RESEARCH & DEVELOPMENT

Storm Water Infiltration and Pollinator Habitat Zones Along Highways

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NCDOT Project 2017-27
FHWA/NC/20YY-NN
November 2020

STORM WATER INFILTRATION AND POLLINATOR HABITAT ZONES ALONG HIGHWAYS

North Carolina Department of Transportation

Project Authorization No. HWY-2017-27

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Technical Report Documentation Page

1. Report No. FHWA/NC/2017-27	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Storm Water Infiltration and Pollinator Habitat Zones Along Highways		5. Report Date November 17, 2020 6. Performing Organization Code
7. Author(s) Richard A. McLaughlin, Shaddy H. Ashraah, Abby M. Haselton, and Joshua L. Heitman		8. Performing Organization Report No.
9. Performing Organization Name and Address Crop and Soil Sciences Dept., Box 7620, North Carolina State University Raleigh, NC 27695		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report August 2016 – November 2020 14. Sponsoring Agency Code *2017-27*
Supplementary Notes:		

16. Abstract

This project explored the possibilities of managing soils on new and existing roadside areas to reduce runoff through increased infiltration. This was pursued through several greenhouse studies, controlled field plots at three sites monitored for three years, and several installations on existing roadside areas. Tillage was very beneficial for improving infiltration in compacted soil, often by a factor of 3X or more. Incorporating compost at the rate tested, 5cm incorporated into 15cm of soil, often had additional benefits but not always. Improved vegetation establishment and resistance to compaction may result from the compost treatment. Traffic from tractor mowers can reduce or eliminate the infiltration benefits, however. Wildflowers as a substitute for grass can provide greater infiltration potential, in part because mowing traffic is reduced from four times per year to one. Among the many wildflowers that were planted as a mix, very few were present in our plots. However, those perennials that dominated (Lanceleaf coreopsis and blanketflower) were quite resilient in both field plots and under different soil conditions in the greenhouse tests, and would be highly recommended based on their ability to grow and develop robust root systems.

17. Key Words Wildflowers, pollinators, tillage, infiltration		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 81	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Acknowledgements

This project involved a large number of people in order to achieve our objectives. Key staff were Jamie Luther, Chris Niewoehner, and Adam Howard, who kept the field and lab work moving forward at all stages. Graduate students Abby Hazelton, M.S. and Shaddy Alshraah, Ph.D., were instrumental in data collection and analysis, along with a number of undergraduate assistants. For the roadside studies, NCDOT staff were very helpful in locating suitable sites. Recognition of the need for research and funding to support it has been and continues to be a reason NCDOT is among the leaders in environmental and water quality improvements associated with our transportation systems.

Executive Summary

This project was intended to explore the possibilities of managing soils on new and existing roadside areas to reduce runoff through increased infiltration. This was pursued through several greenhouse studies, controlled field plots at three sites monitored for three years, and several installations on existing roadside areas.

Wildflower growth responses were evaluated in two field studies and a greenhouse study. The first roadside field study surveyed plantings of single species of wildflowers – *Eschscholzia californica* (California poppy) and *Coreopsis lanceolata* (lanceleaf coreopsis) – for growth at roadside locations varying in soil texture and density. Lanceleaf coreopsis maintained high vegetative coverage (73.8-85.0%) and low weed coverage (0.0-4.6%), while California poppy coverage varied, but had relatively higher weed coverage ranging from 18.8 to 36.4%. The effects of soil pH, texture, and bulk density on wildflower growth were inconsistent, differing by species.

The second field study compared mixed wildflower plantings, including both annuals and perennials, with and without incorporated yard waste compost in the Coastal Plain, Piedmont, and Mountains of North Carolina over two years. Contrary to expectations, compost had minimal effect on wildflower cover. Incorporated compost had a negative effect on wildflower cover in one field site in the first year of establishment, and on wildflower cover at one sampling in the second year, with little effect on subsequent samplings. Species diversity was not affected by compost.

The greenhouse study evaluated the effects of soil density on plant height and shoot and root growth. The species evaluated were *Eschscholzia californica, Coreopsis lanceolata, Chamaecrista fasciculata,* and *Gaillardia aristata* (California poppy, lanceleaf coreopsis, partridge pea, and blanketflower).Lanceleaf coreopsis and blanketflower grew well relative to other species, although the former had some sensitivity to soil bulk density. The perennial species performed as well or better than annuals in the two 3 to 4 month test periods. Overall, the wildflower species studied were not affected by soil density over a moderate range (1.15 to 1.5-g.cm^{-3}), suggesting that they are well adapted to grow in construction-impacted soils.

Based on the greenhouse results, we concluded that the species studied have limited sensitivity to soil density, which was supported by some of the roadside field results. All three studies indicated substantial growth and cover provided by perennials, comparable to or greater than that of annuals, which challenges conventional species recommendations for mixed plantings including need for both annuals and perennials. With the right management decisions (i.e., species selection), wildflowers can provide good ground cover along roadsides, similar to grass, with the added benefits of aesthetic value, pollinator habitat, and reduced maintenance.

The potential differences in wildflower species root development on soil properties were also explored in a greenhouse study. Soil hydraulic properties were monitored during the root development of two species to quantify the effects of roots development over time on soil pore size distribution and hydraulic conductivity. A positive linear correlation between root growth and soil hydraulic conductivity was found under compacted soil conditions.

Field-based studies were also established in 2016 in three regions of North Carolina and monitored for 30 months to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflower mixes. Plots planted in wildflowers tended to have higher soil infiltration compared to grass across all sites. Compost application also enhanced the soil infiltration in two sites out of three sites. Finally, the effect of tractor traffic on

soil infiltration resulting from the mowing process was evaluated for wildflowers and grass. Tractor traffic substantially reduced infiltration rates in the wheel tracks but there was some evidence of recovery in the compost-amended wildflower plots. This study demonstrated the ability of compost to improve some soil properties. It also demonstrated that wildflowers were superior to grass regarding soil infiltration and low maintenance requirements and could be a viable alternative to grass in vegetative stormwater practices.

The last part of this study was to test tillage effects on existing roadside areas. Plots were established at two locations, the intersection of NC 50 and NC 98 (“98”) and on a ramp slope at the US 70 Bypass in LaGrange (“LaGrange”). Runoff was collected from the 15 plots for about a year before treatment to establish “normal” runoff. Five plots each were tilled and planted to either grass or wildflowers, with the remaining five undisturbed. In addition, four large plots were established with tillage with or without compost and planted to either grass or wildflowers. No runoff was collected in the large plots but they were used for soil sampling and infiltration measurements. Large plots were also established on an exit ramp of US 70 in Goldsboro (“Goldsboro”). Runoff was collected for almost a year and in the summer 2020, two years after establishment, both runoff and large plots were sampled for infiltration and bulk density. Infiltration was improved through tillage at the two sites where runoff was collected, but the reduction in runoff volume was less evident in the LaGrange site due to very sandy soil and high infiltration rates already present. The type of vegetation was not a large factor in improving infiltration, but there was some advantage in the combination of compost incorporation and planting wildflowers. Overall, tillage did appear to be effective in soils with inherently low infiltration rates, and compost can increase this effect.

Conclusions

Tillage was very beneficial for improving infiltration in compacted soil, often by a factor of 3X or more. Incorporating compost at the rate tested, 5cm incorporated into 15cm of soil, had additional benefits but not always. Improved vegetation establishment and resistance to compaction may result from the compost treatment. Wildflowers as a substitute for grass can provide greater infiltration potential, in part because mowing traffic is reduced from four times per year to one. Among the many wildflowers that were planted as a mix, very few were present in our plots. However, those perennials that dominated were quite resilient in both field plots and under different soil conditions in the greenhouse tests, and would be highly recommended based on their ability to grow and develop robust root systems.

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Introduction

Vegetated stormwater control measures (SCMs) are a critical tool in NCOT's toolbox of practices for reducing stormwater runoff and its impact. Infiltration is a key feature of these SCMs. Infiltration reduces runoff volume, as well as sediment and nutrient loss. Viable vegetation with proper rooting is essential to achieving infiltration. Establishment and maintenance of vegetated SCMs is often problematic because of poor soil conditions prior to seeding, associated with compaction, and topsoil removal. The result can be poorly vegetated areas that generate high-runoff volumes relative to undisturbed areas.

Recent research has demonstrated that applying tillage to ameliorate compaction on construction sites greatly enhances success in vegetation establishment, increases infiltration, and reduces runoff and erosion. When a strong stand of vegetation is established, the tillage effect appears to remain for at least 2-3 years, based on the period of monitoring, but likely much longer if the area is not disturbed. Incorporating compost improved the vegetation in some cases and helped in preventing recompaction by mower traffic. The effects are likely very specific to soil types and conditions, but relatively high infiltration rates (20-30 cm h^{-1}) in tilled soils were found at most sites during the 2-3 year monitoring period. Current results of a highway installation are also promising, with runoff volumes reduced by roughly 50% when compost was tilled into the soil.

While all of our research into infiltration improvements through tillage has involved planting various grass mixes, there may be many locations where other plant types may be more beneficial. NCDOT has been planting wildflower areas for 30 years, and its expertise developed in this program could be tapped for this project. Deep-rooted perennials may provide additional structural support for the soil to maintain the initial high infiltration rates typical after tillage. Mowing in these areas would be reduced to once per year, or even less. Furthermore, the plants could be selected to be both aesthetically pleasing to the public and to benefit pollinators. There is great concern about declining pollinator populations, and one of the main contributors to the decline has been reductions in suitable habitat. An on-going project has suggested that wildflower planting along highways significantly increases pollinator abundance (O'Brien et al., unpublished data). The combination of these two ecosystem services—high infiltration and pollinator habitat—along with secondary benefits (e.g., low maintenance, increased aesthetics) suggests that establishing these areas along roads would be a multifunctional Best Management Practice.

Result of Literature Review

The North American road network covers nearly 5 million miles (Forman et al., 2002). Road construction methods of cut and fill lead to compacted low fertility soils with sparse vegetation that increases site erodibility and can decrease infiltration (Bochet and García-Fayos, 2004;

Haynes et al., 2013). Roadsides are vegetated relative to site conditions: climate, soil, and purpose (Arnold et al., 1992). This vegetation along roadsides is important for intercepting rainfall and preventing erosion. Plants adsorb the energy of rain and wind which have the potential to erode soil. Roots mechanically strengthen the soil (Styczen and Morgan, 1995). In the long term, vegetation increases soil aggregate stability and infiltration through root activity (Hugo et al., 2009)

Grasses have been traditionally used to vegetate roadsides; however, planting wildflowers in place of grasses may have economic, educational, recreational, ecological, and aesthetic advantages (Aldrich, 2002; Bretzel et al., 2009). Since 1985, the North Carolina Department of Transportation (NCDOT) has been planting wildflowers as part of highway beautification programs. Specific establishment and management techniques have been developed into a manual for NCDOT (North Carolina Department of Transporation, 2017), with the key elements presented in Table 1.1. In general, wildflowers have been planted in managed beds at locations visible to the public. Stormwater management has not been a goal in the existing NCDOT wildflower program. However, as the wildflower program has continued to grow, there is interest in expanding plantings to include areas that have been managed as grass for stormwater infiltration and runoff reduction.

A potential challenge for establishing roadside wildflowers is that soil conditions along roadsides are often relatively harsh. Subsoils are exposed during road construction and construction activities can lead to substantial soil compaction (Kays et al., 2015; Olson et al., 2013). North Carolina soils also often tend to be acidic, especially in the subsoil. Previous work has shown that soil pH does not have linear effect on wildflower growth (Hopkinson et al., 2016), but that as pH approached an optimal range 6.0-7.0 (Salon and Miller, 2012), vegetation cover increases. If wildflower plantings are to be expanded for stormwater management, more information is required to understand the influence of soil conditions on wildflower growth.

Vegetated soils adjacent to roads are a cost-effective, low-tech, first defense for minimizing the runoff leaving linear impervious systems (Perrin et al., 2009), but utilizing vegetated soils to reduce the impacts of stormwater runoff from adjacent road surfaces is only effective if soil conditions permit the infiltration of runoff. Mass grading and other practices associated with road construction degrade the natural structure and function of soil through the removal of vegetation and topsoil, cutting, grading, filling, and compaction by equipment (Gray and Sotir, 1996; Gregory et al., 2006; Olson et al., 2013). These disturbances alter the physical, hydraulic, and vegetative properties of roadside soils by simultaneously increasing bulk density and mechanical resistance to root penetration and reducing porosity, precipitation storage capacity, and infiltration rates (Richard et al., 2001; Zhang et al., 2006). Reduced infiltration and storage limits filtration and transformation mechanisms in the soil matrix, leading to increased transport of nutrients and pollutants in stormwater runoff (Davis et al., 2003; Smith et al., 2013). Additionally, the exposure of nutrient-poor subsoils at the surface may inhibit vegetation establishment and lead to accelerated erosion rates (Macdonald et al., 2001). The combined effects of these physical and hydraulic disturbances of roadside soils during construction increases the quantity and decreases the quality of stormwater runoff from roadway areas, ultimately impacting downstream water quality (Grant et al., 2003).

Vegetated stormwater control measures (SCMs) are an important management tool employed along roads and highways to reduce the impacts of stormwater runoff. SCMs include multiple approaches to stormwater treatment, ranging in size, extent, and treatment method. These include engineered structures such as basins and wetlands that treat piped or channeled runoff in one location, as well as diffuse practices such as vegetated filter strips that utilize the soils adjacent to roadways to treat runoff from adjacent road surfaces (NCDOT 2014). In order to reduce the quantity of runoff leaving roads and surrounding areas, infiltration of stormwater is the primary goal of these SCMs (Hamel et al., 2013). In addition to mitigating runoff volumes, these SCMs provide water quality benefits resulting from filtration, uptake, and transformation processes within vegetated soils (Hunt et al., 2012; Vogel et al., 2015).

Poor soil conditions resulting from construction activities associated with mass grading and topsoil removal may lead to limitated vegetation establishment and infiltration (Gregory et al., 2006). Improving the physical and chemical conditions of post-construction soils may facilitate vegetation cover establishment, reduce compaction, and increase infiltration properties (US EPA, 2011). An increasingly common approach to increase the potential for vegetated roadside soils to reduce runoff from adjacent roads is the use of compost in conjunction with tillage to improve soil conditions (Strecker et al., 2015). In addition to hydrologic benefits of incorporating compost in soils, studies have shown that compost provides multiple co-benefits when added to soils, such as carbon sequestration (Kavehei et al., 2019; Ryals et al., 2014), increased vegetative biomass (Ryals et al., 2016), and increased microbially-mediated nutrient and pollutant transformations (McPhillips et al., 2018).

For compacted soils, the hydrologic response to compost incorporation relative to tillage alone has been shown to be variable, with compost additions increasing infiltration rates at some sites while tillage alone was sufficient to improve infiltration at others (Haynes et al., 2013; Mohammadshirazi et al., 2017, 2016). Most studies on the effects of tillage and compost on improving soil conditions have only examined the effect of soil improvement methods for a few months after vegetation establishment without observing the effects over longer periods (Kranz et al., 2020) or have only assessed long-term effects on one soil type (Bazzoffi et al., 1998). Changing environmental conditions, such as vegetation dormancy, may impact infiltrability, soil water storage capacity, and overall hydrologic functioning of the soil (Leung et al., 2017), and different soils may respond differently to changing conditions depending on soil texture (Curtis and Claassen, 2009).

Soil infiltration is a critical factor when evaluating the efficiency of highway vegetative stormwater control measures (SCM) methods. Many roadside soils are highly disturbed and poorly structured as they are made up of imported soil “fill” and often lack topsoil (Mohammadshirazi et al., 2017). Moreover, these soils are often compacted by construction and maintenance activities. Therefore, quick and vigorous vegetation establishment is recommended to provide high infiltration rates and minimize post-construction stormwater runoff (Haynes et al., 2013).

Among various factors, vegetation plays a major role in altering the soil structure (Bengough et al., 2012) and soil hydrology (Ng et al., 2014) via roots, which are a key component in plant-related effects on soil hydraulic properties. Plant root penetration into the soil is known to alter the soil pore system (Ehler et al., 1983), which could modify soil structure (Angers & Caron, 1998) and subsequently affect the infiltration rate (Leung et al., 2017). However, contrasting and non-conclusive results have often been reported on the effects of roots on soil hydraulic conductivity.

Studies that have reported a decrease in soil infiltration under relatively young plants attributed the decrease primarily to macropore (MCP) clogging by roots under actively growing plants (Barley, 1954; Scanlan & Hinz, 2010; Leung et al., 2015). However, they also reported that decayed roots would create more macropores and enhance the soil hydraulic properties. In contrast, improved soil infiltration has been reported under vegetated soils compared to bare soil (Meek et al., 1992; Vergani & Graf, 2016; Leung et al., 2017), presumably due to development of macropores. Macropores may represent a small portion of the total porosity, but they control the water flow close to saturation, and may be responsible for more than 70% of the total water flow through soils (Watson & Luxmoore, 1986; Wilson & Luxmoore, 1988). Macropores may be created by either live or decayed roots, which appear to be the most important causes for preferential flow, even if not all the roots are necessarily associated with macropore formation (Perillo et al., 1999).

Root effects on soil hydraulic conductivity depend on the soil type and conditions (e.g. disturbance history) (Mohammadshirazi et al., 2017), vegetation type, root characteristics (Bodner, Leitner, & Kaul, 2014), and scale of measurement (Luxmoore, 1981). Due to the many factors regulating the relationship between root characteristics and soil hydraulic properties, measuring the effect of roots on soil hydraulic conductivity presents a unique challenge. Among a wide range of techniques and devices used to quantify the effects of plant roots on soil hydraulic properties is the disk infiltrometer (Dohnal et al., 2010). Disk infiltrometers are widely used for the determination of soil hydraulic properties (e.g., Zhang, 1997; Ronayne et al., 2012; Zhao et al., 2014) and characterizing water-conducting macro- and mesoporosity in surface soils (e.g., Watson & Luxmoore, 1986; Bodhinayake et al., 2004; Moret & Arrúe, 2007; Soracco et al., 2015). They are constructed to maintain adjustable negative (less than atmospheric) water pressure at the soil surface allowing elimination of flow in macropores larger than a specified pore size (the equivalent pore radius) (Angulo-Jaramillo et al., 2000).

An attractive choice recently available for measuring surface hydraulic properties is the mini-disk infiltrometer (MDI). Minidisk infiltrometers (MDI) have become popular due to their compact size and the small amount of water needed for their operation. The Decagon Devices (Pullman, WA, USA) mini-disk infiltrometer can be set to apply pressure heads from −0.5 to −6 cm at the soil surface (Decagon Devices, 2016). The volume of the water reservoir is about 100 mL. It should be noted that MDI measures hydraulic conductivity in a relatively small area. Hence, a large number of measurements are required for field monitoring due to the high variability of soil hydraulic properties (Dohnal et al., 2010).

Chapter 1: North Carolina Department of Transportation Wildflower Cover Analysis

1.1. Field Survey

Stands of two wildflower species, *Eschscholzia californica* and *Coreopsis lanceolata* (California poppy and lanceleaf coreopsis), were assessed at three field sites each managed by the North Carolina Department of Transportation (Figure 1.1). California poppy and Lanceleaf coreopsis plots were selected based on site location and availability. An example of a site is shown in Figure 1.2. Soil properties measured included bulk density, texture, and pH (Table 1.1). Soil textures were loam at Garner and sandy loam at both LaGrange and Goldsboro. The sites had similar soil pH, ranging from 5.9 to 6.0 across sites. The LaGrange site had greater bulk density than the other California poppy sites. The Morrisville 1 and 2 sites were located very close together but differed in landscape position. Morrisville 1 was the bottom of a hill, and Morrisville 2 was at the top of the hill (with a marshy area in between). Textures at the sites were loamy sand at Bethel and loam at both Morrisville 1 and 2. The pH at the Lanceleaf coreopsis sites varied more than for the California poppy sites; pH values ranged from 5.4-8.0 (Table 1.1). Soil bulk density was greater at Morrisville 1 and 2 compared to Bethel.

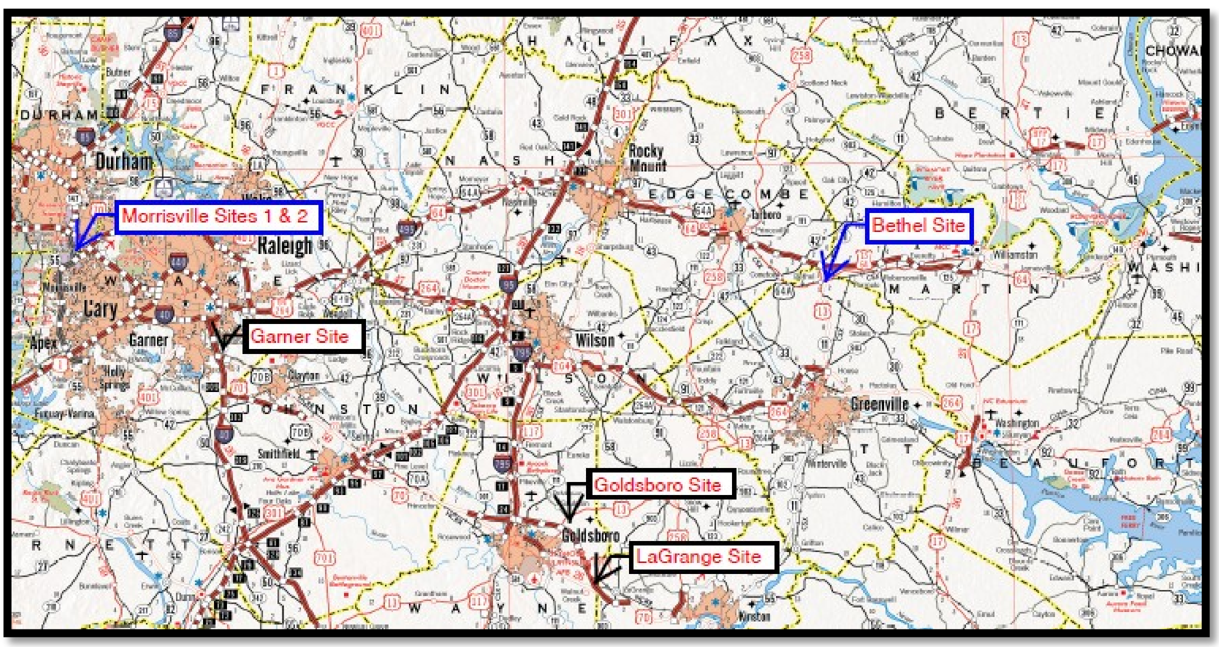

Figure 1.1: NCDOT State Transportation Map with Sampling Sites (NCDOT 2017b)

**Lanceleaf coreopsis sites in blue (Morrisville 1 and 2 and Bethel) and California poppy sites in black (Garner, Goldsboro, and LaGrange).*

Figure 1.2: Garner Sampling Site, 21 May 2018

Table 1.1: Particle Size Distribution, Texture Classifications, Average Bulk Density, and pH

**Significance denoted by letter ($p \leq 0.05$), species evaluated separately.*

California Poppy

Site	Percentage			USDA Classification	g /cm^3	
	Sand	**Silt**	**Clay**		**Bulk Density**	**pH**
Garner	51.9	34.1	14.0	Loam	1.32**b***	5.9
LaGrange	78.5	9.3	12.2	Sandy Loam	1.51**a**	6.0
Goldsboro	70.9	24.3	4.8	Sandy Loam	1.30b	5.9

Lanceleaf Coreopsis

Site	Percentage			USDA Classification	g /cm^3	
	Sand	**Silt**	**Clay**		**Bulk Density**	**pH**
Bethel	78.8	16.6	4.6	Loamy Sand	1.35**b**	5.4
Morrisville 1	41.9	41.1	17.0	Loam	1.56**a**	8.0
Morrisville 2	38.7	41.5	19.8	Loam	1.49**a**	7.4

Wildflower growth responses measured included canopy cover and rooting density. Lanceleaf coreopsis maintained high wildflower coverage (73.8% to 85.0%) and low weed coverage (0.0% to 4.6%), while California poppy coverage varied, but had relatively higher weed coverage ranging from 18.8% to 36.4% Tables 1.2 to 1.3). The effects of soil pH, texture, and bulk density on wildflower growth were inconclusive, with different results for each species.

