RESEARCH & DEVELOPMENT

Investigation of Tillage and Soil Amendments to Increase Infiltration in Vegetated Stormwater Controls

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Investigation of Tillage and Soil Amendments to Increase Infiltration in Vegetated Stormwater Controls

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16. Abstract
Infiltration into vegetated stormwater control measures (SCMs) is critical for reducing stormwater runoff. Applying tillage to ameliorate compaction enhances vegetation establishment, increases infiltration, and reduces runoff. The long-term benefit of tillage as a BMP may be limited by soil reconsolidation with routine traffic and maintenance. Our research evaluated the sustainability of vegetated SCMs following tillage pre-treatment. We simulated post-construction soil conditions on both cut and fill slopes to examine the effects of applying tillage BMPs with and without compost amendments over periods of more than two years at five sites. Additionally, we evaluated tillage BMPs on two active roadways where we compared them to existing stands of grass for runoff reduction. Results from simulated post-construction sites suggest that benefits of tillage can be maintained for two years or more. Compared to controls, bulk density was reduced by an average of 11% for periods >24 months when tillage was applied. Infiltration rates averaged more than three times larger than controls after >24 months. No differences were observed in surface bulk density or infiltration rate based on depth of tillage (6 in vs. 12 in. [15 cm vs. 30 cm]). Compost addition affected infiltration rate in only one of four trials, and in this case mitigated the effect of mower traffic on tillage alone. In two other trials where mower traffic was tested, it had no effect on bulk density or infiltration rate. The two roadway sites differed from the other trials in that the control was established grass. Compared to established grass, tillage and tillage plus compost reduced runoff from natural rainfall by averages of 10 and 43%, respectively, over 18 or more runoff events at each site. At one site, runoff reduction compared to control appeared to diminish within a year of tillage (with or without compost). At the other site, reductions in runoff were mostly maintained throughout monitoring. At the end of monitoring, bulk density and infiltration rate were no different between control and tillage, but bulk density was lower and infiltration rate was higher for tillage with compost addition compared to control. These results suggest that, unless compost is incorporated with tillage, tillage benefits relative to existing grass stands will likely be short-term. Overall, results indicate that tillage BMPs can effectively reduce bulk density, increase porosity, and enhance infiltration for disturbed, new construction soils. Tillage BMPs may also be beneficial in locations which with known infiltration and grass stand issues.

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EXECUTIVE SUMMARY

Infiltration into vegetated stormwater control measures (SCMs) is critical for reducing the impacts of stormwater runoff. Infiltration reduces runoff volume, and sediment and nutrient loss. Establishment and maintenance of vegetated SCMs is often problematic due to poor soil conditions associated with compaction and topsoil removal during construction. These problems persist in time and limit both immediate and long-term SCM effectiveness. Research in North Carolina has demonstrated that applying tillage to ameliorate compaction greatly enhances success in vegetation establishment, increases infiltration, and reduces runoff and erosion. The long-term (> 6-12 months) benefit of tillage as a construction site BMP has not been determined, and may be limited by soil reconsolidation over time with routine traffic and maintenance. Our research was designed to determine the sustainability of vegetated SCMs following tillage pre-treatment. We simulated post-construction soil conditions on both cut and fill slopes to examine the effects of applying tillage BMPs with and without compost amendments on infiltration rate, soil bulk density, soil penetration resistance, and grass establishment over periods of more than two years at five sites representing the three physiographic regions of North Carolina. Additionally, we evaluated tillage BMPs on two active roadways where we compared tillage BMPs to existing stands of grass for runoff reduction from natural storms. Our results from simulated post-construction sites suggest that benefits of tillage can be maintained for two years or more. Compared to controls, bulk density was reduced by an average of 11% for periods >24 months when tillage was applied. Infiltration rates for tillage BMPs were on average more than three times larger than compacted controls after >24 months. No differences were observed in surface bulk density or infiltration rate based on depth of tillage ([15 cm vs. 30 cm]). Compost addition affected infiltration rate in only one of four trials where tested, and in this case mitigated the effect of mower traffic with tillage alone. In two other trials where mower traffic was tested, it had no effect on bulk density or infiltration rate. The two roadway demonstration sites differed from the simulated construction trials in that the control comparison was to established grass to represent a BMP retrofit. Compared to established grass, tillage and tillage plus compost reduced runoff from natural rainfall by averages of 10 and 43%, respectively, over 18 or more runoff events at each demonstration site. At one of these sites, runoff reduction compared to the control grass stand appeared to diminish within a year of tillage treatment (with or without compost). At the other site, reductions in runoff were mostly maintained throughout monitoring. At the end of monitoring for these sites, bulk density and infiltration rate were no different between control and tillage, but bulk density was lower and infiltration rate was higher (by a factor of 2-3) for tillage with compost addition compared to control. These results suggest that, unless compost is incorporated with tillage, tillage benefits relative to existing healthy grass stands will likely be short-term. Overall, results indicate that tillage BMPs can effectively reduce bulk density, increase porosity, and enhance infiltration for disturbed, new construction soils. Tillage BMPs may also be beneficial for soils in locations which are known to have problems with infiltration and grass establishment.

TABLE OF CONTENTS

List of Tables

List of Figures

INTRODUCTION

Much of the flash flooding and impaired stream ecology in urban areas can be attributed to runoff from impervious surfaces. Highly compacted surface soils add to the large runoff volumes, which are often funneled to nearby stream channels. North Carolina is rapidly growing and the impacts on streams, lakes, and estuaries can be significant in both pollutant load and runoff volume. The impacts during construction are largely due to runoff containing high concentrations of suspended sediment being discharged into nearby streams. After construction is complete, the soil at construction sites is often highly degraded and compacted, producing much higher runoff rates than either prior to construction or predicted for typical grassed areas. Establishing vegetation may be very difficult due to the poor soil conditions, and even where vegetation is sparsely established, degraded soils continue to deliver large volumes of runoff and sediment and nutrient loads. The purpose of this project is to address these issues by testing the immediate and sustained benefits of relatively simple, inexpensive Best Management Practices (BMPs), which can be applied throughout the state.

Vegetated stormwater control measures (SCMs) are a critical tool in NCOT's toolbox of practices for reducing the impacts of stormwater runoff. Infiltration is a key feature of these SCMs. Infiltration reduces runoff volume, and sediment and nutrient loss. Viable vegetation with proper rooting is essential to achieving infiltration. Establishment and maintenance of vegetated SCMs is often problematic due to poor soil conditions prior to seeding, associated with compaction and topsoil removal. These problems persist in time and limit both immediate and long-term effectiveness of vegetated SCMs.

Recent research in North Carolina has demonstrated that applying tillage to ameliorate compaction on construction sites greatly enhances success in vegetation establishment, increases infiltration, and reduces runoff and erosion (Haynes et al., 2013; Mohammadshirazi et al., 2016). The long-term (> 6-12 months) benefits of tillage as a construction site BMP have not, however, been determined and may be limited by soil reconsolidation over time with routine traffic and maintenance. It may be necessary to periodically repeat tillage in vegetated SCMs in order to maintain their function. Unnecessary tillage and reseeding add costs, so it is important to determine to what extent, if any, tillage benefits are lost over time. Alternately, the addition of compost amendments during initial tillage application may limit soil reconsolidation and maintain SCM function.

The following studies were designed to determine the sustainability of vegetated SCMs following tillage pre-treatment and to determine the need for repeated tillage over time. We simulated post-construction soil conditions on both cut and fill slopes to examine the effects of applying tillage BMPs with and without compost amendments on infiltration rate, soil bulk density, soil penetration resistance, and grass establishment over periods of more than two years at five sites representing the three physiographic regions of North Carolina. Additionally, we evaluated tillage BMP practices on two active roadways where we compared tillage BMPs to existing stands of grass for runoff reduction from natural storms.

Results of Literature Review

When land is converted from forest or agriculture to urban development, much greater runoff is contributed to stream flows (Line and White, 2007; Burges et al., 1998), which in turn has numerous negative impacts on stream stability and function (Violin et al., 2011; Konrad et al., 2005). While much of this impact is attributed to impervious surfaces such as roads and roofs, the remaining areas can become compacted during construction activities, whether intentionally to increase soil strength or unintentionally by heavy equipment traffic (Batey and McKenzie, 2006; Gregory et al., 2006; Olson et al., 2013). Compaction degrades soil physical properties and hinders vegetative growth, and may occur during construction regardless of site management (i.e., even when practices are intended to minimize disturbance) (Randrup and Dralle, 1997). Compaction has been demonstrated to reduce soil porosity (Schafer-Landefeld et al., 2004; Shestak and Busse, 2005) and infiltration rate (Siyal et al., 2002; Woltemade, 2010), and this may lead to large amounts of runoff and erosion (Booth and Jackson, 1997; Violin et al., 2011). Conversion of forested areas to lawns and pastures may reduce infiltration rates by an order of magnitude (Price et al., 2010) and infiltration rates have been reported to be less than < 1 mm h^{-1} in some urban soils (Schuster et al., 2014; Yang and Zhang, 2011). Root growth may also be limited in compacted soils (Alberty et al., 1984). Plant roots develop channels in soil which may increase infiltration rates over time (Beven and Germann, 1982; Hino et al., 1987), although studies have found that effects of compaction from equipment traffic can persist for decades (Kozlowski, 1999).

In agricultural fields, increases in infiltration rate have been reported following tillage (Lipiec et al., 2006), as well as when tillage is accompanied by amendments such as compost (Bazzoffi et al., 1998). Busscher et al. (2009) found that tillage along with crosslinked polyacrylamide reduced soil penetration resistance, but that this didn't result in greater water content or crop yields over three years. Others have reported that tillage along with gypsum can reduce penetration resistance (Radcliffe et al., 1986) and increase infiltration rate (Amezketa et al., 2005; Yu et al., 2003), while yet some others have found little or no effect of gypsum on soil properties (Buckley and Wolkowski, 2014).

Several studies have also begun to investigate the application of tillage and tillage along with amendments to improve conditions of compacted soil typical of construction sites (Haynes et al., 2013; Olson et al., 2013). Haynes et al. (2013) found that rotary tillage increased infiltration in compacted soil but that hollow tine aeration did not, and that vigorous grass growth was needed to maintain the effect of tillage. In compacted urban park areas, Olson et al. (2013) found that deep tillage (0.4 m) did not consistently improve infiltration over time unless compost was also incorporated. Schmid et al. (2017) found that tillage alone initially improved grass stands but that this effect was lost over two years unless compost was added to the sandy soil. *We are not aware of any studies that evaluated the effects of tillage and amendments on soil physical properties in post-construction, compacted soil for different soils and climates over multiple years.*

Report Organization

The main body of this report includes a summary of methods and results for two primary activities for the project. The first activity involved five trials at three locations spread across the three physiographic regions in North Carolina. Each trial included a comparison of infiltration rates and soil bulk density measured periodically over a period of at least 24 months for compacted control and tillage BMP treatments. Additionally, compost, gypsum, cross-linked polyacrylamide, and liming amendments; controlled traffic, tillage depth; and cut versus fill material were also evaluated in a subset of the trials. The second main project activity involved comparison of tillage BMPs with and without compost to existing roadside grass stands along two active roadways. Runoff from natural rainfall events was measured for periods of 9-12 months at the sites; infiltration rate and bulk density were also evaluated after runoff collection concluded. Following the description of research activities we include a summary of main findings and associated recommendations.

In addition to these main sections of the report we have included three appendices. The first appendix is a more extensive report of from the field trials, published in the peer-reviewed literature. The second appendix includes a study comparing single-ring sprinkle infiltrometers (used as a BMP evaluation tool herein) with the commonly-used ASTM standard double-ring infiltrometer method. The third appendix includes supplemental water quality data collected at the two roadside demonstration sites.

FIELD TRIALS FOR EVALUATION OF TILLAGE TO IMPROVE INFILTRATION

Five field trials were conducted between 2011 and 2015 in the three physiographic regions of North Carolina to determine the effects of tillage with and without amendments on compacted soils. These data have been published in refereed literature (Shirazi et al. 2016). The publication is included in its entirety as Appendix 1, including additional details on methodology, results, and discussion. The research is summarized below.

Materials and Methods

Field trials were conducted to simulate compacted post-construction sites (Table 1). All sites except Piedmont 3 were prepared by removing the existing vegetation and topsoil to expose the subsoil. These are referred to as “cut” sites. This subsoil was graded to no greater than 5% slope, and compacted with a smooth vibratory roller. The Piedmont 3 site was prepared by adding fill soil from a nearby construction site, then grading and compacting the soil as stated above (Fig. 1). Soil textural classes for these sites varied: sand at Sandhills, sandy clay loam in the Mountains, sandy clay at Piedmont 2 and 3, and clay loam fill at Piedmont 3. Treatments, sub-treatments, and time of establishment are summarized in Table 1. These treatments included compost, lime at varying rates, cross-linked polyacrylamide, and gypsum. Sub-treatments included traffic to simulate mowing operations; a residential-type riding mower was used at Mountain and a commercial-type riding mower was used at Piedmont 1 and 2. Measurements included surface bulk density, penetration resistance, infiltration rate, shoot mass, grass coverage, and root density. These parameters were measured between 1 and 32 months after site establishment. Measurements collected at each site are summarized in Table 2.

Table 1. Site preparation and treatments.

Site	Established	Tillage depth[1]	Amendments	Sub-treatment
Sandhills	August 2011	15, 30 cm	compost[2], lime (0, 1.5, 3[3] Mg ha^{-1})	-
Mountain	August 2011	15, 30 cm	compost[2], xPAM[4] (0.32 Mg ha^{-1})	traffic (90 kPa)
Piedmont 1	February 2011	15, 30 cm	lime (0, 1.25, 2.5[3] Mg ha^{-1})	traffic (177 kPa)
Piedmont 2	April 2012	30 cm	compost[2]	traffic (177 kPa)
Piedmont 3	October 2013	30 cm	compost[2], xPAM[4] (0.672 Mg ha^{-1}), gypsum (11.2 Mg ha^{-1})	-

[1]All sites included a compacted control; [2]Compost was applied as a 5-cm depth equivalent; [3]DT treatment only (2X rate); [4]Granular cross-linked polyacrylamide.

Figure 1. Site preparations at Piedmont 3 fill site.

Table 2. Measured parameters and timing of measurements at each site.

Site	Bulk density	Penetration resistance	Infiltration rate	Shoot mass	Grass coverage	Root density
	----------------------------- months after establishment -----------------------------					
Sandhills	1, 6, 23, 27	6	1, 6, 18, 23, 27	4	10	--
Mountain	2, 3, 23, 30	7	2, 3, 23, 30	8	8	--
Piedmont 1	1, 5, 29, 32	6	5, 16, 28, 32	5	5	5
Piedmont 2	7, 13, 19, 26	27	7, 13, 19, 26	27	27	26
Piedmont 3	1, 3, 6, 8, 12, 19, 24	12	3, 8, 12, 19, 24	8	8	8, 12

Results

Bulk Density

Simulated construction traffic was effective in increasing bulk density at all sites. Compared to compacted controls that received no subsequent tillage, tillage significantly lowered bulk density initially, and maintained a significantly lower bulk density throughout the measurement period for all sites, except for the last measurement at the Mountain site (Table 3). Where tested, deep tillage was not different than shallow tillage.

Compared to tillage alone, compost had no significant effect on bulk density for the Sandhills and Mountain Sites (therefore it is included with the tillage main effects in Table 3). Compost reduced bulk density compared to tillage alone at Piedmont 2 and 3 for all measurement times with only one exception, which was possibly due to field conditions at the time of sampling. The difference observed between sites may have been due to the Sandhills and Mountain Sites' coarser-textured soils, which likely settled more readily than the finer-textured soils at the other sites and may also have had a faster rate of compost decomposition.

There was no statistically significant effect of traffic, lime, or xPAM on bulk density.

Penetration Resistance

At all sites except Piedmont 3, tillage significantly reduced penetration resistance to a depth of at least 20 cm (Fig. 1). On sites where there was a shallow and deep tillage treatment, deep tillage significantly reduced penetration resistance more than shallow tillage below the 20 cm depth, but results were the same at depths shallower than 20 cm. Statistically significant results were not observed in penetration resistance at Piedmont 3. This may have been due to the heterogeneity of the fill material applied to the plot area.

There was no statistically significant effect of compost, traffic, lime, or xPAM on penetration resistance where tested.

Infiltration Rate

Infiltration rate was greater on tilled treatments compared to compacted treatments at all sites on most sampling dates (Table 4). Overall, compost had little effect on infiltration rate compared to tillage alone. At the Sandhills and Mountain Sites, compost had no effect on infiltration rate. At

Piedmont 2, the compost's effect in combination with traffic was the most significant. The reduced infiltration rate observed for tilled trafficked treatments was mitigated by the addition of compost.

Results at Piedmont 3 were somewhat more variable, likely due to the heterogeneous nature of the fill material. Tillage with no amendment had significantly lower infiltration rate than tillage with compost at 12 and 24 months, but not at other sampling times. Infiltration rate for xPAM was greater than tilled treatments at the 12 month sampling, but was no different otherwise. The infiltration rate for gypsum was never greater than tillage alone. There was no statistically significant effect of lime on infiltration rate.

Table 3. Bulk density over time measured at each site by treatment.

Treatment	Bulk density[2]						
	Months after establishment						
Sandhills	1	6	23	27			
			g cm^{-3}				
Compacted	1.89a^{a}	1.76a^{a}	1.89a^{a}	1.81a^{a}			
Shallow till	1.12b^{c}	1.45b^{b}	1.76b^{a}	1.63b^{a}			
Deep till	1.11b^{c}	1.37b^{b}	1.74b^{a}	1.68b^{a}			
	Months after establishment						
Mountain	2	3	23	30			
Compacted	1.52a^{a}	1.38a^{a}	1.44a^{a}	1.22a^{b}			
Shallow till	0.92b^{b}	1.15b^{a}	1.21b^{a}	1.22a^{a}			
Deep till	0.84b^{b}	1.05b^{ab}	1.16b^{a}	1.20a^{a}			
	Months after establishment						
Piedmont 1	1	5	29	32			
Compacted	1.48a^{a}	1.49a^{a}	1.44a^{a}	1.52a^{a}			
Shallow till	1.11b^{b}	1.35b^{a}	1.28b^{a}	1.28b^{a}			
Deep till	1.12b^{b}	1.25b^{a}	1.28b^{a}	1.23b^{a}			
	Months after establishment						
Piedmont 2	7	13	19	26			
Compacted	1.48a^{a}	1.34a^{ab}	1.48a^{a}	1.29a^{b}			
Deep till	1.02b^{b}	1.21b^{a}	1.28b^{a}	1.09b^{b}			
Deep till + compost	0.66c^{a}	0.66c^{a}	0.76c^{a}	0.78c^{a}			
	Months after establishment						
Piedmont 3	1	3	6	8	12	19	24
Compacted	1.55a	1.92a	1.70a	1.58a	1.64a	1.52a	1.45a
Deep till	1.29b	1.38b	1.43b	1.32b	1.43b	1.37b	1.28b
Deep till + compost	1.00c	0.67c	1.15c	1.05c	1.31b	1.16c	1.18c
Deep till + xPAM[1]	1.25b	1.31b	1.35b	1.29b	1.24b	1.30b	1.29b
Deep till + gypsum	1.28b	1.30b	1.37b	1.30b	1.32b	1.34b	1.29b

[1]Granular cross-linked polyacrylamide.
[2]Within each site, means followed by the same letter within a column are not different (p = 0.05); superscript letters signify differences within the row (p = 0.05) where present.

