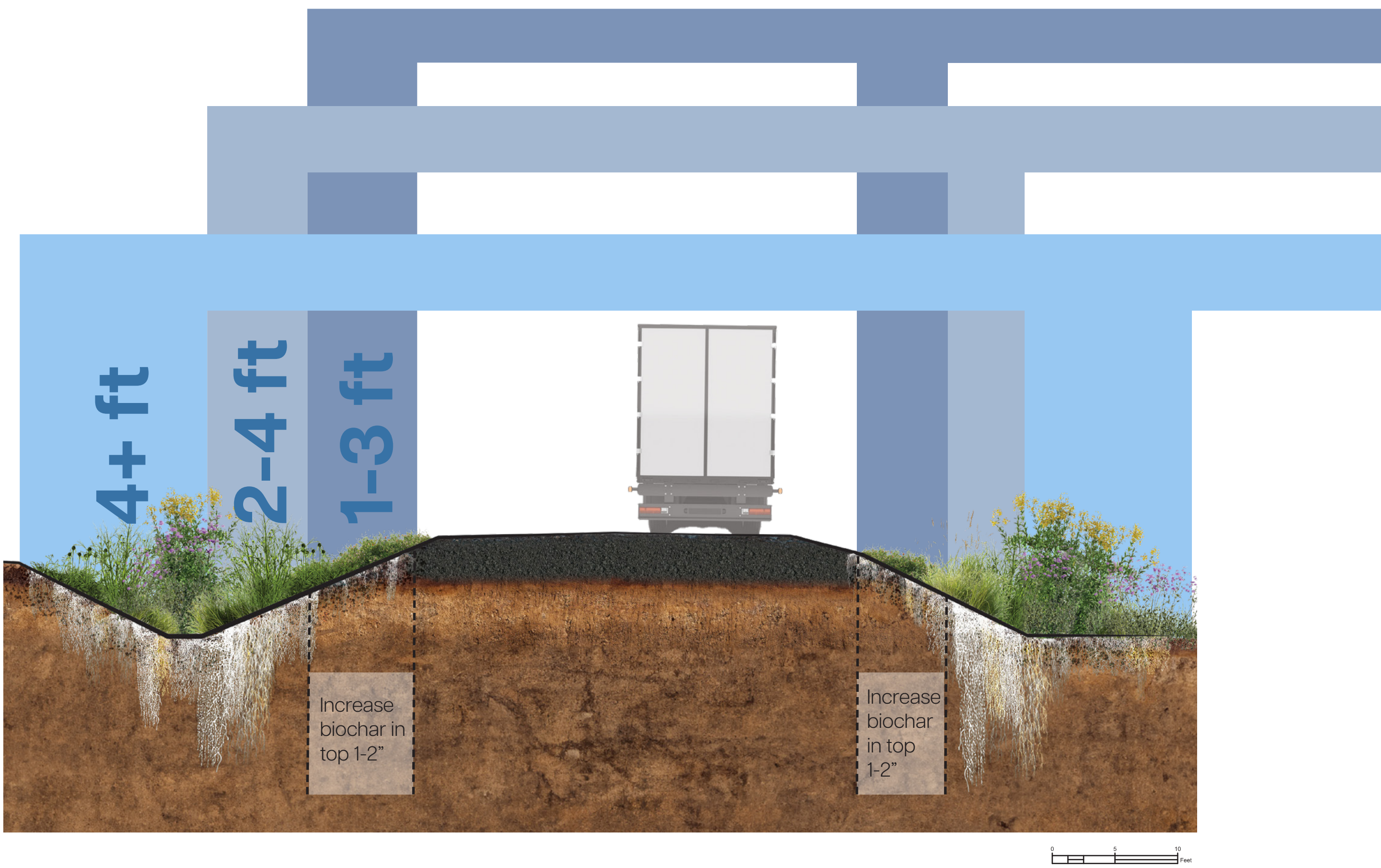
**Deep Root Systems:** Wild native grasses and perennials develop extensive root systems, which contribute to soil stabilization, reduce erosion, and enhance infiltration. Turf grasses have shallow roots and are less effective a infiltrating and preventing erosion.