Table 1.2: North Carolina Department of Transportation Site Canopy Cover by Wildflower, Weeds, and Total Coverage

**Significance denoted by letter ($p \leq 0.05$), species evaluated separately.*

California Poppy

	Percentage		
Location	**Wildflower**	**Weeds**	**Total Coverage**
Garner	57.9a*	36.3**a**	94.2**a**
LaGrange	20.4**b**	18.8**a**	39.2**a**
Goldsboro	40.0**ab**	34.2**a**	74.2**a**

Lanceleaf Coreopsis

	Percentage		
Location	**Wildflower**	**Weeds**	**Total Coverage**
Bethel	73.8**a**	0.4**b**	74.2**a**
Morrisville 1	85.0**a**	0.0**b**	85.0**a**
Morrisville 2	85.0**a**	4.6**a**	89.6**a**

Table 1.3: Average Root Density (mg / cm^3) 0cm to 7.62cm, 7.62cm to 15.24cm, and 0cm to 15.24cm for the Six North Carolina Department of Transportation Sites Separated by Species

**Significance denoted by letter ($p \leq 0.05$), species evaluated separately.*

California Poppy

	mg / cm^3		
DOT Site	**0cm to 7.62cm**	**7.62cm to 15.24cm**	**0cm to 15.24cm**
Garner	1.35**b**	0.52**b**	0.93**b**
LaGrange	1.11**b**	0.54**b**	0.82**b**
Goldsboro	1.86**a**	1.06**a**	1.96**a**

Lanceleaf Coreopsis

	mg / cm^3		
DOT Site	**0cm to 7.62cm**	**7.62cm to 15.24cm**	**0cm to 15.24cm**
Bethel	3.15**a**	0.60**b**	1.88**b**
Morrisville 1	4.88**a**	1.88**a**	3.38**a**
Morrisville 2	3.63**a**	0.77**b**	2.20**ab**

Overall, lanceleaf coreopsis had better wildflower coverage than California poppy and less weed coverage. Many soil factors influence wildflower growth and combine to form favorable or unfavorable growing conditions. In this study, only texture, bulk density and pH were tested. The observations from the field suggest California poppy may be more sensitive to bulk density, while lanceleaf coreopsis roots responded negatively to low pH.

1.2. Greenhouse Study

In order to study the response of wildflowers to different levels of soil compaction, research was conducted in a controlled greenhouse environment at North Carolina State University Horticulture Field Lab in Raleigh, NC. The experimental design was a complete randomized block design with three media conditions, three wildflowers, and two harvest dates for a total of 90 pots each trial. Two trials were conducted, one with media conditions that included a typical North Carolina subsoil (sandy loam) at bulk densities of 1.15-g.cm^{-3} and 1.35-g.cm^{-3}, as well as a potting substrate mix of sphagnum peat and perlite (4:1 ratio on a volume basis). For Trial 2, the subsoil at a bulk density of 1.50-g.cm^{-3} replaced the potting substrate. Soil was fertilized with Osmocote® Plus Outdoor and Indoor fertilizer (15-9-12) based on manufacturer's suggestions (2.28 g / pot).

Trial 1 included *Chamaecrista fasciculata* (partridge pea), *Eschscholzia californica* (California poppy), and *Coreopsis lanceolata* (lanceleaf coreopsis). For trial two, *Gaillardia aristata* (blanketflower) replaced partridge pea because it established well in the field and partridge pea did not grow well in the first trial. Seeds were planted on June 6, 2017, and March 30, 2018, for Trial 1 and 2, respectively.

A sandy loam subsoil (69% sand, 15% silt, 16% clay) from the Raleigh, NC, area was packed into 15.2cm x 30.5cm polyvinyl chloride (PVC) precast molds in 2cm to 3cm depths to achieve the desired compaction levels. Bulk densities of 1.15-g and 1.35-g.cm^{-3} were used in Trial 1, along with a potting substrate mix of sphagnum peat and perlite mixed on a volume basis at a 4:1 ratio (4831 g). For Trial 2, a bulk density of 1.50-g.cm^{-3} replaced the potting soil mix. The pots were watered with drip irrigation adjusted as needed for greenhouse conditions.

For Trial 1, there were two harvest dates planned for each species, pre- and post-flowering. For Trial 1, the second harvest date was much sooner for the partridge pea than the others as it began to senesce. Additionally, not all California poppies bloomed, and no lanceleaf coreopsis bloomed, perhaps because of the addition of shade cloth to the greenhouse in order to reduce daytime temperatures. The Trial 1 first harvest was August 6, 2017, for all species (40 days). The second harvest of partridge pea was September 11, 2017 (75 days), while the second harvest for California poppy and lanceleaf coreopsis was October 23, 2017 and October 24, 2017 (117 and 118 days), respectively.

For Trial 2, the first harvest was May 29th, and the second July 19, 2018 (61 and 112 days). The first harvest was a longer period than the first trial in order to accommodate slow germination and to facilitate more root growth than was found in the first trial. Roots were separated from the soil or potting mix in water and dried before being weighed (Figure 1.3).

Figure 1.3: Representative Pictures of Wildflowers in the Greenhouse, Washing Roots, and a Washed Root Sample

Results

For purposes of this report, the focus will be on the most relevant data to the overall objective of the project. Additional details and data can be found in Haselton, 2018.

The statistical analyses of the studies involved the two factors, species and soil, which sometimes had significant interactions (Tables 1.4 to 1.5). This indicated that the species reacted differently to the different soil conditions in which they were grown. These differences will be discussed as the results are presented. For the most part, difference that occurred at the first harvest were still present in the second harvest, so we will focus on the second harvest results.

Table 1.4: Trial 1 ANOVA P-Values

**Significance assessed at a = 0.05. 1st and 2nd indicate the first and second harvests for the trial.*

	Root Density		Root:Shoot		Shoot Mass		Height	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Species	0.2655	<0.0001	0.8652	<0.0001	0.0024	<0.0001	<0.0001	<0.0001
Soil	<0.0001	0.1959	0.0004	0.6778	<0.0001	0.029	<0.0001	0.0026
Species x Soil	0.2827	0.6181	0.0603	0.5775	0.0023	0.0166	0.0099	0.0951

Table 1.5: Trial 2 ANOVA P-Values

**Significance assessed at a = 0.05. 1st and 2nd indicate the first and second harvests for the trial.*

	Root Density		Root:Shoot		Shoot Mass		Height	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Species	0.7093	0.0006	0.6204	0.1368	0.0717	<0.000	<0.0001	n/a
Soil	0.4963	0.4108	0.0449	0.0404	0.0091	0.4456	0.0621	n/a
Species x Soil	0.01	0.4046	0.5102	0.3237	0.0316	0.8639	0.0964	n/a

For Trial 1, the plants growing in the potting soil exhibited the lowest shoot growth in the first harvest, and this remained for lanceleaf coreopsis and partridge pea at the second harvest (Figure 1.4). There was some evidence of lanceleaf coreopsis and partridge pea having opposite responses to soil bulk density, but this was not statistically significant.

Lanceleaf coreopsis had the greatest root density of the three species, but partridge pea was the tallest (Figure 1.5). The resulting root:shoot ratio illustrates the different growth habits of each species (Figure 1.6), with partridge pea having the smallest root system relative to shoot mass.

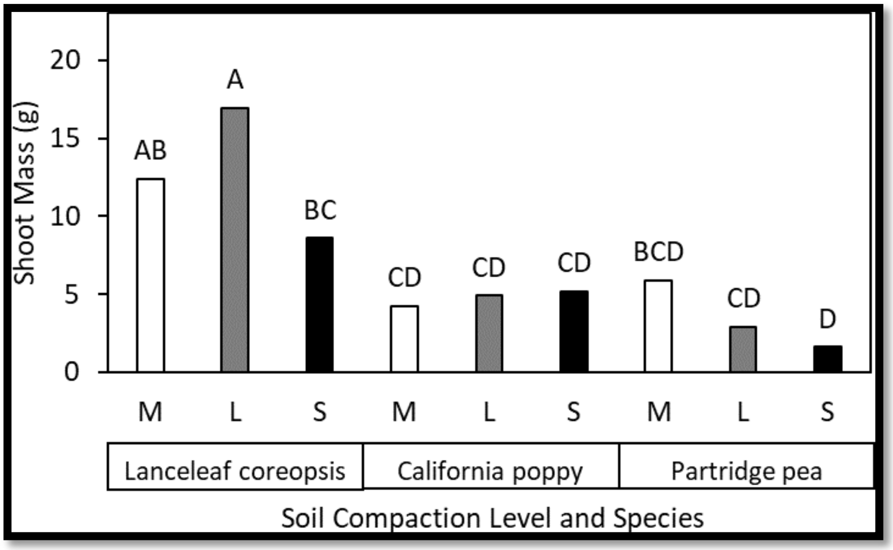

Figure 1.4: Trial 1 Harvest 2 Shoot Mass

**Soil density levels at mid-density (M), low-density (L), and potting soil mix (S). Different letters above the bars indicates significant differences (p≤0.05).*

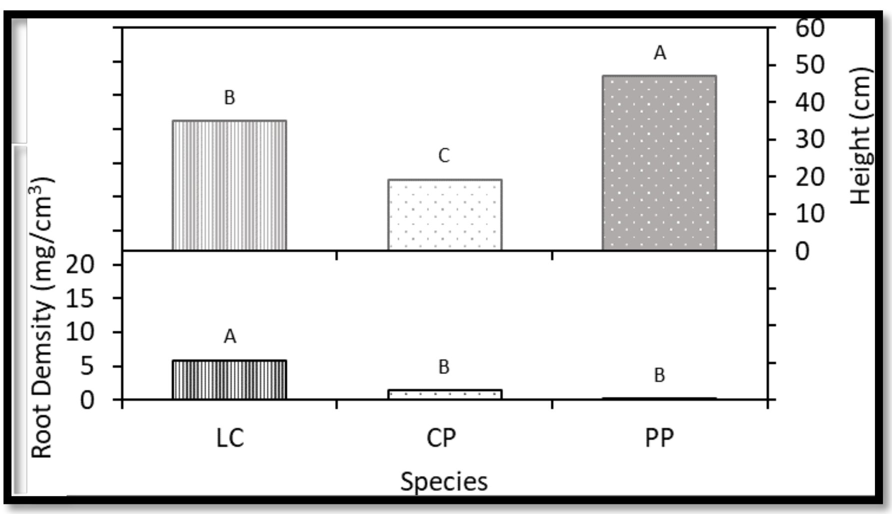

Figure 1.5: Trial 2 Harvest 2 Root Density and Height

**Species are lanceleaf coreopsis (LC), California poppy (CP), partridge pea (PP). Different letters above the bars indicates significant differences (p≤0.05) within each metric.*

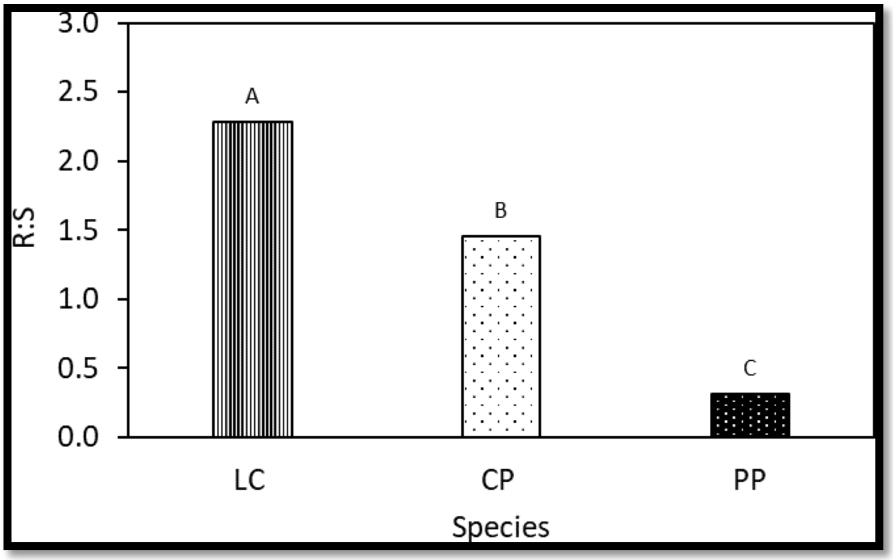

Figure 1.6: Trial 1 Harvest 2 Root:Shoot (R:S) ratio.

**Species are lanceleaf coreopsis (LC), California poppy (CP), partridge pea (PP). Different letters above the bars indicate significant differences (p≤0.05).*

Overall, lanceleaf coreopsis was the most robust of the three species, but none of them appeared to be particularly sensitive to soil compaction at the two levels tested in Trial 1. Trial 2 included a slightly higher compaction level (1.5-g.cm^3), but again the three species did not respond to differences in compaction level (Table 1.5), so we will just discuss the species responses. Shoot growth was different among the three, with lanceleaf coreopsis>blanketflower>California poppy (Figure 1.6). Lanceleaf coreopsis and blanketflower had similar root mass and both were larger than that of the California poppy (Figure 1.8). Across species, the high bulk density reduced the root:shoot ratio compared to the medium bulk density, with the low bulk density in between (Figure 1.9).

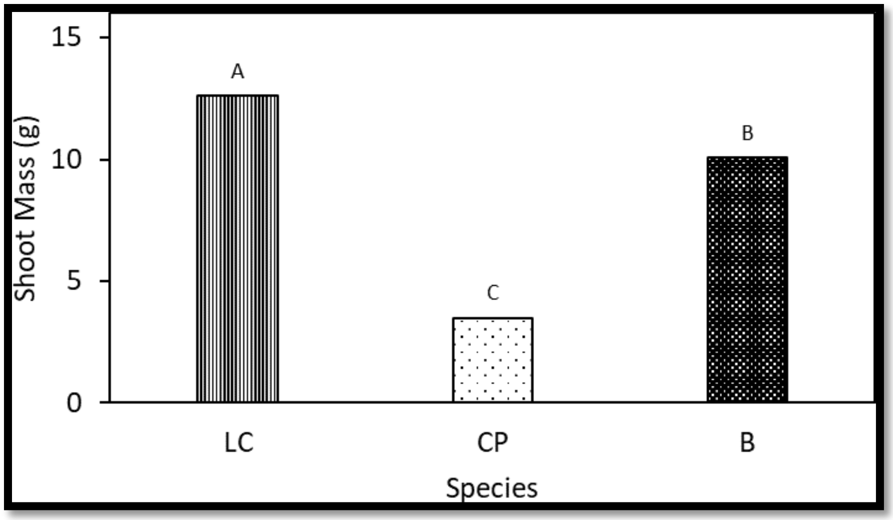

Figure 1.7: Trial 2 Harvest 2 Shoot Mass

**Species are lanceleaf coreopsis (LC), California poppy (CP), blanketflower (B). Different letters above the bars indicates significant differences (p≤0.05).*

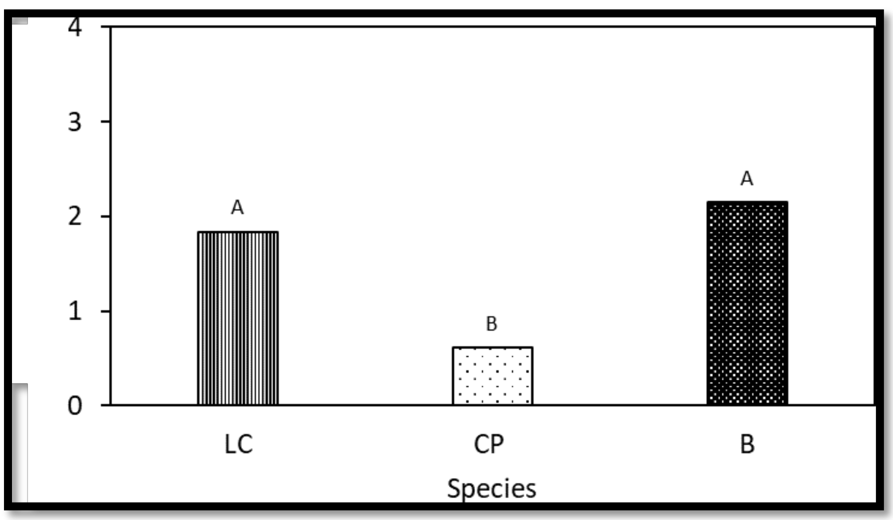

Figure 1.8: Trial 2 Harvest 2 Root Density

**Species are lanceleaf coreopsis (LC), California poppy (CP), blanketflower (B). Different letters above the bars indicates significant differences (p≤0.05).*

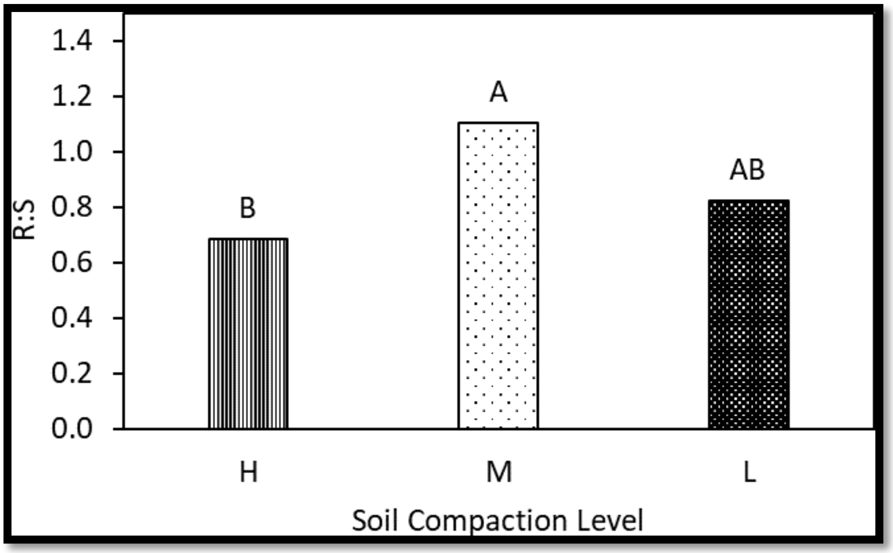

Figure 1.9: Trial 2 Harvest 2 Root:Shoot (R:S) ratio.

**Soil density levels at high-density (H), mid-density (M), and low-density (L). Different letters above the bars indicates significant differences ($p \leq 0.05$).*

The effects of soil density were relatively minor and lessened as time passed, while species effect was significant for both root growth and above-ground growth. Overall, the results indicate that the wildflower species studied are not affected by soil density over a moderate range of density conditions, supporting the potential for their use on roadsides. These data also suggest that perennials, particularly the lanceleaf coreopsis and blanketflower we tested, could be as beneficial as annuals for fast establishment based on growth metrics. However, annuals may be needed to provide flowering over a wider range of time as a benefit to pollinators.

1.3. Field Plot Study

In Fall 2016, three complete randomized designed field studies were established at sites across North Carolina. Sites were selected from each of the main geographic regions of North Carolina: Coastal Plains, Piedmont, and Mountains. In this study, eight wildflower plots were evaluated at each site. The fields were located at the Central Crops (Clayton), Sediment and Erosion Control Research and Education Facility (Raleigh), and Mountain Horticultural Crops (Mills River) research stations, and were established on October 25th, 12th, and 7th, respectively. The texture of the soils ranged from a clay loam to sandy clay loam determined using the hydrometer method (Table 1.6) (Gee and Bauder, 1983). The pH for the compost amended soils ranged from 6.3 to 7.0 while the non-compost pH ranged from 5.2-6.8 (Table 1.6). The plots were tilled to approximately 15cm and then amended with fertilizer (10-20-20; 500 lb ac^{-1}), lime (2,000 lb ac^{-1}), and compost (2” layer) in the compost treated plots, and tilled again. No herbicide was used to control weeds except at Clayton in spring 2017 where a selective grass herbicide was used to control excessive volunteer rye grass.

Table 1.6: Site Soil Characteristics

Location	pH (H_2O 1:1)		Texture	Percentage		
	Compost	Non-Compost		Sand	Silt	Clay
Raleigh	7.0	6.8	Sandy Clay Loam	50.2	20.9	28.9
Clayton	6.3	5.3	Loamy Sand	82.1	13.8	4.1
Mills River	6.7	5.2	Clay Loam	42.0	23.1	34.8

After the plots were prepared, the plots were seeded with the Pollinator Wildflower Seed Mix (Southeast region) (48 kg ha^{-1}; 42 lb ac^{-1}) from American Meadows, Inc. (Shelburne, Vermont) (Table 1.7). For Fall 2017, the fields were over-seeded with *Trifolium incarnatum* (crimson clover) (4.5kg / acre) and the Southeast Wildflower Seed Mix (48 kg ha^{-1}; 42 lb ac^{-1}) from American Meadows, Inc. (Shelburne, Vermont), as the original mix was no longer available (Table 1.8). Plots were broadcast seeded by hand. At the initial seeding, plots were covered with an erosion blanket.