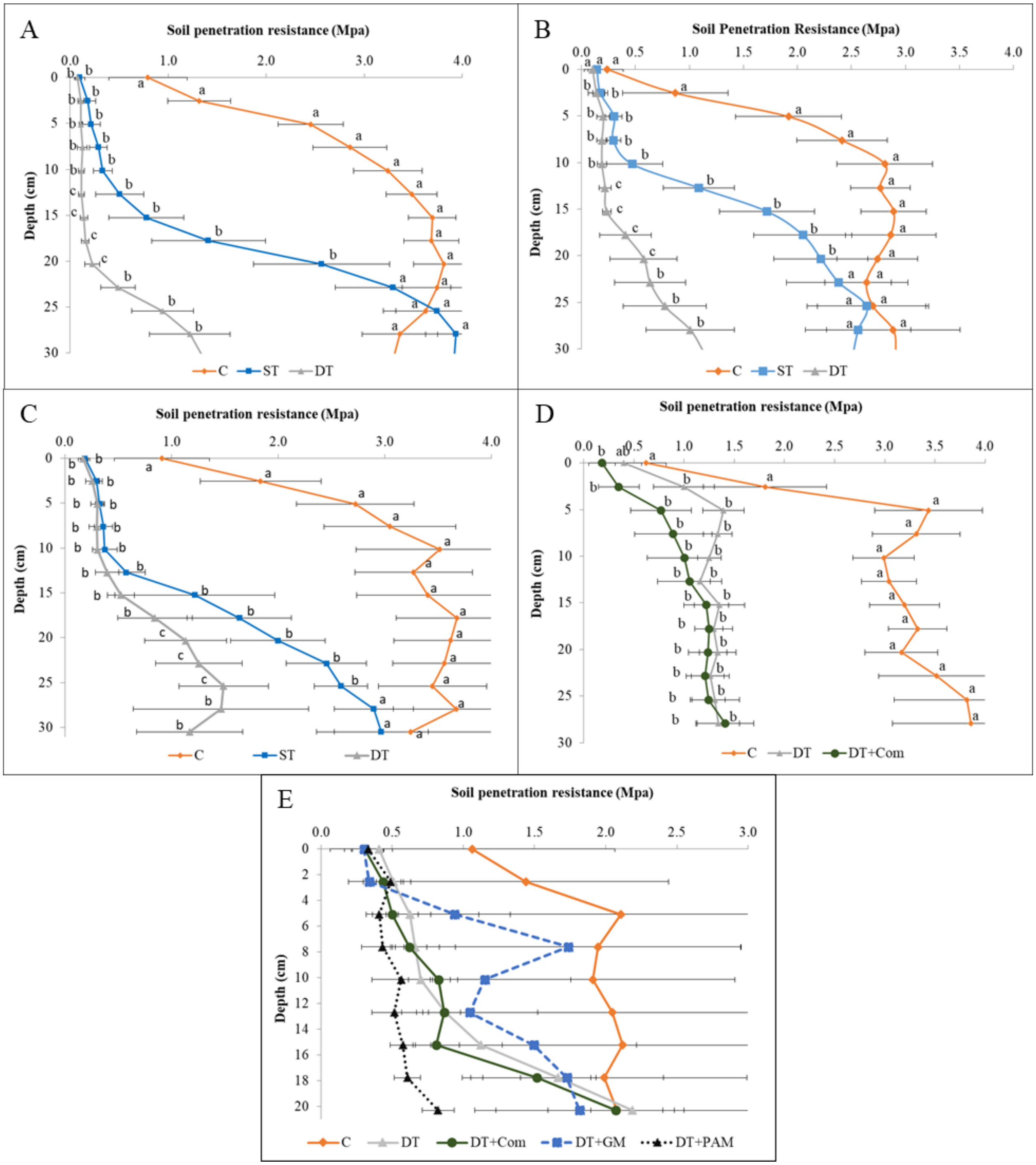

Figure 2. Soil penetration resistance versus depth at Sandhills (A), Mountain (B), Piedmont 1 (C), Piedmont 2 (D), and Piedmont 3 (E). C, ST, DT, Com, GM, and PAM refer to compacted, shallow till, deep till, compost, gypsum, and cross-linked polyacrylamide treatments, respectively. Error bars represent one standard deviation. Same letter with each depth are not different (p=0.05).

Table 4. Infiltration rates over time measured at each site by treatment.

Treatment	Infiltration rate[3]				
	Months after establishment				
Sandhills	1	6	18	23	27
			$cm\ h^{-1}$		
Compacted	0.3b	2.9b	12.4b	7.1b	11.0b
Shallow till	36.1a	33.8a	31.2a	24.2a	34.0a
Deep till	23.1a	38.5a	34.3a	26.7a	33.9a
	Months after establishment				
Mountain	2	3	23	30	
Compacted	0.5b^{b}	0.6b^{b}	7.2b^{a}	8.2b^{a}	
Shallow till	38.4a^{a}	23.8a^{b}	19.2a^{b}	23.7a^{b}	
Deep till	43.0a^{a}	25.6a^{b}	19.5a^{b}	24.0a^{b}	
	Months after establishment				
Piedmont 1	5	16	28	32	
Compacted	3.9b	1.5b	3.0b	6.7b	
Shallow till	20.3a	21.6a	11.5a	22.1a	
Deep till	21.8a	20.6a	17.1a	23.0a	
	Months after establishment				
Piedmont 2[1]	7	13	19	26	
Compacted / NT	0.6c	2.1b	6.8b	2.8b	
Compacted / T	1.1c	4.9b	10.7b	6.0b	
Deep till / NT	26.2ab	12.5b	29.8a	29.4a	
Deep till / T	13.3b	4.3b	12.4b	10.8b	
Deep till + compost / NT	36.6a	31.1ab	31.2a	30.7a	
Deep till + compost / T	29.9ab	31.8a	26.1ab	24.3ab	
	Months after establishment				
Piedmont 3	3	8	12	19	24
Compacted	0.8b^{c}	7.5a^{ab}	3.1c^{b}	4.1c^{abc}	8.6c^{a}
Deep till	14.2a^{a}	9.4a^{a}	14.5b^{a}	17.3a^{a}	24.9b^{a}
Deep till + compost	5.5ab^{c}	11.6a^{bc}	30.9a^{ab}	21.4a^{b}	39.5a^{a}
Deep till + xPAM[2]	6.7ab^{b}	10.8a^{b}	31.1a^{a}	19.4a^{ab}	30.4ab^{a}
Deep till + gypsum	6.5ab^{b}	7.4a^{b}	26.6ab^{a}	24.0a^{a}	31.1ab^{a}

[1]NT and T refer to non-trafficked and trafficked sub-treatments, respectively.
[2]Granular cross-linked polyacrylamide.
[3]Within each site, means followed by the same letter within a column are not different ($p = 0.05$); superscript letters signify differences within the row ($p = 0.05$) where present.

Plant Growth

At Sandhills, Mountain, and Piedmont 3 sites, neither, tillage, amendments, nor traffic had an effect on shoot mass measured 8 months or less after establishment (Table 5). At Piedmont 1, tillage had a positive effect on shoot mass. At Piedmont 2, only tillage with compost showed an increase in shoot mass.

At Mountain and Piedmont 1 sites, tillage showed a positive effect on vegetative cover, while only tillage with compost had a positive effect at Sandhills and Piedmont 2. Compost without tillage actually had a negative effect on cover at Sandhills, and neither tillage nor amendments at Piedmont 3 showed any effect on vegetative cover.

Root density (Table 6) was measured at all the Piedmont sites. At Piedmont 1, root density increased in both tillage treatments at 15-30 cm depth, but only for deep tillage at 0-15 cm. At Piedmont 2, only deep till + compost showed an increase in root density, and only at the 15-30 cm depth. At Piedmont 3, the results are quite mixed. During the first sampling, at 8 months after establishment, tillage with the addition of xPAM had the lowest root densities at all sampled depths. Interestingly, the compacted treatment had the highest root densities at the 0-7.5 and 15-23 cm depths. The gypsum amended tilled treatment had the highest root density at the 7.5-15 cm depth. The sampling at 12 months after establishment showed no differences in root densities at the 7.5-15 and 15-23 cm depth intervals. At the 0-7.5 cm depth, the compost amended tilled treatment had the lowest root density, while compacted, tilled, and gypsum amended tilled treatments were highest.

Table 5. Shoot mass and vegetative cover measured at each site. Note that time after establishment differed between sites (see Table 2).

Treatment	Shoot mass[2]	Vegetative cover[2]
	kg ha^{-1}	%
Sandhills		
Compacted	147a	62b
Compacted + compost	121a	46c
Shallow till	181a	63b
Shallow till + compost	231a	74ab
Deep till	153a	72ab
Deep till + compost	105a	80a
Mountain		
Compacted	997a	73b
Compacted + compost	1,686a	88a
Shallow till	1,426a	81a
Shallow till + compost	1,167a	82a
Deep till	1,648a	80a
Deep till + compost	1,897a	82a
Piedmont 1		
Compacted	946b	42b
Shallow till	1,597a	62a
Deep till	1,566a	56a
Piedmont 2		
Compacted / No traffic	1,311b	68b
Compacted / Traffic	1,588b	52b
Deep till / No traffic	784b	47b
Deep till / Traffic	726b	62b
Deep till + compost / No traffic	5,056a	100a
Deep till + compost / Traffic	4,761a	86ab
Piedmont 3		
Compacted	795a	31a
Deep till	962a	43a
Deep till + compost	812a	45a
Deep till + xPAM[1]	822a	50a
Deep till + gypsum	836a	52a

[1]Granular cross-linked polyacrylamide.

[2]Within each site, means followed by the same letter within a column are not different (p = 0.05).

Table 6. Root density measured at three Piedmont sites.

	Root density[1]					
	Depth					
	cm					
Piedmont 1	0-15	15-30				
	kg m^{-3}					
Compacted	0.50b	0.02b				
Compacted + lime	0.37b	0.01b				
Shallow till	0.62ab	0.12a				
Shallow till + lime	0.50b	0.25a				
Deep till	0.87a	0.25a				
Deep till + lime	1.12a	0.25a				
Piedmont 2	0-15	15-30				
Compacted	1.14a	0.15b				
Deep till	1.05a	0.17ab				
Deep till + compost	1.28a	0.27a				
	8 months after establishment			*12 months after establishment*		
Piedmont 3	0-7.5	7.5-15	15-23	0-7.5	7.5-15	15-23
Compacted	1.84a	0.75ab	0.72a	1.63a	0.51a	0.85a
Deep till	0.60c	0.92ab	0.46ab	2.12a	0.91a	1.01a
Deep till + compost	0.83bc	0.46ab	0.43ab	0.56b	0.45a	0.40a
Deep till + xPAM	0.52c	0.40b	0.29b	1.33ab	0.48a	0.58a
Deep till + gypsum	1.50ab	1.21a	0.83a	1.82a	0.84a	0.56a

[1]Within each site, means followed by the same letter within a column are not different ($p = 0.05$).

DEMONSTRATION SITES ON ACTIVE ROADWAYS

Two field sites were established on active roadsides to determine the efficacy of tillage, as well as amending the soil with compost in concert with tillage, on runoff water quantity and quality.

Materials and Methods

Two studies, one along I-40, and the other along I-85, were conducted to determine the effect of tillage and compost amendment on bulk density, infiltration, and runoff water quantity. Though not a main project objective, supplementary water quality data were also collected and are included in Appendix 3. Both sites had identical randomized complete block plot designs (Fig. 3), with three treatments replicated four times. The treatments consisted of an untreated control (C), tillage (T), and tillage amended with compost (COM). Unlike the field trials in the previous section, C was not intentionally compacted but instead represented the existing roadside conditions with established groundcover. Plots were 1.5 m square, with their top edge beginning approximately 2 m from the edge of pavement (EOP). T and COM plots were tilled with a rear-tine tiller to a depth of at least 15 cm. Compost was added to a 5 cm depth (0.05 m^3 m^{-2}) on COM plots and tilled in. Tilled and COM plots received NCDOT recommended rates of fertilizer (500 lbs $acre^{-1}$ 10-20-20), lime (4000 lbs $acre^{-1}$), and grass seed (tall fescue, centipede, and bermudagrass at rates of 50, 10, and 25 lbs $acre^{-1}$, respectively), and were covered with aspen fiber erosion control blankets.

Garden edging was placed along the sides of the plots and extended to EOP to direct runoff from the road to the plots. This edging was formed into a weir at the bottom of each plot, where a 10 cm diameter PVC pipe was affixed with expanding foam to capture runoff. This pipe directed runoff into a 380 L tank, where the volume of runoff could be determined and subsamples could be collected for analysis. The top of each tank was covered to prevent rainfall from directly entering the collection tank. Between each block, as well as on either end of the plot area, were installed channel drains level with the soil surface at 2 m from EOP. Each channel drain was connected to PVC pipe which drained into a 380 L tank, where water quantity and quality was measured to estimate these parameters incident on the plots. A datalogging rain gauge was installed at each site to measure precipitation.

The site on the eastbound shoulder of I-40 (sandy clay loam; 35.366054, -78.492382) was installed on 4/15/15. Twenty six rainfall events were captured between 4/15/15 and 5/6/16, with suspension of runoff collection between 11/20/15 and 2/29/16 due to concerns of water freezing in the tanks. The site on the northbound shoulder of I-85 (loam; 36.134529, -78.735566) was installed on 9/30/16. Eighteen rainfall events were captured between 9/30/16 and 6/19/17, with suspension of runoff collection between 12/21/16 and 2/28/17 due to concerns of water freezing in the tanks. Measurements for each event included precipitation, runoff volume, total suspended solids, and turbidity. On a subset of runoff samples, further chemical analysis was conducted to measure selected nutrient and heavy metal concentrations. Rainfall totals for each site are summarized by month in Tables 7 and 8.

Bulk density (0-7.5 and 7.5-16 cm depths) and infiltration rates (single-ring sprinkle infiltrometer) were measured at the conclusion of each study, approximately one year and nine months after installation at I-40 and I-85, respectively. As more thoroughly documented in the Appendix, infiltration rate measurements with the single-ring sprinkle infiltrometer were compared to the standard double-ring infiltrometer at several roadside locations. In general the single-ring and double-ring approaches were well-correlated and provided similar infiltration rates.

Table 7. Rainfall during the study period at the I-40 demonstration site.

Month	Rainfall (mm)
April 2015[1]	17
May 2015	64
June 2015	140
July 2015	93
August 2015	90
September 2015	152
October 2015	129
November 2015	163
March 2016	24
April 2016	50
May 2016[1]	58

[1]Partial month collection.

Table 8. Rainfall during the study period at the I-85 demonstration site.

Month	Rainfall (mm)
September 2016[1]	1
October 2016	135
November 2016	13
December 2016[1]	32
March 2017	84
April 2017	188
May 2017	131
June 2017[1]	91

[1]Partial month collection.

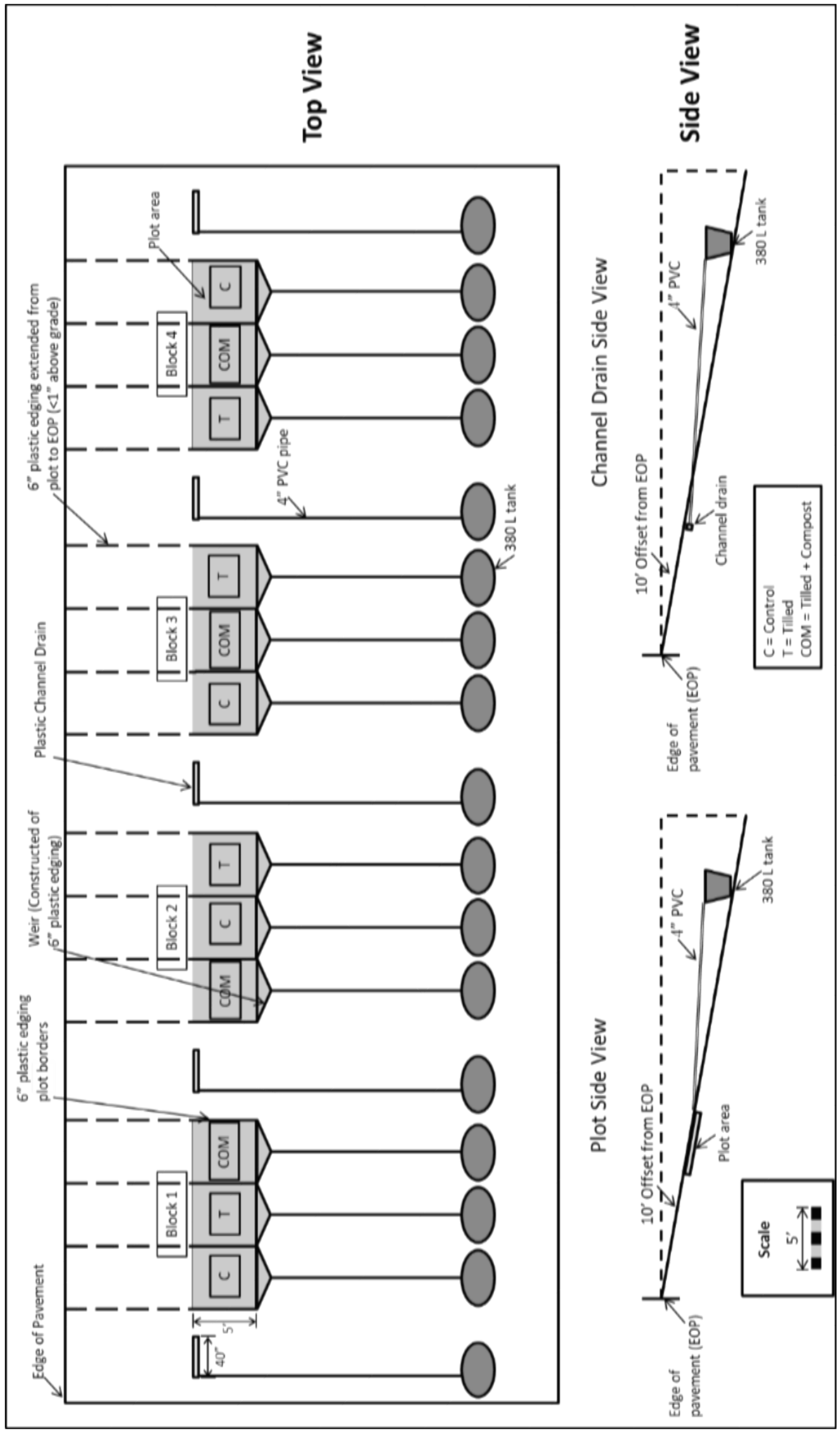

Figure 3. Plot layout for both I-40 and I-85 demonstration sites.

Results and Discussion

Runoff Volume

On the I-40 site, total cumulative runoff reduction (26 events) compared to C was 7.6 and 37.7% with T and COM, respectively. On the I-85 site, total runoff reduction (18 events) compared to C was 12.3 and 47.9% with T and COM, respectively.

On the I-40 site, COM outperformed T in runoff reduction for all months measured in 2015. During July, October, and November 2015, T had more runoff than did C, as did COM in November (Fig. 4A). The T and COM treatments had slightly less runoff than C when the study was reopened in Spring 2016, but the reduction in runoff volume was modest. The decay of efficacy in runoff reduction on I-40 was likely due to settling of the coarse-textured soil. The compost amendment was expected to reduce this settling, but failed to reduce runoff volumes even one year after establishment.

