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MARYLAND DEPARTMENT OF TRANSPORTATION
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RESEARCH REPORT

Understanding the Effects of Slope Ratio, Straw Mulching, and Compost Addition to Topsoil to Establish Permanent Vegetation and Reduce Nutrient Runoff

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FINAL REPORT

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16. Abstract

Soil erosion management is a major environmental challenge facing highway construction. This project analyzes sustainable improvements to current standard procedures for final grade turfgrass establishment on disturbed soils. Using a series of greenhouse studies, two compost types, biosolids and greenwaste, and four compost/topsoil blends were compared with a standard topsoil/straw/fertilizer practice in their ability to reduce soil and nutrient loss and improve the rate, quality, and quantity of green vegetation (GV) establishment. These studies also observed the effects of slope ratio changes and additional straw mulching to composted media. At a 25% slope, straw mulching significantly reduced runoff quantity and improved quality as well as GV cover. On average, straw mulching reduced mass export of nutrients and sediment by 86-91% on tested media. With mulching, no statistical differences were found in the rates of vegetation growth among the compost-amended slopes (all reached >95% cover in 60 days), however, without straw mulching maximum GV cover after 60 days was 31%. Straw mulching with the addition of composted material (excluding 50% compost: topsoil) reduced the total runoff volume (13-59%), sediment mass (64-98%), and nutrient mass (6-82% nitrogen and 4-76% phosphorus) from topsoil application. Observations made for media tested at various slope ratios showed a general increase in nutrient and sediment export with slope ratio increase. Also, the volume, sediment and nutrient export reductions displayed at the 25% slope were less evident at shallower slopes and enhanced at greater slopes.

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Executive Summary

The primary research goals of this project were to incorporate more renewable materials into the Maryland Department of Transportation State Highway Administration (MDOT SHA) stormwater management plan (SMP) for post-construction highway embankments and reduce nutrient and sediment loading to the Chesapeake Bay.

Five greenhouse studies were completed over the course of the year to analyze three variables associated with compost amendment for highway embankment stabilization: the effects of straw mulching, topsoil to compost percentile, and embankment slope ratio. The greenhouse design used a single nozzle rainfall simulator at ~9 ft height and 6 ft x 6 ft adjustable platform with three 6 ft x 2 ft sections, based on designs in Owen et al. (2020b). Media mixtures used (by volume) were the topsoil/straw/fertilizer standard (MDOT SHA spec705), biosolids compost, greenwaste compost, 2:1 topsoil: biosolids, 2:1 topsoil: greenwaste, 2:1 biosolids: topsoil, 2:1 greenwaste: topsoil. Slope angles used for this study were: 20:1, 6:1, 4:1, and 2:1.

All media runoff was collected and analyzed for total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) as well as all P and N species; phosphate, dissolved organic P, and particulate P; nitrate, nitrite, ammonium, and organic N. Vegetation was measured using digital image analysis using the method described in Owen et al., (2020a) which uses image segmentation and classification using a trained computer algorithm based on the tree learning algorithm. Statistical analysis used to analyze data significance, determine trends, and eliminate outliers were the Wilcoxan signed-rank, Mann-Kendall Tau, and modified Thompson tau tests, respectively with a significance level of 5% ($P<0.05$).

The results of straw addition on runoff volume were reductions of 64%, 67%, 98%, and 99% for biosolids, greenwaste, 2:1 topsoil: biosolids, and 2:1 topsoil: greenwaste, respectively. Total mass of sediments and nutrients for biosolids compost was reduced by 98.6% (TSS – not statistically significant), 94.1% TN, and 77.7% TP. Total mass of sediments and nutrients for greenwaste compost was reduced by 64.8% TSS, 72.2% TN, and 68.6% TP. Total mass of sediments and nutrients for 2:1 topsoil: biosolids was reduced by 99.7% TSS, 86.4% TN, and 99.1% TP. Total mass of sediments and nutrients for 2:1 topsoil: greenwaste was reduced by 99.9% TSS, 73.0% TN, and 99.4% TP.

All applied media comparisons were made with straw mulching on top. Compost addition or replacement of the standard topsoil (TS) treatment (with straw mulching) produced generally reduced or comparable runoff EMCs and mass export of nutrients and sediment, except for the two 2:1 compost: topsoil blends tested. The 2:1 topsoil: greenwaste with straw (TGS), 2:1 topsoil: biosolids with straw (TBS), and biosolids with straw (BS) treatments statistically reduced sediment loss EMCs when compared to the TS standard by 47.8%, 77.0%, and 90.8% and reduced average sediment mass export by 73.2%, 97.0%, and 82.5%, respectively. TN EMCs and mass export were not statistically different for any treatment (except the 2:1 biosolids: topsoil with straw (BTS) which exported greater EMCs and N mass export). TN mass export for all treatments (except BTS) was reduced from TS, with BS and TBS having the greatest reduction of 82.3% and 71.5% mass export on average. TP EMCs were seen to be statistically greater than TS for greenwaste with straw (GS), BS, and BTS by 25.7%, 14.4%, and 5%, respectively. TP mass export was lower in all media applications than TS, (except BTS which exported 15% more P) with TBS and TGS having the greatest reduction of 76% and 69%,

respectively. There were no statistical differences in vegetation establishment for any of the tested mixtures with all reaching >95% green vegetation coverage within 60 days

On average, steeper slopes resulted in both larger EMCs and nutrient/sediment mass export than shallower slopes. Vegetation establishment was statistically greater for biosolids no straw (BNS) and greenwaste no straw (GNS) treatments at shallower slopes (>95% establishment for all slopes at 20:1) which had more establishment than steeper slopes (2% and 15% at the 2:1 slope). TS treatment showed the most difference with slope variation with runoff volume, TSS, TN, and TP increasing 23-fold, 142-fold, 31-fold, and 37-fold, respectively, from the 20:1 to 2:1 slope. The GNS treatment was the least affected by slope variation increasing 1.9-fold, 1.7-fold, 15-fold, and 5.6-fold, respectively from the 20:1 to 2:1 slope. Although sediment and nutrient mass exports and concentrations were seen to generally increase with slope ratio increase, the relationship between treatments did not greatly change. GNS typically had greater total export of nutrients and sediment, BNS typically had the least with TS in the middle. There were two observed exceptions to these relationships; at the 4:1 slope BNS had higher total export of nutrients and sediment (average 2.4- fold greater) than TS and at the 2:1 slope TS had higher total export than GNS (average 3.8- fold greater).

It is strongly recommended for MDOT SHA to use straw mulching regardless of treatment applications. The use of 2:1 compost: topsoil blends is not recommended over the current TS standard as the total export of nutrients was greater by 36% for nitrogen and 15% for phosphorus (based on BTS) and 16% for sediment (based on GTS). Both 2:1 topsoil: compost blends and pure compost with straw mulching produced similar or better runoff quality than the TS standard. GS had 57%, 6%, and 4% reduction in sediment, TN, and TP respectively while BS, TBS, and TGS had reductions ranging from 37-97% nutrient and sediment export results. Slope increase resulted in increased nutrient and sediment loss but did not greatly affect the comparisons between media types, therefor slope may not be the deciding factor in choosing one media over another.

Through this study a few opportunities for future research were identified. Additional compost to topsoil mixtures may yield a more optimal ratio for minimized runoff volume and improved runoff water quality. Test a variety of different stormwater management plans (SMP) combined with composted material (straw application was used in this study) may yield better runoff quality results (eg. Geotextiles or silt fence). Water treatment residual and activated charcoal have been seen to reduce phosphorus and nitrogen concentrations in a variety of SMPs, investigation into compost amended with these or other materials may yield further reduction in nutrient export.

Introduction

The use of compost in long construction-related transportation projects has been studied and implemented in parts of the US (USEPA, 2003). Compost is a recycled, renewable resource that is high in organic and inorganic nutrients and can be readily in most places. Depending on the facility and location, feedstocks for composts can include food waste, yard waste (greenwaste), and treated wastewater sludge (biosolids). Each of these feedstocks results in a different composted material with varying physical and nutrient compositions that can affect how well vegetation establishes and how effective the material is as a stormwater management plan (SMP) amendment (Diaz et al., 2007).