Table 1.7: Scientific and Common Names for Pollinator Wildflower Seed Mix (Southeast Region

**From American Meadows, Inc., Shelburne, Vermont, along with the life cycle.*

Scientific Name	Common Name	Life Cycle
Asclepias tuberosa	Butterfly Milkweed	Perennial
Chamaecrista fasciculata	Patridge Pea	Annual
Coreopsis lanceolata	Lance Leaved Coreopsis	Perennial
Coreopsis tinctoria	Plains Coreopsis	Annual
Cosmos bipinnatus	Cosmos Sensation Mix	Annual
Echinacea purpurea	Purple Coneflower	Perennial
Eschscholzia californica	California Poppy	Annual
Gaillardia aristata	Blanket Flower	Perennial
Helianthus annuus	Dwarf Sunspot Sunflower	Annual
Limnanthes douglasii	Meadow Foam	Annual
Lupinus hartwegii	Dwarf Lupine Pixie Delight Mix	Annual
Lupinus perennis	Perennial Lupine	Perennial
Lupinus succulentus	Arroyo Lupine	Annual
Monarda fistulosa	Bee Balm / Wild Bergamont	Perennial
Phacelia tanacetifolia	Lacy Phacelia	Annual
Ratibida columnaris	Mexican Hat	Perennial
Trifolium incarnatum	Crimson Clover	Annual

Table 1.8: Scientific and Common Names for the Southeast Wildflower Seed Mix

**From American Meadows, Inc., Shelburne, Vermont, along with life cycle.*

Scientific Name	Common Name	Life Cycle
Cheiranthus allionii	Siberian Wallflower	Perennial
Chrysanthemum maximum	Shasta Daisy	Perennial
Coreopsis lanceolata	Lance-Leaf Coreopsis	Perennial
Coreopsis tinctoria	Plains Coreopsis	Annual
Cosmos bipinnatus	Wild Cosmos	Annual
Cynoglossum amabile	Chinese Forget-Me-Not	Annual
Dianthus barbatus	Sweet William	Biennial
Echinacea purpurea	Purple Coneflower	Perennial
Eschscholzia californica	California Poppy	Annual
Gilia capitata	Globe Gilia	Annual
Gaillardia pulchella	Indian Blanket	Annual
Gysophila elegans	Baby's Breath	Annual
Lavatera trimestris	Rose Mallow	Annual
Liatris spicata	Blazing Star or Gayfeather	Perennial
Linum grandiflorum rubrum	Scarlet Flax	Annual
Linum perenne lewisii	Blue Flax	Perennial
Lobularia maritima	Sweet Alyssum	Annual
Lupinus perennis	Wild Lupine	Perennial
Lupinus texensis	Texas Bluebonnet	Annual
Oenothera lamarckiana	Evening Primrose	Biennial
Papaver rhoeas	Red Poppy / Shirley Poppy	Annual
Phlox drummondi	Drummond Phlox	Annual
Rudbeckia amplexicaulis	Clasping Coneflower	Annual
Rudbeckia hirta	Black-eyed Susan	Perennial
Rudbeckia gloriosa	Gloriosa Daisy	Perennial
Salvia coccinea	Scarlet Sage	Perennial

Results

The sites had very different amounts of wildflowers, weeds, and total cover in the first sampling in 2017 (Table 1.9). Clayton and Mills River had similar total cover, but most of it was in weeds at Clayton, primarily ryegrass. At the first sampling in 2018, the second year of the plots, the total cover was similar at the Raleigh and Mills River sites, but much lower at the Clayton site due to herbicide treatment to reduce the volunteer ryegrass. Only 20% to 30% of the cover was in the planted wildflowers among all of the sites. The effect of compost incorporation on the species composition was tested at this first 2018 sampling, and compost appeared to reduce wildflowers in favor of weeds (Table 1.11). This may have been a result of the relatively high fertility in these plots, which may have given the weeds a growth advantage as wildflowers typically do not need high fertility. It should be noted the compost effect was primarily at the Mills River site.

Table 1.9: Simple Effects of Site on Weed and Total Cover, 2017

**Differences noted by differing letters (p≤0.05) across rows.*

	Site		
Cover Type	**Raleigh %**	**Clayton %**	**Mills River %**
Weeds	12.9**c***	79.0**a**	45.8**b**
Total Cover	31.3**b**	84.7**a**	75.2**a**

Table 1.10: Simple Effects of Site on Wildflower and Total Cover Sample Period 2 (2018)

**Differences noted by differing letters (p≤0.05) across rows.*

	Site		
Cover Type	**Raleigh %**	**Clayton %**	**Mills River %**
Wildflower	25.1**ab***	8.3**b**	32.8**a**
Total Cover	70.1**a**	49.0**b**	73.2**a**

Table 1.11: Simple Effects of Treatment on Wildflower and Weed Cover at Sampling Period 1 (2018)

**Differences noted by differing letters (p≤0.05) across rows.*

	Treatment	
Cover Type	**Compost %**	**Non-Compost %**
Wildflower	11.18**b***	33.0**a**
Weed	56.4**a**	27.6**b**

In 2017 and 2018, the species present in the plots was determined. In 2017, there were seven planted species at the Raleigh and Mills River sites and only three at Clayton (Table 1.12). Lanceleaf coreopsis, blanketflower, and California poppy were present at all three sites in 2017, and bee balm, Mexican hat, and plains coreopsis were present at Raleigh and Mills River. After a second seed application in Fall 2017, many other species were present in 2018. Over the two seedings, 35 species were planted, yet only 10 to 12 were present in 2018. This suggests that species selection is very important since the majority of the species in the mixes never became established. Field observations suggested that the lanceleaf coreopsis, blanketflower, bee balm, and Mexican hat were the dominant species.

Table 1.12: Observed Species at Each Site

**2017 marked by ☐ and 2018 by x.*

Perennial Species

Species	Site		
	Raleigh	Clayton	Mills River
Coreopsis lanceolata	☐ *x*	☐ *x*	☐ *x*
Gaillardia spp.	☐ *x*	☐ *x*	☐ *x*
Monarda fistulosa	☐ *x*	*x*	☐ *x*
Ratibida columnifera	☐ *x*	*x*	☐ *x*
Rudbeckia gloriosa		*x*	*x*
Rudbeckia hirta	*x*	*x*	*x*
Lupinus spp.	*x*	*x*	*x*

Annual Species

Species	Site		
	Raleigh	Clayton	Mills River
Cosmos bipinnatus	*x*	*x*	
Helianthus annus	*x*	*x*	☐
Phacelia tanacetifolia	☐	*x*	*x*
Coreopsis tinctoria	☐ *x*		☐
Eschscholzia californica	☐ *x*	☐ *x*	☐ *x*
Trifolium incarnatum	*x*	*x*	*x*

1.4. Conclusions: Wildflower Study

The use of wildflowers along roadsides and on construction sites appears promising; however, the benefits of compost remain uncertain based on our results. The NCDOT field study revealed that existing wildflower plantings persist in adverse conditions while the species grown in the greenhouse exhibited potential for plantings in compacted soils. The compost study exposed new and continued opportunities for research although compost had little effect on wildflower growth as measured. Compost plots sometimes had higher weed cover and lower wildflower cover, either due to weed seeds introduced with the compost or weed responses to the compost. In this study, site was often significant when evaluating cover, thus site-specific recommendations regarding management and species selection could be beneficial.

We found that the species studied exhibit more sensitivity to low pH than high pH, which should be considered when planning wildflower plantings and managing them. Given the low number of species present in the wildflower plots, consideration should be given to choosing the species most suited for the site, as opposed to using a prepackaged mix. Our results in the field and greenhouse indicate that perennial wildflower species can establish and provide substantial cover in the field equal to or greater than that of annual species in our seed mixes. This potentially expands the list of suitable wildflowers and suggests that annual wildflowers are not needed as nurse crops for perennials species.

Chapter 2: Effects of Tillage, Compost, and Vegetation Type on Soil Properties

2.1. Wildflowers Root Effects on Soil Hydraulic Conductivity: A Greenhouse Experiment

Introduction

Soil infiltration is a critical factor when evaluating the efficiency of highway vegetative stormwater control measures (SCM) methods. Many roadside soils are highly disturbed and poorly structured as they are made up of imported soil “fill” and often lack topsoil (Mohammadshirazi et al., 2017). Moreover, these soils are often compacted by construction and maintenance activities. Therefore, quick and vigorous vegetation establishment is recommended to provide high infiltration rates and minimize post-construction stormwater runoff (Haynes et al., 2013).

Among various factors, vegetation plays a major role in altering the soil structure (Bengough et al., 2012) and soil hydrology (Ng et al., 2014) via roots, which are a key component in plant-related effects on soil hydraulic properties. Plant root penetration into the soil is known to alter the soil pore system (Ehler et al., 1983), which could modify soil structure (Angers & Caron, 1998) and subsequently affect the infiltration rate (Leung et al., 2017). However, contrasting and non-conclusive results have often been reported on the effects of roots on soil hydraulic conductivity. Studies that have reported a decrease in soil infiltration under relatively young plants attributed the decrease primarily to macropore (MCP) clogging by roots under actively growing plants (Barley, 1954; Scanlan & Hinz, 2010; Leung et al., 2015). However, they also reported that decayed roots would create more macropores and enhance the soil hydraulic properties. In contrast, improved soil infiltration has been reported under vegetated soils compared to bare soil (Meek et al., 1992; Vergani & Graf, 2016; Leung et al., 2017), presumably due to development of macropores. Macropores may represent a small portion of the total porosity, but they control the water flow close to saturation, and may be responsible for more than 70% of the total water flow through soils (Watson & Luxmoore, 1986; Wilson & Luxmoore, 1988). Macropores may be created by either live or decayed roots, which appear to be the most important causes for preferential flow, even if not all the roots are necessarily associated with macropore formation (Perilloet al., 1999).

Root effects on soil hydraulic conductivity depend on the soil type and conditions (e.g., disturbance history) (Mohammadshirazi et al., 2017), vegetation type, root characteristics (Bodner, Leitner, & Kaul, 2014), and scale of measurement (Luxmoore, 1981). Due to the many factors regulating the relationship between root characteristics and soil hydraulic properties, measuring the effect of roots on soil hydraulic conductivity presents a unique challenge. Among a wide range of techniques and devices used to quantify the effects of plant roots on soil hydraulic properties is the disk infiltrometer (Dohnal et al., 2010). Disk infiltrometers are widely used for the determination of soil hydraulic properties (e.g., Zhang, 1997; Ronayne et al., 2012; Zhao et al., 2014) and characterizing water-conducting macro- and mesoporosity in surface soils (e.g., Watson & Luxmoore, 1986; Bodhinayake et al., 2004; Moret & Arrúe, 2007; Soracco et al., 2015). They are constructed to maintain adjustable negative (less than atmospheric) water pressure at the soil surface allowing elimination of flow in macropores larger than a specified pore size (the equivalent pore radius) (Angulo-Jaramillo et al., 2000).

An attractive choice recently available for measuring surface hydraulic properties is the mini-disk infiltrometer (MDI). Minidisk infiltrometers (MDI) have become popular due to their compact size and the small amount of water needed for their operation. The Decagon Devices (Pullman, WA, USA) mini-disk infiltrometer can be set to apply pressure heads from −0.5 to −6 cm at the soil surface (Decagon Devices, 2016). The volume of the water reservoir is about 100 mL. It should be noted that MDI measures hydraulic conductivity in a relatively small area. Hence, a large number of measurements are required for field monitoring due to the high variability of soil hydraulic properties (Dohnal et al., 2010).

While there is a significant body of knowledge on soil-root interaction and how roots modify the soil hydraulic conductivity and pore system, we recognized two shortcomings: (i) most studies were focused on the roots-soil infiltrating interaction under saturated conditions where macropore flow alone is dominant, masking the contribution of smaller pores when unsaturated condition existed; and (ii) species specific root-soil effects are rarely evaluated under the same soil with different compaction levels.

The objectives of our study were to:

i. quantify the effects of two wildflower species with contrasting root systems (tap vs fibrous roots) on soil hydraulic conductivity during early establishment;

ii. determine the effects of actively growing roots on the soil pore system; and

iii. evaluate the effects of soil compaction levels on the soil hydraulic conductivity between and within the selected species.

2.2. Greenhouse Infiltration Study

Two wildflowers species were tested, lanceleaf coreopsis (*Coreopsis lanceolata*) and partridge pea (*Chamaecrista fasciculate*), which represent two plants with contrasting root systems. The lanceleaf coreopsis (LC) is a perennial species with a fibrous root system, and the partridge pea (PP) is an annual species with a tap root system**.** These species were selected because they are native wildflowers found throughout much of the United States, grow well in disturbed and infertile soils (USDA- NRCS, 2012), and they are listed in the North Carolina roadside wildflowers booklet.

The plants were established from seed in cylindrical polyvinyl chloride (PVC) pots (M.A. Industries Incorporated, Peachtree City, GA) with 15cm diameter and 35cm height. Sandy loam fill soil (69% sand, 15% silt, 16% clay) from a construction site near Raleigh, NC was used to fill the pots in increments of 5cm until the targeted soil thickness (30cm) and bulk density (1.15 or 1.35-g.cm^{-3}) were achieved. For the higher bulk density pots, the soil was manually compacted after each layer was added. The lower bulk density represents a bulk density for a recently tilled soil (loose) while the higher bulk density represents post-tillage settled soil (compacted). For simplicity, we hereafter refer to bulk densities of 1.15-g.cm^{-3} and 1.35-g.cm^{-3} as non-compacted and compacted, respectively.

Measurements on plants and soil were made after two growing periods; 40 days and again at either 80 days for the PP or 120 days for the LC. Five replicates for each species plus control (bare soil), each at two bulk density levels, accounting for 60 total pots, were arranged in a completely randomized block design. Control pots were treated the same way as the planted pots. Fertilizer was added and mixed with soil before planting seeds according to North Carolina Department of

Transportation wildflower program guidelines (NCDOT, 2012). Five replicates for each condition were measured at each growth period; pots used in the first growth period were not reused.

At the end of each growing period, before the hydraulic conductivity measurement, the effective height of the soil in the pot was measured to account for soil setting and to calculate the bulk density. A minidisk infiltrometer (MDI) was used to estimate the hydraulic conductivity (Decagon Devices Inc. 2012; Vergani and Graf 2016).

One hydraulic conductivity measurement was taken per pot for both planted and control pots every 40 days at a constant distance from the plant stem (2.5 cm). Hydraulic conductivity measurement at h = -0.5 cm was chosen to represent conditions as close as possible to saturation, followed by hydraulic conductivity measurements at h = -3 and -6cm, applied in this order to the same area. Conductivity between the -0.5cm and -3cm is considered macropore flow, while that between -3cm and -6 cm is mesopore flow. This corresponds to pore radii of between 0.3cm and 0.05cm, and between 0.05 and 0.025 cm, respectively.

To account for different soil compaction levels due to the soil settling over time and to compare the hydraulic conductivity results at different plant ages, normalized hydraulic conductivity values were used for all tensions by dividing each hydraulic conductivity value by the average of the corresponding control pots (Vergani & Graf, 2016):

After the hydraulic conductivity tests, each species roots were carefully excavated from the pots, washed, and cleaned with water and collected over a 2mm sieve. Roots were oven dried at 65^{o}C for 48 hours, weighed, and used as a plant growth indicator. Root density was then calculated for each species.

Results and Discussion

The effects of plant species, compaction level, and time were varied, but generally the presence of a plant (as opposed to the control bare soil) and increased bulk density had negative impacts on hydraulic conductivity (HC). For partridge pea, in both non-compacted (Figure 2.1) and compacted (Figure 2.2) soil, after 80 days of growth the HC was less compared to bare soil, sometimes significantly. For lanceleaf coreopsis, the effect changed over the 120 days, sometimes positive and sometimes negative (Figures 2.3 and 2.4).

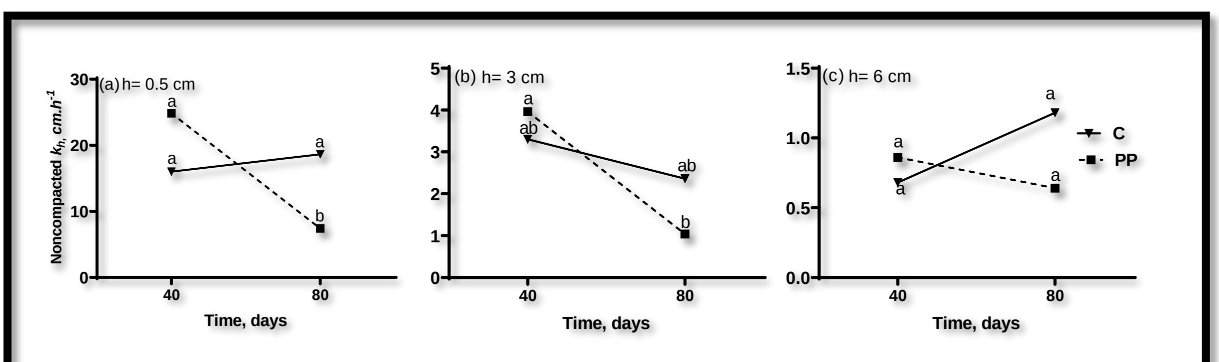

Figure 2.1: Hydraulic Conductivity

**Over time for the control (C) and partridge pea (PP) under non-compacted soil at tensions (h) (a) h = 0.5cm, (b) h = 3cm, and (c) h = 6cm. Significant differences (p<0.05) are indicated if values do not share a letter.*

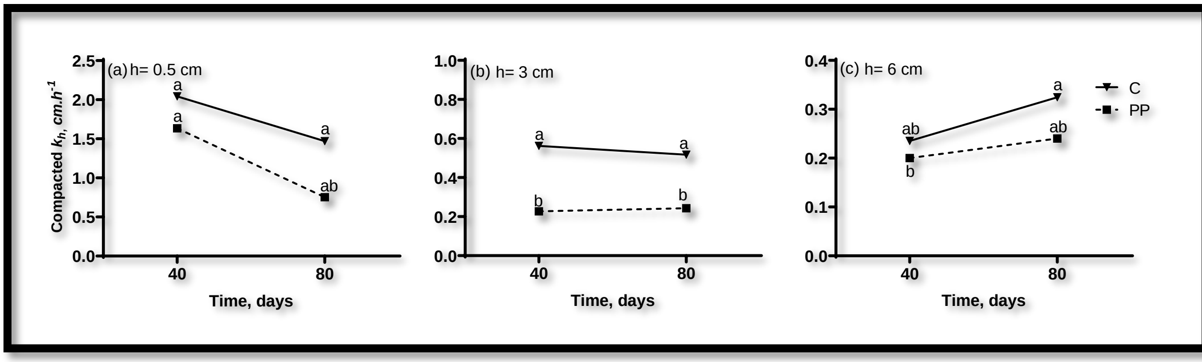

Figure 2.2: Hydraulic Conductivity

**Over time for the control (C) and partridge pea (PP) under compacted soil at tensions (h), (a) h = 0.5cm, (b) h = 3cm, and (c) h = 6cm. Symbols with different letter in a column differ at P≤0.05.*

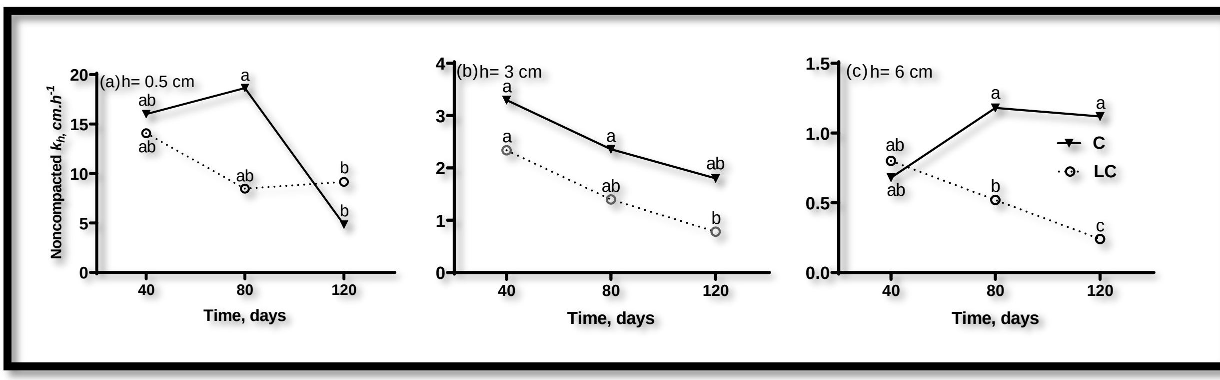

Figure 2.3: Hydraulic Conductivity

**Over time for the control and Lanceleaf coreopsis (LC) under non-compacted soil at tensions () (a) h = 0.5cm, (b) h = 3cm, and (c) h = 6cm. Symbols with different letter in a column differ at P≤0.05.*

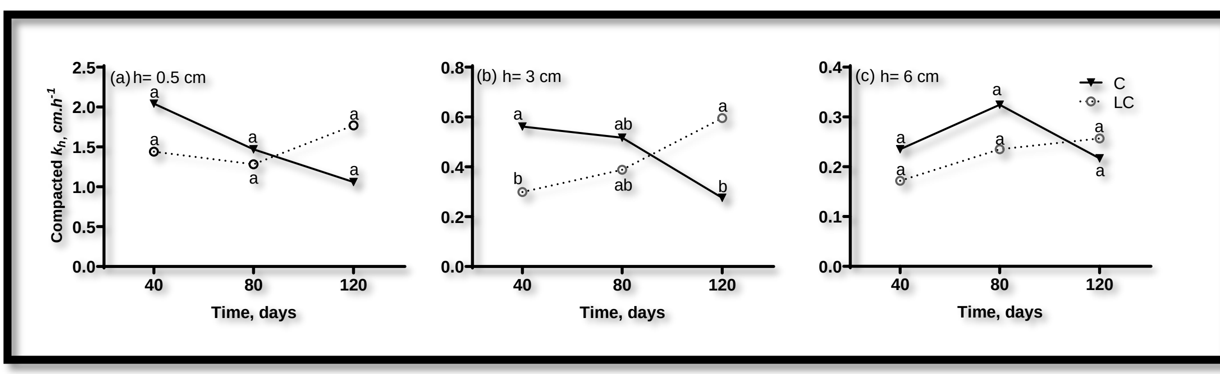

Figure 2.4: Hydraulic Conductivity

**Over time for the control (C) and Lanceleaf coreopsis (LC) under compacted soil at tensions (h) (a) h = 0.5cm, (b) h = 3cm, and (c) = 6cm. Symbols with different letter in a column differ at P≤0.05.*

Our results show contrasting effects of root growth on soil hydraulic conductivity. Under the noncompacted soil condition, we found a reduction of hydraulic conductivity at all tensions over time and relatively lower conductivity than for the control. In contrast, the hydraulic conductivity increased with plant growth under the compacted conditions when the root growth was significant over time, particularly under the LC treatment. Several contrasting observations were reported in different studies that focus on relatively young plants to quantify the relationship between the active root growth and soil hydraulic properties. For example, Leung et al. (2015) reported a lower hydraulic conductivity under vegetated soil (grass) than bare soil and found the difference of hydraulic conductivity between the vegetated and bare soil could be as large as 100% at the beginning of testing. Another study reported a reduction in hydraulic conductivity by 40% after two months of growth under cotton (Meek et al., 1990). On the other hand, Leung et al. (2017) found increased hydraulic conductivity induced by root growth by up to an order of magnitude compared with bare soil during early plant establishment.