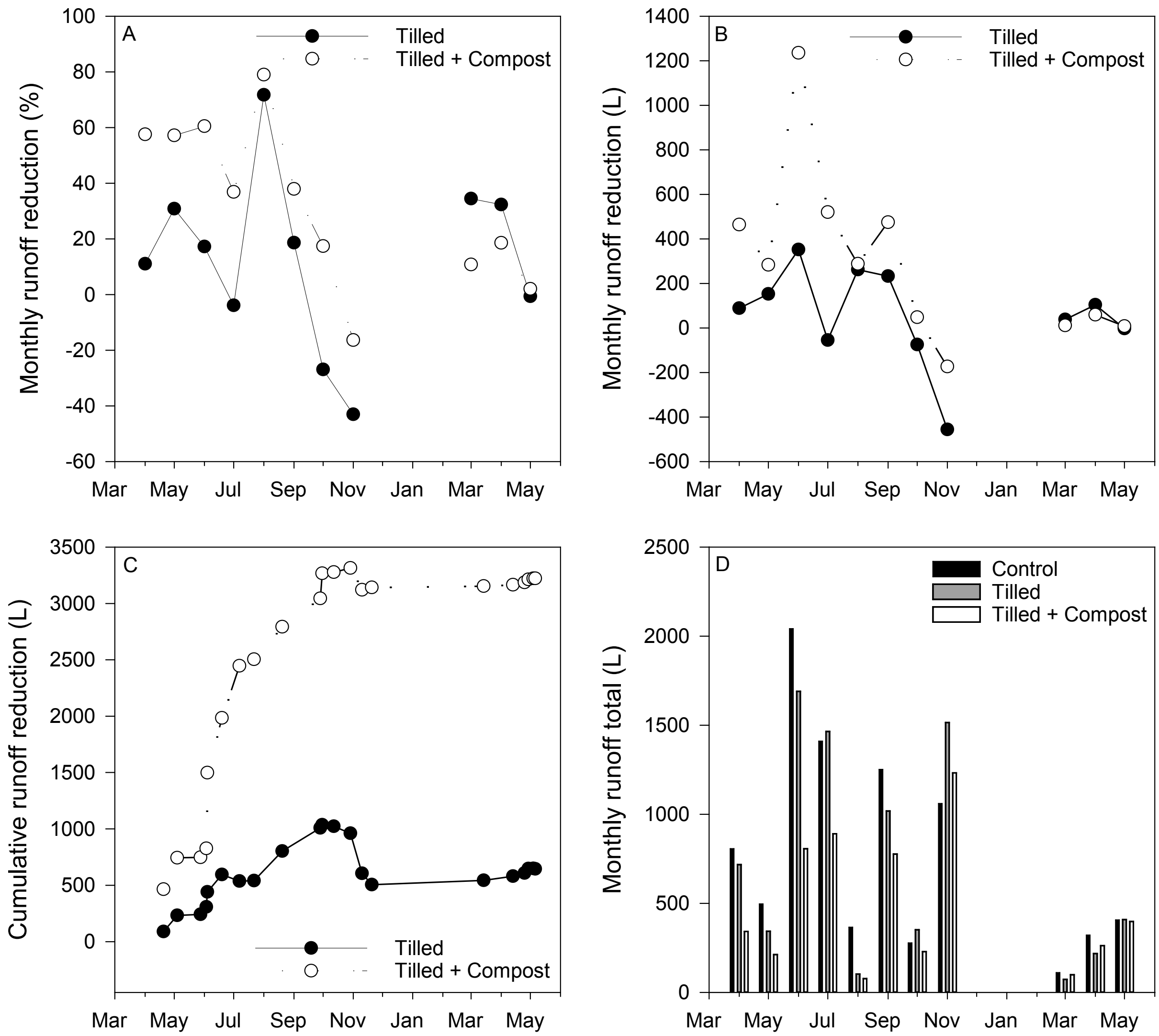

Figure 4. I-40 demonstration site runoff data from March 2015 to May 2016. Percent runoff reduction from control (A), runoff reduction volume from control (B), cumulative runoff reduction volume from control (C), and monthly runoff volume totals (D).

On the I-85 site, COM outperformed both C and T for all months (Fig. 5A, B, and D). Although the plots were established at the end of September 2016, there were only 3 rainfall events resulting in runoff between September and December when data collection was suspended. Two of those events were in December, while the third resulted in all tanks overflowing from the remnants of Hurricane Matthew in October (data not shown). In March and April 2017, T allowed slightly more runoff than C (Fig. 5 A, B, and D).

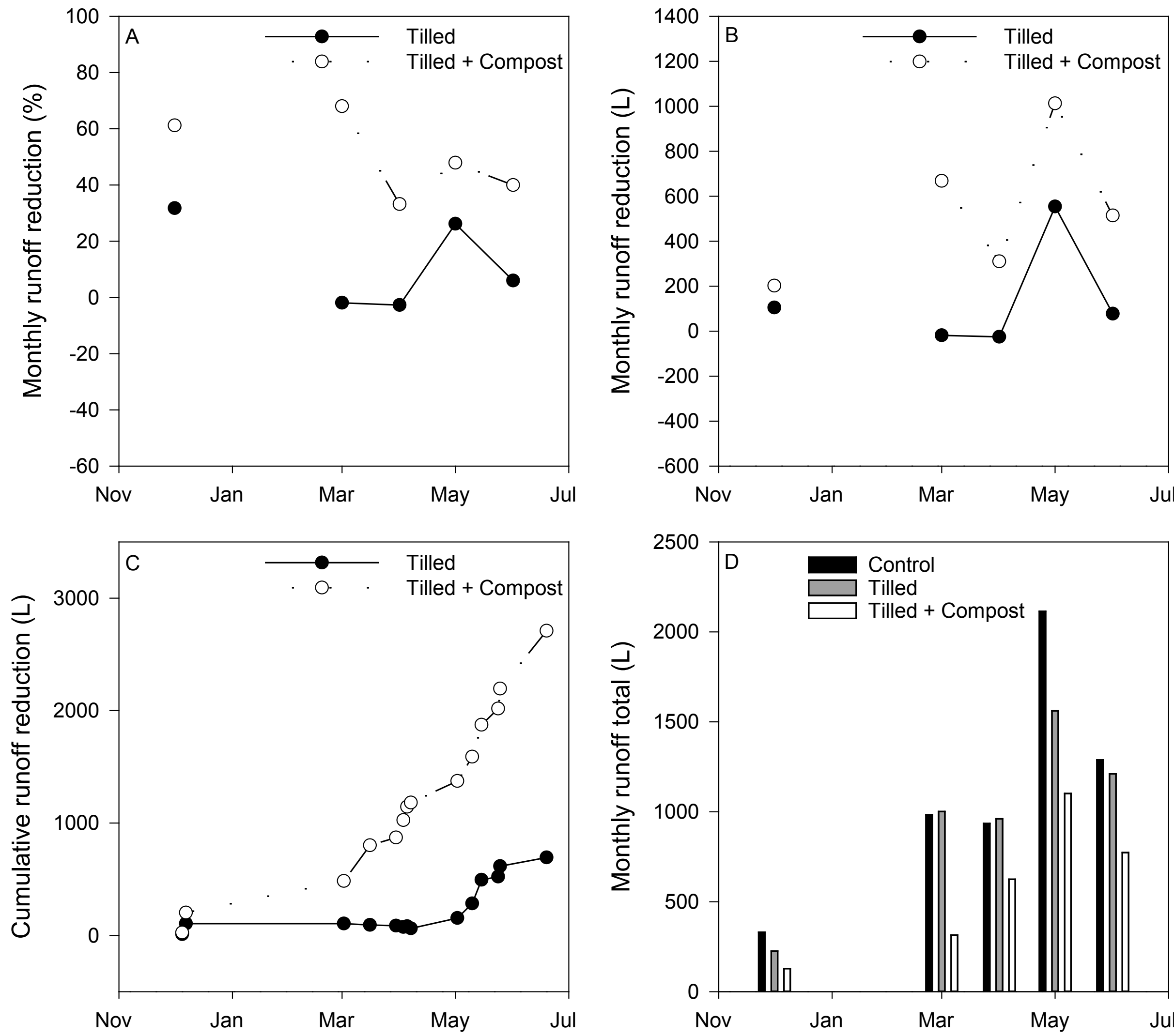

Figure 5. I-85 demonstration site runoff data from December 2016 to June 2017. Percent runoff reduction from control (A), runoff reduction volume from control (B), cumulative runoff reduction volume from control (C), and monthly runoff volume totals (D).

While runoff reduction rates decreased or stabilized at I-40 (Fig. 3 C) as the study progressed, these rates continued to increase at I-85 (Fig. 5 C) for the COM treatment. This may be due to the slightly more clayey soil at I-85 settling less quickly than the coarser textured soil at I-40.

Bulk Density and Infiltration Rate

At the I-40 site, bulk density values for all treatments were the same for the shallow depth (Fig. 6). At the 7.5-15 cm depth, COM bulk density was lowest, while C was highest. The infiltration rates were highest in COM, while C was lowest. This observation is in contrast to the negligible runoff reduction by COM toward the end of runoff measurements (Fig. 4). The difference in patterns between runoff observations and infiltration measurements may be due to the relatively small measurement area of the infiltrometer or due to the large area (including the impervious road surface) contributing water inputs to the plot area for runoff relative to the small size of the treated (tilled) area within the plot.

At the I-85 site, bulk density was highest in T and lowest in COM for both depths sampled. This was likely due to the tillage event destroying soil structure in the slightly more clayey soils at this site. The addition of compost likely helped to mitigate the destruction of soil structure from tillage, resulting in higher measured infiltration rates and lower total runoff volumes captured from the plots.

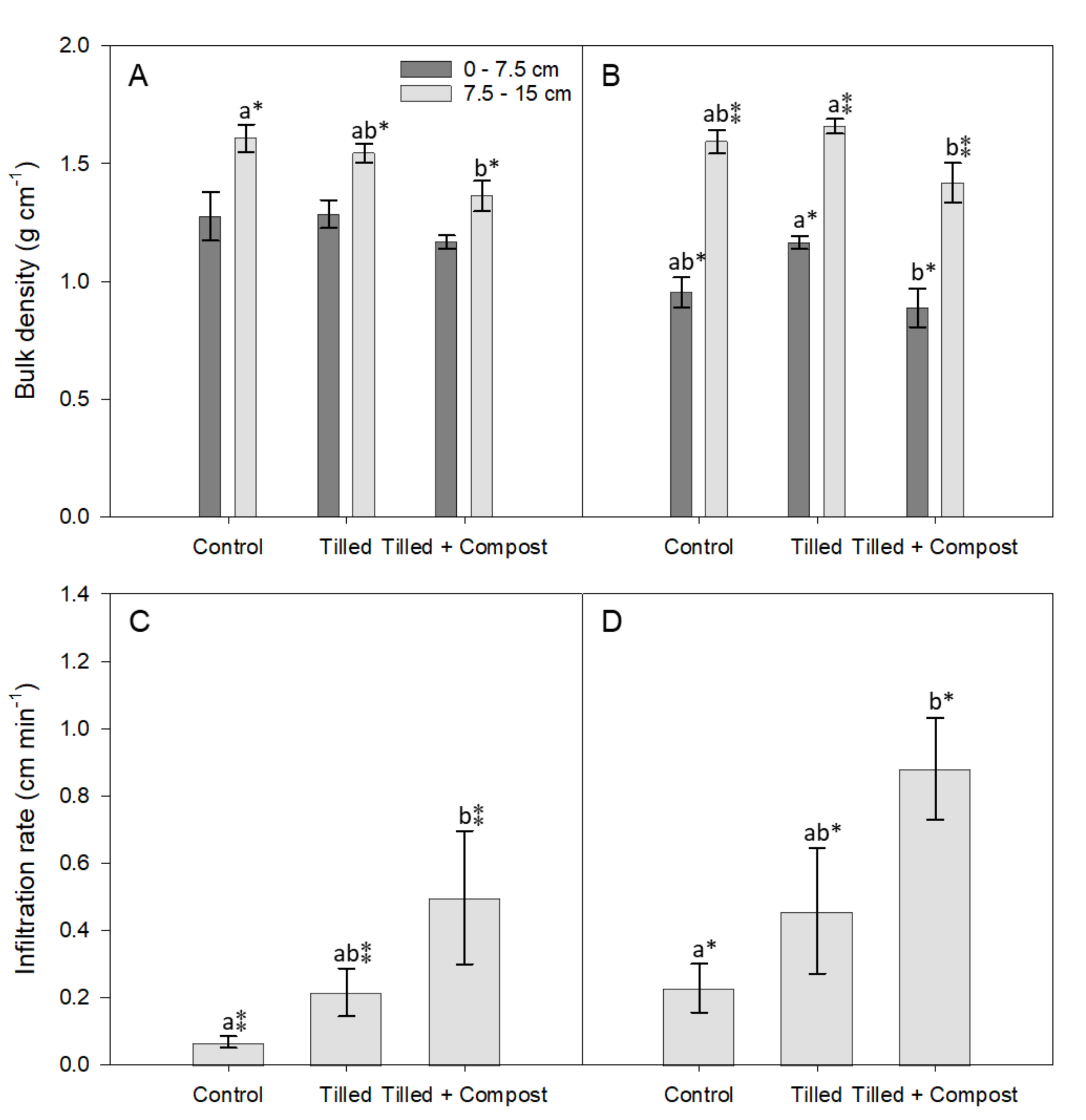

Figure 6. Bulk density and infiltration rate for I-40 (A and C) and I-85 (B and D). Measurements were collected 1 year and 9 months, respectively, after tillage treatments were applied at each site. Different letters within a series denote significant differences at the following levels: * = p < 0.05, ⁑ = p < 0.10. Error bars indicate standard error.

FINDINGS AND CONCLUSIONS

Road construction and maintenance activities can severely impact soil physical conditions and limit their capacity to infiltrate stormwater. Prior research has demonstrated short-term benefits of tillage to reduce soil bulk density and increase surface infiltration rates on compacted soils.

Based on our study, including five trials where infiltration rate and bulk density were measured for a minimum of 24 months, benefits of tillage appear to be maintained for at least two years. Compared to compacted controls, bulk density following tillage was an average of 11% lower than that of control after 24 months or more. This translates into an average increase in soil porosity of 15%. Some small changes were sometimes observed within in the first few months after tillage, but there was generally little change (i.e., increase in bulk density) beyond the first 6 months post-tillage.

Surface infiltration rates with tillage averaged more than three times larger than compacted controls. At a minimum, infiltration rates were just less than double those observed for compacted control fill material. There was not a consistent trend upward or downward in infiltration rates from the first to the last set of observations following tillage. Compacted controls did, however, sometimes show subtle increases in infiltration rate with time.

Tillage depth was evaluated in three trials with shallow tillage targeted at 15-cm depth and deep tillage targeted at 30-cm depth. No differences were observed in surface bulk density or infiltration rate based on depth of tillage. There was an effect in terms of penetration resistance, with deeper tillage resulting in reduced penetration resistance at deeper depths within the soil profile. This may provide some long-term benefit for plant growth, but this was not evident in our observations.

Compost amendment along with tillage was tested in four of five trials. There was no effect associated with compost addition in two of the trials, which had the coarsest textured soils. In the other two trials, compost further reduced bulk density (and increased porosity) compared to tillage alone. In these two trials, only one showed increased surface infiltration with compost compared to tillage alone. Other amendments applied with tillage in one trial (cross-linked polyacrylamide and gypsum) were generally no different than tillage alone.

Traffic from routine mowing was evaluated in three trials. There was no significant effect of traffic on bulk density in any of these trials. There was an effect of traffic on infiltration rate in one trial. In that trial, traffic following tillage decreased infiltration rate compared to tillage with no traffic. When compost was added, there was no effect of traffic compared to tillage with or without compost addition.

Overall, results from the field trials suggest that applying tillage to compacted soils post construction can have a substantial short-term benefit for reduced bulk density, increased porosity, and increased infiltration rate. These benefits appear to be maintained over periods of two years or more. Traffic may reduce benefits under some circumstances, but the addition of compost can potentially mitigate this effect.

Tillage with and without compost amendment was also evaluated in two demonstration sites along active roadways. A major difference in these evaluations was that the control comparison was an existing stand of grass rather an intentionally compacted control in the field trials. As such, these demonstration sites represent a retrofit of tillage practices to existing grass as opposed to a new construction or problem soil, which is more consistent with the control in the five field trials. For natural rainfall events at the two demonstration sites, tillage reduced runoff compared to the existing grass stand by 8 and 12% over 26 and 18 events, respectively. For the same natural rainfall events, tillage plus compost reduced runoff compared to existing grass by 38 and 48%, respectively. At one of these sites, runoff reduction compared to the control grass stand appeared to diminish within a year of tillage treatment (with or without compost). At the other site, reductions in runoff were mostly maintained throughout monitoring, although reduction was more modest with tillage alone. At the end of monitoring for each of these demonstration sites, bulk density and infiltration rate were no different between control and tillage, but bulk density was lower and infiltration rate was higher (by a factor of 2-3) for tillage with compost addition compared to control. These results suggest that there may be limited benefits of tillage in healthy grass stands unless compost is incorporated into the soil with the tillage.

RECOMMENDATIONS

- Tillage can provide an effective best management strategy to reduce bulk density, increase porosity, and enhance infiltration for disturbed, new construction soils. It may also be beneficial for soils in locations which are known to have problems with infiltration and grass establishment. After tillage, establishment of a vigorous grass stand is important to maintain benefits.

- Benefits of tillage for existing grass stands where there are no observed/known problems are likely to be short-term or minimal. Under these circumstances, compost addition may help to increase infiltration compared to existing grass stands.

- Depth of tillage should be targeted to loosen soil to 6-8 inches in order to lower surface density and increase surface infiltration. Tillage to greater depth did not provide an obvious benefit for stormwater management when tested in our field trials.

- Routine mowing traffic (under favorable soil moisture conditions) does not substantially reduce infiltration benefits from tillage, once grass is established. Mowing under non-ideal (wet) conditions when soil strength is reduced may have a detrimental effect on infiltration rates, and this effect will likely persist unless the soil is re-tilled. Addition of compost may help to maintain the benefit of tillage practices when more traffic is expected or necessary.

- Compost does not provide a consistent benefit under all circumstances. A single rate of compost addition was evaluated in the present studies. Additional work is needed to assess the conditions under which compost addition is necessary and the rates at which it should be applied.

- Benefits of tillage for enhanced soil porosity and increased stormwater infiltration was found to persist for two or more years, suggesting it will likely be a permanent condition unless trafficked under wet conditions.

IMPLEMENTATION

Our research results and associated recommendations can improve implementation of low-cost tillage BMPs in vegetated SCMs. We anticipate that NCDOT will be able to immediately implement our recommendations for tillage BMPs on active and new construction sites, as well as in identified problem areas along existing roadways. Implementation should come at relatively low cost compared to implementing alternate SCMs. Our results and recommendations should also inform decisions about maintenance and longevity for tillage BMPs.

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APPENDIX 1: A MULTI-YEAR STUDY OF TILLAGE AND AMENDMENT EFFECTS ON COMPACTED SOILS

Please see attached file: Appendix 1.pdf

Mohammadshirazi, F., R.A. MacLaughlin, J.L. Heitman, and V.K. Brown. 2017. A multi-year study of tillage and amendment effects on compacted soils. J. Environmental Management. 203: 533-541. (Open Access)

APPENDIX 2: EVALUATION OF SPRINKLE INFILTROMETER

A single-ring Cornell Sprinkle Infiltrometer (CSI) was used throughout the research outlined in the preceding sections of this report to evaluate infiltration rates. Shown below, the infiltrometer includes a small rainfall simulator that is positioned over a single ring, which is inserted into the soil surface. During measurement, water from the rainfall simulator that does not infiltrate into the soil (i.e., runoff) is collected from a small outlet in the ring, installed flush with the soil surface. Infiltration rate is computed as the difference between the rainfall rate and the runoff rate. The CSI was selected because it included a mini rainfall simulator, which better mimics rainfall partitioning at the soil surface (compared to ponded infiltrometers) and because the single ring approach was less disruptive (i.e., one ring insertion per measurement vs. two rings per measurement with the double ring infiltrometer) to small plot areas requiring repeated measurements over time. A concern with this approach was that results from the CSI may be somewhat high compared to common double ring approaches due to the potential for lateral water flow below the confining infiltrometer ring, especially with tillage over compacted soil. As such, we conducted a complimentary study to compare the CSI and double ring infiltrometer approaches. This research is summarized below. A full report is available as part of an NCSU M.S. Thesis (Lewis, J. 2016. Assessment of a Single-ring Sprinkle Infiltrometer Method for Evaluating Soil-Based Stormwater Management Practices.).