In general, compost addition to soils has shown increased porosity and decreased bulk density, which leads to an increase in soil stability, aggregation, and water holding capacity (Khaleel et al., 1981; Mitchell, 1997; Kirchoff et al., 2003; Duzgun et al., 2020). Composted material has also been used for centuries to improve vegetation establishment and reduce sediment runoff (Glanville, 2004; Harrell & Miller, 2005; Curtis & Claassen, 2007; Mukhtar et al., 2008; Hansen et al., 2012).

Establishment of a healthy and dense ground cover plays a major role in minimizing nutrient and sediment runoff production (Pan et al., 2006). Composted material and its benefits to plant nutrition and soil fertility are well-established (Darmody et al., 1983; O’Keefe et al., 1986; Sikora & Yakovchenko, 1996; Pascual et al., 1997). However, the use of compost in stormwater management plans for erosion control has had mixed results; Glanville et al. (2003), Faucette et al. (2005), and Mukhtar et al. (2008) observed a reduction in runoff volume for compost amended slopes when compared to bare topsoil, there were substantially greater, 4-10-fold, nutrient concentration in the runoff.

Research presented in Owen et al. (2020b) showed similar advantages and disadvantages to the use of compost in both field and greenhouse observations, with 2-9-fold increase in nutrients in runoff compared to topsoil with fertilizer and a straw mulch cover. Greenhouse studies presented in Owen et al. (2020b) examined field applications of pure uncovered biosolids and greenwaste compost blankets along with uncovered 2:1 topsoil: biosolids and 2:1 topsoil: greenwaste blankets as they compared to the a current topsoil standards (Maryland Department of Transportation State Highway Administration, MDOT SHA). Although the nutrient concentrations were higher (2-9-fold higher concentration than the topsoil standard), a noticeably larger reduction in runoff volume was found with pure compost, especially biosolids, when compared to topsoil. The volume reduction by compost led to comparable mass export of nutrients to topsoil. From field applied materials observed in Owen et al. (2020b), an initial period within the first 25-35 cm of applied rainfall was identified where both vegetation establishment and 2-20-fold greater (than continued measurements) concentrations of total nitrogen and phosphorus occurred. This identified a critical period of nutrient and sediment loss that coincided with the initial vegetation establishment phase.

Each of the previous studies (Faucette et al., 2005; Mukhtar et al., 2008; Owen et al., 2020b) focused on the use of uncovered composted material vis-à-vis some form of topsoil control, but none have analyzed composted material with additional stormwater management practices (e.g., straw mulching). To respond to this need, a series of greenhouse experiments carried out at a variety of slope ratios were designed to determine the implications of composted material amendment to current stormwater management practices with and without straw mulching.

The experiments were designed to examine the critical period of vegetation establishment for nutrient and sediment export, found by Owen et al. (2020b). The goal of this study was to incorporate composted material into current and future stormwater management practices for highway embankments with the aim of reducing nutrient and sediment loadings to the local water environments. Direct comparisons are drawn between compost/topsoil mixture blankets using two types of compost, greenwaste compost (Leafgro® made from yard trimmings and grass clippings) and biosolids compost (Aberdeen MD wastewater treatment facility).

Objectives for this study were to observe and identify critical elements involved in runoff generation and quality from (1) compost media application with straw mulch application, (2) increased ratio of compost: topsoil, and (3) variations in slope ratio from length to height.

Metrics used to evaluate success of the treatment applications were rapid and healthy growth of green vegetation, reduced runoff volume, and reduced concentrations and total mass export of nutrients and sediments from the slopes. Information on compost performance at varying slopes with and without straw mulching obtained from this project can lead to increased use of composted materials for use in highway embankment stabilization.

Methodology

MATERIALS

Five greenhouse studies were completed to analyze three variables associated with compost amendment for highway embankment stabilization; the effects of straw mulching, topsoil to compost ratio, and embankment slope ratio. Table 1 has a detailed description of all slopes and treatments tested throughout the experiment. All media ratios presented in Table 1 are based on volume (TG and TB correspond to average dry mass compost of $9.3 \pm 1.4\%$ and GT and BT correspond to average dry mass compost of $29 \pm 2\%$). A total of four slopes were used to test media (5%, 17%, 25%, and 50%).

All soil media tested throughout the experiment adhere to current Maryland Department of Transportation, State Highway Administration (MDOT SHA) specifications. Topsoil was collected from The Rock Store in Hanover, MD; greenwaste compost was produced by Leafgro®; and biosolids compost was produced by the Aberdeen wastewater treatment facility. Both composted materials were produced aerobically.

All surface media was seeded with an MDOT SHA turf grass mixture, from Chesapeake Valley Seed, of 95% tall fescue and 5% Kentucky bluegrass at a rate of 2000 lbs/ac. Plots that received initial straw coverage (Table 1) were applied at 4000 lbs/ac with straw from Home Depot. The topsoil standard media received additional fertilizer provided by Keymar Fertilizer Inc. with a ratio of 20: 16: 12 (N: P: K, 83% ureaform with monoammonium phosphate and sulfate of potash) and applied at a rate of 2000 lbs/ac.

Table 1: List of all tested slopes and treatments. Some slopes were repeated and are represented by a multiplier (eg. x2). Media treatments: topsoil with straw and fertilizer (TS), biosolids (B), 2:1 biosolids: topsoil (BT), 2:1 topsoil: biosolids (TB), greenwaste (G), 2:1 greenwaste: topsoil (GT), 2:1 topsoil: greenwaste (TG). With straw mulching is denoted by an additional S and without is an NS.

5% Slope	17% Slope	25% Slope	50% Slope
TS	TS	TS x3	TS
BNS	BNS, BS	BNS, BS	BNS
GNS	GNS	GNS, GS	GNS
	TBS	TBS x2, TBNS	
	TGS	TGS x2, TGNS	
		GTS	
		BTS	

GREENHOUSE EXPERIMENTAL DESIGN

The methodology for this work follows that of Owen et al. (2020b) for the greenhouse experimental setup, soil materials, chemicals used, and nutrients and sediments analyzed. Two 6 ft by 6 ft platforms, one pictured in Figure 1a, were used to test three medium applications at a time, each covering a 2 ft wide by 6 ft long section of the platform, as described in Owen et al. (2020b). Each of these sections was designed to capture all surface runoff from a 2 in deep soil layer and allow water infiltrated through the surface medium to exit the system; a cross sectional view is shown in Figure 1b.

The same rainfall simulator designs (single 0.5 in. HH-30 W SQ Fulljet® nozzle at ~9 ft height) presented in Owen et al. (2020b) and pictured in Figure 2a during an applied rainfall event, were used in this research to produce uniform applied rainfall events. The duration and frequency of each applied rainfall event are shown in Table 2 for all designed plot studies. University of Maryland tap water was used for these experiments and was analyzed for nutrients throughout the study.

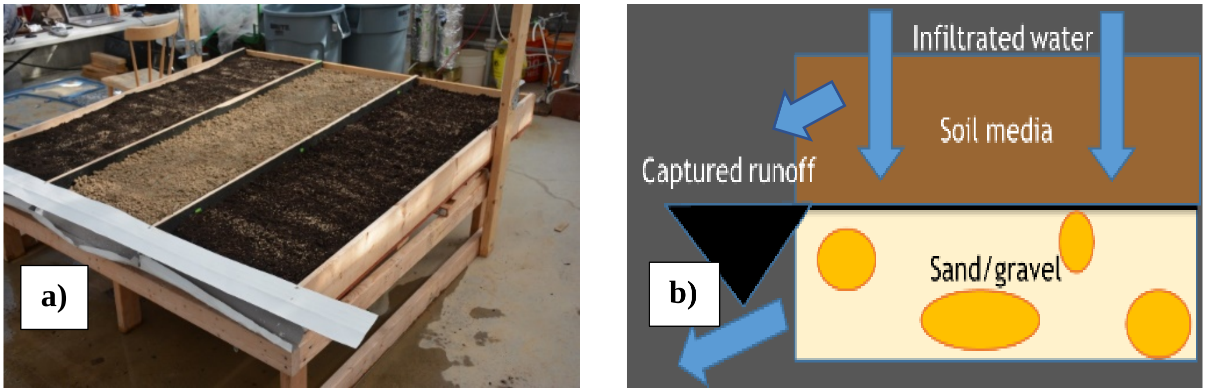

Figure 1: (a) 6 ft x 6 ft platform design with 3 sections which drain according to (b) the cross-sectional view. Runoff is captured in the gutter system for collection and analysis with a rain guard to protect the effluent from dilution due to applied rainfall.