The nature of the relationship between the hydraulic conductivity and root growth appeared to be controlled by both soil conditions and root characteristics. There could be two different mechanisms induced by root growth. Under the noncompacted (loose) soil, in addition to soil settling, we hypothesized a temporal pore-clogging mechanism (Morgan et al., 1995) or division of the larger pores into smaller pores due to root growth into existing pores (Scanlan & Hinz, 2010). In compacted soil, a biological drilling mechanism by the root growth has been proposed, and penetrating the soil matrix can cause enlargement of existing pores while compressing adjacent soil pores (Cresswell & Kirkegaard, 1995; Bengough, 2012). During soil penetration, roots exert axial and radial pressures, pushing aside soil particles creating a continuous pore system and channels that affect hydraulic conductivity.

In our study, the soil was extremely disturbed and structureless, particularly under the compacted condition due to the preparation steps (excavation, sieving, and compacting), leaving the soil with minimal existence of fast draining pores (meso and macropores) or even disconnected pores. Therefore, introducing plants to such soils may ameliorate the soil pore system, enhancing hydraulic properties and conditioning the soil for subsequent plants.

It was expected that hydraulic conductivity in the compacted soil would increase under the PP due its coarser roots system that would increase the macroporosity, as compared to the LC with a dense, finer root system that might decrease the macropores volume by occupying more space in the macropores range. The shallow PP observed roots in our experiment probably had limited effectiveness in the pots. The deeper LC roots may have been able to alter the soil pore distribution by increasing the mesoporosity volume and creating interconnected root channels, as was reflected in the hydraulic conductivity at the end of the experiment. This highlights the capacity of the root system to improve soil hydraulic properties during a short period in compacted soils. The increase in hydraulic conductivity was more prominent under lower tensions (unsaturated conditions) within the mesopore range.

Despite the considerable role of the macropore flow in soil saturated hydraulic conductivity, it is important to note that the nature of the rainfall events is often of a low intensity, and the soil surface may remain unsaturated and pre-ponding conditions can prevail for considerable periods. Therefore, mesopore flow becomes crucial in infiltrating stormwater and therefore, reducing runoff and erosion.

2.3. Effect of Vegetation Type and Compost Amendment on Disturbed Soil Properties Over Time

Introduction

Urban stormwater runoff often contains a wide variety of sediments and pollutants generated from transportation and non-transportation activities (Kayhanian et al., 2019), and runoff from impervious highways can degrade environmental conditions in adjacent waterbodies (Walsh et al., 2005). Management of stormwater runoff from highways is an essential and integral component of highway design (NCDOT, 2015), and transportation agencies are always searching for cost-effective, efficient, and low-maintenance methods to manage and treat stormwater runoff and meet regulatory requirements (Henderson et al., 2016).

Roadside vegetation plays a critical role in decreasing runoff and associated pollutants by improving the soil hydraulic conditions. Vegetation improves soil function by increasing infiltration, which reduces runoff volumes and pollutant concentrations in runoff (Popov et al., 2006). Therefore a vigorous vegetation stand is critical to maintain high infiltration when managing urban soils to reduce runoff volumes from paved highways (Haynes et al., 2013). During road construction, roadside soils are disturbed, excavated or graded, and compacted. In many cases, the existing topsoil is totally removed, reducing soil quality and fertility, and limiting future plant establishment (Risse and Faucette, 2009; Mohammadshirazi et al., 2017). As a result, conditioning the soil prior to vegetation establishment is essential to improve soil physical properties and plant growth. From agricultural tillage studies (Meek et al., 1992) to reforestation (Greenwood & Buttle, 2014) and mine soil reclamation (Gao-Lin et al., 2016) projects, soil conditioning practices are increasingly recognized as essential tools to restore landscapes environmental services altered by human activities.

Tillage can be used to improve the physical properties of compacted soils. Primarily, tillage loosens the soil surface by breaking the massive structures, thus increasing soil pore space and allowing water to infiltrate and roots to penetrate through the soil profile (Loper et al., 2010).

Additionally, organic additions to soil have long been considered important in maintaining the quality of both natural and managed soils (Adugna, 2016). The addition of organic amendments such as compost or manure to soils can help to stabilize soil structure (Thomas et al., 1996), improve soil physical (Aggelides & Londra, 2000) and chemical properties (Loper et al., 2010), and enhance plant growth (Cogger, 2005). Tillage and compost were reported individually or together in experimental field plots that have been constructed to simulate construction sites and residential landscapes, and they were found to be effective in increasing infiltration rate in actual or simulated construction sites (Haynes et al., 2013; Olson et al., 2013; Mohammadshirazi et al., 2017).

Grass is the dominant groundcover used in roadside areas. It is generally planted for rapid growth, soil stabilization, erosion prevention and to provide a perennial and year-round landscape. However, over the last few decade, many responsible agencies have sought to incorporate wildflowers into new roadside plantings to achieve alternative management objectives (Hopwood et al., 2015). North Carolina Department of Transportation (NCDOT) has incorporated wildflowers in roadside areas since 1985 as part of highway beautification programs (NCDOT, 2012). Wildflower meadows provide ecological, economical, and aesthetic benefits (Ahern et al., 1992) and offer ecosystem services to local plant populations in terms of climate regulation, pollination, and improvement in soil and air quality (Aldrich, 2002; Norcini & Aldrich, 2004).

Despite the amount of literature that exists on the subject of wildflowers integration into urban and roadside areas, no studies have yet quantified the impact of wildflowers on stormwater infiltration compared to grasses. We conducted field experiments for 30 months in three different locations at North Carolina representing Coastal Plain, Piedmont, and Mountain geographic regions to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflowers. The bulk density, infiltration rate, and root mass density and distribution were evaluated to:

i. quantify the potential improvements in infiltration through the use of tillage alone or together with compost; and

ii. evaluate the use of wildflowers as an alternative vegetation to grass in stormwater infiltration zones.

Materials and Methods

Sites Description and Preparation

Field plots were constructed at three sites in North Carolina representing Coastal Plain (CP), Piedmont (PD), and Mountain (MT) geographic regions of North Carolina. Experiments were located at the Central Crops Research Station (Clayton), Lake Wheeler Road Field Laboratory (Raleigh), and Mountain Horticulture Crops Research Station (Mills River), respectively. The sites mapped as Cecil (Fine, kaolinitic, thermic Typic Kanhapludults), Wagram (Loamy, kaolinitic, thermic Arenic Kandiudults), and Bradson (Clayey, parasesquic, mesic Typic Hapludults) for CP, PD, and MT sites, respectively (Soil Survey Staff, 2016). Composite soil samples (0cm to 15cm depth) were collected from each site for texture analysis. The soil texture was determined using a hydrometer method (Gee and Bauder, 1983) and ranged from clay loam to sandy clay loam (**Error! Reference source not found.**). Plot preparation at all sites was similar. Coastal Plain, PD, and MT plots were established in fall 2016 on 7, 25, and 25 October, respectively. Existing vegetation was incorporated by tilling the soil to approximately 15cm depth using a rotary tiller. At the MT site only, a backhoe was used to loosen the soil first before tillage

Treatments

Experimental treatments consisted of 2 x 2 factorial of vegetation type and soil amendment. The vegetation covers were grass or wildflowers and amendments were with or without compost across all sites, resulting in four treatments:

1. grass without compost (G);
2. grass with compost (GC);
3. wildflowers without compost (W); and
4. wildflowers with compost (WC).

The source of the compost was McGill Environmental Systems (New Hill, NC) sold by American Soil and Mulch (Cary, NC). The specific product used in this study was Merry Oaks Soil Builder which is manufactured from a wide variety of blended feedstocks.

Two grass mixtures were chosen from the NCDOT seeding and mulching manual, namely (a) east, and (b) west mixes (NCDOT 2016). The east mix included tall fescue (*Festuca arundinacea*) and bermudagrass (*Cynodon dactylon*), seeded at the CL site, while both PD and MT sites were seeded with the west mix which was made up of tall fescue, Kentucky bluegrass (*Poa pretensis*), hard fescue (*Festuca brevipila*), and rye (*Secale cereal*). A pollinator wildflower seed mix of 10 annuals and 7 perennials was initially seeded in Fall 2016. The wildflower plots were over-seeded with crimson clover (*Trifolium incarnatum*) and a southeast wildflower seed mix of 15 annuals and 11 perennials and biennials in Fall 2017 and 2018 after mowing, as the original mix was no longer available. A list of the wildflower species is provided in Chapter 1. Treatments were organized in a 2 x 2 factorial randomized complete block design with four replications.

Plot Setup

Plots were 6.1 x 3m at CL and PD and 4.6 x 3m at MT (due to limited available area at MT), with a 0.6 m width alley in the middle of each plot for plot accessibility and mowing operations. Prior to seeding, plots were amended with a granular fertilizer (10-20-20; 560kg ha^{-1}) and lime (4,480kg ha^{-1}) according to NCDOT recommendations for roadway areas. Compost was applied to the designated plots at a rate of 300mg ha^{-1}, equivalent to 5cm depth at estimated 600kg m^{-3} density (Ginkel et al,. 1999). Plots were re-tilled by a rotary tiller for incorporation. Next, grass and wildflowers seed mixtures were sown by hand at application rates recommended by NCDOT (grass) and American Meadows (wildflowers). After seeding in 2016, plots were covered with excelsior matting anchored with metal sod staples.

Grass plots were mowed four to five times each year at 15cm mowing height. Wildflower plots were mowed once each year at 15cm in late November. A rotary cutter (Bush Hog) attached to a tractor was used in a controlled mowing pattern where two tractor wheels went down the middle of the plots and the other wheels between the plots.

Measured Parameters

Before taking measurements, each plot was subdivided into 12 subplots (90 x 120cm) where all measurements were conducted within the same subplot at a given sampling time, and this location was not used again for subsequent sampling times. Infiltration (IR), bulk density (BD), penetration resistance (PR), and root mass density (RMD) were measured every six months for a period of 30 months (five sample dates). The measurements started six months after plots establishment (October 2016). One measurement was taken per plot for each parameter at each sampling time. Measurements were conducted in May and November in 2017, 2018, and 2019, representing spring and fall growing seasons. This report will focus on the infiltration rate as that is the most important parameter for reducing stormwater runoff.

Constant head infiltration measurements were taken using a single ring infiltrometer consisting of a reservoir 150cm high, with inner diameter of 10cm connected to a metal ring with 11cm diameter. The ring was gently driven into the ground to depth of 7.5cm. A thin layer of gravel was placed on the soil surface to minimize disturbance at the beginning of the infiltration process. A pressure head of 5cm was established at the soil surface and the rate of fall of the water level in the reservoir was recorded over time intervals until five consecutive consistent readings were achieved, which typically occurred within 60 minutes. The IR was calculated using the Reynolds & Elrick (1990) method.

Results and Discussion

The addition of compost reduced bulk density (Figure 2.5) at all sites and increased infiltration rates except at the CP site (Figure 2.6, Table 2.1). The plots planted to wildflowers also had higher infiltration rates compared to the grass plots at all three sites (Table 2.1). Over the five sampling periods, the infiltration rate did fluctuate significantly, however, there was no clear trend for it to decrease (Table 2.1). Overall, there were no large differences in the root mass or distribution among grass and wildflowers (data no shown), but there was a trend of the wildflower root systems increasing in density over time (Figure 2.7).

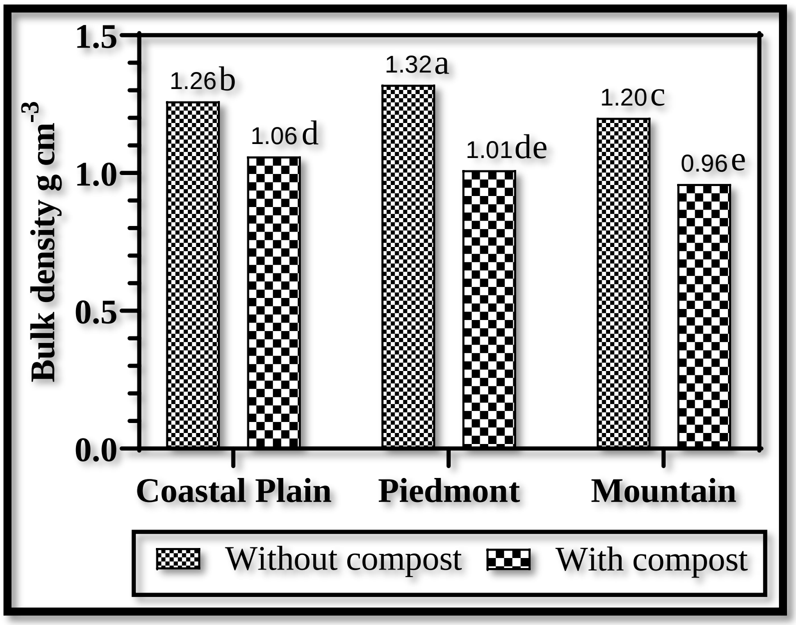

Figure 2.5: Bulk Density Data Collected Across Locations and Years for Location x Compost Interaction Effect at Coastal Plain, Piedmont, and Mountain Sites

**Values with the same letter are not different (p=0.05).*

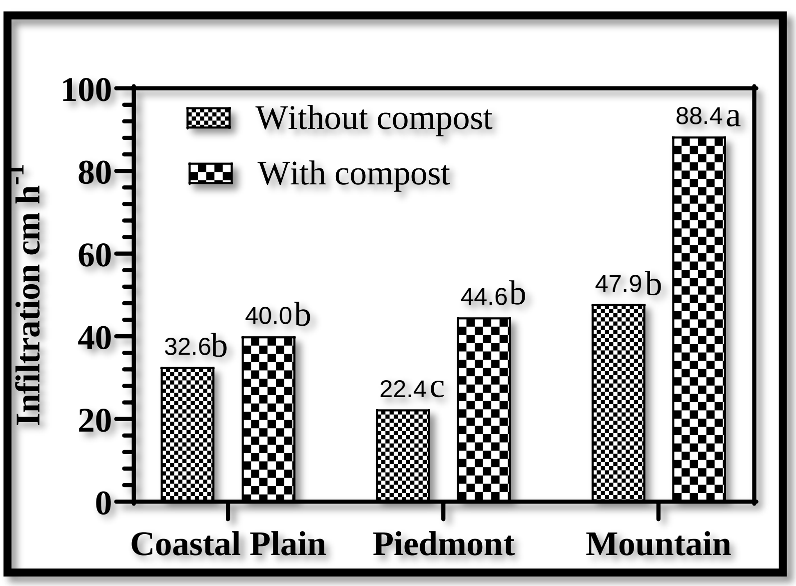

Figure 2.6: Infiltration Rate Data Collected Across Locations and Years for Location x Compost Interaction Effect at Coastal Plain, Piedmont, and Mountain Sites

**Values with the same letter are not different (p=0.05).*

Table 2.1: Infiltration Rates (IR) Over Time Measured at Each Site by Treatment

**Within each treatment level per site means followed by the same letter within a column are not different (p=0.05).*

Infiltration Rate, cm h^{-1}

Treatment	Levels	Coastal Plain	Piedmont	Mountain
Compost	With	40.0**a**	44.6**a**	88.4**a**
	Without	33.1**a**	22.4**b**	47.9**b**
Vegetation	Grass	26.5**b**	24.9.8**b**	56.3**b**
	Wildflowers	46.6**a**	42.3**a**	80.0**a**

Infiltration Rate, cm h^{-1}

Treatment	Months	Coastal Plain	Piedmont	Mountain
Time	6	42.6**a**	35.6**a**	84.8**a**
	12	46.2**a**	40.8**a**	60.9**a**
	18	40.9**a**	40.2**a**	53.7**ab**
	24	18.8**b**	21.3**a**	22.3**b**
	30	34.2**ab**	21.3**a**	119.3a

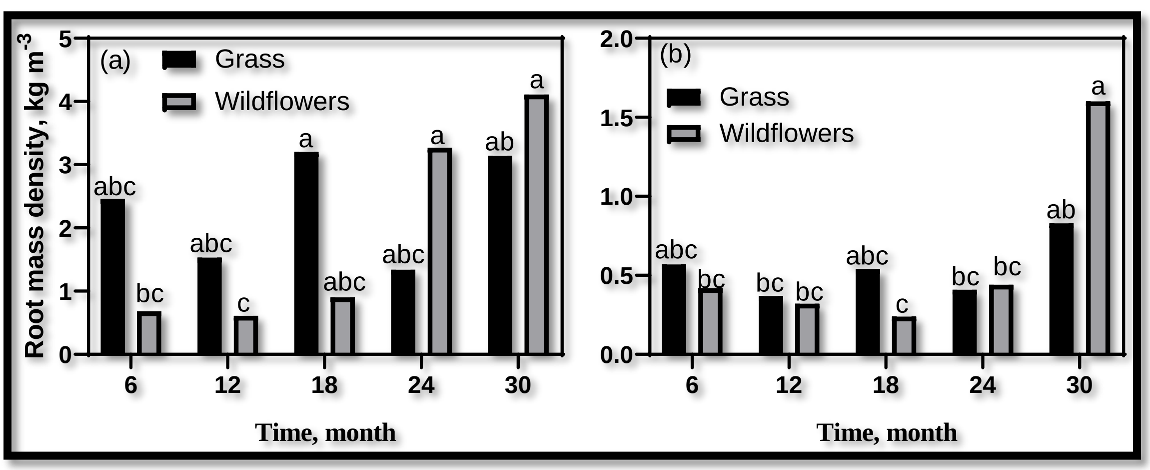

Figure 2.7: Interaction between Vegetation Roots and Time

**For (a) Piedmont site at depth (0cm to 75cm), and (b) Mountain site at depth (7.5cm to 15cm). Values sharing the same letters within each site are not different (p=0.05).*

Implications and Challenges

Our results suggest that this approach is a viable practice and could be integrated with stormwater mitigation practices in urban areas with best management practices and low impact developments. The IR values were relatively high and ranged from 40cm to 88.4cm h^{-1} under compost and wildflower treatments, which might accommodate high-intensity storms (return period ≥ 10 years) or in low-lying areas that receive stormwater. Therefore, wildflowers strips with soil compost amendments may be a practical management solution for linear transportation systems or highway interchanges to mitigate the effects of highway runoff on receiving waters or on areas that were not designed for stormwater management. Moreover, wildflower planted-areas can be seen as a low-mow maintenance regime as in our study wildflowers were mowed once a year as compared to four times for the grass, which complies with the NCDOT objectives to reduce mowing costs by implementing cost-effective practices. Based on the economic analysis of roadside vegetation management within the NCDOT by Martin & Gaustad (2017), the estimated savings were about $ 2.5 million when one to two mowing cycles were eliminated by plant growth regulators for grass.

One of the challenges that may arise when utilizing wildflower groundcovers is the differences in seed price between wildflowers and grass seeds. In this study, the cost (dollar / seeded m^2) of the wildflower mix was double and triple that of the west and east grass mixes, respectively. However, taking into consideration the low maintenance of the wildflowers may reduce or compensate for these cost differences. The ability of wildflowers stands to compete with invasive weeds is another potential challenge, therefore, appropriate establishment techniques are necessary to maintain the longevity of wildflowers on roadsides.

Another challenge might be the decomposable nature of compost which might limit the long-term beneficial impacts; a periodic application of compost has been recommended (Logsdon et al., 2017). However, according to Olson et al. (2013), if successful vegetation is present and taking advantage of compost, roots might penetrate deep into the soil profile creating macropores that may extend the beneficial impacts provided by the compost. Also, compost appeared to be more effective in fine-textured soils than course- textured soils, therefore, future research should determine how to optimize compost application rates for different soil textures to maximize its effectiveness as a remediation technique for urban soils restoration

Conclusions

1. Compost application along with tillage significantly reduced soil BD compared to tillage alone across all sites. The effects of tillage and compost on BD were maintained for 30 months after establishment. Neither grass nor wildflowers affected the soil BD.
2. Compost was effective in improving IR for the Piedmont and Mountain sites by about 50 and 46%, respectively, compared to tillage alone, suggesting that the effectiveness of compost on IR is site specific and might relate to soil texture at each site.
3. Wildflowers improved IR by 43, 41, and 30% for the Coastal Plain, Piedmont, and Mountains, respectively, compared to grass. This trend did not appear to relate to root mass density differences between wildflowers and grass. Root densities were similar between cover types and were largest within the tilled layer.
4. This study demonstrated that wildflowers were superior to grass regarding IR and low maintenance requirements and could be a viable alternative vegetative cover in vegetative stormwater practices.
5. Cost of the wildflowers seed, longevity of stand, and invasive weeds may present major challenges when utilizing wildflowers in roadside areas.

2.4. Mower Traffic on Effects on Soil Properties in Grass and Wildflowers With and Without Compost

Introduction

Soil compaction may be the most detrimental effect of vehicle traffic. Frequent traffic of machinery and equipment causes a breakdown of soil structure in the topsoil layer and considerable compaction in the lower layers (Chan et al., 2006; Reintam et al., 2009; Chamen et al., 2015). The infiltration rate is an essential parameter of soil, which is influenced by agricultural traffic and its intensity. Therefore, the IR of the soil is a good indicator of the soil compaction (Halvorson et al., 2003). In compacted soils the IR of rainwater decreases and the risk of surface runoff increases (Li et al., 2001), which lead to erosion due to low aggregate stability and reduced soil pores. Li et al. (2001) found that the non–compacted soil had four or five times higher IR than compacted soil.

Traffic compaction results in an increase in soil BD values which negatively affect the soil IR in comparison to the non–trafficked soil (Botta et al., 2006). The BD is also one of the key indicators of the soil compaction (Hamza & Anderson, 2005). As soil compaction occurs, the BD increases due to constant mass and reduced volume (Halvorson et al., 2003). Soil compaction naturally varies with soil type; sandy soils have naturally higher BD than clay soils due to the many small pores associated with clays. Bulk density values of clay, clay loam, and silt loam soils normally range from 1.00 to 1.60 while sand and sandy loam soils normally range from 1.20 to 1.80 g cm^{-3} (Brady, 1974). Compacted soils may have BD values of near 2.00 g cm^{-3} if severely trafficked (Raper, 2005).