Materials and Methods

Steady-state infiltration (i_S) rate determined using two infiltration measurement techniques, the CSI and the ASTM double-ring infiltrometer (DRI), was compared at four locations in Wake County. These sites included: The Sediment and Erosion Control Research and Extension Facility (SECREF), the Central Crops Research Station (CCRS), the Lonnie Poole Golf Course (LP), and the I-40 eastbound off-ramp at Jones Sausage Rd. The study at SECREF is the same site described earlier as Piedmont 3. The sites differed in soil physical properties (Tables A1 and A2). SECREF, LP, and JS were plot-scale study sites at which tillage, amendments, and vegetation were being evaluated on compacted soils. One condition at CCRS was a fallow hay field, while the other was a tilled field without crop production at the time of measurements. Table A2 describes treatments applied at each site. All amendments were tilled into the soil at the tillage depth noted. Four replications of 13 conditions at 4 sites were measured for a total of 52 paired CSI and DRI measurements.

Table A1. Soil texture for layered materials at four sites.

	Particle Size Distribution			Texture
Soil Layer	Sand	Silt	Clay	
		%		
Sediment and Erosion Control Research and Extension Facility (SECREF)				
Surface (0-30 cm)	46.8	19.8	33.4	Sandy Clay Loam
Subsurface (>30 cm)	39.4	21.2	39.4	Clay Loam
Central Crops Research Station (CCRS)				
†Surface (0-30 cm)	94.7	4.7	0.6	Sand
†Subsurface (>30 cm)	86.0	8.3	5.7	Loamy Sand
‡Surface (0-30 cm)	87.8	11.0	1.2	Loamy Sand
‡Subsurface (>30 cm)	86.6	11.8	1.6	Loamy Sand
Jones Sausage Rd. highway off-ramp (JS)				
Surface (0-15 cm)	56.1	27.4	16.5	Sandy Loam
Subsurface (>15 cm)	61.2	20.2	18.6	Sandy Loam
Lonnie Poole Golf Course (LP)				
Surface (0-15 cm)	47.1	22.8	30.0	Sandy Clay Loam
Subsurface (>15 cm)	42.9	19.9	37.1	Clay Loam

† Field was tilled and between rotations.
‡ Fallow hayfield.

Table A2. Site management practices and bulk density by depth for surface and subsurface materials.

Site	Management Practice	Tillage Depth	Bulk Density			
			Surface Material			Subsurface Material†
			0-7.5 cm	7.5-15.0 cm	15.0-22.5 cm	
		cm	g cm^{-3}			
SECREF‡	Tillage (T)	30	1.41 (± 0.09)	1.42 (± 0.17)	1.49 (± 0.11)	1.53 (± 0.18)
	Tillage, gypsum incorporated (TG)		1.30 (± 0.06)	1.35 (± 0.11)	1.40 (± 0.13)	1.49 (± 0.11)
	Tillage, compost incorporated (TC)		1.16 (± 0.06)	1.26 (± 0.19)	1.38 (± 0.05)	1.49 (± 0.26)
	Tillage, polyacrylamide incorporated (TP)		1.34 (± 0.04)	1.39 (± 0.09)	1.49 (± 0.11)	1.38 (± 0.11)
	No management practice (N)	—	1.55 (± 0.05)	1.59 (± 0.03)	1.60 (± 0.07)	1.47 (± 0.13)
CCRS	Tillage (T)	30	1.44 (± 0.05)	—	—	1.83 (± 0.06)
	Fallow (F)	—	1.45 (± 0.04)	—	—	1.78 (± 0.07)
JS	Tillage (T)	15	1.41 (± 0.09)	—	—	1.74 (± 0.11)
	Tillage, compost incorporated (TC)		1.22 (± 0.05)	—	—	1.69 (± 0.11)
	Previous management practice (N)	—	1.62 (± 0.07)	—	—	1.74 (± 0.11)
LP	Tillage (T)	15	1.39 (± 0.10)	—	—	1.48 (± 0.16)
	Tillage, compost incorporated (TC)		1.16 (± 0.02)	—	—	1.48 (± 0.16)
	Previous management practice (N)	—	1.46 (± 0.11)	—	—	1.53 (± 0.02)

† Subsurface material represents material below tillage depth.
‡ Samples were collected at multiple 7.5 cm increments in surface material.

CSI measurements were made following the method outlined in its manual. Rainfall rates were between 30 and 60 cm h^{-1} to ensure that runoff was generated. DRI measurements were made following the ASTM standard. The height of ponding was between 5 and 10 cm above the soil surface.

It was hypothesized that manipulation of existing soil conditions with tillage and amendments would result in two layers with differing hydraulic and physical properties. We therefore sampled these two layers, dependent on the depth of tillage, separately into surface and subsurface samples. Measurements of saturated hydraulic conductivity (K_S), bulk density, and particle size distribution were made on these samples.

Saturated hydraulic conductivity and i_S data were analyzed in a number of ways. Arithmetic mean (i_{AR}, K_{AR}), geometric mean (i_{GM}, K_{GM}) and coefficients of variation (CV) were calculated for both i_S and K_S by condition. Analysis of variance (ANOVA) and linear regressions were performed on selected parameters.

Results and Discussion

Soil physical properties within and between sites were variable (Tables A1 and A2), providing a wide range of conditions under which to compare CSI and DRI measurements.
CSI i_S variability was minimal for most conditions, except for LP N conditions (C = 106%) (Table A3). DRI i_S variability was greater, having four conditions with CV values over 64%. Only two conditions showed significant differences in i_S between measurement methods at the p=0.05 level: SECREF TC and JS N.

Table A3. Comparison of steady infiltration rate (i_S) values measured using Cornell Sprinkle Infiltrometer (CSI) and ASTM double-ring infiltrometer (DRI) methods.

		CSI				DRI				p¶
Site	**Management Practice**	i_{GM}†	i_{AR}‡	**Range**	**CV§**	i_{GM}	i_{AR}	**Range**	**CV**	
		—— log 10^{-4} m day^{-1} ——			%	—— log 10^{-4} m day^{-1} ——			%	
SECREF	Tillage (T)	4.67	4.69	4.05-5.03	9.84	4.99	4.99	4.61-5.44	6.88	0.33
	Tillage, gypsum incorporated (TG)	4.95	4.95	4.78-5.10	2.68	5.02	5.03	4.86-5.25	3.22	0.52
	Tillage, compost incorporated (TC)	4.89	4.89	4.79-5.00	3.98	5.20	5.20	4.97-5.30	3.02	0.05*
	Tillage, polyacrylamide incorporated (TP)	4.85	4.85	4.61-5.00	3.91	4.70	4.71	4.44-5.04	5.74	0.43
	No management practice (N)	4.08	4.09	3.78-4.60	8.92	1.53	2.51	0.16-3.62	**64.1**	0.10
CCRS	Tillage (T)	4.37	4.37	4.12-4.73	4.30	4.22	4.22	4.01-4.43	4.50	0.39
	Fallow (F)	4.62	4.63	4.33-4.77	5.90	4.27	4.28	4.01-4.56	5.30	0.06
JS	Tillage (T)	3.68	3.69	3.29-3.99	7.87	1.32	2.06	0.16-3.29	**65.1**	0.78
	Tillage, compost incorporated (TC)	4.07	4.07	3.87-4.40	5.63	3.60	3.62	3.16-4.10	10.8	0.26
	Previous management practice (N)	3.99	4.00	3.76-4.17	4.75	1.11	1.66	0.16-2.77	**66.0**	0.01*
LP	Tillage (T)	3.43	3.44	3.22-3.76	6.97	3.24	3.30	2.53-4.00	20.8	0.71
	Tillage, compost incorporated (TC)	3.75	3.77	3.30-4.41	12.4	3.50	3.53	2.96-4.14	16.2	0.55
	Previous management practice (N)	0.74	1.80	0.16-3.64	**106**	1.39	2.22	0.16-3.45	**65.4**	0.78

*Significant at 0.05 probability. Arithmetic means were used to test significance.
† Geometric mean.
‡ Arithmetic mean.
§ Coefficient of variation. i_{AR} was used in calculating CV.
¶ Statistical difference between i_S measurements based on i_{AR}.
CV values in bold represent conditions with high i_S variability.

Linear regressions (Fig. A1) between CSI i_S and DRI i_S showed strong correlation ($R^2 = 0.79$) with the equation y = 1.03x, indicating that CSI i_S was only 3% greater overall compared to DRI i_S. When correction factors from the CSI manual intended to correct for lateral water flow below the ring are applied, the correlation remains unchanged while the equation becomes y = 1.02x (Fig A2). The small significance of the correction factors may be due to the impact of the layered soil conditions.

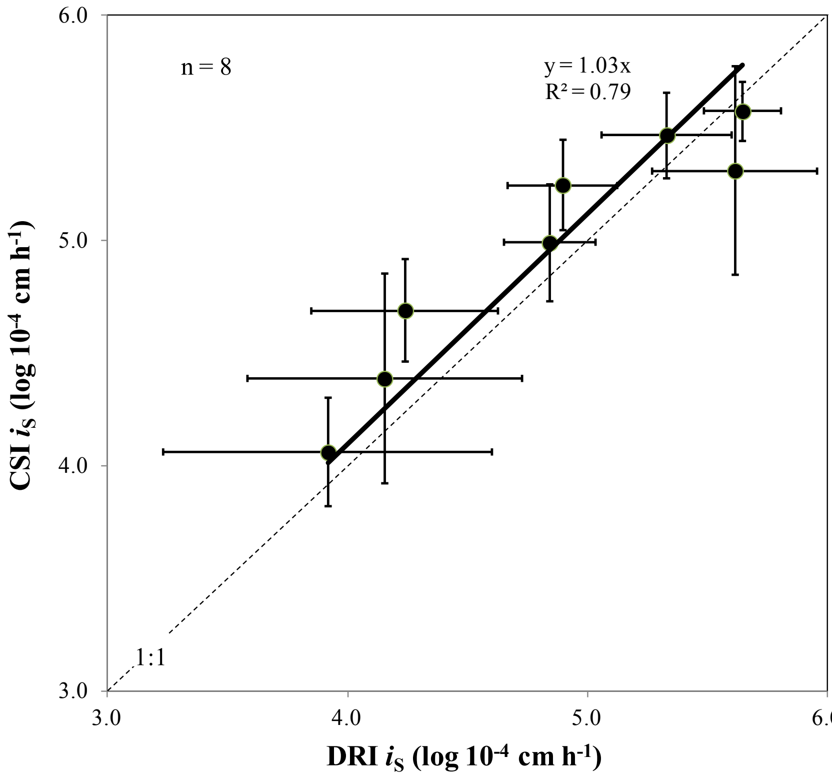


Figure A1. Linear regression of ASTM double-ring infiltrometer (DRI) steady infiltration rate (i_S) versus Cornell Sprinkle Infiltrometer (CSI) i_S for layered conditions. Points are geometric means of i_S for each set of conditions. Error bars are one standard deviation from the mean.

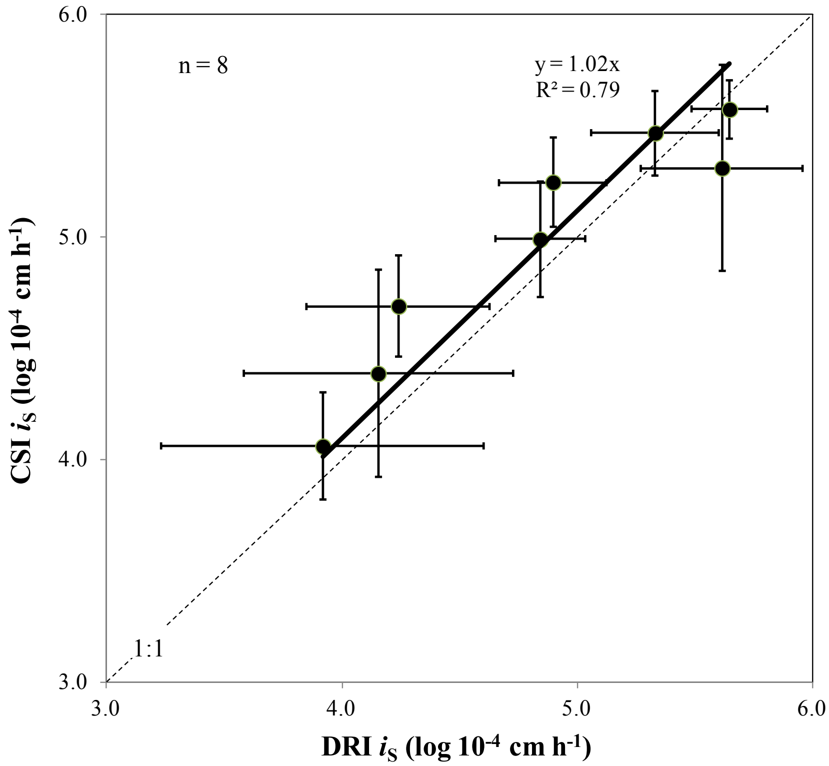


Figure A2. Linear regression of ASTM double-ring infiltrometer (DRI) steady infiltration rate (i_S) versus Cornell Sprinkle Infiltrometer (CSI) i_S with texture-based correction applied for CSI measurements. Points are geometric means of i_S for each set of conditions. Error bars are one standard deviation from the mean.

As is commonly observed in laboratory K_S measurements, K_S values were quite variable, with overall variability greater than i_S from either measurement method (Table A4). This variability was likely due to the relatively small sample size, as well as the soils at the sites. Soil at the SECREF site was fill material, the JS site's soil was transported and compacted, while LP was likely shaped to form the desired topography. CCRS was likely less drastically manipulated, as only agricultural management practices were applied to it.

Table A4. Saturated hydraulic conductivity (K_S) values for surface and subsurface materials.

Site	Management Practice	Surface Material				Subsurface Material				p¶
		K_{GM}†	K_{AR}‡	Range	CV§	K_{GM}	K_{AR}	Range	CV	
		—— log 10^{-4} m day^{-1} ——			%	—— log 10^{-4} m day^{-1} ——			%	
SECREF#	Tillage (T)	2.30	3.06	0.48-4.50	60.2	3.82	3.85	3.16-4.44	13.9	0.44
	Tillage, gypsum incorporated (TG)	3.00	3.24	1.64-4.40	41.4	3.73	3.76	2.98-4.15	14.1	0.50
	Tillage, compost incorporated (TC)	4.68	4.73	3.75-5.58	16.3	3.97	3.98	3.71-4.35	7.53	0.12
	Tillage, polyacrylamide incorporated (TP)	2.30	2.59	1.50-5.00	62.5	3.89	3.99	2.75-5.13	25.5	0.19
	No management practice (N)	1.61	2.03	0.62-3.40	69.0	4.11	4.12	3.88-4.69	9.33	0.03*
CCRS	Tillage (T)	4.88	4.88	4.83-4.91	0.80	3.60	3.66	2.66-4.28	19.0	0.01*
	Fallow (F)	4.52	4.53	4.19-4.87	7.20	3.79	3.83	3.10-4.60	16.2	0.09
JS††	Tillage (T)	3.05	3.47	1.13-4.64	45.9	1.04	1.51	0.16-2.22	60.9	0.08
	Tillage, compost incorporated (TC)	4.55	4.56	4.17-4.99	7.78	1.32	2.18	0.16-3.91	75.8	0.03*
	Previous management practice (N)	2.83	2.88	2.34-3.65	21.2	1.04	1.51	0.16-2.22	60.9	0.05*
LP††	Tillage (T)	3.39	3.64	1.85-5.03	40.4	0.75	1.88	0.16-3.97	107	0.21
	Tillage, compost incorporated (TC)	3.80	3.89	2.60-4.74	23.6	0.75	1.88	0.16-3.97	107	0.54
	Previous management practice (N)	3.61	3.62	3.23-4.16	10.8	0.52	3.02	0.16-4.35	67.2	0.07

*Significant at 0.05 probability level. Arithmetic means were used to test significance.
† Geometric mean.
‡ Arithmetic mean.
§ Coefficient of variation. K_{AR} was used in calculating CV.
¶ Statistical difference between surface and subsurface K_S based on K_{AR}.
# Values for surface material represent effective K_S, measured for depths of 0 to 7.5 cm, 7.5 to 15.0 cm, and 15.0 to 22.5 cm.
†† Individual measurements were not made from each plot to characterize subsurface conditions.

Linear regressions between subsurface K_S and both CSI and DRI i_S were conducted to determine if these variables were related. Correlations between subsurface K_S and both CSI i_S ($R^2 = 0.87$) and DRI i_S ($R^2 = 0.83$) were strong (Fig. A3). Though the correlations were strong, there is a distinct clustering of two groups. These groups correspond to tillage depth, with the shallower tillage corresponding to the lower values, suggesting a possible effect of depth to the subsurface layer on i_S.

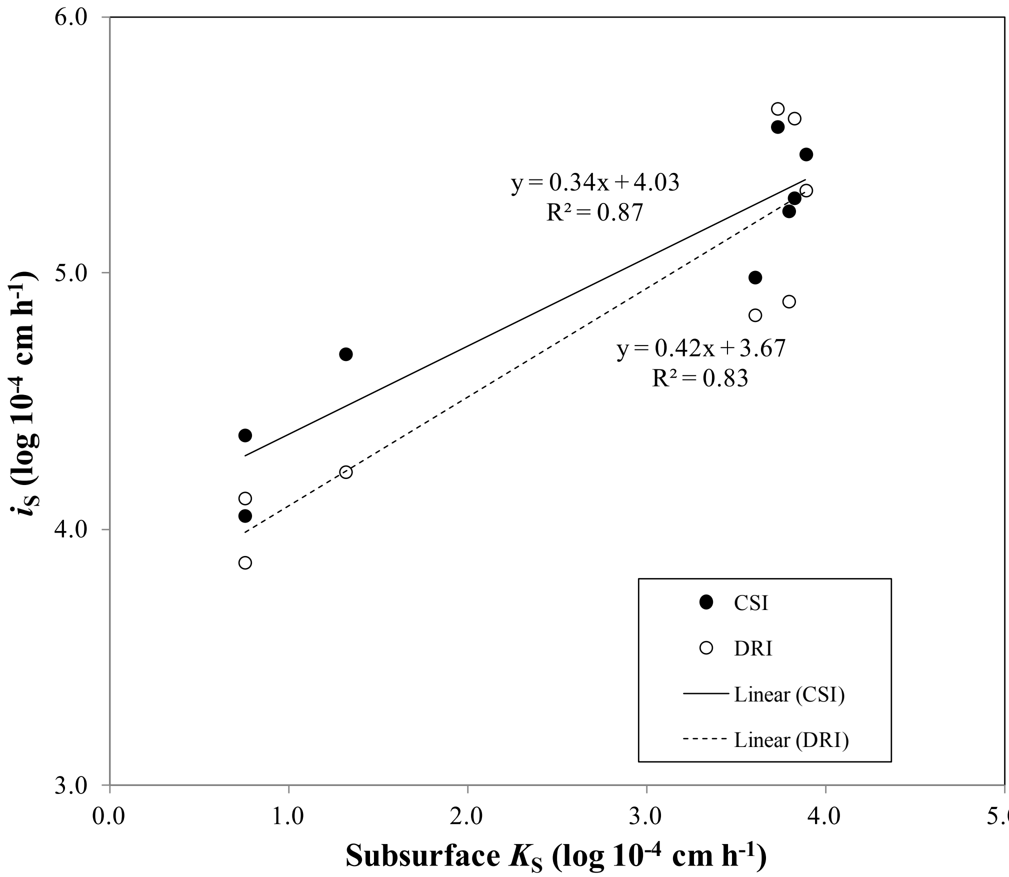


Figure A3. Linear regressions of steady infiltration rate (i_S) measured using the Cornell Sprinkle Infiltrometer (CSI) and ASTM double-ring infiltrometer (DRI) methods versus saturated hydraulic conductivity (K_S) for subsurface layers.