Table 2: Synthetic stormwater application schedule and durations for greenhouse simulations.

Days since seeding	0-2	6-8	13-15	20-22	27-29	34-36
Duration	15-min	15-min	30-min	30-min	45-min	45-min
Rainfall Volume (in.)	1	1	2	2	3	3
Accumulated Rainfall (in.)	1	2	4	6	9	12

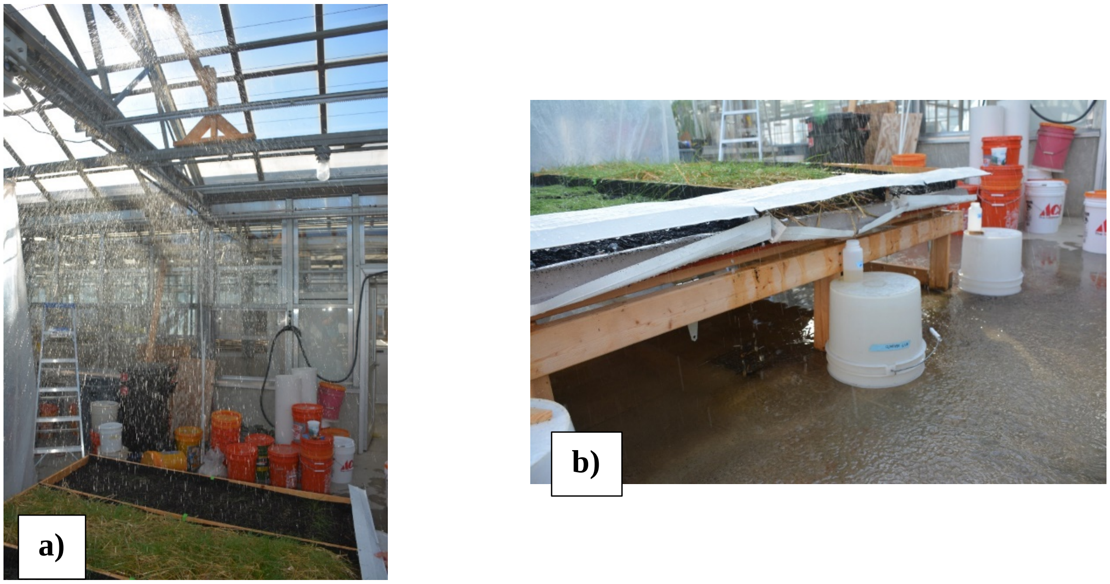

Figure 2: (a) Rainfall simulator with a single jet nozzle to produce synthetic rainfall which produced surface runoff collected in (b) sample bottles at the base of the slope.

RUNOFF SAMPLING

All surface runoff produced from applied rainfall was collected, as pictured in Figure 2b, and analyzed for total suspended solids (TSS), nitrogen (total nitrogen (TN), ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^{2-}), and organic N), and phosphorus (total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved organic phosphorus (DOP), and particulate (P)). Where runoff volume was large enough, independent grab samples were taken throughout the duration of the event in 100-250 mL bottles. Occasionally there were instances where runoff volume was not large enough for measurement of nutrient speciation or suspended sediments.

PLANT GROWTH ANALYSIS

Plot Coverage

Vegetation was captured via a Nikon D7100 digital camera with an AF-S DX NIKKOR 18-140mm f/3.5-5.6G ED VR lens in JPG format with the auto focus feature, maximum pixel size of 4000 x 6000, without a lens zoom, and at a hard sharpness and normal saturation. Images were captured regularly before each applied rainfall event, which occurred based on the schedule outlined in Table 2. Total plot coverage was measured based on the method described in Owen et al. (2020a). Coverage results include green vegetation (GV), straw/dormant vegetation, and exposed soil. This method utilizes the decision tree algorithm along with image color, texture, and oriented gradients to classify pixel blocks within each image.

Figure 3 shows the processing steps (described in Owen et al. (2020a)) images underwent before input into the algorithm, 1) image capture, 2) images were cropped to the region of interest 3) images were segmented into smaller subsets (pixel blocks), and 3) feature descriptors were extracted (based on green color, texture, and oriented gradients) from the subsets to represent the image pixel blocks. These feature descriptors were then input into a decision tree-trained algorithm to classify coverage for each block; these values were then combined with all pixel blocks from the original image to return a total ground coverage per image.

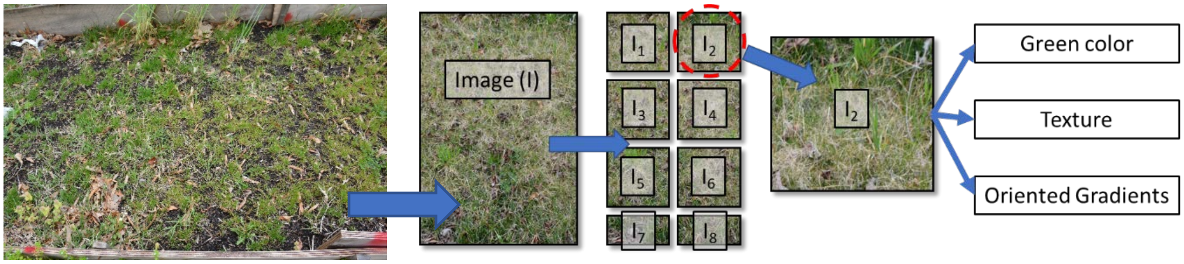

Figure 3: Flow chart of (left to right) the original image captured, cropping to the region of interest, segmentation into subsections, and extractions of feature descriptors for algorithm input.

Each 6-ft long greenhouse plot was divided into two sections, a top and bottom half (3 ft x 2 ft). Each of these sections produced one image at 0° and one at ~5° from vertical center. The four total images were input into the algorithm and used to represent coverage for a single application at a single point in time.

WATER QUALITY

Both total nitrogen and total phosphorus were measured using unfiltered, vortexed samples from greenhouse studies. All speciation measurements were taken after vacuum filtration through a 0.22-µm membrane to remove suspended particles. Samples that were not immediately measured were stored at 4°C.

Before use, glassware and plasticware were washed with Liquinox soap, rinsed with deionized (DI) water, placed in an acid bath for a minimum of 4 hours, rinsed with DI water, and allowed to air dry. Any samples outside of the standard curves were diluted to fit within the range of standard values; 0-1 mg-P (or N)/L for TP, SRP, DP, and ammonium; 0-1.5 mg-N/L nitrite; and 0-10 mg-N/L for TN and nitrate. Measurements below the detection limit of the test were presented as half the stated detection limit ("AMC Technical Brief" 2001); for all tests this detection limit was 0.05 mg-P (or N)/L. Many nitrite measurements were below the detection limit.

Applied rainfall used in the greenhouse studies was tap water supplied by the UMD greenhouse facility. The tap water had average nutrient concentrations of 1.9 ± 1.2 mg-N/L and 0.51 ± 0.52 mg-P/L with no measurable suspended solids. Much of the nitrogen was in the form of nitrate at $75 \pm 24\%$ and much of the phosphorus was SRP at $81 \pm 29\%$.

Sediment

Sediment was measured as total suspended solids and followed the standard method 2540D (2005) using 30-50 mL sample runoff. Some samples contained settleable solids, which were rinsed from the container with additional DI water to ensure all solids from the sample were accounted for. Measurement results are presented as mg-sediment/L for grab samples and EMCs and mg-solids for mass export.

Nitrogen

All total nitrogen measurements were made using a Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer. Nitrate measurements for filtered samples were measured using ion chromatography on a Dionex ICS-1100 with ASRS 4 mm suppressor and a Dionex IonPac AS22 column. Ammonium and nitrite were both measured using the SEAL AQ300 Discrete Nutrient Analyzer using Standard Methods 4500-NH_3 H (1997) and Standard Methods 4500-NO_2 B (2000), respectively.