Soil compaction can also be evaluated using a penetrometer where soil PR are evaluated. The PR measurement has advantages over BD as data from a whole soil profile can be simply obtained but limited by the penetrometer length (Raper, 2005). On the other hand, the PR measurement has also some disadvantages, the main one is its soil moisture dependence (Nawaz, 2016). Also, variation in soil texture and other physical properties among locations or soil horizons may complicate PR interpretation as an indicator of soil compaction (Mulqueen et al., 1977).

Management strategies such as conservation tillage, reduced tillage and soil organic matter application have been suggested to avoid the detrimental effects of intensive tillage and traffic (Raper, 2005; Batey, 2009). Organic matter is generally assumed to reinforce the soil to reduce compaction (Mujdeci et al., 2017), and to decrease its sensitivity to mechanical damage even when severe mechanical disruption occurs (Arvidsson, 1998).

Therefore, the aim of this study was to investigate the effects of both mower traffic soil compaction and compost addition on PR, BD, and IR under two vegetation typess with different mowing frequencies (tractor traffic) for a period up to 30 months in three different geographic regions across North Carolina, USA.

Materials and Methods

This study was part of the same study described in 2.2, but involved measuring the infiltration rate within the mower wheel tracks to compare to the untrafficked portion of the plots. Grass plots were mowed to 15cm four times a year between May and November , and wildflower plots were mowed once a year in late November after senescence. A rotary cutter tractor (Table 2.2) (Bush Hog) was used in a controlled mowing pattern where two wheels went down the middle of the plots and the other wheels between the plots. Infiltration (IR), bulk density (BD), and penetration resistance

(PR) were measured every six months for a period of 18 months in the traffic and no traffic plots. The measurements started 12 months after plots establishment in Fall 2017. One measurement was taken per plot for each parameter at the sampling time. Measurements were conducted in May (Spring) and November (Fall) and repeated periodically for 2017, 2018, and 2019, representing spring and fall growing seasons. The methods of measurement were described earlier in the chapter.

Table 2.2: Tractor Models, Weight and Engine Power

**All tractors specifications were obtained from TractorData LLC, Prior Lake, MN 55372 (https://www.tractordata.com/).*

Site	Tractor Model*	Weight (kg)	Engine Power (KW)
Coastal Plain	Massey Ferguson 4609M	3,289	67.0
Piedmont	Ford 5000	2,660	51.5
Mountain	5205 John Deere	1,848	35.8

Results and Discussion

For purposes of this report, the data for PR and BD were omitted to focus on the IR results. A short discussion of the PR and BD results is included, however. For those details, see Alshraah, 2020.

Penetration Resistance

Penetration resistance had a tendency to increase with depth regardless of vegetation and traffic treatments, likely as a result of changes in soil texture, gravel content, and structure with depth (Tolon Becerra et al., 2010). Mower traffic in the grass plots usually increased PR but did not in the wildflower plots. This difference may be attributed to the mowing frequency (4 vs. 1 per year) or the vegetation, or some combination. The incorporation of compost did not protect the soil from traffic compaction. Botta et al. (2006b) reported that high traffic frequency (10 and 12 tractor passes in the same tracks of a light tractor (3.1mg)) produced significant increases in PR and dry BD in the entire soil profile to 60cm depth. Penetration resistance increased under intensive traffic in all sites particularly in the grass plots within the tilled layer (15cm) and somewhat down to 20 cm at the CP and MT sites. At all sites, PR exceeded 2Mpa between 5cm and 10cm, which might restrict root growth and penetration, as suggested by Martino & Shaykewich (1994). On the other hand, PR for the wildflowers remained below 2Mpa within the tillage layer and was not affected by traffic.

Bulk Density

Mower traffic substantially increased the BD in the grass plots. Higher BD was expected for the grass plots as a result of four mowing cycles per year compared to wildflowers with one mowing cycle per year. But it appeared that the initial traffic was enough to increase the BD in the wildflower plots without compost. Similar observations were reported by Botta et al. (2008), who reported a significant increase in BD down to 15cm after one tractor pass. Bakker & Davis (1995) who found that an initial pass of a tractor compacted the topsoil layer. Also, Botta et al. (2008) reported a significant increase in BD down to 15cm after one tractor pass. In fact, traffic did not increase BD from fall 2017 to spring 2019 in most of the cases. Our observations are in agreement with previous results reported by Botta et al. (2006) who found that BD tended to be less responsive to the number of the tractor passes compared to the PR.

Compost incorporation reduced the negative effects of traffic on both the PR and BD. Despite the increase in BD in the grass plots under traffic, BD remained lower than the without compost plots. Also, compost appeared to be effective when low traffic intensity applied as in the case of wildflowers. These results are similar to those reported by Mujdeci et al. (2017) who found lower BD when compost (35t ha^{-1}) was mixed into the soil (10cm) compared to tillage alone after one and three tractor passes. Also, they found that the effect of the traffic was more negative in 0 -10 cm depth as the number of passes increase.

Infiltration

Across all locations, traffic drastically decreased IR in grass and wildflowers regardless of compost incorporation. However, greater IR values were recorded for wildflowers compared to grass in the traffic zone (Figure 2.8). For the grass, the relative reduction in IR caused by traffic were 86.3% and 83.7 in plots not amended and amended with compost, respectively. While wildflowers were less affected by traffic, and IR decreased by 69.0% and 58.1% for the without compost and compost amended plots, respectively.

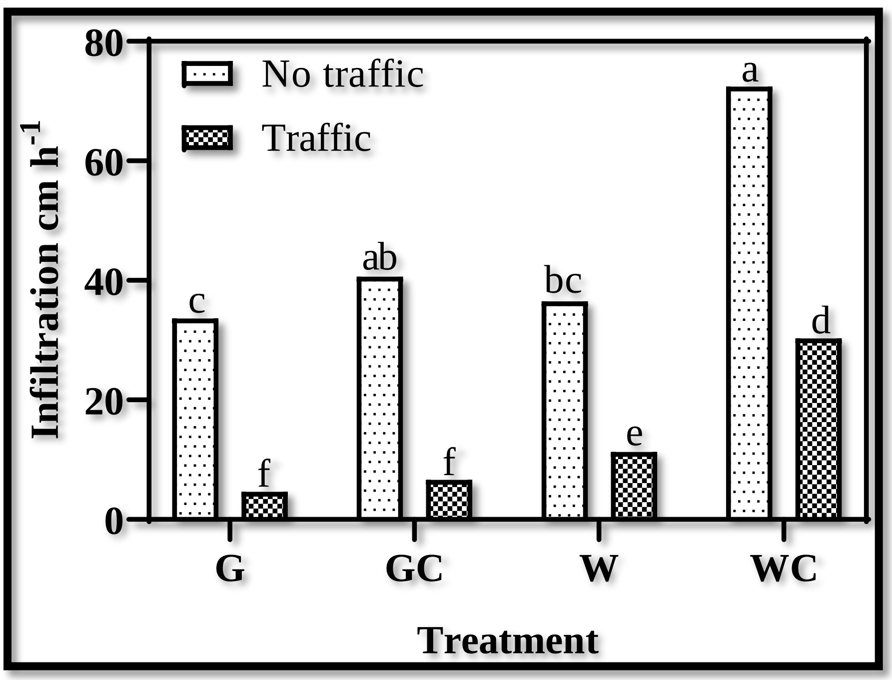

Figure 2.8: Infiltration Rate Across Locations and Years

**For grass (g), grass + compost (GC), wildflowers (W), and wildflowers + compost (WC) under traffic and no traffic. Values with the same letter are not different (p=0.05).*

Coastal Plain

At the CP site, traffic reduced IR by 74% and 90% for grass and wildflowers, respectively 2.9). However, the IR for wildflowers was higher than grass, either with or without traffic. Compost had no effect on IR treatments irrespective of vegetation and tractor traffic. For the grass plots, the traffic zone always had lower IR than the other areas of the plots (Figure 2.10A). Infiltration increased by 72% and 78% in the no-mowing periods (6 months) between fall 17 and spring 18, and between Fall 2018 and Spring 2019, respectively, and decreased by almost 91% between Spring 2018 and Fall 2018 when four mowings occurred in this period. Immediately after the first mowing (Fall 2017), IR decreased by 78% in the wildflowers. However, IR slightly recovered and was not different from non-traffic areas six months after mowing (Spring 2018), but decreased from 22.9cm h^{-1} to 4.5cm h^{-1} as a result of the second mowing in Fall 2018 (Figure 2.10B).

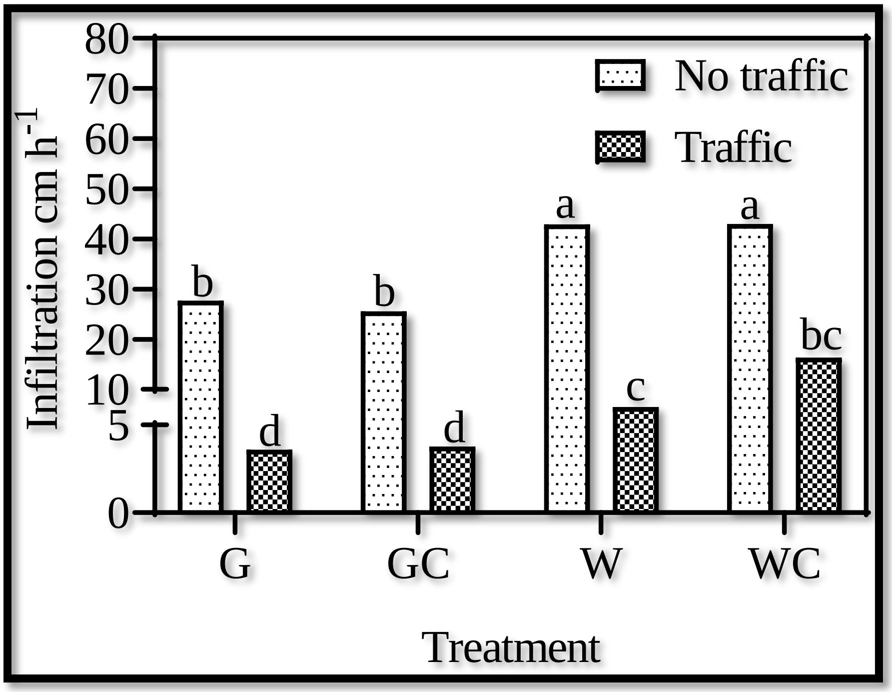

Figure 2.9: Infiltration Rate Across Times at Coastal Plain

**For grass (G), grass + compost (CG), wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).*

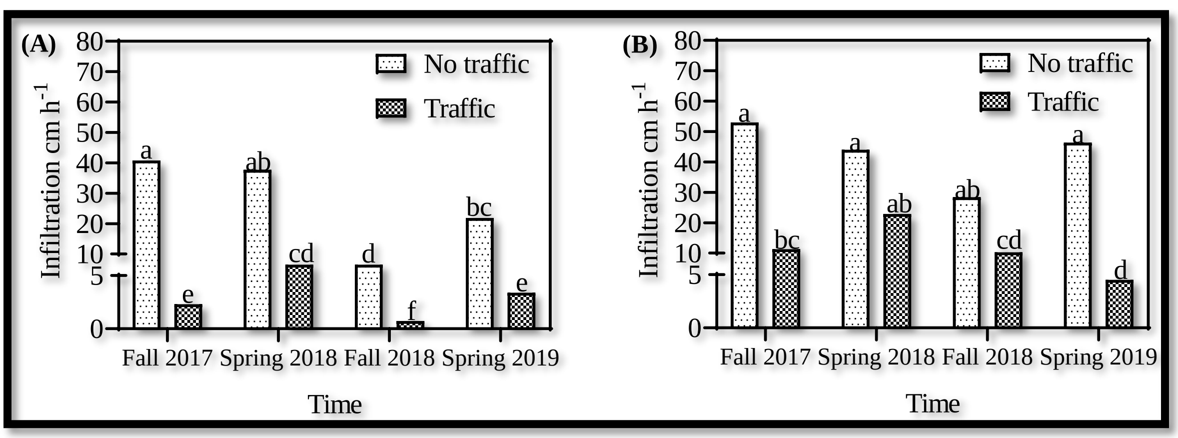

Figure 2.10: Infiltration Rate at Coastal Plain

**For vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers season infiltration rate. Values with the same letter within each group are not different (p=0.05).*

Piedmont

At the PD site, the IR response to traffic compaction was similar to the CP site. Tractor traffic significantly reduced IR regardless of vegetation and compost incorporation. The IR in traffic areas in wildflowers was higher than grass by approximately 87% and 76% for with and without compost treatments, respectively, suggesting the detrimental effect multiple mowings on IR in the wheel track (Figure 2.11). In Fall 2017, mowing traffic reduced IR from 67.1cm to 2.5cm h^{-1} and from 14.4cm to 0.5cm h^{-1} in the grass and wildflowers, respectively (Figure 2.12A-B). Surprisingly, IR was only recovered in the wildflowers after six months (Spring 2018) and was relatively similar to the corresponding IR in the non-trafficked areas, and was maintained until after 12 months (Fall 2018). We did not observe a recovery in IR after the second mowing occurred in the wildflower plots in Fall 18, and IR decreased from 20cm to 4cm h^{-1} in Spring 2019 (Figure 2.12B).

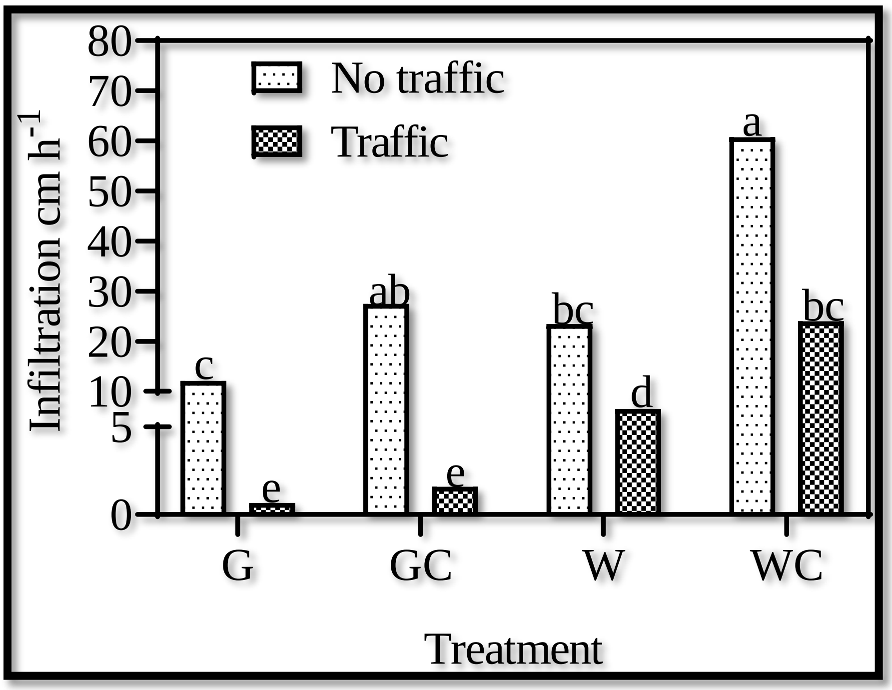

Figure 2.11: Infiltration Rate Across Times at Piedmont

**For grass (G), grass + compost (GC), wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).*

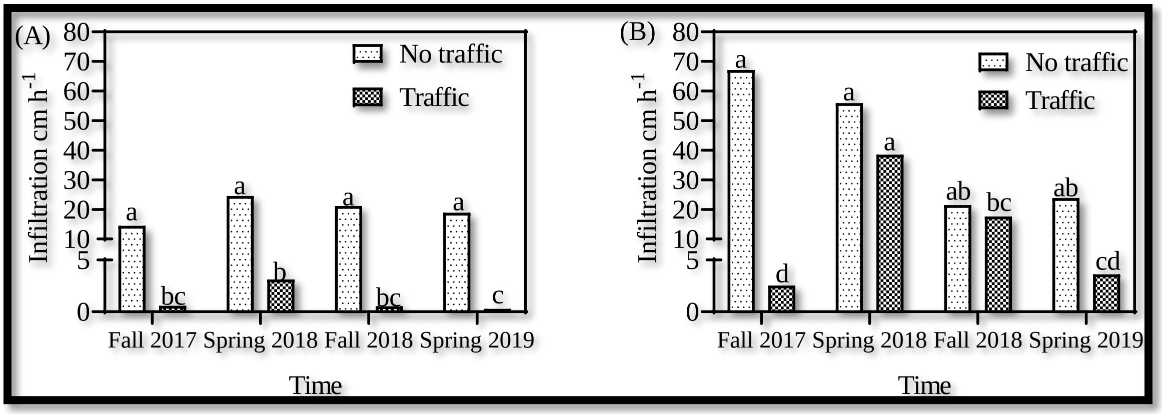

Figure 2.12: Infiltration Rate at Piedmont

**For vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers seasonal infiltration rate. Values with the same letter within each graph are not different (p=0.05).*

Mountain

At the MT site, wheel traffic markedly decreased IR by 84%, 88%, 52% in grass, grass + compost, and wildflowers treatments, respectively, while IR for the wildflowers + compost was less affected by traffic (Figure 2.13). The negative impact of traffic on IR was less drastic in the wildflower plots compared to the grass plots, and IR was always higher. Similar to CP and PD sites, the first year of mowing substantially decreased the IR in both grass and wildflowers (Figure 2.14A-B). After six months (Spring 2018) without traffic, IR increased from <1cm h^{-1} to 3.4 and 7.6cm h^{-1} for grass and wildflowers, respectively (Figure 2.13 A-B). Different form CP and PD sites, IR increased in Spring 2019 despite the traffic (four times for grass and one time for wildflowers) that occurred prior to measurement.

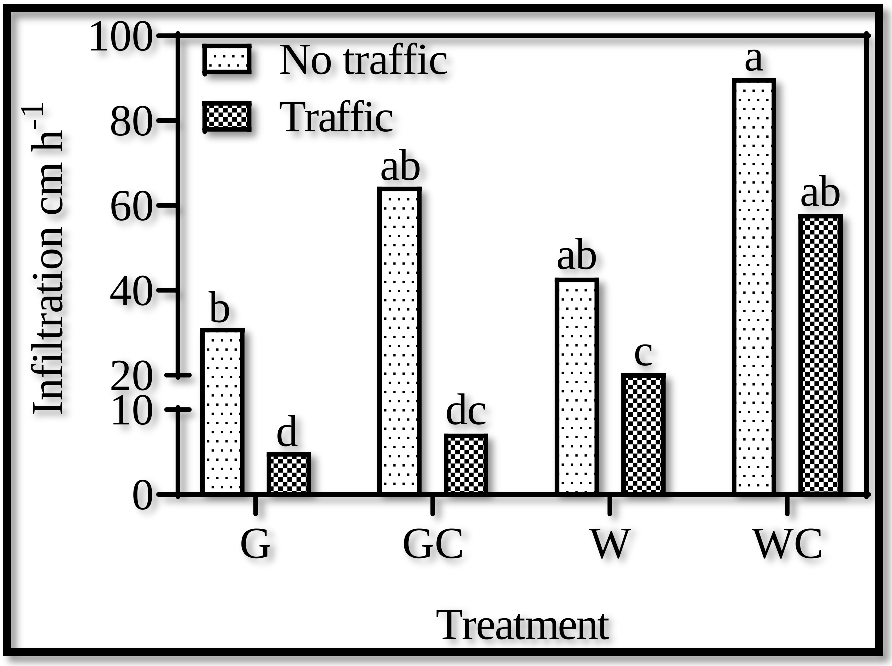

Figure 2.13: Infiltration Rate Across Times at Mountain

**For grass (G), grass + compost (GC), wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).*

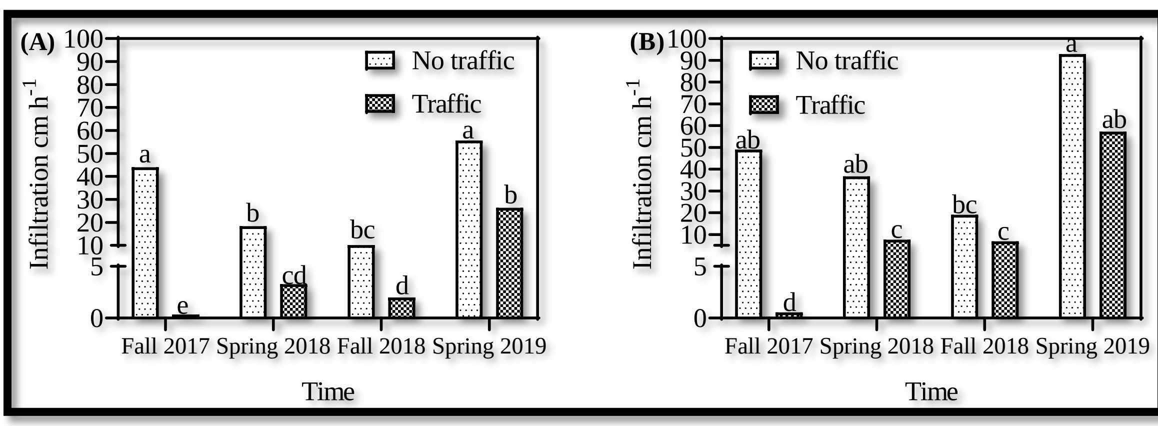

Figure 2.14: Infiltration Rate at Mountain

**For vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers seasonal infiltration rate. Values with the same letter within each graph are not different (p=0.05).*

Our results from the three sites showed that the soil compaction induced by traffic drastically decreased IR, and the amount of reduction in IR was substantially related to the intensity of the traffic. Across all sites, the IR under traffic for the grass was seventimes lower than IR under traffic treatment, while two times lower IR in no traffic compared to traffic for the wildflowers. These results indicate the detrimental impacts of mower traffic on IR and that the severity of the damage increases with repeated mowing. The lower IR due to increasing tractor passes agrees with those reported by of Li et al. (2001), who reported that wheel traffic had a large and significant effect on the IR of heavy clay soil, reducing the IR by four to five fold. Alamooti & Navabzadeh, (2009), also reported a reduced IR after two and three tractor passes.

Compost incorporation was effective in reducing the negative effects of the traffic on IR in two sites with fine-textured soils. However, this was only evident when light traffic was applied as in the case of the wildflowers. Under traffic, the IR was two to three times higher in the wildflowers + compost compared to wildflowers at any site. This can be explained by the BD in the trafficked wildflowers plots, which ranged from 1.2-g to 1.45-g cm^{-3} in without compost plots compared to approximately 1.0-g cm^{-3} in plots amended with across all sites.