Conclusion

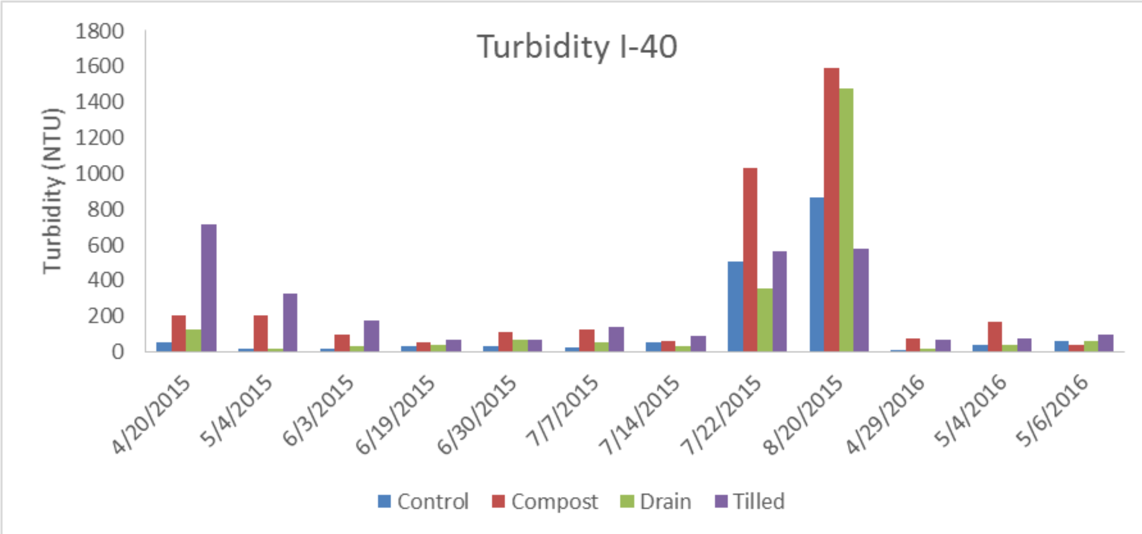
Two methods for measuring surface infiltration rate: CSI and DRI were well correlated with one another. Overall, the steady infiltration rate measured by the CSI method was about 3% greater than that measured by the DRI. Standard correction factors for the CSI had no effect on correlation, and had little effect on agreement between the methods. The infiltration rate from both methods correlated well with subsurface K_S, which suggests that infiltrometer results should provide a reasonable indication of unconfined, downward water flow expected with water movement through the profile. This relationship is important for evaluating the practical effect of surface tillage treatment on infiltration by avoiding overestimation due to lateral water flow below the depth of infiltrometer rings.

APPENDIX 3: SUPPLEMENTARY WATER QUALITY MEASUREMENTS FOR ROADSIDE DEMONSTRATION SITES

Turbidity, Total Suspended Solids, Nutrient, and Metal Content in Runoff

This appendix includes water quality measurements taken at various times throughout the roadside runoff studies along with runoff measurements. This data collection was not a specific study objective and was thus not comprehensive. Extensive statistical analyses were not undertaken; no obvious trends were noted. It is also important to note that the nutrient and metal samples were collected at different times (both relative to the season and relative to time after site establishment) at the I-40 and I-85 studies. Samples were collected soon after establishment at I-40, while samples were collected near the end of the I-85 study.

For all parameters other than turbidity, two graphs are shown. The first is the average concentration. The second is load, computed as the product of the average concentration and the average runoff for that treatment. “Drain” refers to analysis of water samples collected at the edge of pavement drain; only concentrations are included from the drain since runoff volumes were collected from an undefined area that cannot be directly compared to the plot areas.



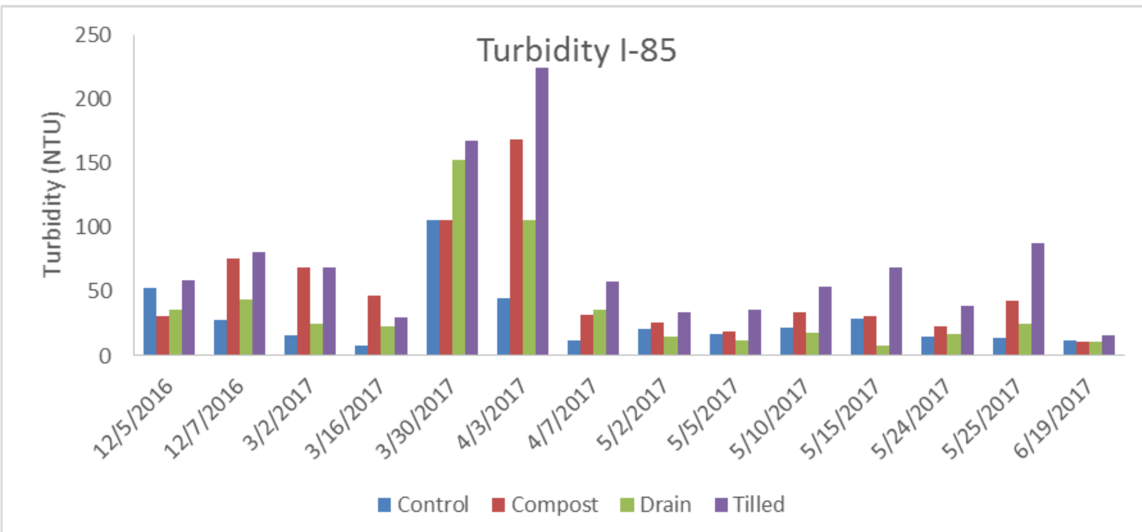
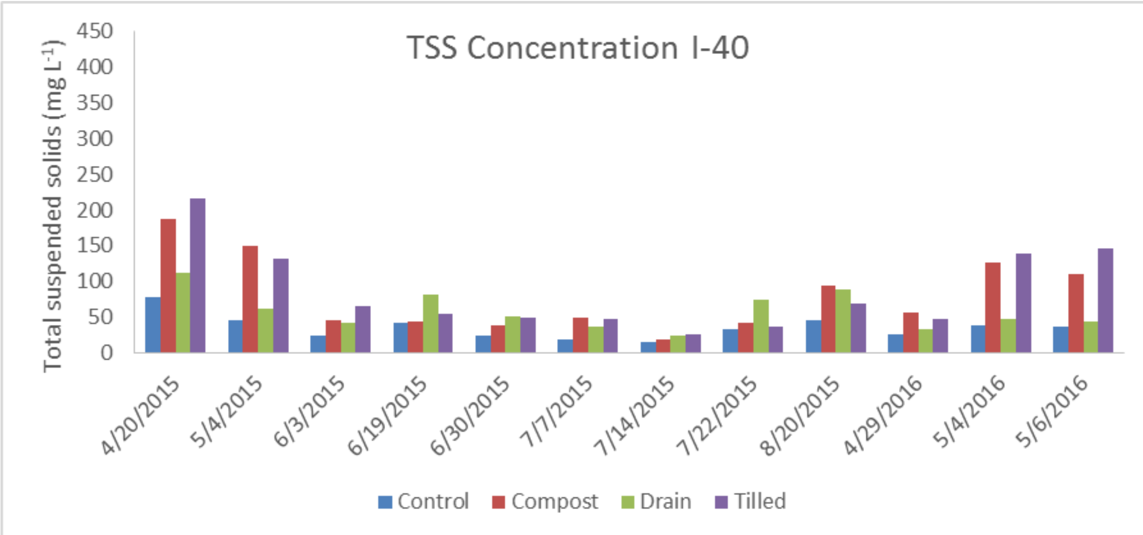


Figure A4. Turbidity in runoff at I-40 and I-85.



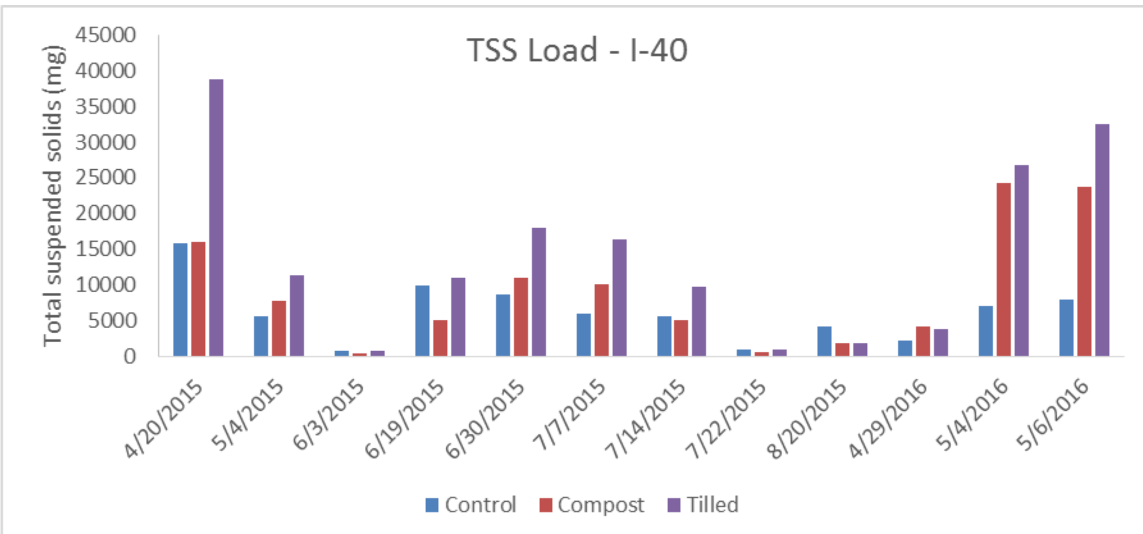
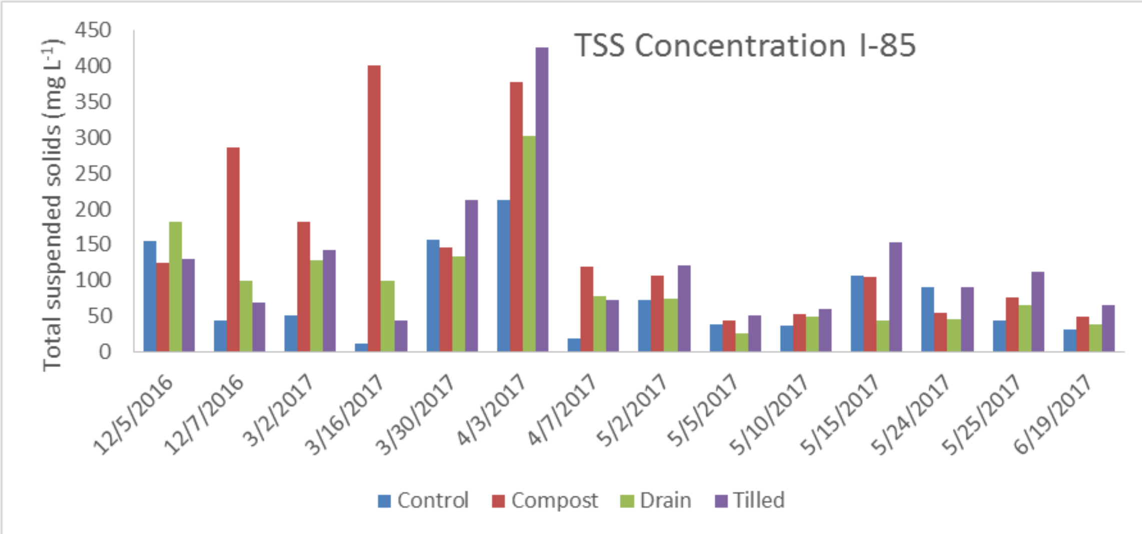


Figure A5. Total suspended solids (TSS) concentration and load at I-40.



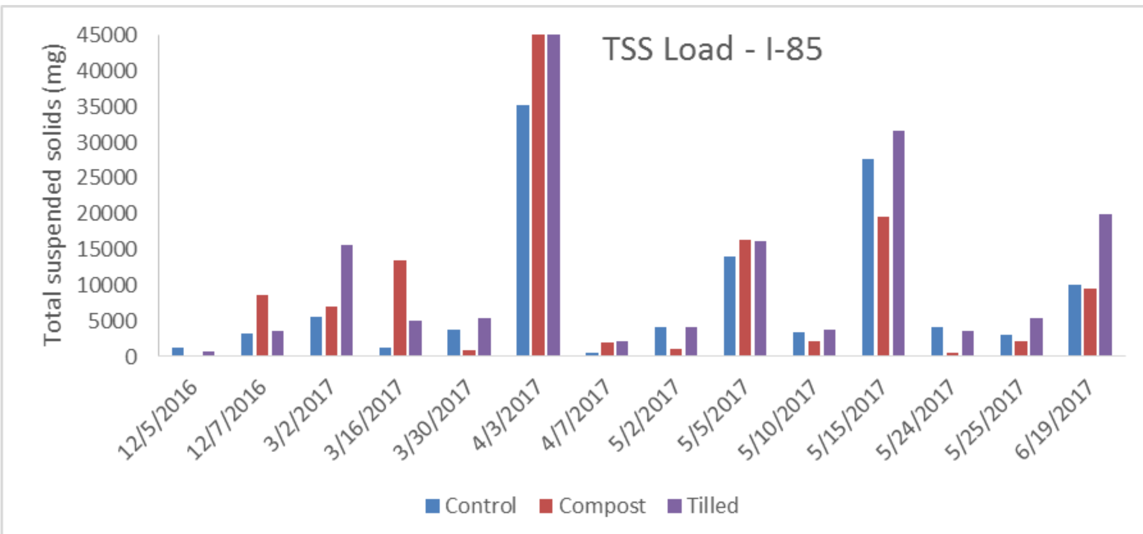
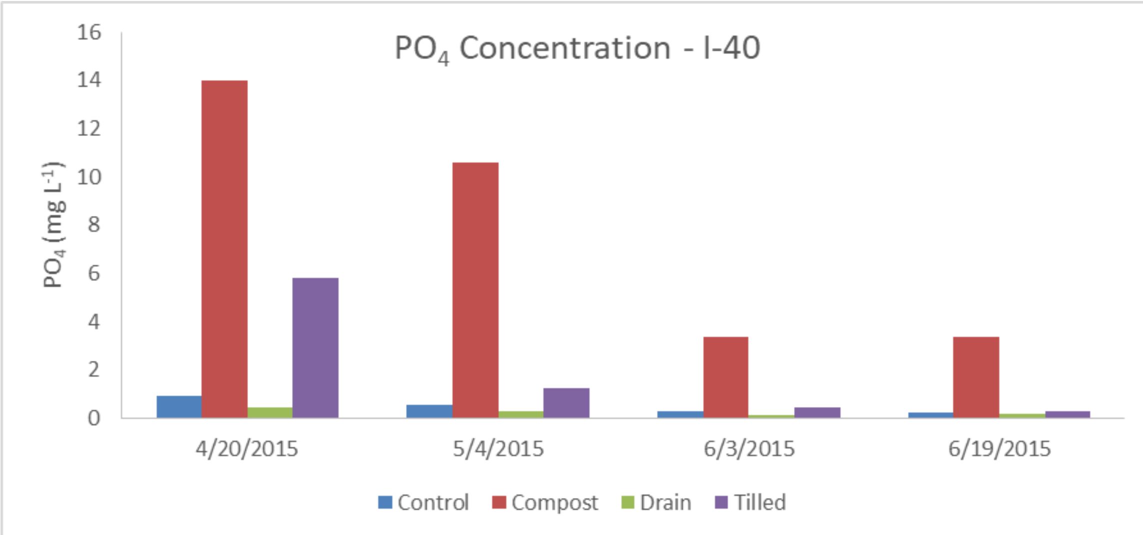


Figure A6. Total suspended solids (TSS) concentration and load at I-85.



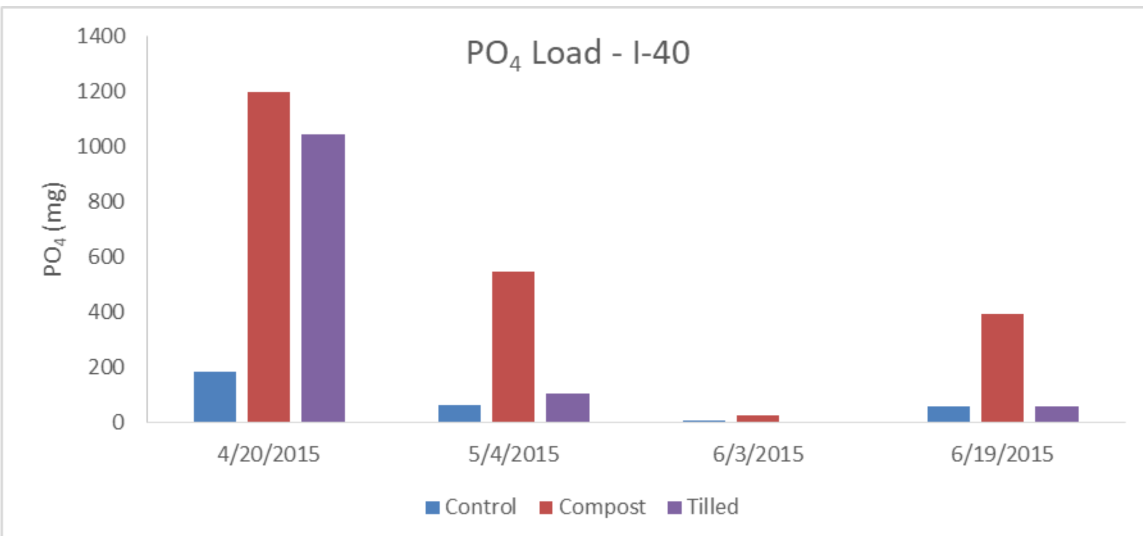
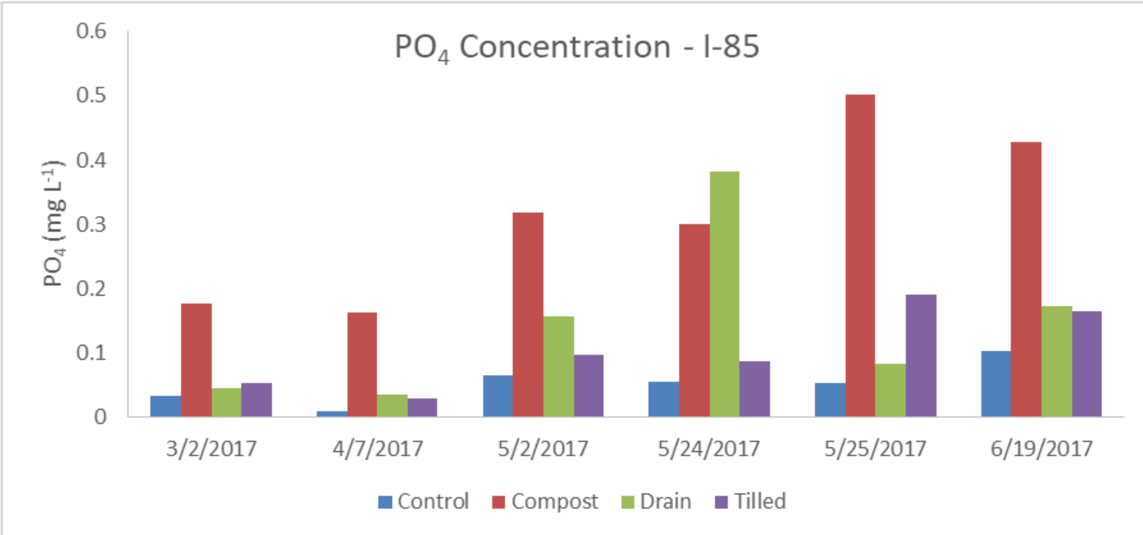


Figure A7. PO_4 concentration and load at I-40.