**Salt Tolerance and Phytoremediation:** Native species, including halophyte, exhibit varying degrees of salt tolerance and can even assist in removing salts from soil through phytoremediation. Halophytes particularly adept at adsorbing and storing salt ions, effectively reducing salt concentrations in the soil. Turf grasses may tolerate moderate salt exposure, but are less effective at soil remediation.

**Ecological Benefits:** Native plantings support biodiversity by providing habitat and food sources for a wide range of insects, birds and other wildlife. This contributes to a healthier ecosystem and enhances the overall environmental quality of roadside area.

**Enhanced Aesthetics:** Native plantings can create visually appealing roadside landscapes that enhance the aesthetic value of communities and contribute to a sense of place.

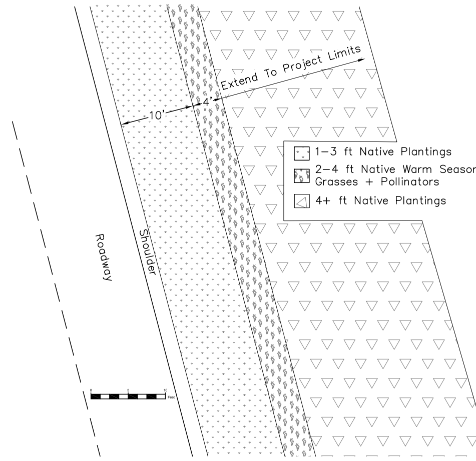
# Typical Mowed Turf Roadside
## Section View




# Recommended Roadside Planting
## Section View

# Planting Plan

Proposed roadside planting design follows three distinct vegetative strips which run successively parallel to the roadway. This creates layered rows of plants, providing a structured and effective roadside enhancement to help in the mitigation of road salts. The planting layers are distinguished by height to account for Clear Zone considerations and safety precautions for roadside use in emergencies.



*Recommended Planting Plan (Typ.)*

**1-3 ft**

The first strip planting strip adjacent to the roadway should extend 10 ft from the road if possible. This strip consists of shorter native groundcovers and flowering species (1-3 ft or less) that are hearty, winter-resistant, and salt-tolerating since these plants get the brunt of salt exposure and function as the first layer of the "filter".

**Plant Suggestions:** Halophytes that may be considered here are Saltmeadow cordgrass (*Spartina patens*), Saltmarsh Sedge (*Carex salina*), and American Sea Rocket (*Cakile edentula*). Native grasses to be considered in this mix are Little Bluestem (*Schizachyrium scoparium*) and Prairie Dropseed (*Sporobolus heterolepis*). Native pollinators could include Prairie Verbena (*Glandularia bipinnatifida*): Butterfly Milkweed (*Asclepias tuberosa*), and Golden Alexander (*Zizia aurea*).

**2-4 ft**

The second planting strip is made up of meadows are prairie plants (2-4 ft). This planting strip is intended to be implemented along the bottom half of the foreslope of the roadside which meets the edge of the swale or final planting strip. Native warm season grasses and various flowering native perennials are recommended for this location because of their stable root systems which reinforce swale edges and provide extra support to flowering meadow and prairie species that are mix in.

**Plant Suggestions:** Big Bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*), and Switchgrass (*Panicum virgatum*). Mixed in with NWGS is the opportunity to integrate pollinators such as New England Aster (*Symphyotrichum novae-angliae*), Coneflower (*Echinacea purpurea*), and Wild Bergamot (*Monarda fistulosa*).