The mowing cycles for both grass and wildflowers simulated the roadside vegetation management in North Carolina. On average, the number of mowing cycles across all road types is between 4 and five times per year in North Carolina (Martin & Gaustad, 2017). The traffic treatments in this study were applied to the same area (controlled traffic) over time, while roadside grass mowing is most likely to be random and thereby spreading traffic impacts over a larger area. A study on soil compaction related to field traffic during corn harvest revealed that 63% of the field area was exposed to traffic during a single harvest (Duttmann et al., 2014). After the one annual mowing in the wildflower plots, the IR recovered after six and 12 months, suggesting that random mowing traffic may have less impact in these areas.

The NCDOT has adopted the Integrated Roadside Vegetation Management approach aiming to encourage stable, self-sustaining vegetation with limited use of mowing and herbicides to reduce the annual maintenance cost for interstate and primary routes (NCDOT, 2019). Therefore, wildflowers, in addition to the IR improvement, might be considered as a cost-effective and efficient approach since wildflowers required less maintenance compared to grass.

Chapter 3: Tillage and Compost Effects on Existing Roadsides

A field study was conducted to determine the effect of tillage on road runoff into established roadside shoulders. This involved planting the tilled areas back into grass or with wildflowers. At two sites, 15 plots were established which received road runoff and the runoff from the plots was collected for a period of time to determine the typical discharge from each plot. Then three treatments were imposed: a control, or existing vegetation, tillage planted to grass, and tillage planted to wildflowers. These three treatments were applied to the plots so that each treatment had a similar range of pre-treatment runoff among those plots. The two sites were located on slopes adjacent to NC 98 (98) where it intersects NC 50 near Raleigh, and on the US 70 bypass in LaGrange (LG; Figure 3.5).

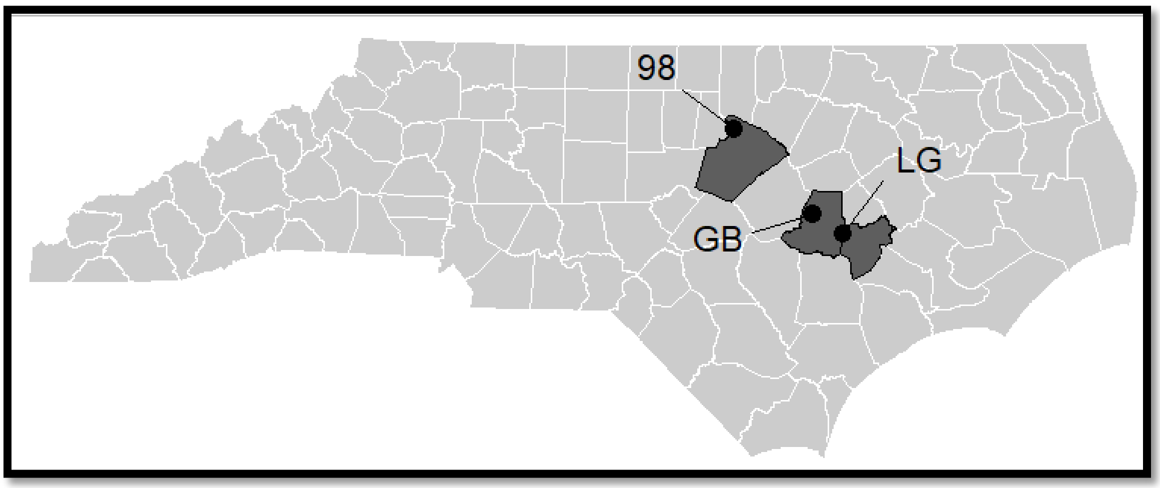

Figure 3.1: Location of Test Sites

The plots were established with plastic garden borders to funnel the runoff into 100 gallon livestock tanks (Figure 3.6). After approximately a year of monitoring runoff, in May 2018 10 of the 15 plots were tilled and five each had either a grass seed mix or a commercial wildflower mix. The tilled plots were covered with excelsior blankets after lime, fertilizer, and seed were applied.

At both sites as well as a third site (Goldsboro, US 70 exit shoulder), an area was also established to include compost as a treatment. Each site had 10’ x 20’ plots established with tillage, with or without compost, and planted to either grass or wildflowers, for a total of four plots. These were established primarily in order to do destructive sampling – soil cores and infiltration measurements – so the runoff plots would not be disturbed. The grass plots were mowed with a push mower and the wildflower plots were cut with a trimmer at the end of the first growing season. The soil textures at these sites were loam, loamy sand, and sandy clay loam for 98, LaGrange, and Goldsboro, respectively.

Figure 3.2: Plot Establishment at the 98 Site Near Raleigh, NC

At the end of the monitoring period in June 2020, both the runoff and the large plots were sampled for bulk density and infiltration rate and all equipment removed (Figure 3.7).

Figure 3.3: Measurement of Infiltration

**By single ring infiltrometer and soil bulk density by soil core removal at the LaGrange site at the end of the study June 2020.*

Results

The soils were quite different at the two runoff sites, sandy clay loam at the 98 site and sand at the LaGrange site, so the results were also quite different. Bulk density measured at the end of the two year monitoring period was not affected by the tillage treatment at the shallow (0cm to 3cm) depth but was reduced in both grass and wildflowers at 3cm to 6cm at 98 and in wildflowers at LaGrange (Figure 3.8). It should be noted that the bulk density of the shallow soil was relatively low for the textures found there. Infiltration rates were increased with tillage at both sites, and either type of vegetation had similar values.

Runoff volume generally followed the bulk density and infiltration rate data. At 98, the post-treatment period had less runoff for all treatments, but tillage reduced the volume regardless of vegetation type (Figure 3.9). The results were the same at LaGrange, except during the post-treatment period runoff increased from the control plots. As a proportion of runoff expected from the adjacent road surface, tillage significantly reduced the runoff volume at 98 (Figure 3.10) but not at LaGrange (Figure 3.11). In the heavier texture soil at 98, the proportion of infiltration went from approximately 70% to 90% with tillage. In the sandy soil at LaGrange, infiltration was already above 90% of runoff with no treatment, so the improvements were only marginal. In the large plot areas at 98 and LaGrange, as well as at Goldsboro, after two years only the compost + wildflower treatment resulted in improved infiltration at all three sites (Figure 3.12). At LaGrange, compost + grass also improved infiltration compared to the existing condition. At this site, the soil was very sandy and the compost may have helped to improve soil conditions for plant growth and structure, creating more macropores for infiltration.

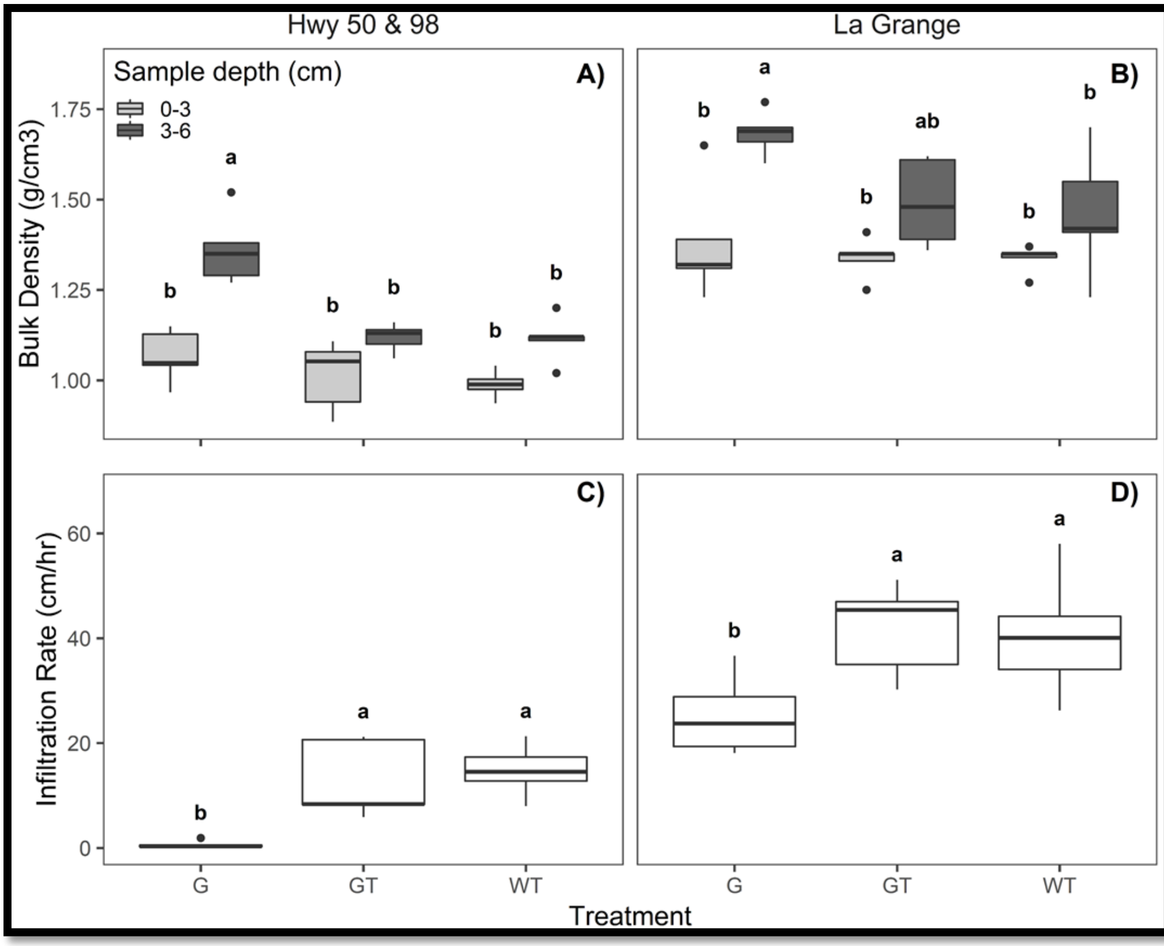

Figure 3.4: Bulk Density and Infiltration Rate

**In the runoff plots at 98 (A, C) and LaGrange (B, D) sites. Treatments are G = control (existing vegetation), GT = tillage + grass, and WT = tillage + wildflowers. Different letters above the values indicate significant differences (p<0.05) within a graph.*

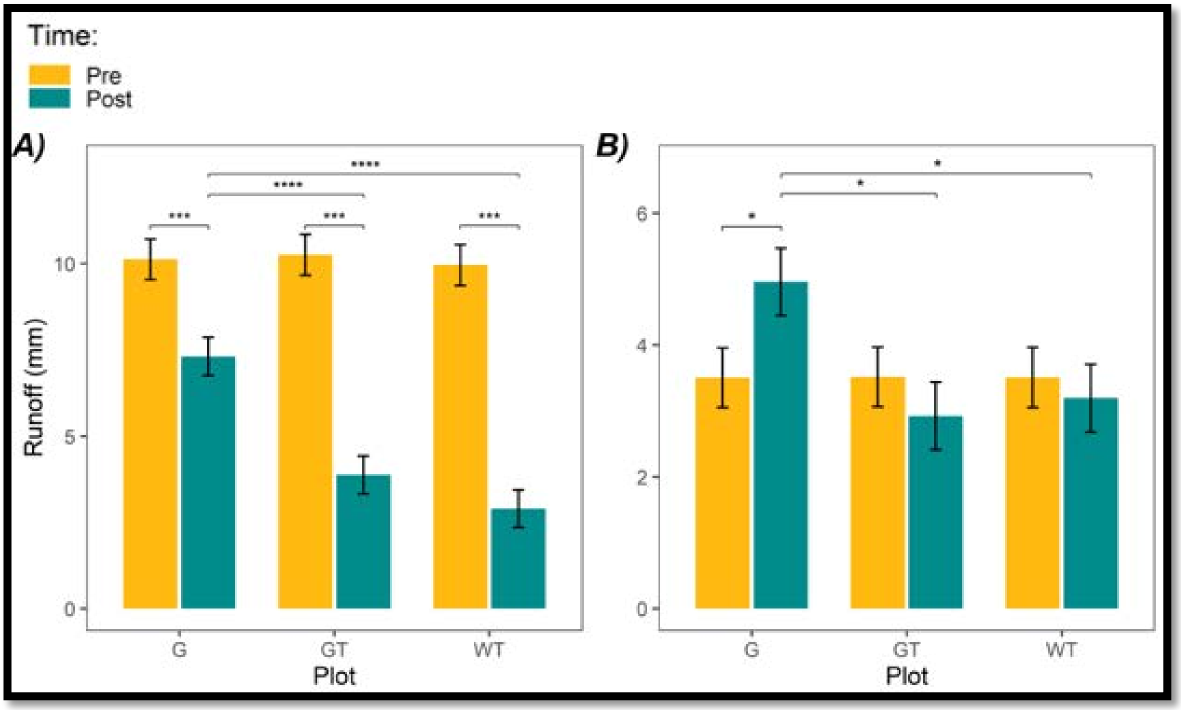

Figure 3.5: Runoff Volumes

**From the plots at 98 (A) and LaGrange (B), before and after tillage treatments. Treatments are G = control (existing vegetation), GT = tillage + grass, and WT = tillage + wildflowers. Statistical differences are shown above the values between different groups of treatments. Asterisks represent *p<0.05, **p<0.01, ***p<0.001, and ****p<0.0001.*

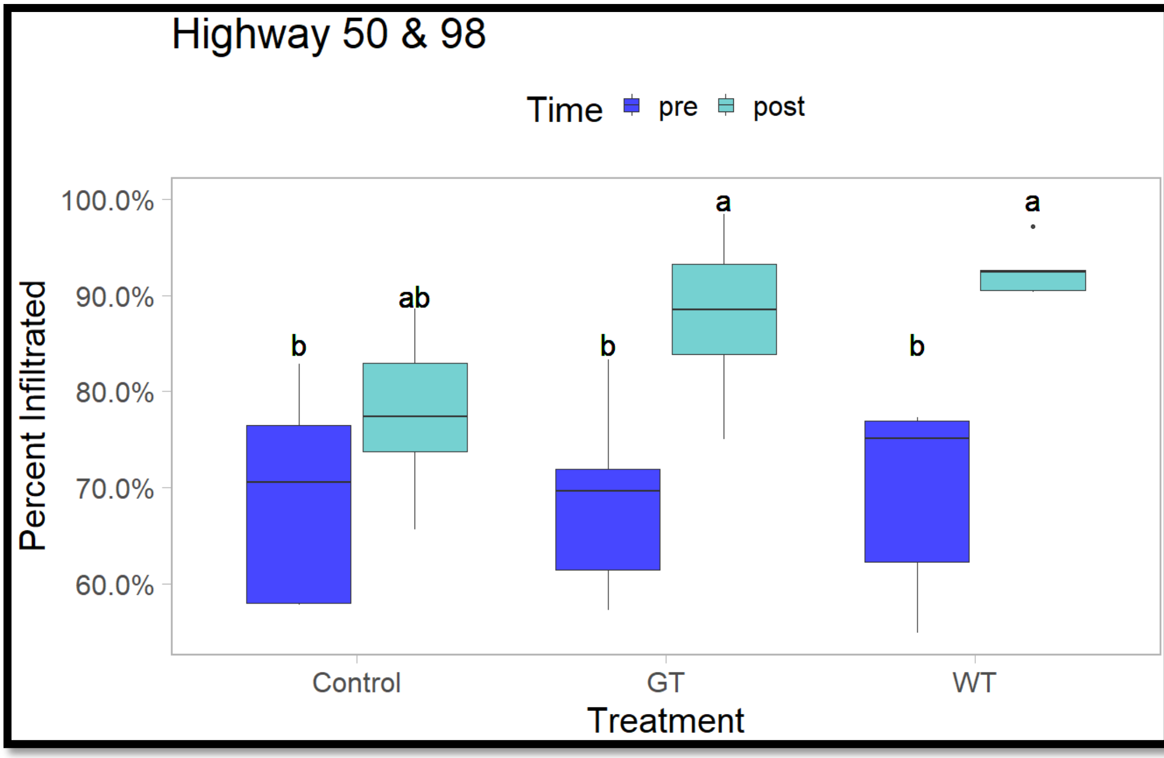

Figure 3.6: Proportion of Runoff Infiltrated at the 98 Site

**Based on calculated runoff from the road area adjacent to the plots. Treatments are G = control (existing vegetation), GT = tillage + grass, and WT = tillage + wildflowers. Different leaders above the values indicate significant differences (p<0.05).*

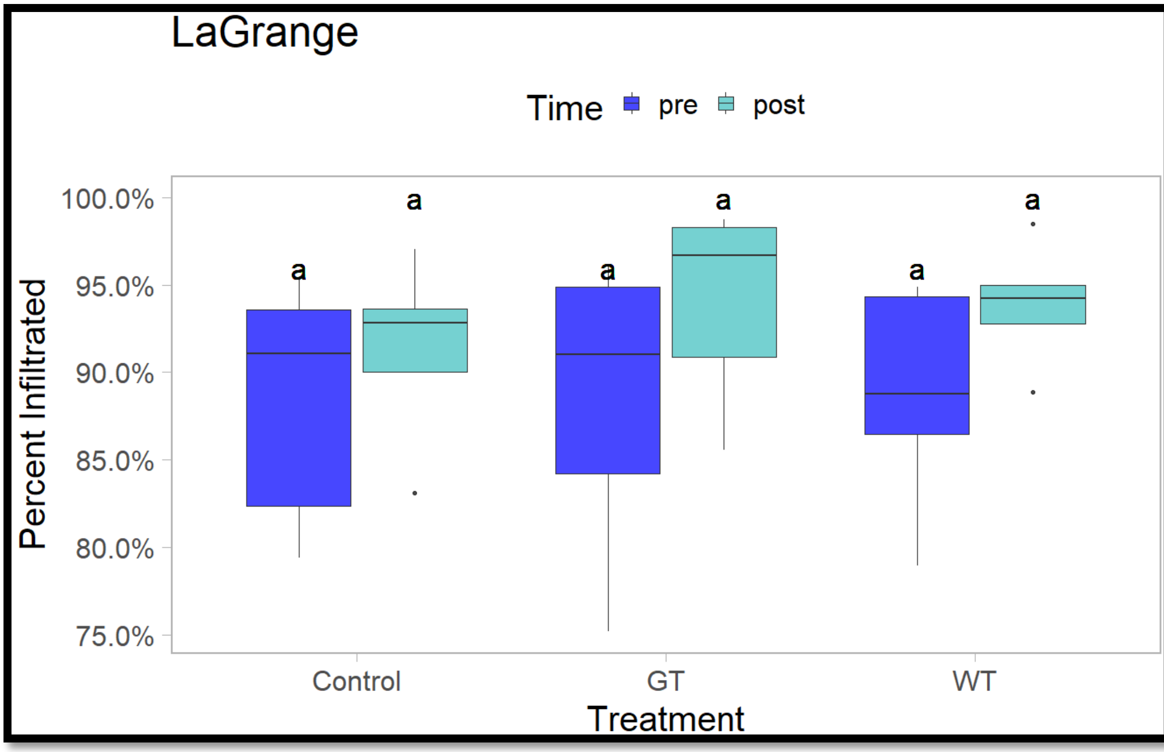

Figure 3.7: Proportion of Runoff Infiltrated at the LaGrange Site

**Based on calculated runoff from the road area adjacent to the plots. Treatments are G = control (existing vegetation), GT = tillage + grass, and WT = tillage + wildflowers. Different letters above the values indicate significant differences (p<0.05).*

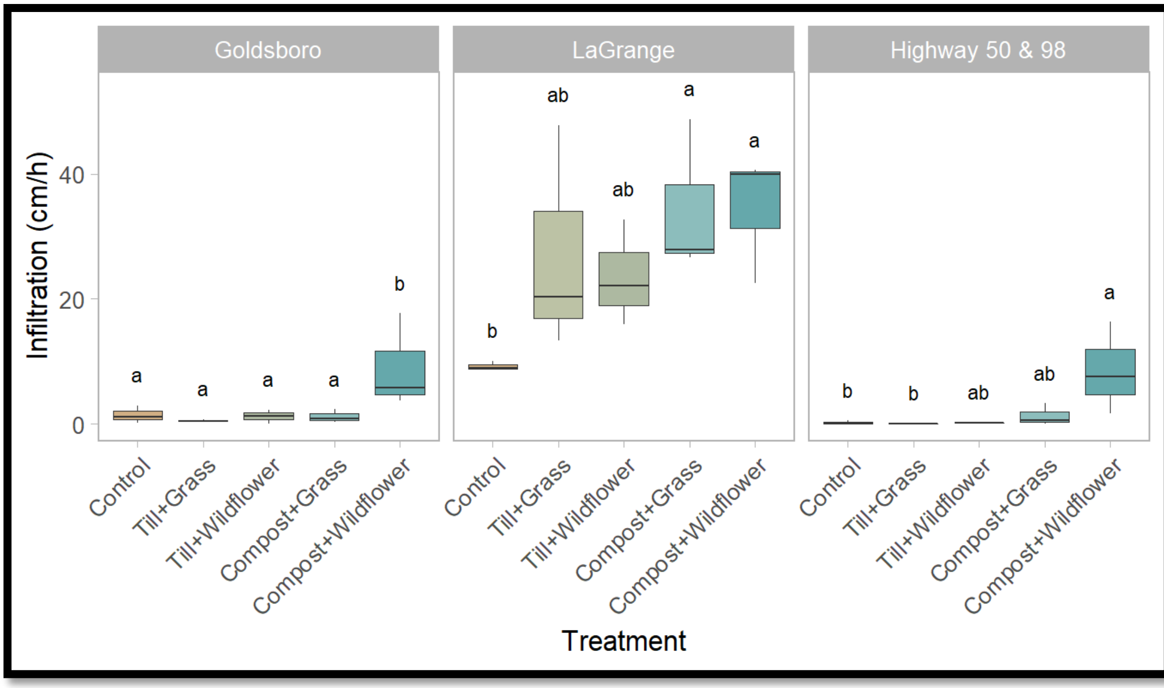

Figure 3.8: Infiltration Rate in the Large Plot Areas

**At three sites receiving tillage with and without compost and either grass or wildflower seeding. Different letters above the values indicate significant different (p<0.05).*

Conclusions

Infiltration was improved through tillage at the two sites where runoff was collected, but the reduction in runoff volume was less evident in the LaGrange site due to very sandy soil and high infiltration rates already present. The type of vegetation was not a large factor in improving infiltration, but there was some advantage in the combination of compost incorporation and planting wildflowers. Overall, tillage did appear to be effective in soils with inherently low infiltration rates, and compost can increase this effect.

Findings and Conclusions

There were three central questions which this project pursued: how might wildflowers respond to typical roadside growing conditions, how do grass and vegetation covers maintain the benefits of tillage for stormwater infiltration, and can this approach be applied to existing roadside areas? Within these questions are many additional lines of inquiry, some of which were pursued as well. The three chapters in this report address the findings of the work that was done to answer those three questions.