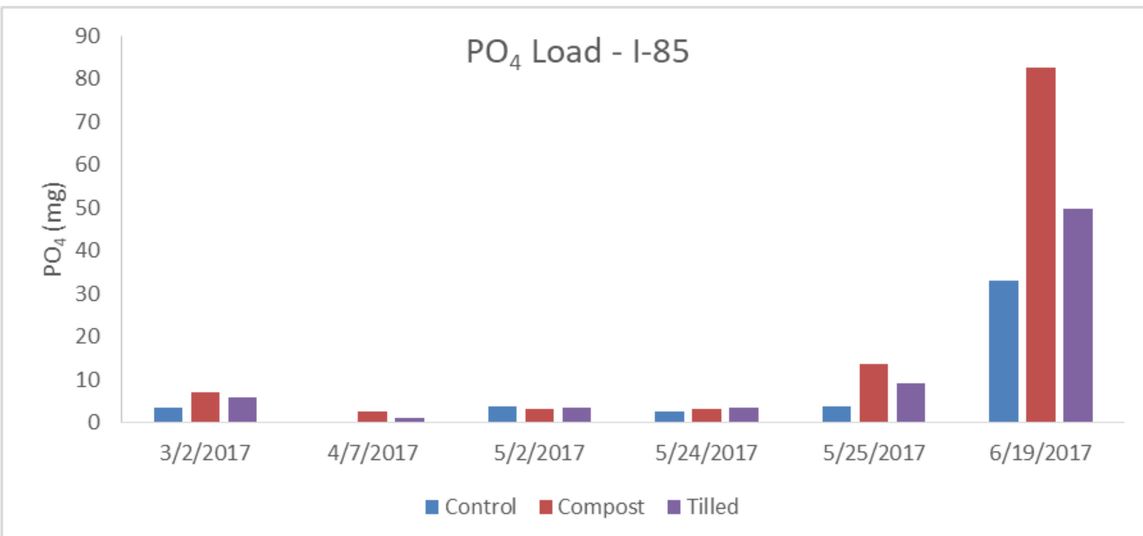
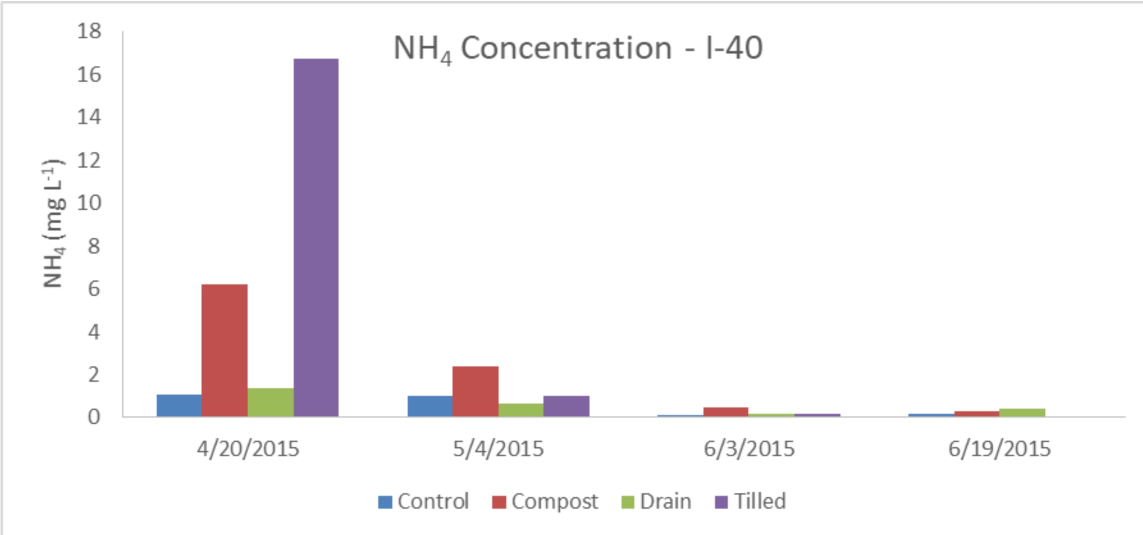


Figure A8. PO_4 concentration and load at I-85.



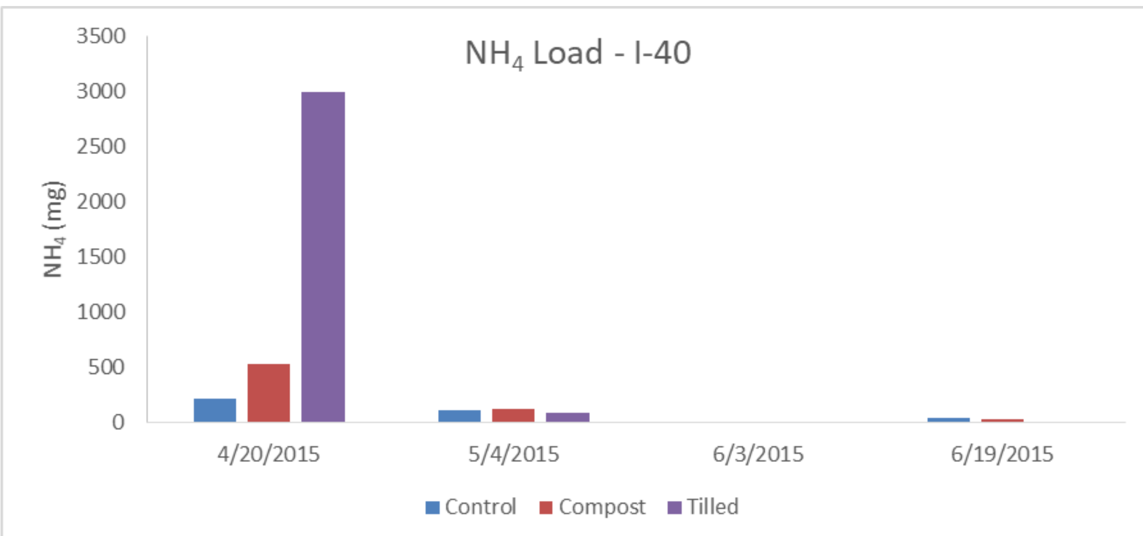
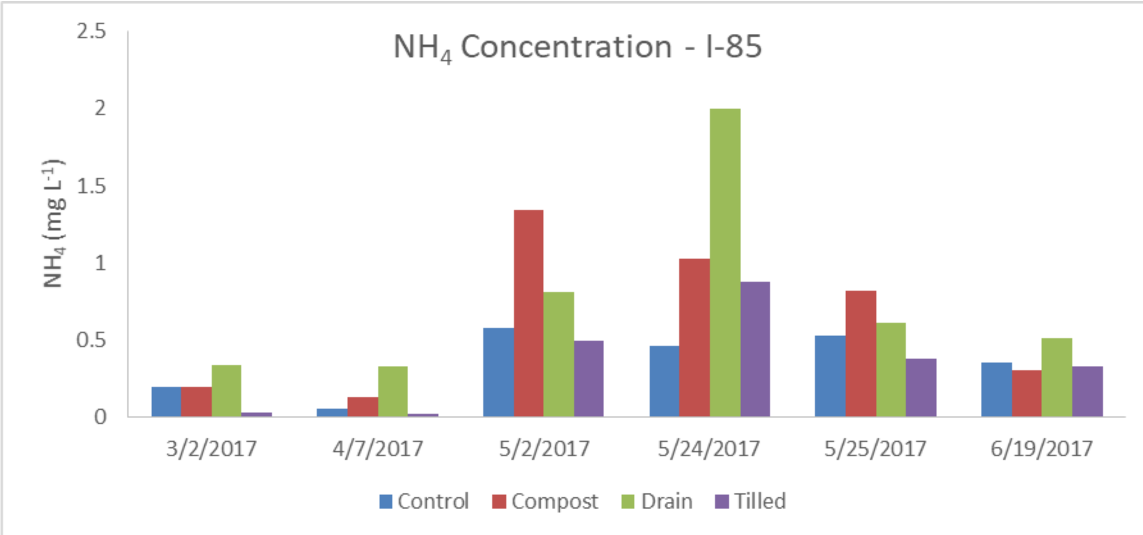


Figure A9. NH_4 concentration and load at I-40.



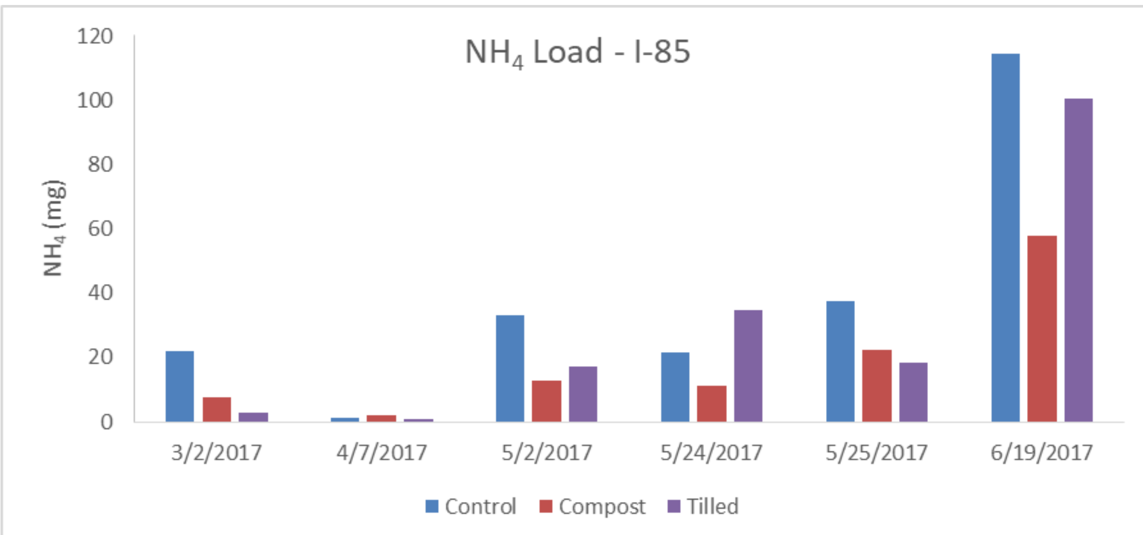
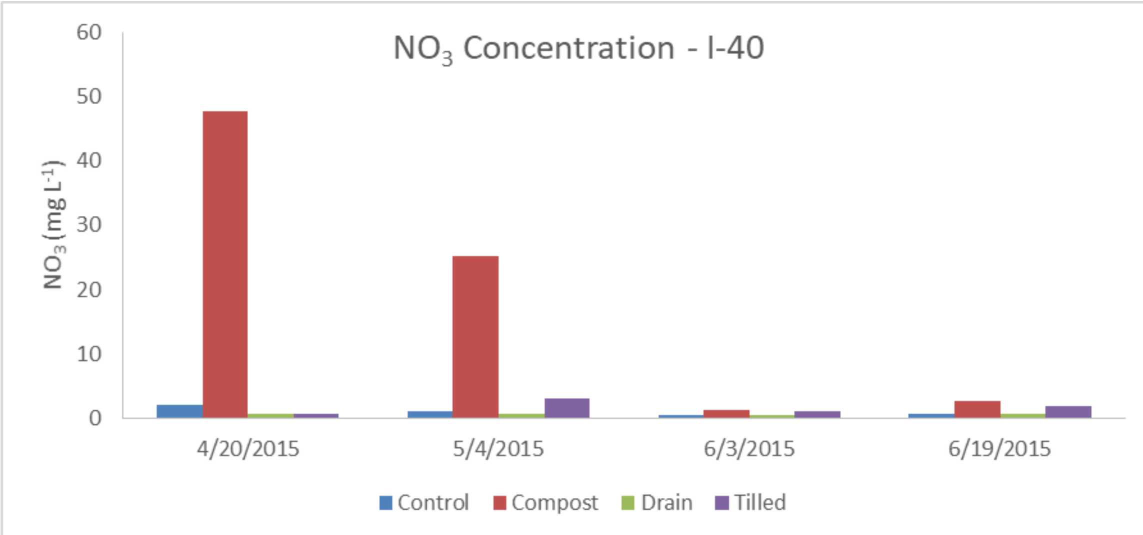


Figure A10. NH_4 concentration and load at I-85.



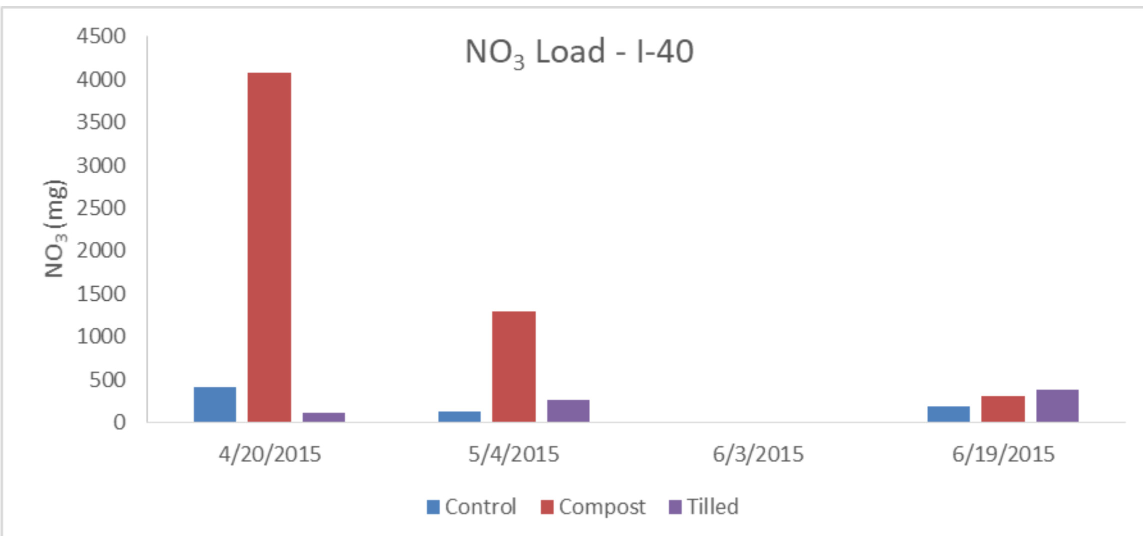
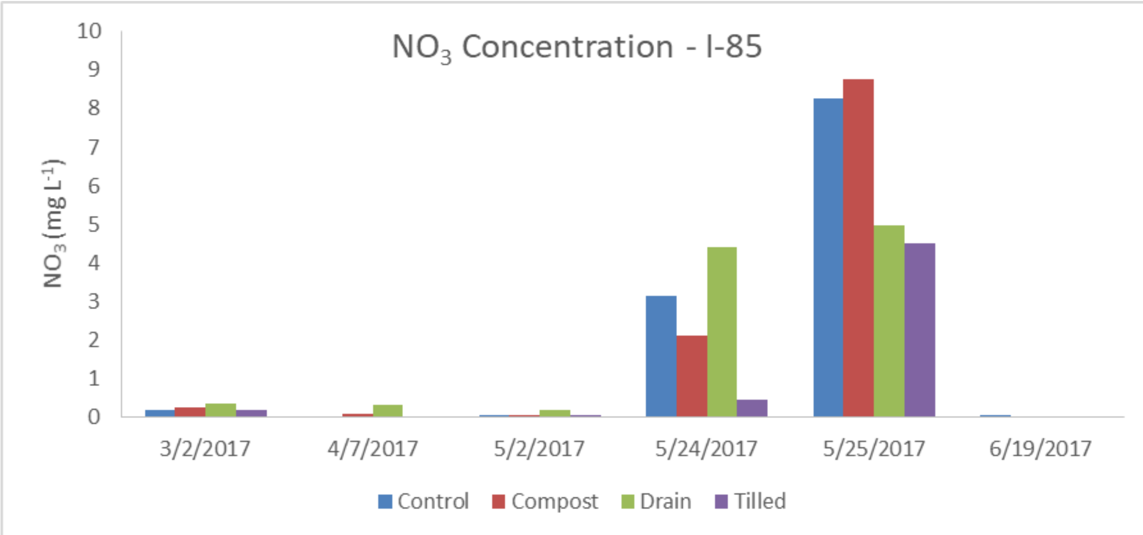


Figure A11. NO_3 concentration and load at I-40.



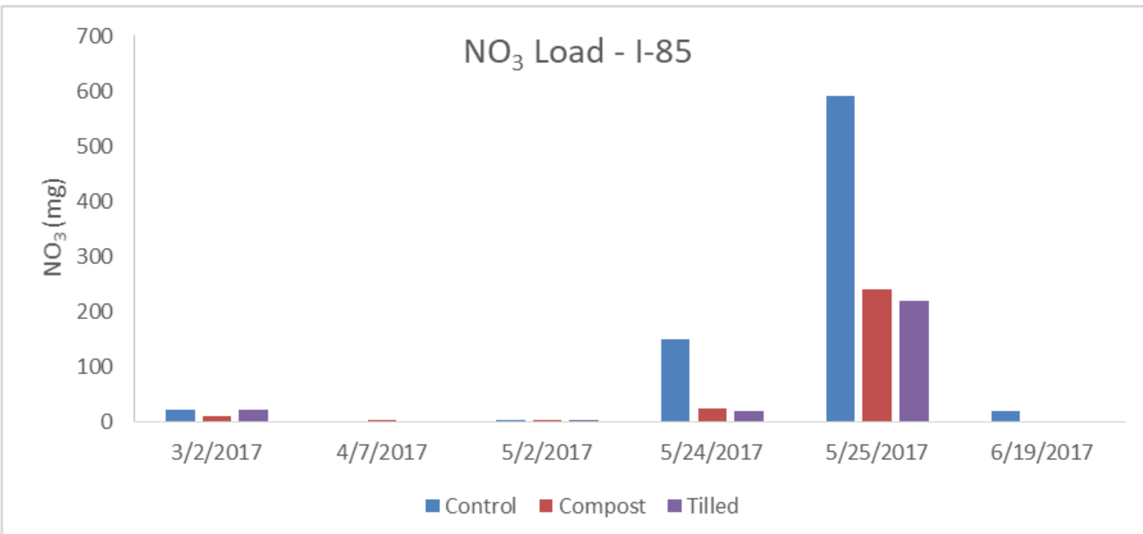


Figure A12. NO_3 concentration and load at I-85.