Both nitrate and TN standards were made using a 1000-ppm nitrogen as nitrate stock solution. Ammonium and nitrite standards ranged from 0-1 mg-N/L and were prepared from a 1000 mg-N/L stock solution produced from ammonium chloride (A649-500) and sodium nitrite (7632-00-0) stock solutions, respectfully. Organic nitrogen was calculated as total nitrogen minus all nitrogen speciation.

Phosphorus

The persulfate oxidation method for phosphorus digestion was used, based on Murphy and Riley (1977), along with the Standard Method 4500-PF (1999) to measure total phosphorus and dissolved phosphorus. Standard Method 4500-PF (1999) was also used to measure SRP without oxidation. TP, DP, and SRP were measured between 0-1 mg-P/L using a SEAL AQ300 Discrete Nutrient Analyzer. All standards were created using a stock solution of Lab Chem Inc. 1000-ppm phosphate as phosphorus.

Particulate P was calculated as the difference between TP and DP. DOP was calculated as the difference in DP and SRP.

ANALYTICAL PROCEDURES

Mass Export

All grab sample bottle and cumulative sample bucket volumes were measured before sample testing. These volumes were then multiplied by the discrete concentrations measured for each sample/bucket and summed together to obtain the total mass of nutrient exported per applied rainfall event.

Event Mean Concentration (EMC)

The EMC was calculated as the total mass of nutrient exported divided by the total volume of event runoff, calculated as the sum of all discrete volumes. This EMC is the average concentration produced from that specific applied rainfall event.

STATISTICAL ANALYSIS

All values are presented as the average ± the standard deviation, unless otherwise stated. Statistical analysis was done within individual storm events for trends and significance as well as across all six storm events. Tests for data significance were done using the non-parametric Wilcoxan signed-rank test. Data trends were determined via the nonparametric Mann-Kendall Tau test. A statistical significance level of 5% ($P<0.05$) was used to determine rejection of the null hypothesis for all statistics but p values were also included.

Results

All treatments that received straw mulching had ≥95% straw coverage prior to rainfall application. This was confirmed with via image analysis.

PLOT COVERAGE

Initial straw mulching had a substantial impact on vegetation growth for all tested treatments at the 25% slope, which can be seen in the average growth rates presented in Figure 4a. All four compost applications tested with straw mulching reached >95% grass coverage within 60 days of seeding with 30 cm of applied rainfall while both non-straw mulched slopes only reached 3% for GNS and BNS and 29% and 35% for the TGNS and TBNS treatments, respectively. The average rates presented in Figure 4a are all statistically greater for straw mulching versus no straw mulching ($p = 0.004-0.04$).

Straw mulching has been seen to improve GV establishment through physical protection of seeds and consistent soil moisture through reduced evaporation (Adams, 1966; Hensler et al., 2001). From moisture readings prior to storm application, the moisture contents of the materials tested in the current study were as much as 35% greater with straw mulching than without.

Figure 4b gives GV establishment as a function of percent compost for both greenwaste and biosolids composts at the 25% slope. All slopes reached >95% coverage within the 60 days of experimental study and 30 cm of applied rainfall with no statistical differences in rate of establishment. Although not statistically significant, there was an initial improvement in growth rates for both compost mixtures which reduced with increased compost addition. This was most likely due to the relationship between compost addition and porosity which leads to faster evaporation. Duzgun et al. (2020) also found that both saturated hydraulic conductivity (K) and wilting point values were 1-3 orders of magnitude and 124-127% greater in B and G than in T. Vegetative growth requires nutrients, light, and moisture based on photosynthesis. Although compost addition provided a substantial amount of nutrients (as evidenced by the runoff nutrient concentrations and soil extractions) compost was also more prone to drying out due to the increased porosity. Owen et al. (2020) suggested that this drying process would not be as significant in field application based on shorter average drying periods and longer average rainfall events.

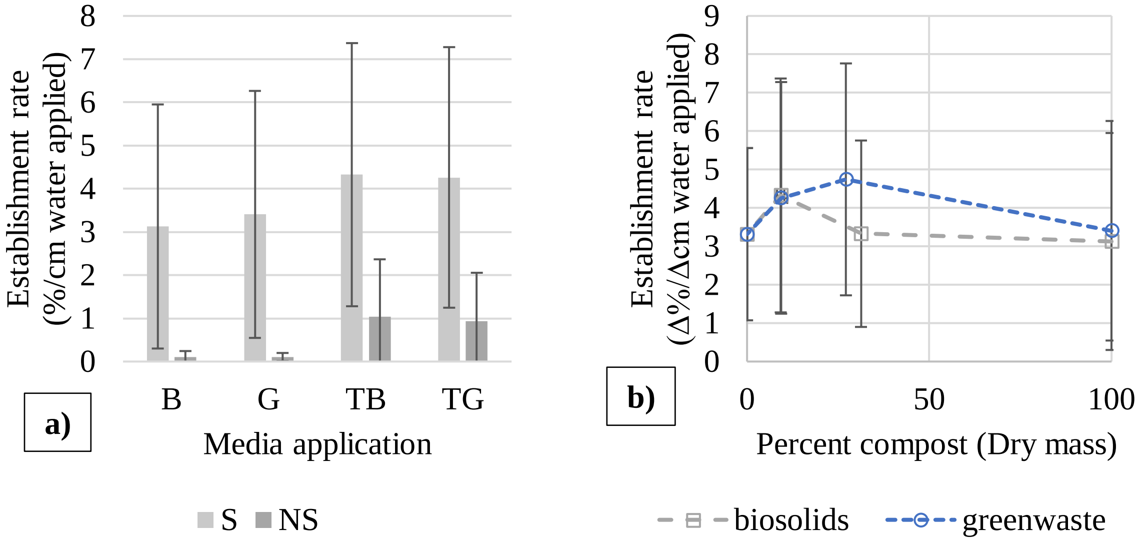

Figure 4: Average GV growth rate at a 25% slope for (a) straw vs no straw and (b) various compost mixtures for greenwaste and biosolids.

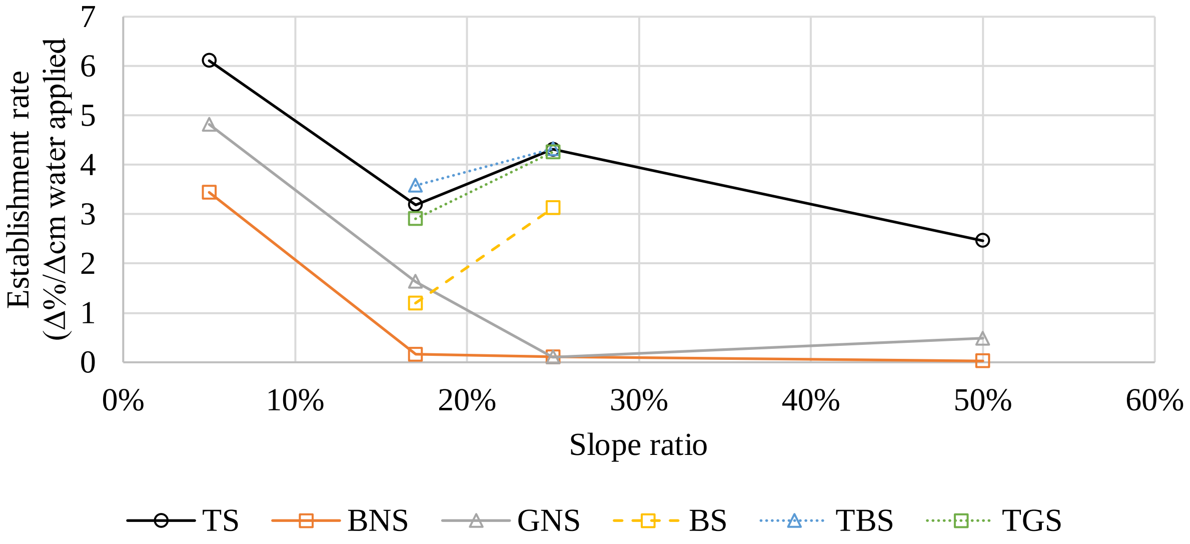

Figure 5: Slop ratio effect on establishment rate for the various tested materials.