Wildflower growth responses were evaluated in a greenhouse study and two field studies. The roadside field study assessed single species wildflower – *Eschscholzia californica* (California poppy) and *Coreopsis lanceolata* (lanceleaf coreopsis) – growth at roadside locations varying in soil texture and density. Lanceleaf coreopsis maintained high vegetative coverage (73.8% to 85.0%) and low weed coverage (0.0-4.6%), while California poppy coverage varied, but had relatively higher weed coverage ranging from 18.8% to 36.4%. The effects of soil pH, texture, and bulk density on wildflower growth were inconsistent, differing by species. The greenhouse study evaluated the effects of soil density on plant height and shoot and root growth. The species evaluated were Eschscholzia californica, Coreopsis lanceolata, Chamaecrista fasciculata, and Gaillardia aristata (California poppy, lanceleaf coreopsis, partridge pea, and blanketflower).

Lanceleaf coreopsis and blanketflower grew well relative to other species, although the former had some sensitivity to soil bulk density. The perennial species performed as well or better than annuals in the two 3-4 month test periods. Overall, the wildflower species studied were not affected by soil density over a moderate range (1.15-g – 1.5-g cm^{-3}), suggesting that they are well adapted to grow in construction-impacted soils. The second field study compared mixed wildflower plantings, including both annuals and perennials, with and without incorporated yard waste compost in the Coastal Plain, Piedmont, and Mountains of North Carolina over two years. Contrary to expectations, compost had minimal effect on wildflower cover. Incorporated compost had a negative effect on wildflower cover in one field site in the first year of establishment, and on wildflower cover at one sampling in the second year, with little effect on subsequent samplings. Species diversity was not affected by compost. Based on the greenhouse results, we concluded that the species studied have limited sensitivity to soil density, which was supported by some of the roadside field results. All three studies indicated substantial growth and cover provided by perennials, comparable to or greater than that of annuals, which challenges conventional species recommendations for mixed plantings including need for both annuals and perennials. With the right management decisions (i.e. species selection), wildflowers can provide good ground cover along roadsides, similar to grass, with the added benefits of aesthetic value, pollinator habitat, and reduced maintenance.

The potential differences in wildflower species root development on soil properties were explored in a greenhouse study. Soil hydraulic properties were monitored during the root development of two species to quantify the effects of roots development over time on soil pore distribution and hydraulic conductivity. A positive linear correlation between root growth and soil hydraulic conductivity was found under compacted soil conditions. Field-based studies were also established in 2016 in three regions of North Carolina and monitored for 30 months to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflowers. Plots planted in wildflowers tended to have higher soil infiltration compared to grass across all sites. Compost application also enhanced the soil infiltration in two sites out of three. Finally, the effect of tractor traffic on soil infiltration resulting from the mowing process was evaluated for wildflowers and grass. Tractor traffic substantially reduced infiltration rates in the wheel tracks but there was some evidence of recovery in the compost-amended wildflower plots. This study demonstrated the ability of compost to improve some soil properties that makes it such a useful amendment for poor urban soils. Also, wildflowers were superior to grass regarding soil infiltration and low maintenance requirements and could be a viable alternative to grass in vegetative stormwater practices.

The effects of tillage with and without compost on 1) bulk density and infiltration rates, 2) runoff volumes, and 3) runoff water quality were evaluated during multiple storm events along two long-established interstate roadsides in North Carolina during 2015 and 2017. Experimental plots were established in the grassed areas adjacent to roads and consisted of an untreated control, tillage only, and tillage amended with compost. Tillage alone did not reduce runoff in roadside soils, however, tillage with compost did improve runoff capture. The patterns in hydrologic performance within and among sites suggests that the incorporation of compost in tilled soils may influence storage potential through different effects on soil properties, such as decreasing bulk density or improving vegetation establishment, thereby increasing evapotranspirative withdrawals, depending on soil texture. Tillage increased sediment concentrations in runoff, however, net export of sediments was reduced with the inclusion of compost due to the reduction of runoff quantities compared to undisturbed areas and tillage alone. Control and treatment plots were equally effective in reducing dissolved nutrient and metal concentrations, however, the improved hydrologic performance in plots with compost decreased net nutrient and metal export in most storms. The results of this study suggest that the incorporation of compost in roadside soils may provide significant improvements for biological and physical soil properties that affect stormwater interception and infiltration.

Conclusions

Tillage was very beneficial for improving infiltration in compacted soil, often by a factor of 3X or more. Incorporating compost at the rate tested, cm incorporated into 15cm of soil, had additional benefits but not always. Improved vegetation establishment and resistance to compaction may result from the compost treatment. Wildflowers as a substitute for grass can provide greater infiltration potential, in part because mowing traffic is reduced from four times per year to one. Among the many wildflowers that were planted as a mix, very few were present in our plots. However, those perennials that dominated were quite resilient in both field plots and under different soil conditions in the greenhouse tests, and would be highly recommended based on their ability to grow and develop robust root systems.

Recommendations

This project is one of a series in which we've demonstrated that tillage and vigorous vegetation can provide tremendous increases in infiltration rates in compacted soils. This can greatly reduce the amount of runoff that has to be handled by stormwater systems. This practice would be very beneficial in new construction where slopes are not steep. On existing roadside areas, benefits are not as great but are still evident except in very sandy soils. However, it is important that these areas be managed as infiltration areas with careful attention to equipment travel such as mowers in order to avoid losing those benefits to traffic compaction. There are often large areas that are not needed for emergency pullovers which could be designated for infiltration, for example. Replacing the mowed grass in these areas with wildflowers after tillage would reduce the mowing costs, provide pollinator habitat, and reduce the impact of mower traffic on infiltration capacity. Several perennials (lanceleaf coreopsis and blanketflower) performed well in both field and greenhouse testing.

Implementation and Technology Transfer Plan

The project produced the following findings:

- Wildflowers perform as well or better than grass at maintaining high infiltration rates after tillage.
- High infiltration rates after tillage are maintained for almost three years with vigorous vegetation, and likely for much longer.
- Traffic can eliminate the benefits by compaction in the wheel lane, so careful management of infiltration areas is important.
- The benefits of tillage are not as great in existing roadside areas as in new construction, but are still present except in sandy soils with naturally high infiltration rates.
- Adding compost to tillage can have benefits but these were not always evident.

The practices studied would be most applicable to those in the Roadside Environmental and the Hydraulics and Stormwater areas. These could be applied to new construction areas and as augmentation of existing stormwater practices in areas adjacent and upstream of them. There is likely minimal training needed, but management plans for these areas would need to be developed.

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Appendix 1: ABSTRACT: Wildflower Chapter

Construction activities necessary to develop roadway infrastructure can leave behind poor quality soils. In particular, soil compaction caused by traffic and heavy machinery can limit infiltration and plant growth, leading to excessive runoff and erosion. These areas are often planted with grass; however, wildflowers could be planted along roadways with the added benefits of providing pollinator habitat and lowering management costs. The overall goal of this research was to determine wildflower growth response to various growing conditions such as roadside establishment and maintenance, simulated compaction, and compost amendment.

Wildflower growth responses were evaluated in a greenhouse study and two field studies. The roadside field study assessed single species wildflower – *Eschscholzia californica (*California poppy) and *Coreopsis lanceolata* (lanceleaf coreopsis) – growth at roadside locations varying in soil texture and density. Lanceleaf coreopsis maintained high vegetative coverage (73.8% to 85.0%) and low weed coverage (0.0% to 4.6%), while California poppy coverage varied, but had relatively higher weed coverage ranging from 18.8% to 36.4%. The effects of soil pH, texture, and bulk density on wildflower growth were inconsistent, differing by species. The greenhouse study evaluated the effects of soil density on plant height and shoot and root growth. The species evaluated were *Eschscholzia californica, Coreopsis lanceolata, Chamaecrista fasciculata,* and *Gaillardia aristata* (California poppy, lanceleaf coreopsis, partridge pea, and blanketflower).

Lanceleaf coreopsis and blanketflower grew well relative to other species, although the former had some sensitivity to soil bulk density. The perennial species performed as well or better than annuals in the two 3 to 4 month test periods. Overall, the wildflower species studied were not affected by soil density over a moderate range (1.15-g – 1.5-g cm^{-3}), suggesting that they are well adapted to grow in construction-impacted soils. The second field study compared mixed wildflower plantings, including both annuals and perennials, with and without incorporated yard waste compost in the Coastal Plain, Piedmont, and Mountains of North Carolina over two years. Contrary to expectations, compost had minimal effect on wildflower cover. Incorporated compost had a negative effect on percent wildflower cover in one field site in the first year of establishment, and on percent wildflower at one sampling in the second year, with little effect on subsequent samplings. Species diversity was not affected by compost. Based on the greenhouse results, we concluded that the species studied have limited sensitivity to soil density, which was supported by some of the roadside field results. All three studies indicated substantial growth and cover provided by perennials, comparable to or greater than that of annuals, which challenges conventional species recommendations for mixed plantings including need for both annuals and perennials. With the right management decisions (i.e., species selection), wildflowers can provide good ground cover along roadsides, similar to grass, with the added benefits of aesthetic value, pollinator habitat, and reduced maintenance.

Appendix 2: Chapter 1.1: Methods Details

Cover

A modified Daubenmire method (Daubenmire, 1959) was used to assess percent cover at each site. Two evenly-spaced transects were established with three cover measurements randomly taken over the length of each transect (Figure 1.8.). The planted species were recorded, and other species were considered weeds and recorded as such. The Daubenmire method utilizes the 20cm x 50cm quadrat frame which is placed at multiple positions along a transect. The cover class of each species is analyzed within the area of the quadrat. There are six cover classes, 1 to 6, which correspond to a range of coverage: 0% to 5%, 5% to 25%, 25% to 50%, 50% to 75%, 75% to 95%, 95% to 100%, respectively. Cover classes are assigned individually to each species, and canopy overlap is included, so total cover may exceed 100%. The viewer visually assesses and assigns cover class to each species. Canopy cover per quadrat sample was calculated as $\%\ canopy\ cover = cover\ class \times midpoint\ of\ coverage\ range$. The sum of wildflower and weed coverage was recorded as total coverage.

Root Sampling

Root cores were collected from the center of the sampling frame used for the cover measurements. A 7.62cm diameter core sampler was used to take a 15.24cm deep sample from each location. The core sampler had an attached slide hammer to drive the core cylinder into the ground. Cores were processed in the lab by cutting into two 7.62cm long sections, washing with water over a 2mm sieve to collect the roots, and oven drying at 65^{o}C. Using this procedure, six root samples were collected per depth (i.e., 0cm to 7.62cm and 7.62cm to 15.24cm depth increments) and per site. Root density was calculated by dividing the dried root mass by the volume of the sample. The root densities from each depth were also averaged to compare total (0cm to 15.24cm depth) root density for each site.

Soil Sampling

Bulk density samples were collected using a slide hammer sampler with 7.62cm diameter by 7.62cm length rings from beneath the quadrat frame (six samples per site). Samples were oven-dried at 105^{o}C for 48 hours, weighed, and bulk density (ρ_b) was calculated as the ratio of dry soil mass to the sample volume.

Additional soil samples were collected from six random locations within each subplot with a push probe (0cm to 15.2cm depth), combined, and used for texture and pH analysis. Texture was determined using the hydrometer method (Gee and Bauder, 1983) and soil pH was measured in 0.01M $CaCl_2$ (1:1 ratio) (Peech, 1965).

Statistical Analysis

All data were analyzed using SAS 9.4 PROC GLM at α= 0.05 using the LINES option to differentiate LS-MEANS. The canopy cover measurements and bulk densities were analyzed within species and across sites. Root densities were analyzed by species, depth, and across sites.

Appendix 3: Chapter 1.2: Methods Details

Wildflowers

Wildflower species were selected based on concurrent field trials and NCDOT species lists. Skousen and Venable (2008) recommended using a mix of annuals and perennials to establish groundcover and prevent erosion, since annuals are often faster to establish than perennials. We selected one perennial (lanceleaf coreopsis) and two annual (California poppy and partridge pea) based primarily on their performance in concurrent field studies using seed mixes. Trial 1

included *Chamaecrista fasciculata* (partridge pea), *Eschscholzia californica* (California poppy), and *Coreopsis lanceolata* (lanceleaf coreopsis). For trial two, *Gaillardia aristata* (blanketflower) replaced partridge pea because it established well in the field and partridge pea did not grow well in the first trial. Seeds were planted on June 6, 2017, and March 30, 2018, for Trial 1 and 2, respectively.

These specific species were chosen for their growth habits, life cycle, field success, and / or use in NCDOT plantings. Partridge pea seed was purchased from Prairie Moon Nursery® (Winona, MN). It was stratified and inoculated with rhizobia as recommended by the nursery. It is an annual wildflower that can grow to two feet tall and is native to eastern and central United States (NCDOT, 2015).

California poppy and blanketflower seed were purchased from Eden Brothers® (Arden, NC). California poppy is an annual under most North Carolina weather conditions, although it can be a perennial in the warmer, far-southeastern part of the state (Smither-Kopperl, 2018). The species of blanketflower selected is a perennial wildflower, and is different from the species used by the NCDOT (*Gaillardia pulchella*; NCDOT, 2015).

Lanceleaf coreopsis seed was purchased from Prairie Nursery (Newton, WI). Lanceleaf coreopsis is a perennial wildflower that blooms from April to June and is often planted along roadsides (NRCS, 2012).

Soil

A sandy loam subsoil (69% sand, 15% silt, 16% clay) from the Raleigh, NC, area was used for this study. The pots for the study were 15.2cm x 30.5cm polyvinyl chloride (PVC) precast molds (M.A. Industries Incorporated, Peachtree City, GA). The pot dimensions were chosen to allow for greater root growth than typical pots used for plant propagation. Pots were packed in steps by adding 2cm to 3cm of soil and compacting it to the desired bulk densities, followed by another 2cm to 3cm of soil. Bulk densities of 1.15-g and 1.35-g cm^{-3} were used in Trial 1 along with a potting substrate mix of sphagnum peat and perlite mixed on a volume basis at a 4:1 ratio (4831 g).

Potting substrate pH of 4.0 was measured on a 1:1 volume / volume ratio of fresh sample to deionized water (Eaton et al., 2005). The soil pH was 7.5 as measured in 0.01*M* $CaCl_2$ (1:1 ratio) (Peech, 1965). For Trial 2, a bulk density of 1.50-g cm^{-3} replaced the potting soil mix. To achieve the desired bulk densities the pots were filled to 26.5cm depth. At harvest, the amount of soil settling for each pot was measured to estimate the change in bulk density. For Trial 2, the average low-bulk density increased 0.09-g cm^{-3}, while the mid- and high-bulk densities decreased by 0.02-g and 0.03-g cm^{-3} on average, respectively.

Water

Drip irrigation was used throughout the study (Rain Bird 1892.7 cm3 hour-1 emitters, Azusa, CA). For Trial 1, the watering regime began at 3.45 cm day-1 for two week and then decreased to 1.73cm day-1. The soil was watered once a day at 5:00 a.m., but the potting substrate was watered twice a day thus receiving twice the amount of water because it dried out much faster. Watering was decreased for the soil system again at the end of July to 1.21cm day-1 and maintained as such for the remainder of the growing season. After the first trial, a water retention curve was developed for the soil under both high and low pressure. At field capacity (approximately 1/3 bar), the volumetric water content was 0.122cm3 cm^{-3}. Based on the field capacity measurements and previous work which recommended irrigating 0.6cm day-1 for three weeks to establish wildflowers (Aldrich, 2002), the watering regime for the second trial was adjusted to 0.345cm day-1 at 5:00 a.m. and was increased to 0.52cm day-1 as temperature rose. It was reduced from the recommended rate because of the field capacity measurement and to ensure aeration. The reduced watering regime necessitated misting the soil surface daily in order to maintain a moist soil surface until roots were well established.

Harvest

For Trial 1, there were two harvest dates planned for each species, pre- and post-flowering. For Trial 1, the second harvest date was much sooner for the partridge pea than the others as it began to senesce. Additionally, not all California poppies bloomed, and no lanceleaf coreopsis bloomed, perhaps because of the addition of shade cloth to the greenhouse in order to reduce daytime temperatures. The Trial 1 first harvest was August 6, 2017, for all species (40 days). The second harvest of partridge pea was September 11, 2017 (75 days), while the second harvest for California poppy and lanceleaf coreopsis was October 23, 2017 and October 24, 2017 (117 and 118 days), respectively.

For Trial 2, the first harvest was May 29, 2018, and the second July 19, 2018 (61 and 112 days). The first harvest was a longer period than the first trial in order to accommodate slow germination and to facilitate more root growth than was found in the first trial.

The heights reported were measured at each harvest. The height was measured from the base of the plant to the top of the three tallest leaves and averaged. Height was not reported for the second harvest of the second trial because for many plants there were not three suitable leaves to measure. At harvest, the aboveground biomass was cut at the soil surface and oven dried at 60°C for 48 hours before weighing.

Root Washing

After the aboveground biomass was removed, soil settling was recorded, and the soil and roots were removed from the pot. The roots were separated from the soil by washing under running water on a 2mm sieve (Figure 2.1.). For the potting soil samples, the roots were removed from the substrate dry or floated in water as needed. Roots were then oven dried at 65°C for 48 hours and weighed. Root mass was converted to root density by dividing the dry mass by the volume of the soil in the pot.

Statistical Analysis

Data were analyzed using SAS 9.4 Proc GLIMMAX and means were separated using a Tukey test excluding Trial 2 Harvest 1 root:shoot data which were analyzed using SAS 9.4 Proc GLM and

LINES (SAS, Cary, NC). Data were analyzed by trial and harvest date. Interaction between species and soil was evaluated, and if it was not significant the data were analyzed without interaction (α=0.05).

Appendix 4: Chapter 1.3: Methods Details

Cover Sampling

A modified Daubenmire method (Daubenmire, 1959) was used to assess percent cover for each plot. One transect was established with three cover measurements randomly taken over the length of each transect for each of eight plots at the three sites. The planted species were recorded, and other species were considered weeds and recorded as such. The Daubenmire method utilizes the 20cm x 50cm quadrat frame which is placed at multiple positions along a transect. The cover class of each species is analyzed within the area of the quadrat. There are six cover classes, 1 to 6, which correspond to a range of coverage: 0% to 5%, 5% to 25%, 25% to 50%, 50% to 75%, 75% to 95%, 95% to 100%, respectively. Cover classes are assigned individually to each species, and canopy overlap is included, so total cover may exceed 100%. The viewer visually assesses and assigns cover class to each species. Canopy cover per quadrat sample was calculated as:

$\%\ canopy\ cover = cover\ class \times midpoint\ of\ coverage\ range$. The sum of wildflower and weed coverage was recorded as total cover.

Species Diversity

Species diversity was evaluated by the presence or absence of each species from the quadrats used in the cover analysis. The total number of species was calculated from Table 3.3. and 3.4. Due to their similarity and often lack of differentiating features (i.e., flowers), the *Lupinus* and *Gaillardia* species were combined by genus for evaluation. The species diversity between treatments and sites was evaluated by summing the number of species present in each plot from the three quadrats.

Statistical Analysis

Data were analyzed using SAS 9.4 Proc GLM and Tukey test. Data were analyzed by site, treatment, type of cover, and sampling date (α=0.05). Interaction between site and treatment was analyzed for each type of cover. If interaction was not significant, data were analyzed without interaction.

Pollinator Survey

In late August-early September 2017, the insect populations around the wildflower plots and nearby grassed areas was surveyed to determined that number and kinds of insects found there. The idea was to get a general idea of the impact of the wildflowers on the insect population. Bowls of soapy water were placed at these locations in the morning and retrieved late in the day. The trapped insects were later identified in the laboratory.

The Raleigh and Mills River site had the expected results of much higher bees and pollinator numbers in the wildflower area compared to the grassed area nearby. At Clayton, the weed pressure, primarily ryegrass, reduced the amount of wildflower cover and so there were no differences between the two areas. The detailed insect data collected is available from the authors (McLaughlin or Heitman).

Site	Cover	Non-Pollinators	Bees	Total Pollinators
Raleigh	Wildflowers	2	578	607
Raleigh	Grass	14	290	322
Clayton	Wildflowers	4	77	116
Clayton	Grass	24	50	119
Mills River	Wildflowers	569	46	749
Mills River	Grass	11	17	137

Appendix 5: Chapter 3: Materials and Methods Details

2.2 Runoff Sampling and Analysis

Nineteen rainfall events were captured at the I-40 site, and 14 rainfall events were captured at the I-85 site. Tipping bucket rain gauges were installed at each site to measure rainfall depths. The tipping bucket rain gauge logged each tip interval with tips occurring every 0.2mm of rainfall depth, enabling the summation of rainfall depth and calculation of intensity. Rainfall events were discretized over the period of time between sample collection events. The total rainfall depth for each event was summed over this duration, and 1-minute rainfall intensities were determined. Following a rainfall event, the volume of runoff collected in each 380 L tank was measured, the water was thoroughly mixed, a grab sample of the runoff was collected for laboratory analysis of water quality, and tipping bucket data were downloaded. The collection tank volume accommodated up to 23mm of runoff from each plot, and events during which tanks were filled to capacity were considered overflow events and were omitted from analyses. Runoff samples were stored in polypropylene bottles at 4ºC until analysis. All runoff samples were analyzed for total suspended solids (TSS), and a subset of runoff samples were analyzed for nutrients [nitrate (NO_3^-), ammonium (NH_4^+), orthophosphate (PO_4^{3-})], and heavy metals [cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn)]. TSS concentrations were determined by filtration using standard methods for water and wastewater analysis (Rice et al., 2012). Runoff samples were filtered through 0.45 µm filters for dissolved nutrient and metals analyses. Dissolved nutrients were analyzed using a Lachat Instruments QuikChem 8000 Flow Injection Analyzer (Loveland, CO), and dissolved metals were analyzed using a PerkinElmerSciex Elan DRC II inductively coupled plasma mass spectrometer using standard methods (Rice et al., 2012).

2.3 Soil Physical Properties

Soils were collected at 0cm to 15cm and 15cm to 30cm depths in the native soil prior to treatment at each site and were analyzed for particle size distribution using the hydrometer method (Gee and Bauder, 1986). Bulk density and infiltration rate were measured in each plot following the period of stormwater collection at each site. Neither parameter was measured prior to the collection period to avoid artificial disturbances within the plots. Bulk density was determined using the core method (Blake and Hartge, 1986). Soils were collected for bulk density measurements with a 7.5cm diameter Uhland core sampler from 0cm to 7.5cm and 7.5cm to 15cm (AMS Inc., American Falls, ID). Samples were oven dried at 105ºC until constant weight was reached. Infiltration rates were determined using a Cornell Sprinkle Infiltrometer (Ogden et al., 1997). The 24.1cm diameter metal infiltration ring was inserted into the soil to a depth of 7.5cm with the runoff port level with the soil surface. The infiltrometer tank was positioned on top of the infiltration ring, filled with water, and rainfall rates were set to generate runoff during measurements. Runoff was collected in a beaker that was placed in an excavated hole adjacent to the infiltration ring, and runoff volume was measured every minute until a constant rate of runoff was reached. Infiltration rates were determined as the difference between the volume of water irrigated and the volume of runoff after a constant runoff rate was reached.