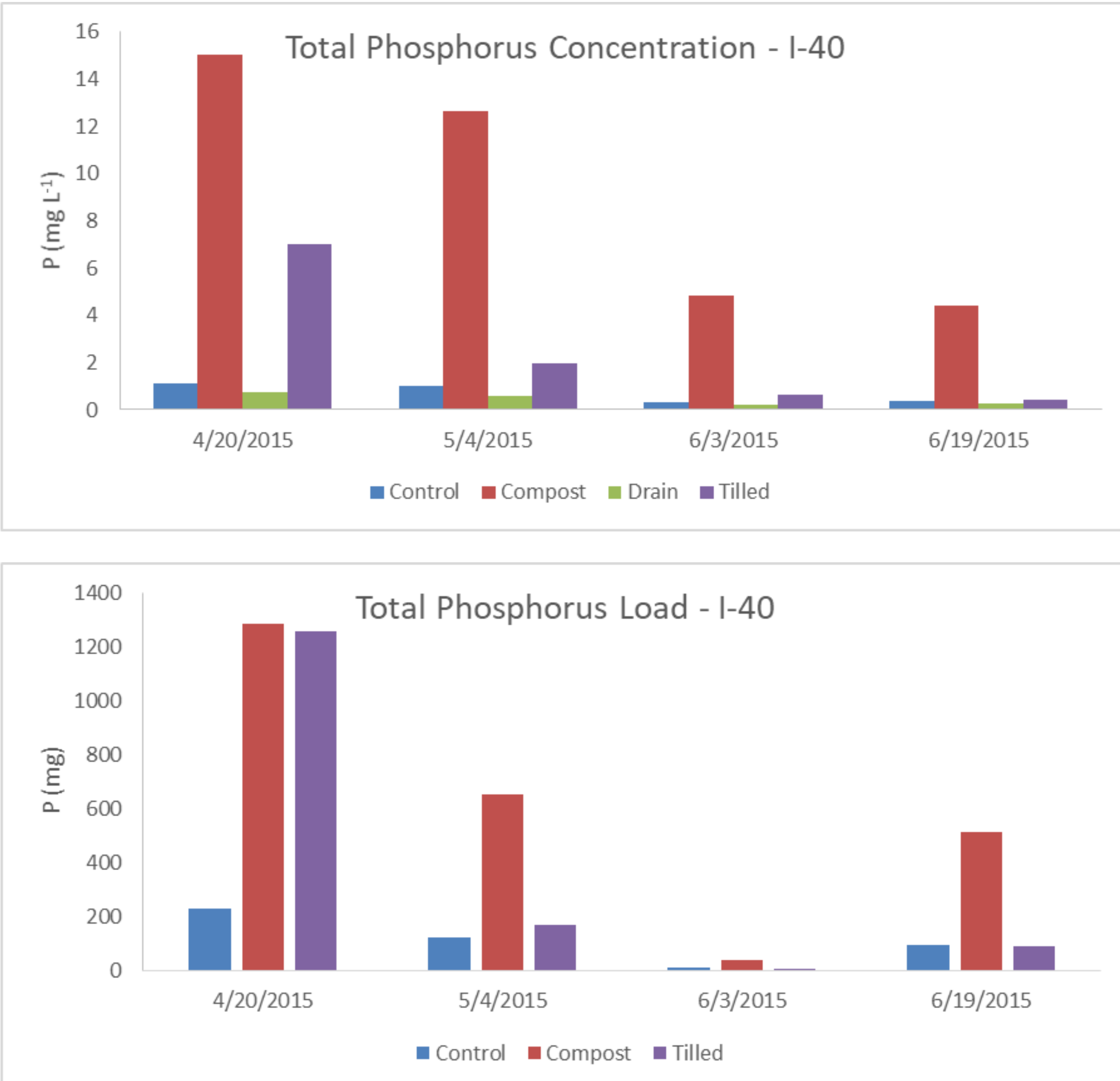
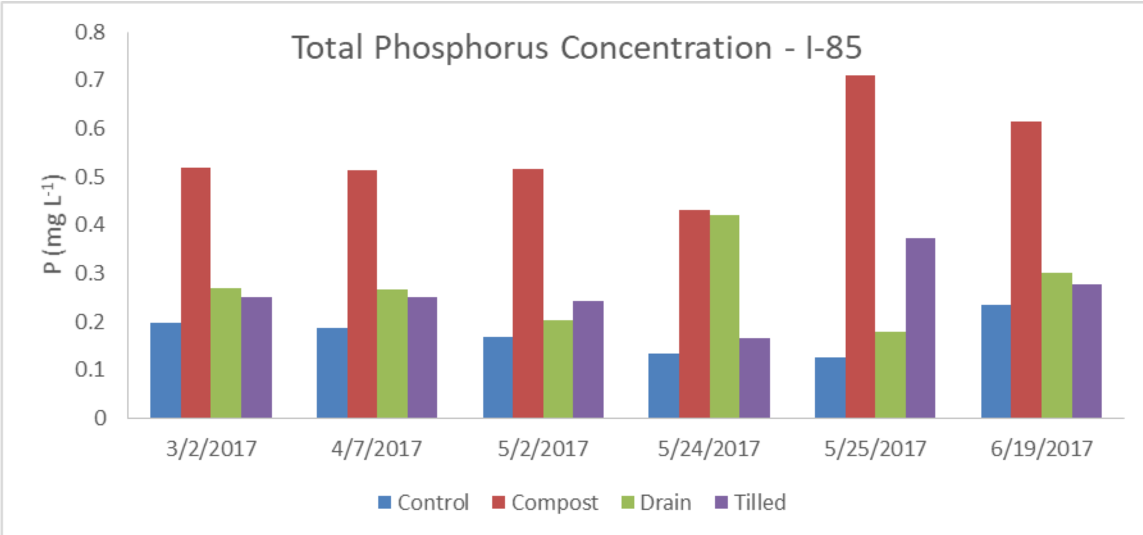


Figure A13. Total phosphorus concentration and load at I-40.



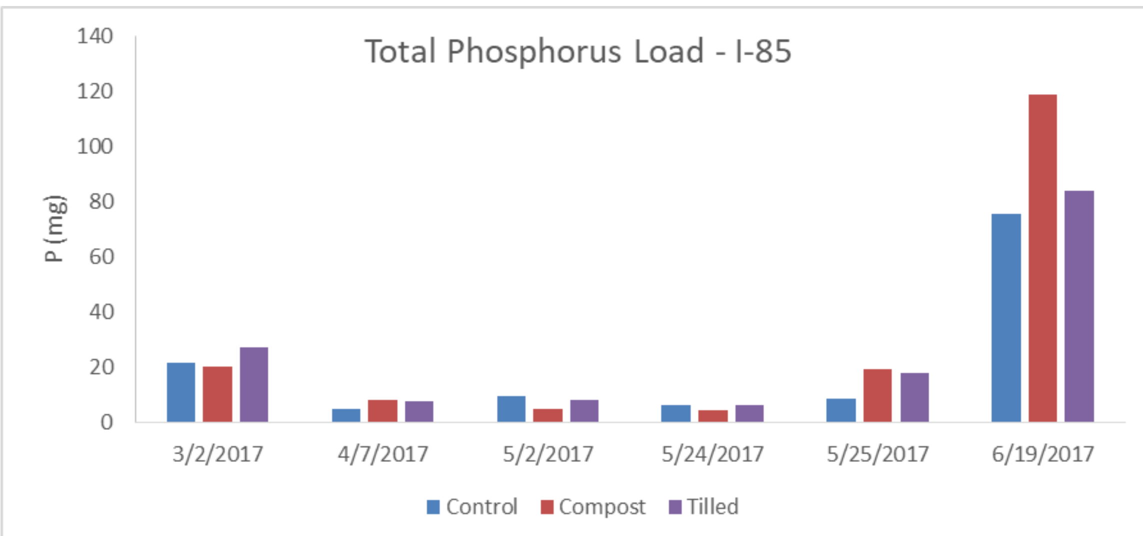
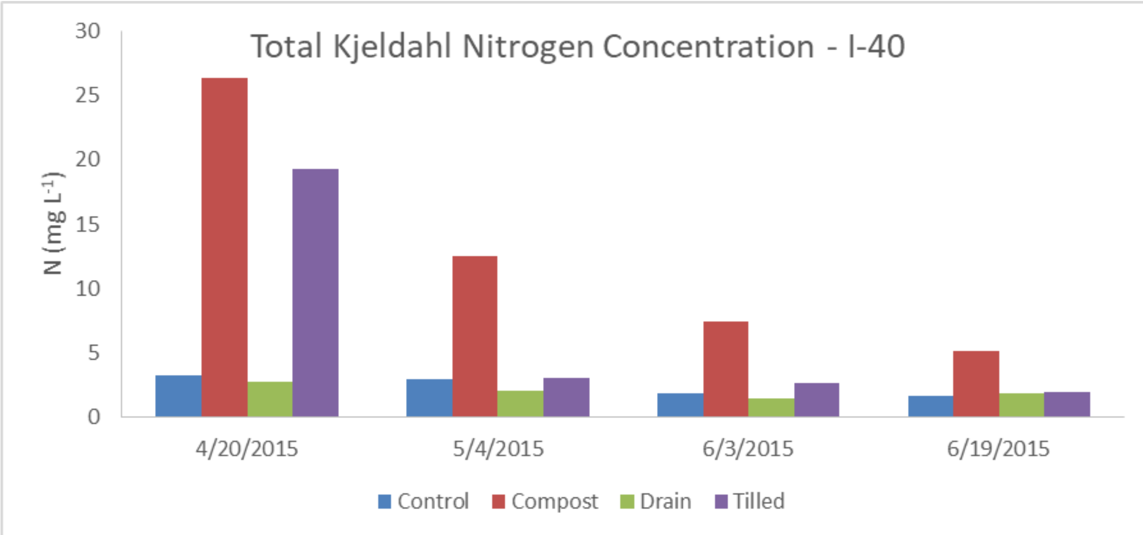


Figure A14. Total phosphorus concentration and load at I-85.



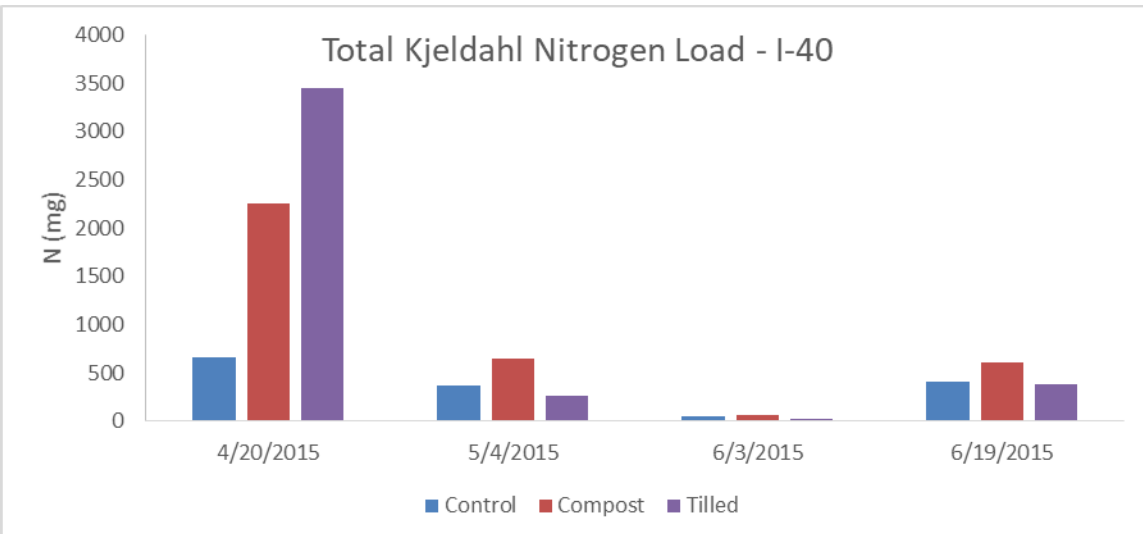
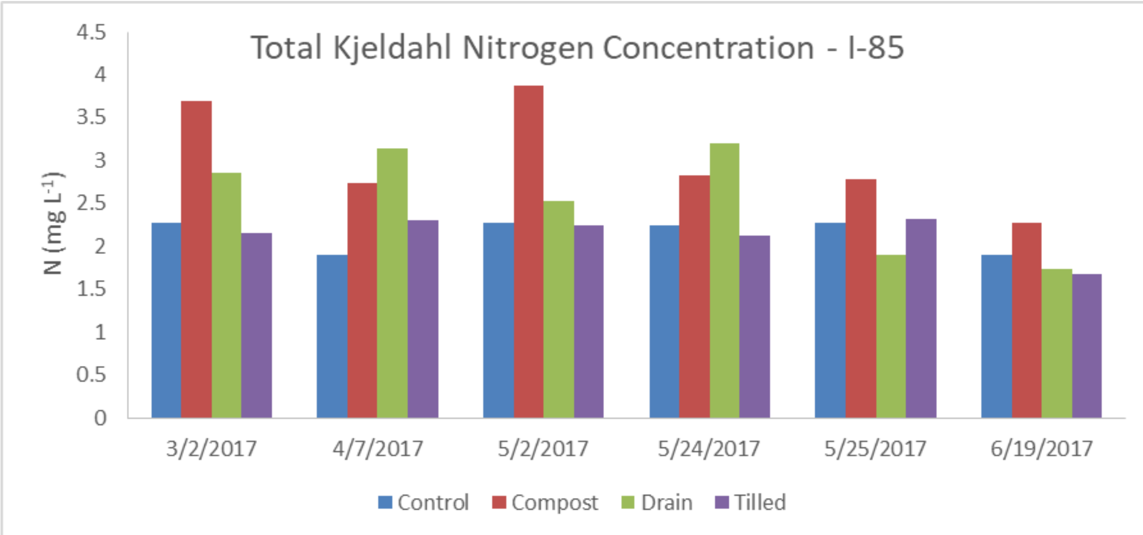


Figure A15. Total Kjeldahl nitrogen concentration and load at I-40.



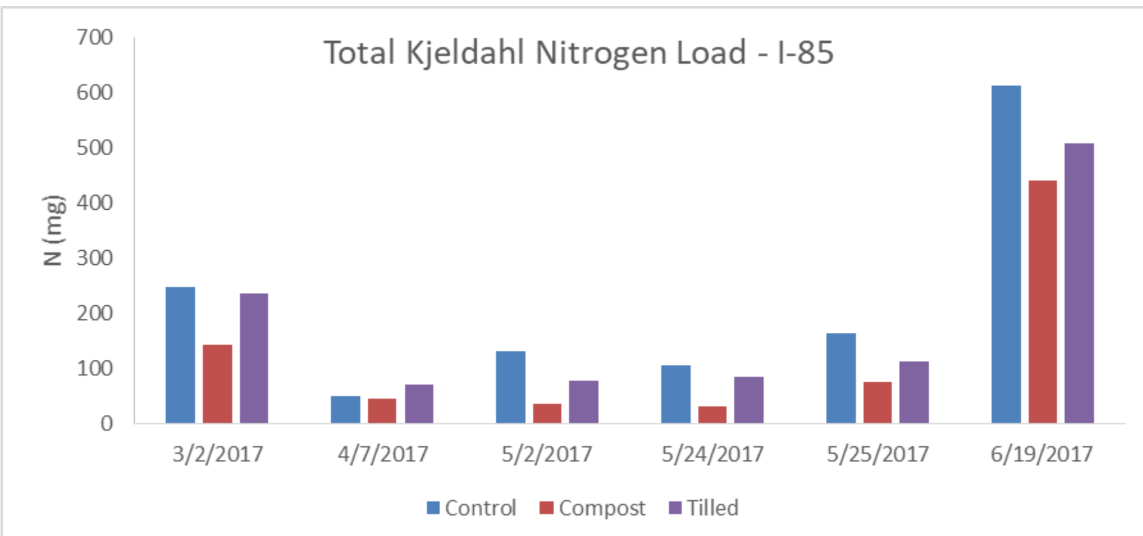
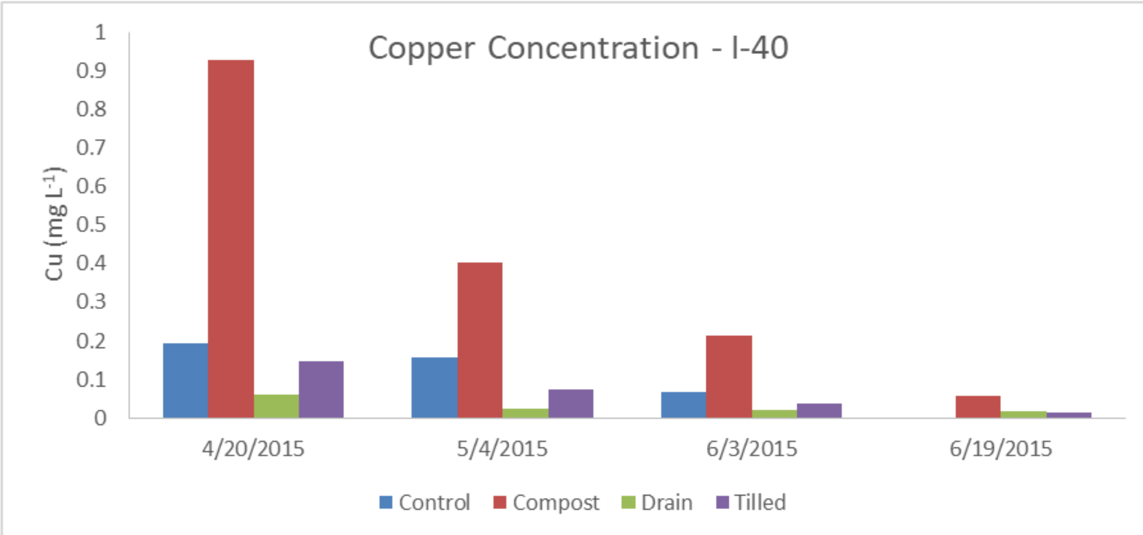


Figure A16. Total Kjeldahl nitrogen concentration and load at I-85.



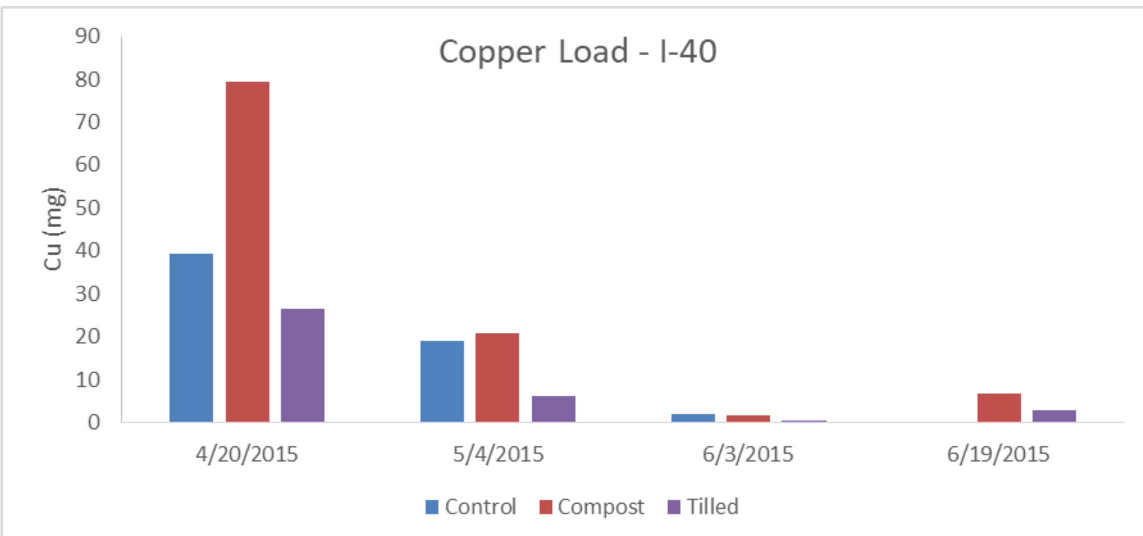
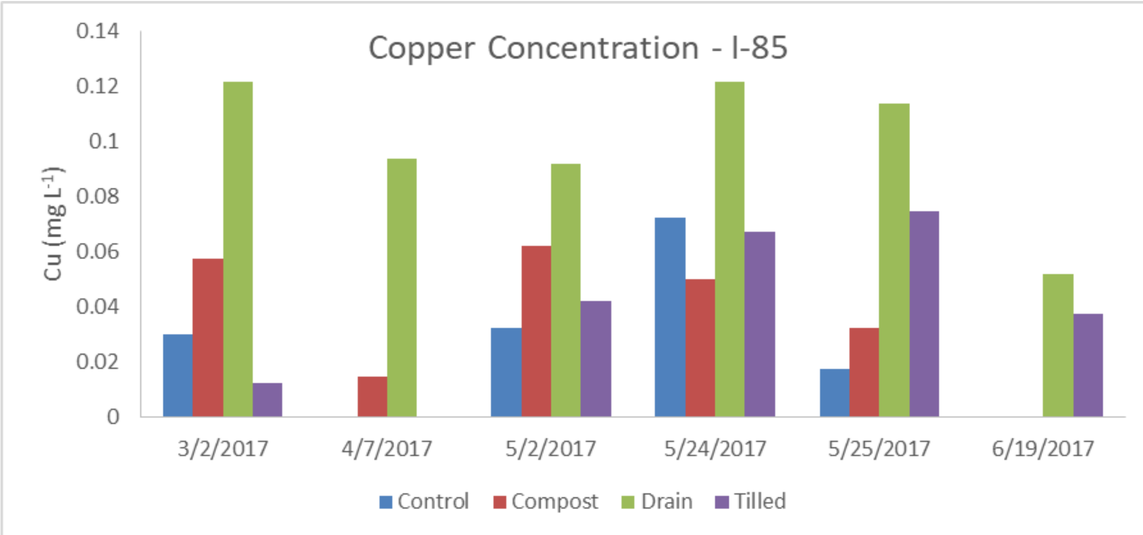


Figure A17. Copper concentration and load at I-40.