Figure 5 shows average GV establishment rates at each tested slope ratio. For TS, GNS, and BNS there is a negative correlation between growth rates and slope ratio. The lack of growth at steeper slopes was likely due to moisture availability after gravity filtration. Based on the 5 cm medium layer applied, gravity had increasing distance to work on soil moisture. From the 5% slope to the 50% slope there would be 12% increase in gravitational head causing reduced soil moisture. Between the 17% and 25% slope, BS, TBS, and TGS showed slight increase in average growth rates, however, this was not statistically significant ($p \geq 0.15$). This change could have been due to changes in greenhouse temperature or humidity which could have caused changes in soil drying rates.

RUNOFF VOLUME

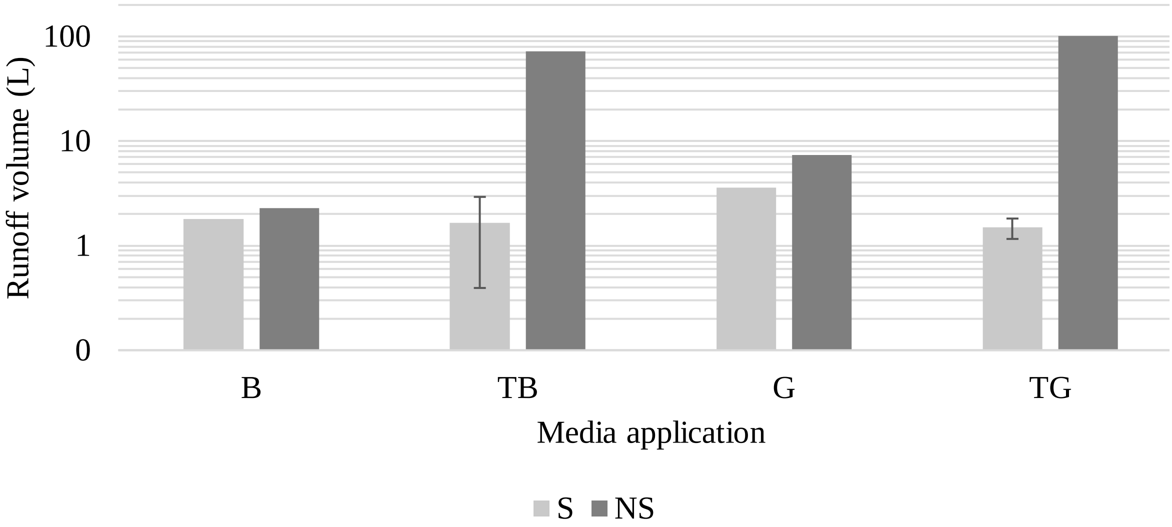

Figure 6: Total runoff volume after 30 cm. of applied rainfall for straw mulched (S) vs non-straw mulched (NS) media. and b) all treatment applications on a compost dry mass basis; both were measured at a 25% slope.

Runoff volumes are presented in Figure 6 for all treatment applications as total runoff (L) after 30 cm (330 L) of applied rainfall a) with or without straw mulching and b) at the varying compost ratios. As seen in Figure 6, runoff from all applications was reduced with straw mulching; this was statistically significant for TB ($p = 0.05$) and TG ($p = 0.001$), but not for B or G ($p = 0.53$ and $p = 0.12$, respectively). Error bars represent the range found from the duplicate (TB and TG) or triplicate (TS) studies described previously. Total runoff volume reduction was the greatest for TB and TG, which showed runoff volume reductions of 97.8% and 98.5%, respectively.

Rainfall impact and the transference of both KE and rainfall momentum lead to soil compaction, slaking, particle segregation and pore clogging through soil splash and sealing (Hillel, 2004; Armenise et al., 2018). Owen et al. (2020b) presented evidence of soil sealing for both TB and TG soil mixtures without straw mulching after 30 cm of applied rainfall. By incorporating the initial straw layer, rainfall KE and momentum was intercepted prior to soil impact; as evidenced by the lack of an increase in normalized volume runoff as a function of time for all straw mulched media. A few major added water management mechanisms, as demonstrated in Figure 7, result from the addition of straw mulching: kinetic energy (KE) dissipation from rainfall impact (the protective layer at A_2), increased surface roughness (surface runoff flows through the straw layer at B_2), and increased storage volume (identified by the second ‘captured water’ in the straw layer in Figure 7) (Mannering and Meyer, 1963; Poesen and Lavee, 1991; Jordan et al., 2010; Liu et al., 2012). Each mechanism significantly affects soil sealing, soil infiltration, and runoff contact time with soil.

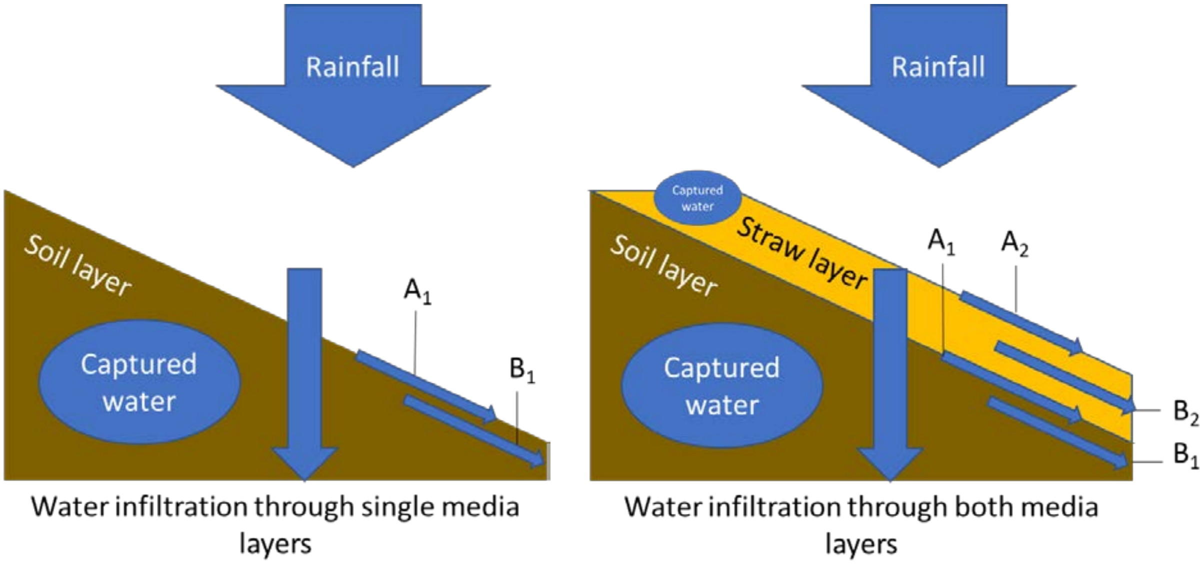

Figure 7: Theoretical diagram of water runoff from no straw mulching to straw mulching. A_1 is surface flow from the soil layer, B_1 is subsurface flow through the soil layer. A_2 is surface flow through the straw layer and B_2 is subsurface flow through the straw layer.

The Daily Morgan-Morgan Finney (DMMF) model (Equation give in Appendix B) calculates the KE as a function of the effective rainfall (mm) (rainfall times the cosine of slope angle), estimated KE of direct throughfall (rain that bypasses the coverage layer; based on the universal power law equation (Shin et al., 2016)), leaf drainage KE based on plant height, and canopy cover. For all plant heights below 14 cm (i.e., grass or straw layers) leaf drainage is equal to 0 and for all tests on the 25% slope rainfall and throughfall KE were constant, thus KE is linearly related to canopy cover. Additionally, the DMMF model identifies a modified Manning’s roughness coefficient based on plant stem diameter and number of stems per unit area (Appendix B)(Petryk and Bosmajian, 1975). This roughness coefficient is then inversely proportional to flow velocity by (Petryk and Bosmajian, 1975). By incorporating straw mulching, flow velocity is divided by the square root of straw diameter per unit area.

With rainfall KE reduced linearly with straw canopy cover, soil splash, particle re-organization, and soil dispersion are less likely to occur which reduces the potential for soil sealing which was seen to significantly reduce infiltration, especially for lower organic matter materials like TB and TG, discussed previously. Lower flow velocity due to dense straw mulching leads to longer contact time with the soil surface for infiltration, thus reducing surface runoff.