2.5 Statistical Analyses

Soil variables (bulk density, infiltration rate) met statistical assumptions for parametric analysis and were untransformed prior to analysis. One-way analysis of variance (ANOVA) with Tukey's honestly significant difference (HSD) pairwise comparison was used to evaluate differences between treatments for bulk density and infiltration rate.

Samples across treatments and storms were not spatially or temporally independent, violating the statistical assumption of independence. The randomized complete block plot design resulted in plots nested within blocks, and each plot was sampled repeatedly across multiple precipitation events. Linear mixed effect models were used to account for the spatial and temporal correlation resulting from the study design. Repeated measures correlation analyses were performed to determine relationships between runoff characteristics (volume and TSS) and storm event variables (total depth, intensity, antecedent drying duration). Repeated measures correlation takes into account the within-subject correlation when analyzing observations that are made on the same subject on multiple occasions, yielding an r_{rm} coefficient (repeated measures analogue to the standard Pearson correlation coefficient, r) that describe the strength of the relationship. A one-way ANOVA was performed for each storm event to determine treatment effect on runoff and water quality loads, with treatment as a fixed effect and plot within block as a random variable in order to account for native differences among treatment blocks (Zuur et al., 2009). Untransformed values of runoff and water quality variables were used in analyses, and model diagnostics were evaluated to confirm normality of residuals and homoscedasticity of the data. The performance of each treatment (T, TCP) was evaluated on the basis of its ability to reduce runoff below the levels generated on C plots across multiple storm events at the I-40 and I-85 sites.

All statistics were performed in R version 3.6.1 (R Core Team, 2019). Alpha values were set at α=0.1 in all analyses.

Table 3: Average Bulk Density and Infiltration Rates for Other Studies in Compacted Soils

**For studies that stimulated compaction activities, and the time of measurement follow plot establishment is indicated. Not all studies included infiltration rate measurements.*

**Plots were in situ conditions representing past construction activities with no additional manipulation.*

Source	Location	Time after Establishment	Soil Texture	Bulk Density (g cm^{-3})	Infiltration Rate (cm hr^{-1})
Haynes et al., 2013	Raleigh, NC	7 to 11 weeks	Sandy Loam	1.6	0.1 to 2.7
Mohammadshirazi et al., 2017	Raleigh, NC	5 to 13 months	Sandy Clay	1.34 to 1.49	1.5 to 2.1
		12 months	Clay Loam	1.64	3.1
Rivenshield and Bassuk, 2007	Ithaca, NY	<1 week	Sandy Loam	1.76	N/A
		<1 week	Clay Loam	1.84	N/A
Gregory et al., 2016	Gainesville, FL	*	Loamy Sand	1.49	18.8
(Somerville et al., 2018)	Melbourne, Australia	*	Coarse Sandy Loam	1.67	N/A

Table 4: Repeated Measure Correlation Coefficient (r_{rm}) and Statistical Significance

*$^{O}p<0.10$; *$p<0.05$; **$p<0.01$; ***p0.0001; not displayed: $p>0.1$.*

		Control		Tilled		Tilled + Compost	
Site	**Rainfall Variables**	**Runoff**	**TSS**	**Runoff**	**TSS**	**Runoff**	**TSS**
I-40	Total rainfall	**0.45*** **	0.03	**0.44*** **	-0.04	**0.54*** **	0.11
	Peak intensity	**0.26***	-0.22	**0.25***	**-.36***	**0.23***	-0.14
	Antecedent drying days	**0.21***	-0.27	**-0.23***	**-0.57** **	-0.18	**-0.48** **
I-85	Total rainfall	0.09	-0.1	0.06	-0.13	0.07	-0.15
	Peak intensity	**0.79*** **	**0.8*** **	**0.75*** **	**0.69*** **	**0.81*** **	**0.72*** **
	Antecedent drying days	-0.1	-0.17	-0.07	-0.03	-0.19	-0.16

Table S1: Rainfall, Average Runoff, and Average Percent Infiltrated (±SE)

***For Control (C), Tilled (T), and Tilled + Compost (TCP) plots at the I-40 site from 20 April 2015 to 20 November 2015.*

**Percent infiltration not presented due to low rainfall; runoff may be reflective of rainfall the preceding day.*

	20-Apr	4-May	3-Jun	4-Jun	19-Jun	30-Jun	7-Jul	14-Jul	22-Jul	20-Aug	1-Sep	28-Sep	30-Sep	7-Oct	12-Oct	29-Oct	4-Nov	10-Nov	20-Nov
Total Rainfall (mm)	31.5	27.2	38.6	1.8	34	55.2	41	45.6	12.2	46.2	43.8	79.4	21.8	93	11.2	24.8	84.4	38.8	21.8

Runoff (mm)	20-Apr	4-May	3-Jun	4-Jun	19-Jun	30-Jun	7-Jul	14-Jul	22-Jul	20-Aug	1-Sep	28-Sep	30-Sep	7-Oct	12-Oct	29-Oct	4-Nov	10-Nov	20-Nov
C	12.22	7.38	1.68	14.82	14.44	22.13	19.73	23.03	1.64	5.53	21.08	8.79	10.17	22.73	0.69	3.5	21.46	8.71	7.34
	(3.46)	(2.04)	(0.19)	(3.65)	(2.49)	(0.4)	(2.41)	(0.17)	(0.46)	(1.42)	(1.89)	(3)	(2.75)	(0.23)	(0.29)	(1.3)	(1.57)	(2.67)	(1.84)
T	10.86	5.2	0.68	12.81	12.1	22.49	20.6	22.79	1.59	1.56	21.55	5.67	9.75	22.91	0.89	4.44	23.03	14.11	8.84
	(1.18)	(0.34)	(0.25)	(0.91)	(0.8)	(0.18)	(0.96)	(0.28)	(0.16)	(0.53)	(1.05)	(1.04)	(0.6)	(0.21)	(0.31)	(0.83)	(0.28)	(1.99)	(0.81)
TCP	5.18	3.14	0.49	4.64	7.09	17.21	12.72	16.46	0.77	1.16	15.07	4.96	6.8	21.45	0.53	2.93	18.52	11.66	7.01
	(2.48)	(1.05)	(0.25)	(2.26)	(1.99)	(3.86)	(3.65)	(4.17)	(0.33)	(0.37)	(4.74)	(0.94)	(2.23)	(1.27)	(0.1)	(0.97)	(3.73)	(4.2)	(2.43)

% Infiltrated	20-Apr	4-May	3-Jun	4-Jun	19-Jun	30-Jun	7-Jul	14-Jul	22-Jul	20-Aug	1-Sep	28-Sep	30-Sep	7-Oct	12-Oct	29-Oct	4-Nov	10-Nov	20-Nov
C	61.28	72.88	95.65	*	57.54	59.91	51.87	49.49	86.56	88.02	51.88	88.93	53.35	75.56	93.82	85.88	74.57	77.55	66.34
	(10.97)	(7.51)	(0.5)		(7.32)	(0.72)	(5.89)	(0.38)	(3.74)	(3.08)	(4.31)	(3.78)	(12.63)	(0.25)	(2.55)	(5.25)	(1.86)	(6.88)	(8.43)
T	65.57	80.9	98.23	*	64.41	59.26	49.74	50.02	89.96	96.62	50.79	92.85	55.29	75.37	92.08	82.12	72.71	63.63	59.45
	(3.75)	(1.25)	(0.64)		(2.34)	(0.33)	(2.35)	(0.61)	(1.34)	(1.14)	(2.4)	(1.31)	(2.77)	(0.23)	(2.8)	(3.35)	(0.33)	(5.13)	(3.69)
TCP	83.57	88.45	98.74	*	79.16	68.82	68.98	63.91	93.68	97.49	65.59	93.75	68.81	76.94	95.23	88.2	78.05	69.95	67.83
	(7.85)	(3.85)	(0.64)		(5.86)	(7)	(8.89)	(9.14)	(2.7)	(0.8)	(10.81)	(1.19)	(10.22)	(1.37)	(0.89)	(3.91)	(4.42)	(10.81)	(11.15)

Table S2: Rainfall, Average Runoff, and Average Percent Infiltrated (±SE)

**For Control (C), Tilled (T), and Tilled + Compost (TCP) plots at the I-85 site from 2 March 2017 to 19 June 2017.*

	2-Mar	16-Mar	30-Mar	3-Apr	5-Apr	7-Apr	2-May	5-May	10-May	15-May	24-May	25-May	6-Jun	19-Jun
Total Rainfall (mm)	19.6	28.2	16.8	19.4	9.2	9.2	180.2	43.4	11.8	21	25.8	9.2	58.8	41

Runoff (mm)	**2-Mar**	**16-Mar**	**30-Mar**	**3-Apr**	**5-Apr**	**7-Apr**	**2-May**	**5-May**	**10-May**	**15-May**	**24-May**	**25-May**	**6-Jun**	**19-Jun**
C	6.62	6.84	1.44	10.04	2.57	1.56	3.48	22.37	5.69	15.69	2.84	4.33	22.79	19.51
	(1.03)	(0.97)	(0.39)	(1.33)	(0.59)	(0.34)	(0.48)	(0.12)	(0.56)	(0.99)	(0.91)	(0.53)	(0)	(1.15)
T	6.62	7.03	1.53	10.23	2.46	1.85	2.08	19.54	3.73	12.5	2.41	2.92	22.08	18.34
	(1.51)	(1.93)	(0.57)	(1.33)	(0.8)	(0.69)	(1.02)	(3.09)	(1.42)	(2.78)	(1.86)	(1.35)	(0.71)	(1.6)
TCP	2.36	2.03	0.38	7.71	0.77	0.98	0.58	22.31	2.41	11.4	0.65	1.65	19.07	11.71
	(0.97)	(0.92)	(0.23)	(0.84)	(0.42)	(0.3)	(0.3)	(0.1)	(0.64)	(1.61)	(0.25	(0.67)	(2.15)	(1.76)

% Infiltrated	**2-Mar**	**16-Mar**	**30-Mar**	**3-Apr**	**5-Apr**	**7-Apr**	**2-May**	**5-May**	**10-May**	**15-May**	**24-May**	**25-May**	**6-Jun**	**19-Jun**
C	66.24	75.75	91.44	48.27	72.02	83.09	98.07	48.47	51.78	25.27	88.99	52.9	61.24	52.42
	(5.27)	(3.44)	(2.35)	(6.87)	(6.36)	(3.66)	(0.27)	(0.27)	(4.72)	(4.71)	(3.51)	(5.71)	(0)	(2.8)
T	66.24	75.07	90.92	47.26	73.22	79.88	98.85	54.98	68.43	40.47	90.65	68.23	62.45	55.28
	(7.7)	(6.83)	(3.41)	(6.85)	(8.71)	(7.55)	(0.57)	(7.12)	(12.07)	(13.26)	(7.22)	(14.65)	(1.21)	(3.91)
TCP	87.98	92.81	97.72	60.27	91.59	89.31	99.68	48.6	79.54	45.73	97.47	82.06	67.57	71.43
	(4.93)	(3.25)	(1.37)	(4.35)	(4.52)	(3.32)	(0.16)	(0.23)	(5.44)	(7.68)	(0.96)	(7.28)	(3.66)	(4.31)

Table S3: Total Suspended Solids Concentrations

**In mg L*$^{-1}$ *(±SE) in runoff from Drain (D), Control (C), Tilled (T), and Tilled + Compost (TCP) plots during sampled storms in 2015 at the I-40 site.*

	20-Apr	13-May	29-May	4-May	19-Jun	3-Jun	30-Jun	14-Jul	22-Jul	7-Jul	20-Aug
D	11.4	82.2	213.19	61	81.46	41.66	51.1	24.02	73.75	36.6	89.02
	(11.81)b	(20.04)bc	(50.23)a	(9.08)b	(41.5)a	(8.08)b	(13.38)a	(3.57)a	(41.16)a	(4.32)a	(24.49)a
C	78.25	50.75	132.13	46	41.23	24.1	23.78	14.7	32.41	18.03	44.73
	(18.57)b	(12.59)c	(27.92)a	(5.05)b	(9.36)a	(2.27)c	(1.44)b	(3.71)b	(7.99)a	(2.25)b	(9.54)b
T	216.5	127.5	215.63	132.25	54.68	65.95	48.5	25.8	36.36	47.98	68.25
	(7.88)a	(19.6)ab	(44.42)a	(5.19)a	(5.91)a	(4.4)a	(2.8)ab	(3.46)a	(2.62)a	(3)a	(4.29)ab
TCP	187.75	153.25	128.79	149.25	43.15	45.68	38.73	18.7	42.46	48.3	94.23
	(28.2)a	(25.22)a	(45.06)a	(5.68)a	(4.83)a	(4.11)b	(2.15)ab	(2.3)ab	(12.22)a	(4.8)a	(16.2)ab

Table S4: Total Suspended Solids Concentrations

**In mg L*$^{-1}$ *(±SE) in runoff from Drain (D), Control (C), Tilled (T), and Tilled + Compost (TCP) plots during sampled storms in 2017 at the I-85 site.*

)	2-Mar	16-Mar	30-Mar	3-Apr	7-Apr	2-May	5-May	10-May	15-May	24-May	25-May	19-Jun
D	127.21	100.18	132.61	303.18	77.39	73.91	26.48	49.72	43.49	45	65.78	37.38
	(28.69)a	(45.12)a	(23.36)a	(38.81)ab	(34.97)a	(32.55)a	(4.28)a	(12.32)a	(8.52)c	(10.92)b	(14.04)bc	(7.03)b
C	50.99	13.6	155.95	212.77	18.49	72.32	37.99	37.12	106.91	89.72	43.27	31.37
	(15.19)a	(4.55)a	(56.1)a	(28.38)b	(3.99)a	(30.85)a	(8.63)a	(4.46)a	(19.28)ab	(60.32)b	(10.8)c	(14.63)b
T	142.52	43.29	213.13	426.18	72.65	121.25	50.02	59.99	152.86	90.99	111.51	65.67
	(56.03)a	(3.56)a	(24.5)a	(89.96)a	(19.87)a	(35.19)a	(19.75)a	(1.92)a	(30.15)a	(32.73)ab	(36.46)a	(9.63)a
TCP	181.71	401.71	145.68	378.46	119.42	107.22	44.31	52.74	104.55	53.73	76.32	48.9
	(104.3)a	(283.69)a	(37.47)a	(117.41)a	(55.9)a	(70.12)a	(10.68)a	(12.04)a	(27.73)b	(13.51)a	(22.56)ab	(6.5)ab

Table S5: Water Quality Constituent Concentrations (+SE)

**In runoff from Drain (D), Control (C), Tilled (T), and Tilled + Compost (TCP) plots during sampled storms at the I-40 site in 2015. Treatments were excluded from pairwise comparisons if all plots were below the detection limit of analysis.*

	mg / L					
	PO_4^{-3}	**NO_3^-**	**NH_4^+**	**Pb**	**Cu**	**Zn**
20-Apr						
D	0.49 (0.18)c	0.78 (0.59)b	1.35 (0.39)c	N.D.	0.08 (0.02)a	0.06 (0)c
C	0.98 (0.51)c	2.09 (1.17)b	1.08 (0.19)c	N.D.	0.2 (0.08)a	0.1 (0.02)bc
T	5.83 (0.99)b	0.63 (0.52)b	16.75 (2.37)a	N.D.	0.15 (0.05)a	0.17 (0.02)ab
TCP	14 (2.55)a	47.7 (8.29)a	6.23 (0.81)b	N.D.	0.93 (0.6)a	0.14 (0.02) ab
4-May						
D	2.56 (1.12)a	6 (2.88)a	2.26 (1.26)a	0.06 (0.01)a	1.47 (1.52)a	0.1 (0.02)a
C	6.2 (3.56)a	13.93 (8.78)a	1.33 (0.44)a	N.D.	0.16 (0.08)a	0.07 (0.01)ab
T	3.23 (2.73)a	8.31 (7.15)a	1.6 (0.97)a	N.D.	0.28 (0.21)a	0.06 (0.01)b
TCP	0.61 (0.22)a	1.99 (0.73)a	1.02 (0.48)a	0.07 (0.01)a	0.15 (0.09)a	0.06 (0.01)b
13-May						
D	1.39 (0.85)a	0.58 (0.22)a	0.42 (0.07)a	0.06 (0)	0.08 (0.02)a	N.D.
C	4.33 (2.65)a	1.13 (0.71)a	0.57 (0.11)a	N.D.	N.D.	0.06 (0.01)
T	2.67 (2.25)a	0.91 (0.66)a	0.64 (0.25)a	N.D.	0.11 (0.04)a	N.D.
TCP	0.35 (0.06)a	0.59 (0.24)a	0.29 (0.02)a	N.D.	N.D.	N.D.
28-May						
D	0.35 (0.14)b	0.56 (0.12)a	1.85 (0.47)a	N.D.	0.92 (0.3)a	0.21 (0.05)a
C	1.62 (0.38)a	0.61 (0.11)a	2.4 (0.35)a	N.D.	0.37 (0.18)a	0.16 (0.04)a
T	0.62 (0.23)b	0.58 (0.12)a	3.85 (1.34)a	N.D.	0.82 (0.23)a	0.2 (0.05)a
TCP	0.41 (0.1)b	0.77 (0.09)a	2.6 (0.43)a	N.D.	0.76 (0.19)a	0.21 (0.05)a
3-Jun						
D	0.5 (0.14)a	0.68 (0.27)a	0.77 (0.6)a	0.06 (0.01)a	0.11 (0.04)a	0.1 (0.05)a
C	2.48 (1.45)a	1.19 (0.53)a	0.38 (0.11)a	0.06 (0)a	0.07 (0.01)a	0.07 (0.01)a
T	1.19 (0.88)a	0.64 (0.16)a	0.2 (0.07)a	N.D.	0.17 (0.1)a	0.06 (0.01)a
TCP	0.2 (0.06)a	0.74 (0.17)a	0.15 (0.01)a	N.D.	0.06 (0.01)a	0.06 (0.01)a
19-Jun						
D	0.81 (0.51)a	1.48 (0.49)a	N.D.	N.D.	N.D.	N.D.
C	1.79 (0.94)a	1.7 (0.58)a	0.53 (0.29)a	N.D.	0.06 (0.01)a	N.D.
T	1.19 (0.97)a	1.39 (0.61)a	0.29 (0.08)a	N.D.	0.07 (0.02)a	N.D.
TCP	0.2 (0.04)a	1.23 (0.25)a	0.18 (0.04)a	N.D.	N.D.	N.D.

N.D. = No detection. Detection limit was <0.1 mg / L for dissolved nutrients, and <0.05 mg / L for dissolved metals.

Table S6: Water Quality Constituent Concentrations (±SE)

**In runoff from Drain (D), Control (C), Tilled (T), and Tilled + Compost (TCP) plots during sampled storms at the I-85 site in 2017. Treatments were excluded from pairwise comparisons if all plots were below the detection limit of analysis.*

	mg / L				
	PO_4^{-3}	**NO_3^-**	**NH_4^+**	**Cu**	**Zn**
2-Mar					
D	0.05 (0.02)b	0.35 (0.04)a	0.34 (0.07)a	0.15 (0.09)a	0.09 (0.03)a
C	0.03 (0.01)b	0.19 (0.02)a	0.2 (0.02)b	0.07 (0.02)a	0.11 (0.02)a
T	0.05 (0.01)b	0.2 (0.02)a	N.D.	N.D.	0.12 (0.02)a
TCP	0.18 (0.02)a	0.29 (0.12)a	0.23 (0.05)b	0.08 (0.02)a	0.11 (0.01)a
7-Apr					
D	0.04 (0.02)b	0.32 (0.11)a	0.35 (0.13)a	0.1 (0.03)	0.24 (0.07)a
C	0.01 (0)b	N.D.	N.D.	N.D.	0.23 (0.03)a
T	0.03 (0)b	N.D.	N.D.	N.D.	0.19 (0.01)a
TCP	0.16 (0.05)a	0.15 (0.05)ab	0.18 (0.08)ab	N.D.	0.17 (0.03)a
2-May					
D	0.16 (0.06)b	0.19 (0.02)a	0.81 (0.33)a	0.1 (0.03)a	1.34 (0.37)a
C	0.07 (0.02)b	0.11 (0.01)b	0.58 (0.24)a	0.06 (0.01)a	0.78 (0.25)a
T	0.1 (0.03)b	0.13 (0.03)b	0.5 (0.17)a	0.06 (0)a	1.31 (0.56)a
TCP	0.32 (0.09)a	0.12 (0.02)b	1.34 (0.92)a	0.08 (0.02)a	1.13 (0.37)a
24-May					
D	0.38 (0.15)a	4.39 (2.96)a	2 (0.65)a	0.13 (0.05)a	0.43 (0.15)a
C	0.06 (0.01)a	3.2 (3.03)a	0.46 (0.07)a	0.07 (0.01)a	0.4 (0.14)a
T	0.09 (0.02)a	0.48 (0.19)a	0.95 (0.85)a	0.07 (0.01)a	0.4 (0.04)a
TCP	0.3 (0.07)a	2.1 (1.6)a	1.03 (0.66)a	0.08 (0.02)a	0.36 (0.12)a
25-May					
D	0.08 (0.02)b	5.01 (3.44)a	0.61 (0.14)a	0.13 (0.07)a	0.76 (0.2)a
C	0.05 (0.01)b	8.33 (6.33)a	0.53 (0.26(a)	0.06 (0.01)a	0.76 (0.1)a
T	0.19 (0.12)b	4.57 (4.41)a	0.4 (0.15)a	0.08 (0.01)a	1.15 (0.57)a
TCP	0.5 (0.12)a	8.85 (8.75)a	0.82 (0.37)a	0.06 (0)a	0.48 (0.1)a
19-Jun					
D	0.17 (0.06)b	0.12 (0.02)b	0.51 (0.08)a	0.08 (0.03)a	0.4 (0.07)a
C	0.1 (0.02)b	0.11 (0.01)a	0.36 (0.04)b	N.D.	0.56 (0.07)a
T	0.17 (0.04)b	N.D.	0.33 (0.05)b	0.06 (0.01)a	0.74 (0.27)a
TCP	0.43 (0.01)a	N.D.	0.3 (0.05)b	N.D.	0.47 (0.1)a

N.D. = No detection. Detection limit was <0.1 mg / L for dissolved nutrients, and <0.05 mg / L for dissolved metals.