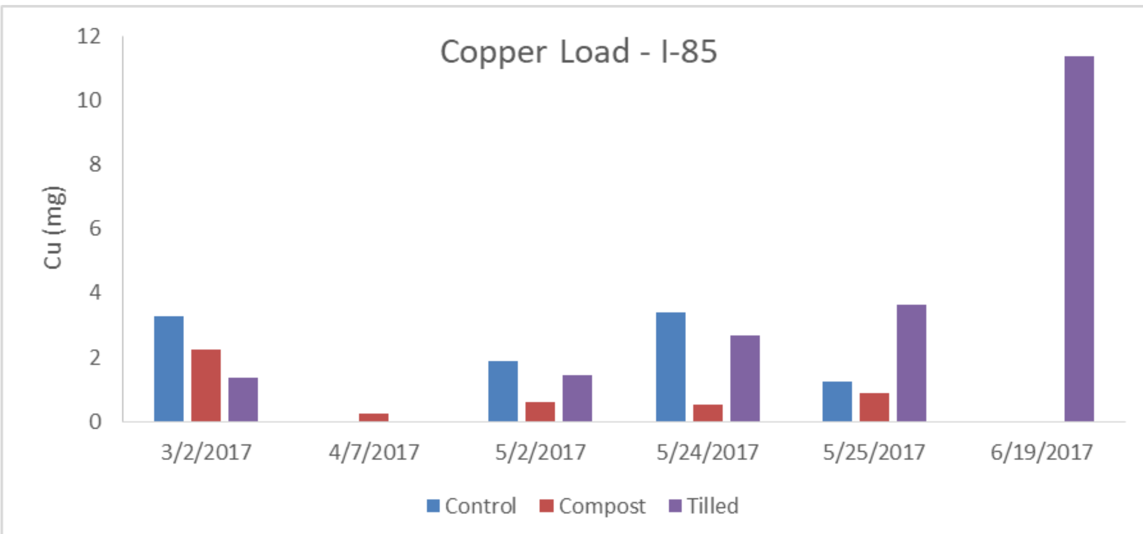
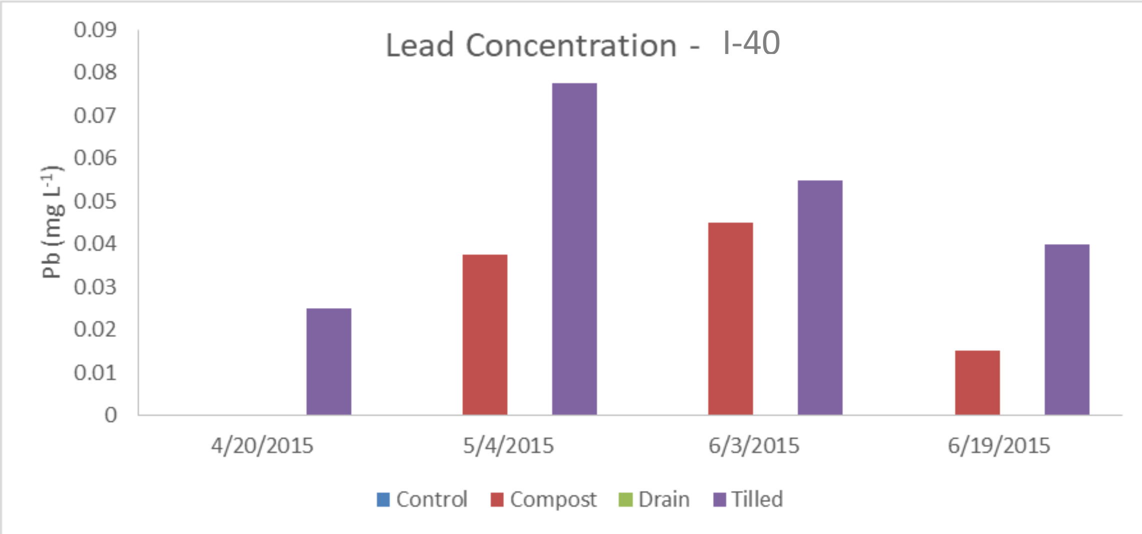


Figure A18. Copper concentration and load at I-85.



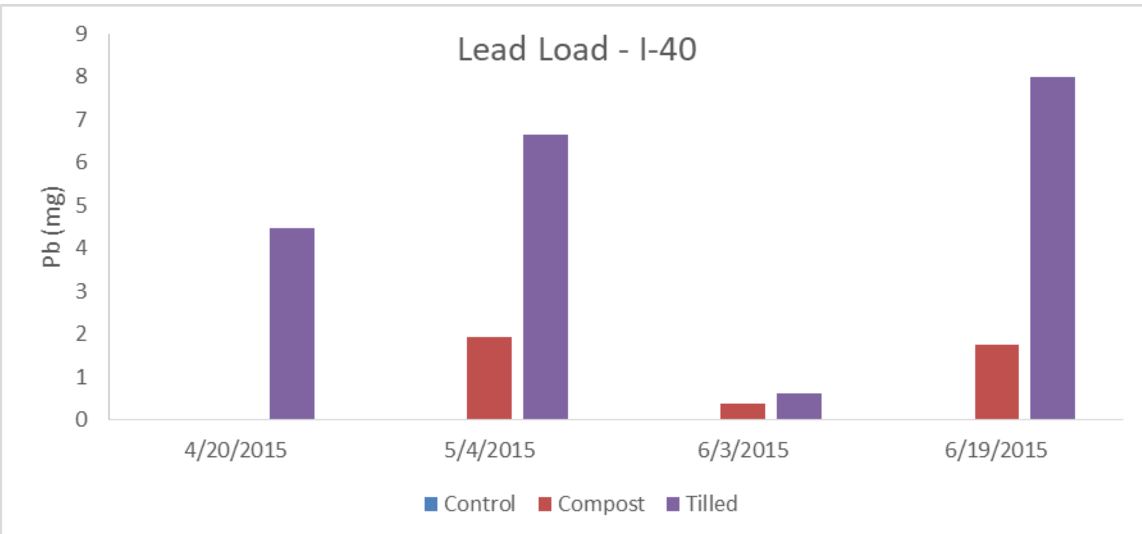
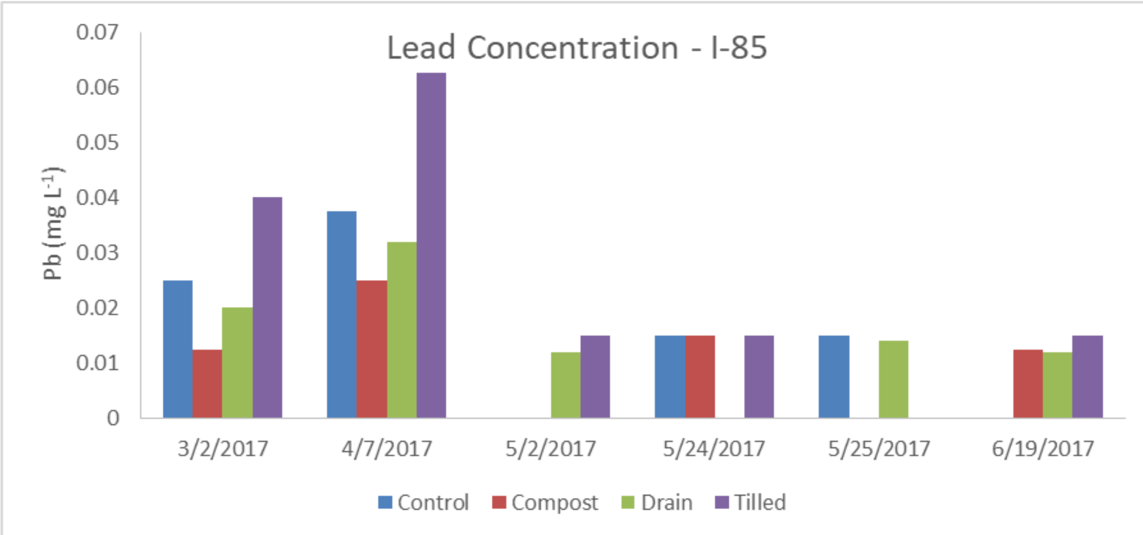


Figure A19. Lead concentration and load at I-40.



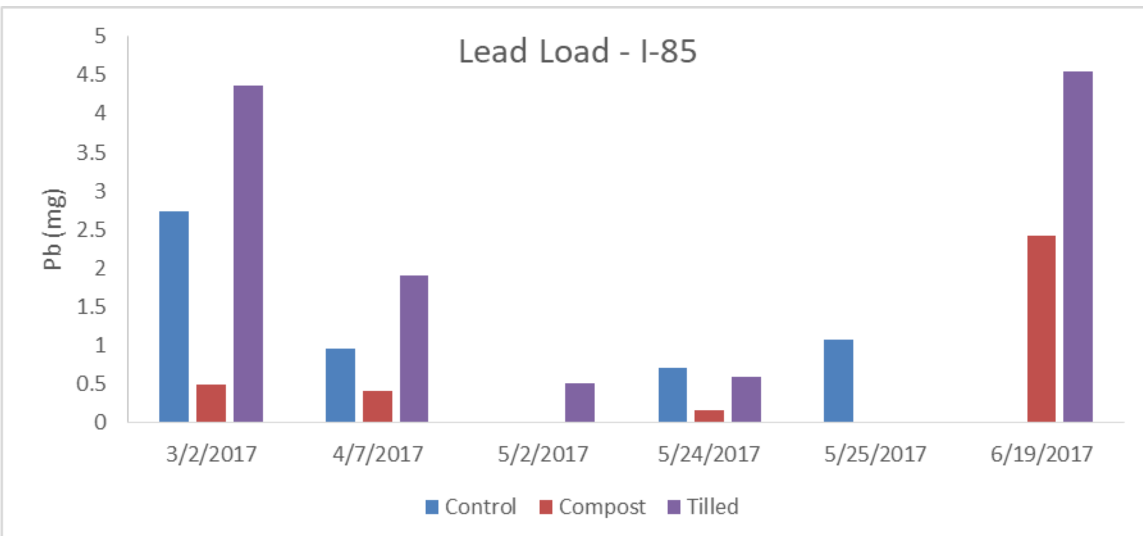
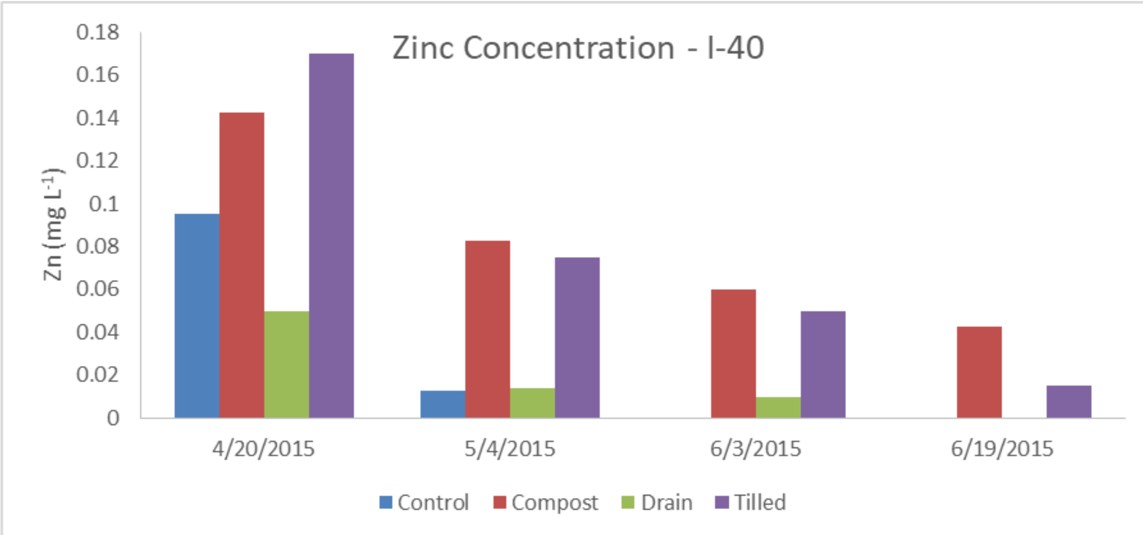


Figure A20. Lead concentration and load at I-85.



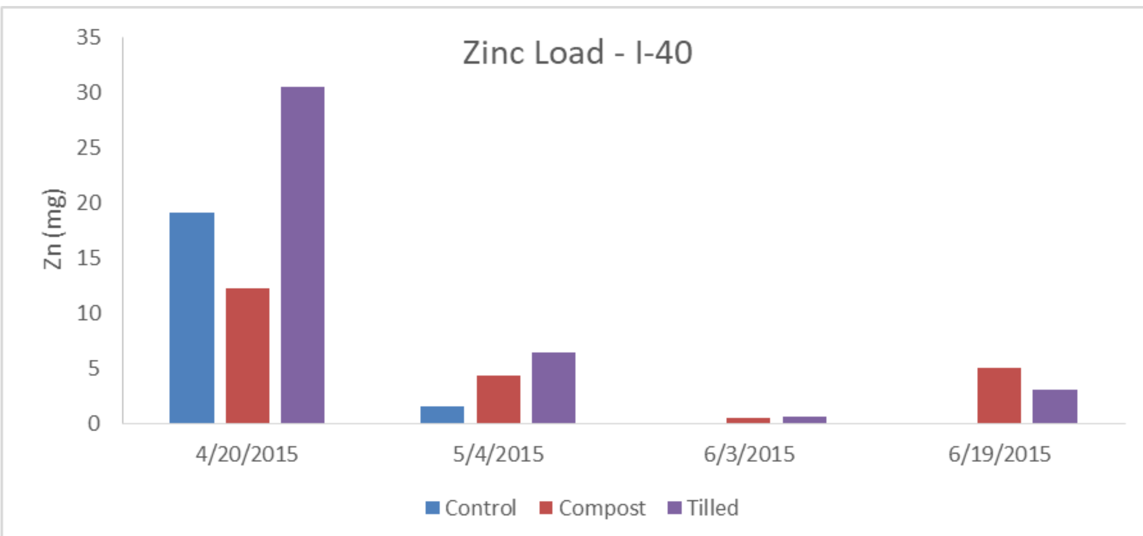
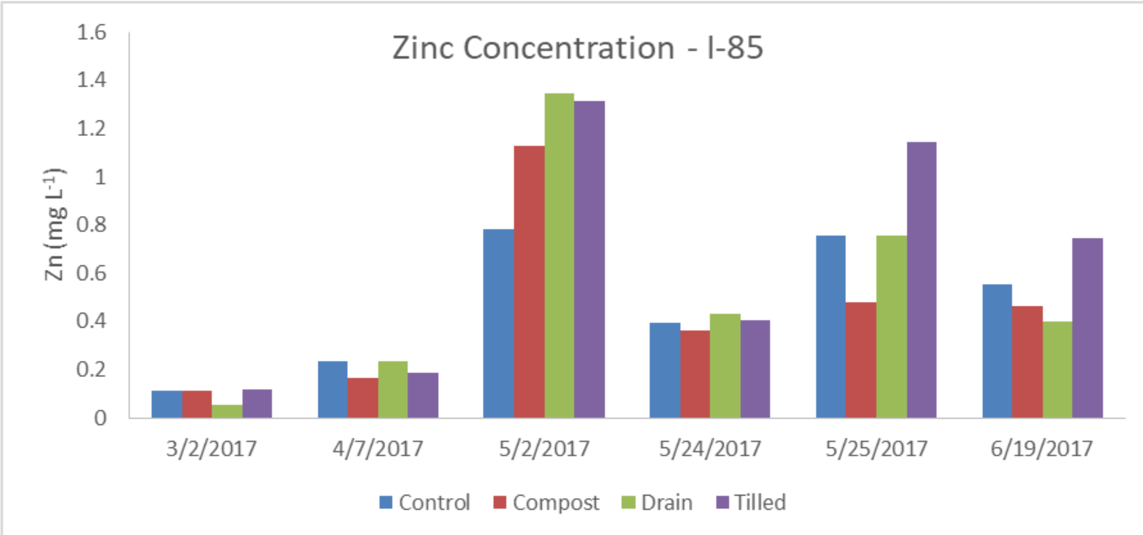


Figure A21. Zinc concentration and load at I-40.



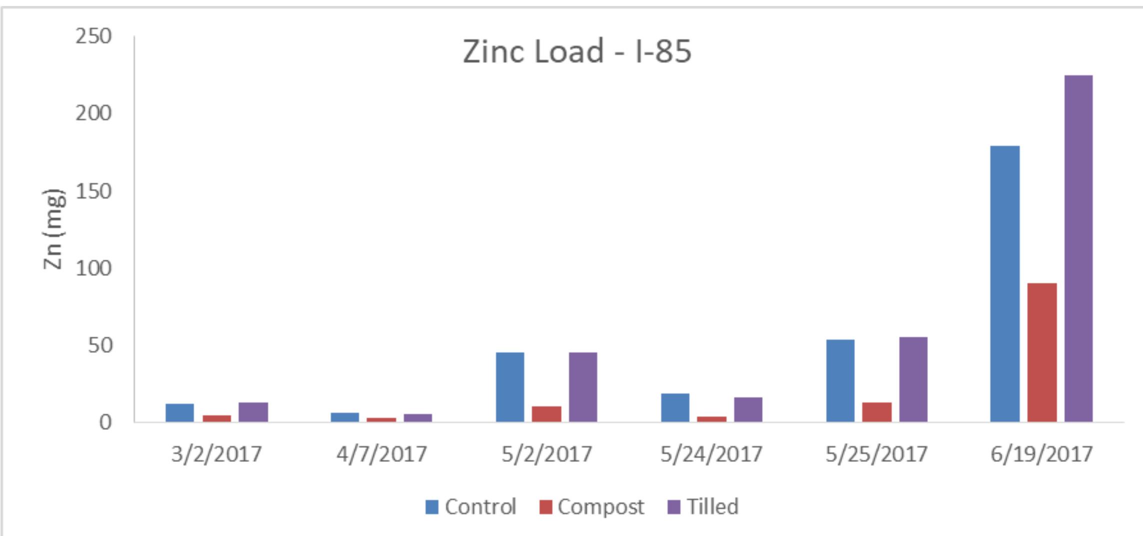


Figure A22. Zinc concentration and load at I-85.