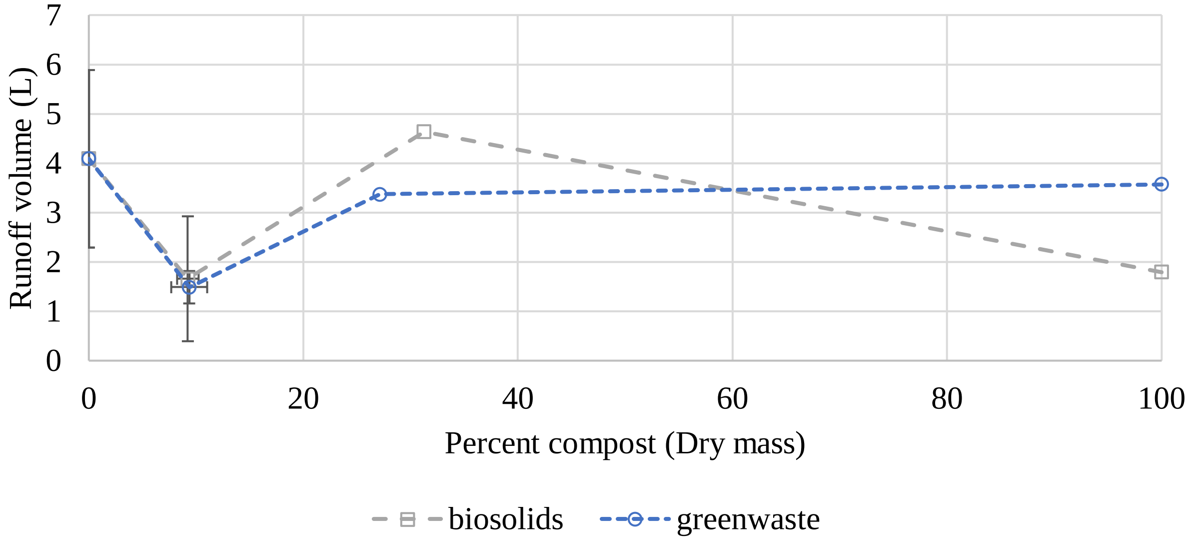

Figure 8: Total runoff volume after 30 cm. of applied rainfall for all treatment applications on a compost dry mass basis; measured at a 25% slope.

Focusing on the various treatment soil types with straw mulching (Figure 8), TS had greater total runoff volume 4.1±1.8 L than all compost amended media except BTS (which had 13% greater runoff volume than TS; $p > 0.2$); this was statistically significant for BS ($p = 0.022$), TBS ($p = 0.023$), and TGS ($p = 0.026$), but not for GS ($p = 0.180$) or GTS ($p > 0.2$). The greatest reduction in total volume runoff occurred for BS and TBS with reductions of 56% and 59%, respectively.

Runoff volume is largely influenced by the infiltration rate and the water holding capacity (also known as field capacity) of the soil; faster infiltration with higher field capacity produces lower runoff volume. Based on the revised Green-Ampt model (Appendix B) infiltration is positively correlated with hydraulic conductivity K_s and saturated volumetric water content (Mein and Larson, 1973). Duzgun et al. (2020) found that K_s, field capacity (defined as saturated volumetric water content), and saturated water content were positively correlated to increased compost addition; values increased by 14-6170-fold, 1.5-2.6-fold, and 1.4-2.8- fold, respectively. Hydraulic conductivity and field capacity are both positively correlated to infiltration rate by the revised Green-Ampt model and indicate that increased compost addition leads to increased infiltration and reduced runoff volume, which was seen for all materials except BTS.

All runoff volumes are presented in Figure 9a; no statistical trends were seen in runoff volume generation with slope ratio change. However, both TS and BNS showed statistical differences between some runoff volumes produced at different slope ratios. The TS treatment had significantly greater runoff volume generation at the 50% slope ($p \leq 0.008$) than the other slope ratios and BNS had statistically greater volume runoff at the 25% and 50% slopes ($p \leq 0.01$) runoff than the 5% and 17% slopes. GNS, BS, TGS, and TBS treatments at the various slopes did have statistically different runoff values ($p \geq 0.1$).

Table 3:Total volume runoff (L) for all media tested at multiple slope ratios.

	5%	***17%***	***25%***	***50%***
TS	2.4	4.3	4.1	56
BNS	0.10	0.31	2.3	1.2
GNS	8.6	23	7.4	16
BS		1.1	1.8	
TBS		3.5	1.7	
TGS		5.6	1.5	

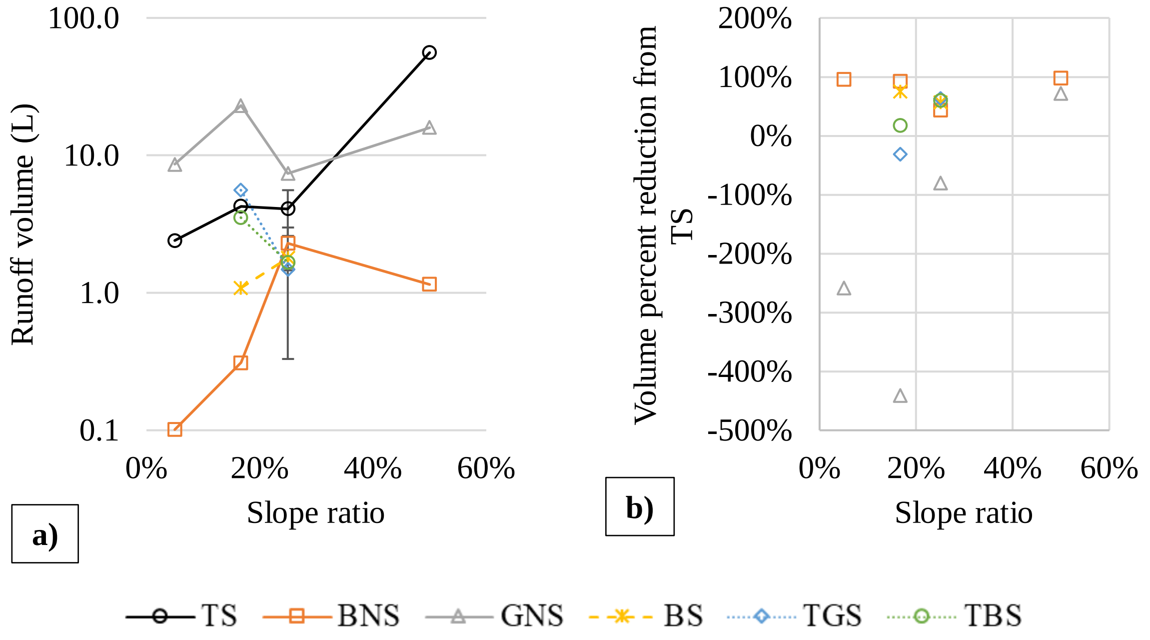

Figure 9: (a) total volume runoff and (b) volume runoff reduction from TS versus slope ratio change.

Figure 9b displays the volume percent reduction for each slope. Many general comparisons (e.g., BNS reduces volume runoff) found at the 25% slope continued to other slopes, however, the percent reductions did not remain consistent and appeared to be correlated to slope ratio. Compared to TS the runoff volume from GNS at the 5% slope was 2.6-fold greater which reduced (except at the 17% slope) with slope rate increase until (at the 50% slope) GNS showed 71% reduction in volume runoff. Although the respective total runoff volumes in Table 3 did not show statistical change from 17% to 25% slopes for the TBS and TGS treatments, the ratio of total runoff reduction from TS were also seen to decline with slope reduction, like the GNS ratios. The trend would indicate that increase in slope ratio increases the effectiveness of compost amendments found at the 25% slope compared to TS.

The revised universal soil loss equation (RUSLE) predicts that a steeper slope will result in greater runoff volume (Renard et al., 1997); due to gravity acting on ponding water, the contact time a water surface has moving across the soil surface is reduced based on cosine of slope angle. However, Chen and Young (2005) developed a modified Green-Ampt infiltration model for sloping surfaces which indicates that due to the surface angle to gravitational normal, both the soil layer vertical depth and ponding head are increased with increased slope; which would increase cumulative water infiltration with slope ratio increase. Compost amended slopes at the 25% slope showed potential for increased runoff infiltration (compared to TS, Figure 8) which indicates greater infiltration capacity. As slope ratio increases, based on the modified Green-Ampt theory provided by Chen and Young (2005), the infiltration capacity will increase for all materials by the same soil layer vertical depth and ponding head which will lead to greater volume reduction potential for compost compared to TS.