**4+ ft**

The last planting strip consists of tall meadow species (4+ feet). This area generally has stormwater runoff directed into a vegetated swale or water runoff perpendicular to the road way out of the right-of-way. The plantings in this area are along the swale bottom and the backslope of the roadside. Species in this area should be salt-tolerant and provide opportunities for pollinators and provide habitat for small organisms. It is important to choose species without aggressive or woody roots to avoid damage to the swale function of conveying excessive runoff away from the roadway to prevent flooding.

**Plant Suggestions:** Prairie Cordgrass (*Spartina pectinata*). Additionally, pollinators such as Joe-Pye Weed (*Eutrochium purpureum*), Ironweed (*Vernonia fasciculata*), American Beachgrass (*Ammophila breviligulata*), and Maximilian Sunflower (*Helianthus maximiliani*)

# Monitoring Landscape Performance

Through methodical monitoring of biochar amendments and native plantings, landscape architects and transportation professionals can effectively evaluate the performance of biochar-amended roadside landscapes, make informed adjustments, and optimize the long-term benefits of biochar in mitigating the negative impacts of road salt on the environment.

## Stormwater Runoff

Measurements of volume and flow rate of stormwater entering and leaving the project site should be tracked. This helps in assess the effectiveness of site interventions for reducing runoff volume and peak flows. One way to achieve this is to install flow meters and automated water samplers in trench drains or piping systems at the inlet and outlet of the biochar-amended area. Water samples should also be tracked for chloride, nutrients (nitrogen and phosphorus), sediments, heavy metals, and dissolved organic carbon. Tracking changes in pollutant concentrations over time can help determine the effectiveness of biochar and plants have in removing constituents.

## Soil Properties

Biochar can change the physical properties of soil significantly in some cases. Tracking hydraulic conductivity and water retention of soil can indicate if the application rate is sufficient. Hydraulic conductivity is monitored by testing the saturated and unsaturated hydraulic conductivity of soil to assess biochar's impact on soil permeability and infiltration rates. This can be achieved using a Guelph tension disk infiltrometer or similar devices which lend accurate results compared to soil boring and pits. Water retention can be determined using intact soil cores and laboratory analysis . Soil structure should be observed for bulk density, aggregate stability, and porosity as well as key chemical properties of soil, such as pH, electrical conductivity (EC), cation exchange capacity (CEC), organic matter content, and nutrient availability. These factors can all provide insights into biochar's influence on soil fertility and its ability to mitigate salt stress on plants.

Fig. 5: (Lisa Fotios 2024)

*Typical Roadway in Snowy Climate During Winter*

# Monitoring Landscape Performance (cont.)

## Vegetation Performance

Tracking vegetation survival rates can imperative to the establishment of roadside vegetation. The suitability of chosen species and the influence of biochar on plant growth can be determined through regular vegetation surveys which monitor plant health, density and coverage. Vegetation surveys should include plant height, diameter and biomass production to evaluate the impact of biochar on mitigating salt stress on plants. Plant tissues may also be analyzed for salt ion concentrations to assess effectiveness of halophytes in removing salts form the soil and to monitor potential salt-stress on non-halophytic species.

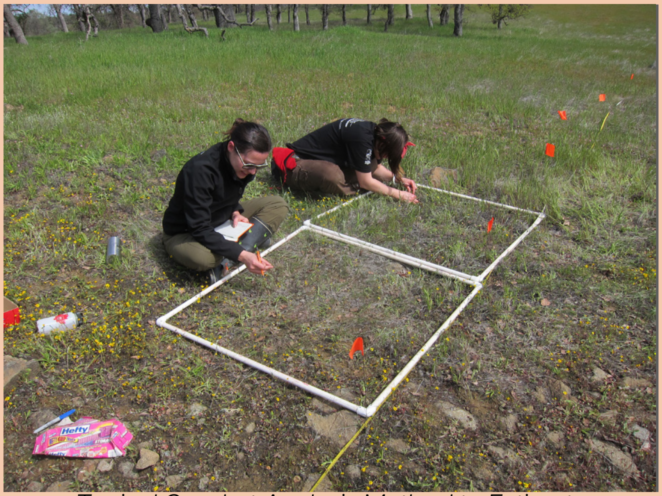


Fig. 6: (Dystopos, 2006)