The limited runoff volume produced throughout the experiment for some treatments, especially biosolids at shallow slopes, limited the number of tests available per storm event. Due to this limitation TN and TP were prioritized over TSS due to the reduced volume needed for those chemical tests. This resulted in a reduced number of TSS data points for some treatments.

SEDIMENT

Reduction in sediment loss was seen for all soil media with straw mulching and can be seen in Figure 10a for the total mass export after 30 cm of applied rainfall and Figure 10b for average EMC and standard deviation throughout the six applied rainfall events.

The reduction in sediment mass export was statistically significant for TB ($p = 0.03$), TG ($p = 0.001$), and G ($p = 0.001$), but B ($p = 0.28$). Straw mulching on the TB and TG treatments was the most effective with greater than 99% reduction for both treatments, average reductions in sediment from 18500 ± 16400 mg-sediment to 52.8 ± 76.5 mg-sediment for TB and from 56300 ± 47300 mg-sediment to 67.4 ± 89.4 mg-sediment for TG. For G and B sediment export was reduced by 71% and 98%, respectively. The mass export of sediment given in Figure 10a was not solely due to the volume reduction in runoff presented in Figure 6. EMC reductions with straw mulching were seen for all tested media with average percent reductions of 99% ($p = 0.06$), 50% ($p = 0.05$), 92% ($p = 0.002$), and 94% ($p = 0.001$) for B, G, TB, and TG, respectively (Figure 10b). Although not specifically analyzed for composts, significant reduction in sediment yield with straw mulching compared to bare soils has been seen, consistently, in previous research (Jordan et al., 2010; Wang et al., 2011; Liu et al., 2012; Wang et al., 2015).

Although compost addition has been shown to improve soil runoff (Morgan, 1986; Poesen and Lavee, 1991; Shock et al., 1997; Faucette et al., 2007; Muhktar et al., 2008; Gholami et al., 2012; Prosdocimi et al., 2016) it is still an exposed soil surface. As discussed previously for volume reduction, straw mulching reduced rainfall impact and the KE and momentum transference into the soil profile. With the reduced energy, soil particles in all media were less likely to detach and move through the surface flow, resulting in lower sediment transports.

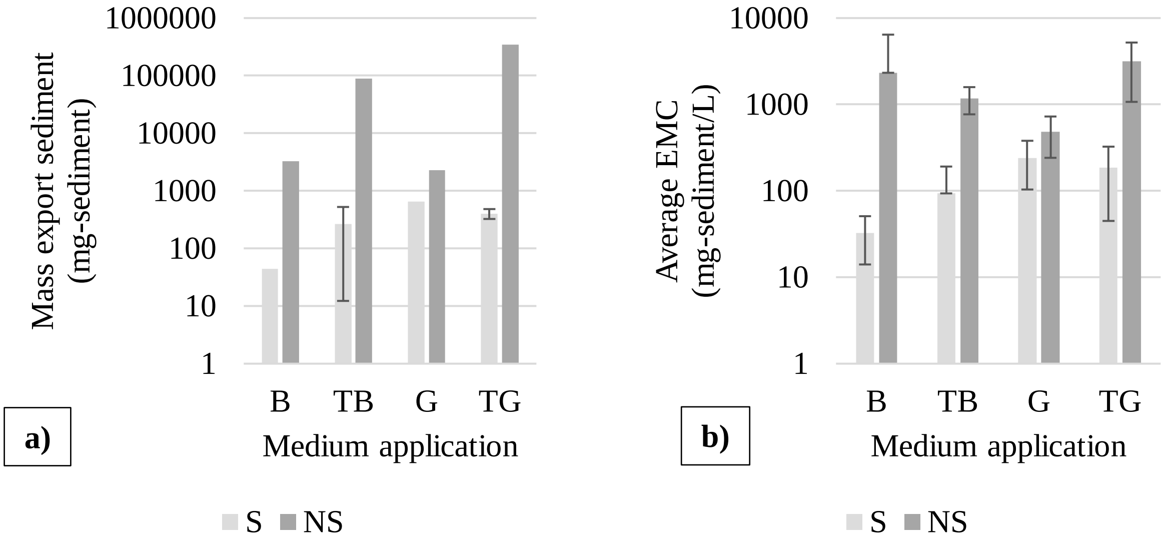

Figure 10: Straw mulching (S) versus non-straw mulched (NS) effects based on a) total sediment mass export after 30 cm. of applied rainfall and b) average sediment EMC.

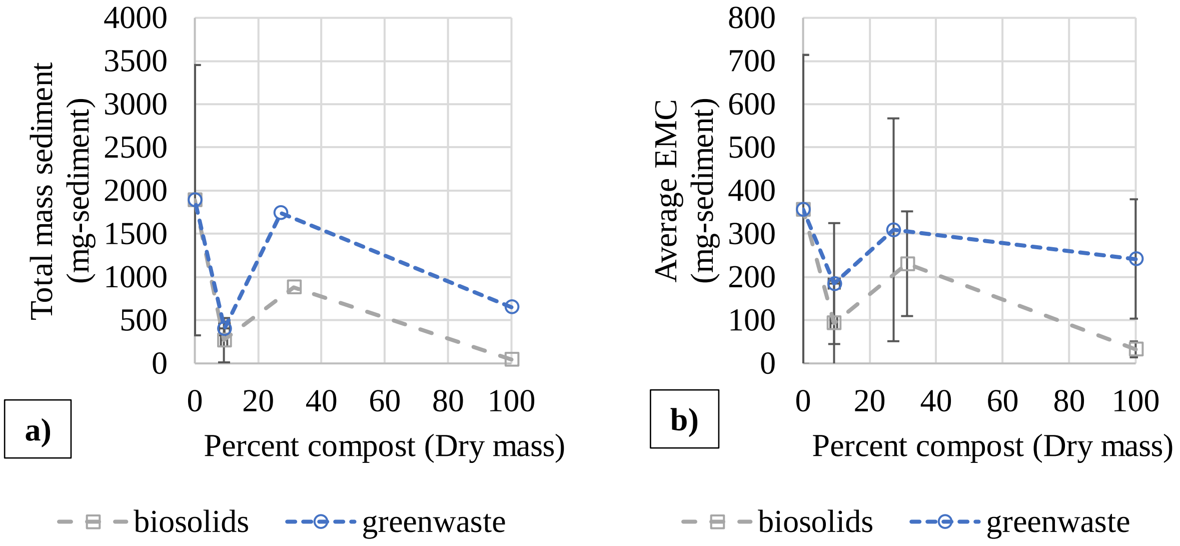

Figure 11:Dry mass compost effects on a) total mass export sediment and b) average sediment EMC.

Figure 11 shows total dry mass export and average EMC throughout the testing period based on dry mass percent compost. The TS standard had greater average sediment export per storm (400 ± 618 mg-sediment) and average EMC (356 ± 357 mg-sediment/L) than all compost amended treatments. Compared to TS, BS ($p = 0.008$) and TBS ($p = 0.04$) treatments showed the greatest reduction in sediment export (98% and 86%, respectively) and were the only treatments to have statistically significant EMC reductions of 91% ($p = 0.008$) and 74% ($p = 0.04$), respectively. Both BTS ($p = 0.20$) and GTS ($p = 0.39$) showed the least reduction in sediment runoff at 53% and 8%, respectively. Although compost addition consistently showed reduction in sediment runoff, there was no observed correlation between sediment export and percent compost mixture.

Reduction in sediment loss was largely due to improvements in aggregation within the soil. Compost had increased organic matter from 2.6% in TS to 47% and 39% in B and G. Organic matter improves soil aggregation through physico-chemical clay and oxide interactions and by offering a healthy growing community for microorganisms that can bind soil (Hillel, 2005). Improved aggregate formation naturally resists the fragmentation, scouring, and dispersive forces from rainfall impact and overland flow, which lead to increased sediment runoff.

When all media were straw mulched, as was the case in this study, the results show reduction in sediment loss with compost addition. The reduction seen here is consistent with previous studies which compared both bare compost and bare soil and found sediment reductions with compost application (Morgan, 1986; Poesen and Lavee, 1991; Shock et al., 1997; Faucette et al., 2007; Gholami et al., 2012; Prosdocimi et al., 2016).