*Typical Quadrat Analysis Method to Estimate Vegetation and Habitat Properties*

## Additional Monitoring Considerations

Road salt application rates and frequencies in the vicinity of the project site should be tracked to correlate with data gathered from the biochar-amended site. Additionally, weather data, including precipitation, temperature, and wind speed can be referenced to understand changes in project site performance.

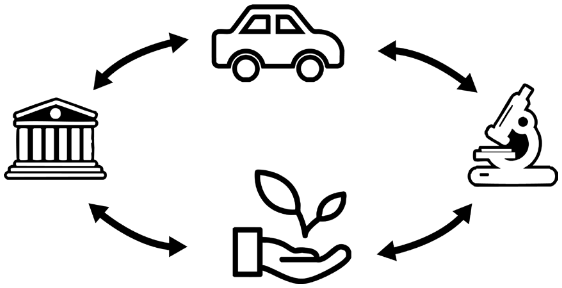
Cost-benefit-analysis should be conducted over time to evaluate the economic feasibility of biochar amendments and planting regimes. Factors for project implementation, such as costs of biochar production, transportation, application, and monitoring as well as potential benefits, such as reduced infrastructure costs and improved ecosystem services should be considered as determinants of the analysis

## Frequency

Monitoring frequency should be determined based on site-specific conditions, project objectives, and available resources. Initial monitoring should be more frequent to track the immediate impacts of biochar amendments. As the system stabilizes, monitoring frequency can be reduced. It is generally recommended to monitor over multiple years to assess long-term trends and biochar stability before ultimate impacts are assessed.

## Collaboration and Data Sharing

Collaboration with research institutions, environmental organizations, and state DOTs can leverage expertise, share data, and contribute to a broader understanding of biochar's effectiveness in mitigating road salt impacts.



# Summary

This guide has presented a compelling case for using biochar as a sustainable tool to address the environmental challenges posed by road salt. By enhancing soil properties, improving infiltration, and reducing the transport of road salts, biochar offers a nature-based solution that aligns with the goals of protecting water resources, enhancing soil health, and supporting resilient roadside vegetation. The recommendations provided, grounded in scientific research and field studies, offer a practical roadmap for implementing biochar-based strategies in roadside environments.

It is important to acknowledge that biochar is not a one-size-fits-all solution. Site-specific conditions, such as soil type and existing vegetation, play a crucial role in determining the effectiveness of biochar amendments. The variability in biochar performance across different environments highlights the need for ongoing monitoring and adaptive management to ensure optimal outcomes.

Embracing biochar as a component of roadside management represents a shift towards a more sustainable and resilient approach to infrastructure development. By integrating biochar into roadside designs, transportation agencies and municipalities can contribute to a circular economy that reuses valuable resources, sequesters carbon, and minimizes environmental impacts. As we move towards a future where environmental stewardship is paramount, biochar stands as a promising tool for creating healthier and more sustainable roadsides for generations to come

# Additional Resources

## Biochar Production + Sourcing

USBI Directory- https://biochar-us.org/directory

USDA Biochar Basics- https://research.fs.usda.gov/rmrs/products/sycu/biochar-basics-z-guide-biochar-production-use-and-benefits

## Establishing Roadside Vegetation

FWHA- http://www.nativerevegetation.org/learn/manual_2017/

## Climate Action

ASLA Climate Action Plan- https://www.asla.org/climateactionplan.aspx

Precedence for Field-Scale Experiment

TRB Highway Innovations Deserving Exploratory Analysis (IDEA) Program's Reducing Stormwater Runoff with Biochar Addition to Roadway Soils.
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