Total sediment export and percent reduction from TS for all media tested at various slope ratios are presented in Figure 12, in Figure 12b the value at 17% for GNS was -3400% and was not included on the graph, for clarity. Only TS had significant increase ($p \leq 0.002$) in sediment export from the 5-25% slopes to the 50% slope. All other tested media at the various slopes were not statistically different ($p \geq 0.07$).

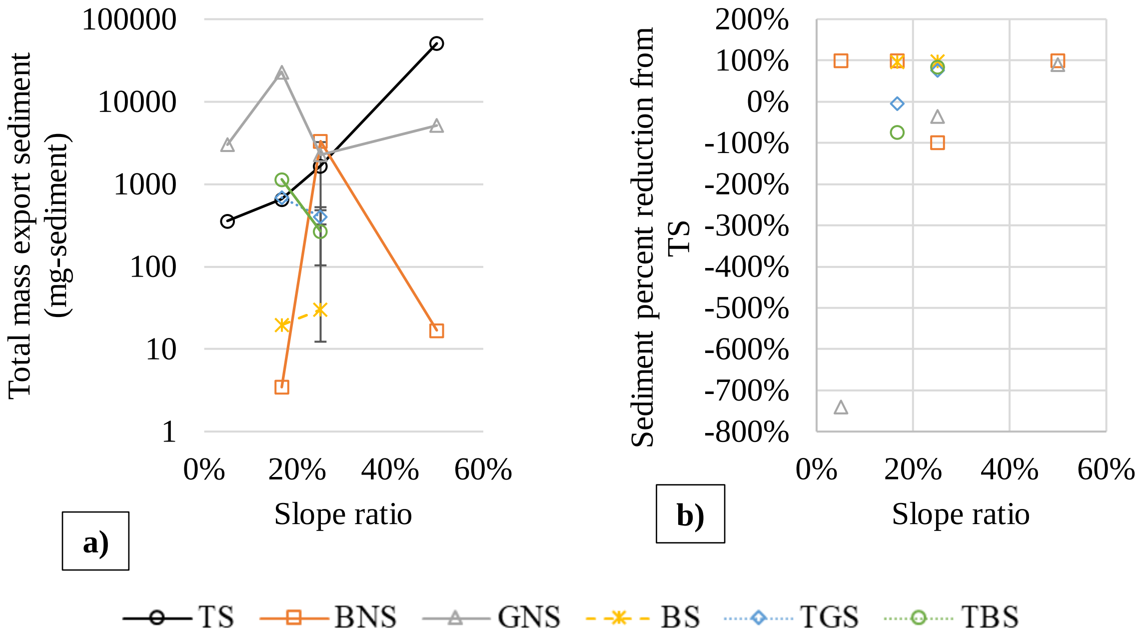

Figure 12: (a) sediment total mass export and (b) percent reduction from TS for all media applications at each slope ratio tested. GNS had one data point at 17% that was -3400% (not shown).

Although many differences within a specified treatment were not statistically different at various slope ratios, the same trends in sediment percent reduction from TS seen in volume appear in Figure 12b. Aside from GNS at 17% slope ratio, the GNS, TGS, and TBS reductions compared to TS increase with slope ratio increase and the BNS (except at 25%) and BS soils do not show significant change in percent reduction from TS. As discussed previously, sediment transport is strongly affected by rainfall impact and overland flow rate and volume. Based on the volume generated with slope ratio increase, discussion previously, greater volumes at higher slope ratios naturally leads to greater sediment runoff. Additionally, with increased slope ratio the angle of impact for rainfall decreases (closer to parallel with the soil surface) which leads to more lateral force on sediment splash particles. Aggregate bonding (through organic matter increase) and grain size improvements to soil stability, discussed previously, would become more important at higher slope ratios which leads to the greater reduction potentials seen here.

NITROGEN

All composted media tested with straw mulching showed reduction in mass export of nitrogen after straw addition, which can be seen in Figure 13a; this was statistically significant for B ($p = 0.001$), G ($p = 0.013$), and TG ($p = 0.047$) but not for TB ($p = 0.15$). Both B and TB had the greatest average reduction in nitrogen export with 92% and 89%, respectively.

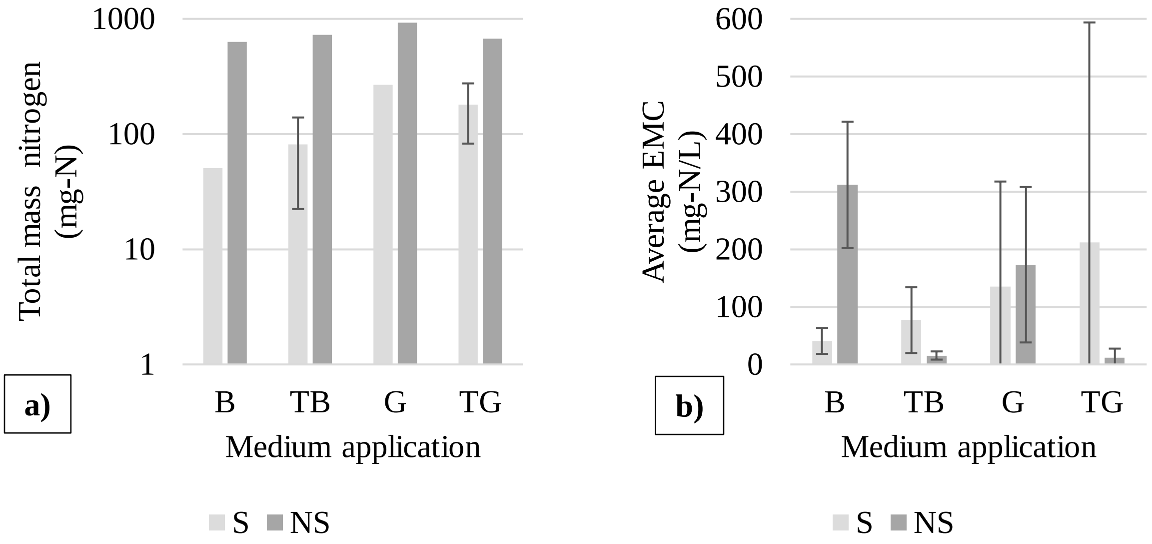

Figure 13: Straw mulching effects based on a) total nitrogen mass export after 30 cm. of applied rainfall and b) average nitrogen EMC.

Lower total volume runoff resulted in reduced mass export for all straw mulched treatments, however, these treatments also showed a decrease in nitrogen EMC for both B and G (87% for B and 22% for G), Figure 13b. The EMC reductions seen for both composts can be attributed to the additional storage and transport of applied rainfall through the straw layer, as shown in Figure 7 and discussed previously. Water passing on top of and through the straw layer, A_2 and B_2 in Figure 7, export significantly less nitrogen than water that interacts directly with the soil layer, A_1 and B_1 in Figure 7.

Unlike the B and G treatments, TB and TG saw an increase in average EMC from straw non-mulched to mulched media applications. This was due to dilution of EMC values by concentrations in the later phase of runoff. A ‘first flush’ is often attributed to storm events in which the initial runoff generated carries a disproportionately larger mass of nutrients than the later stages (Thornton and Saul, 1987). Due to greater runoff volume per storm, discussed previously, the EMC provided by both TB and TG would naturally be lower and more dominated by later phase runoff than a storm with lower runoff on similar media.

Comparisons between the various soil treatments, Figure 14a, showed that TS standard treatment had a greater average mass export of nitrogen (47 ± 15 mg-N) than all media types, except the BTS mixture (p = 0.40) which increased nitrogen mass export on average by 38% (65 ± 41 mg-N). Of the other mixtures B (p = 0.001), TB (p = 0.002), and GT (p = 0.047) all had statistically lower average mass nitrogen export, with B (average 8.4 ± 3.8 mg-N) and TB (average 14 ± 8.3 mg-N) reducing the most (82% and 72%, respectively). Although percent compost added by dry mass did not appear to be correlated to the total nitrogen export for biosolids, greenwaste phosphorus mass export appeared to be positively correlated with compost addition with a correlation coefficient of 0.997.

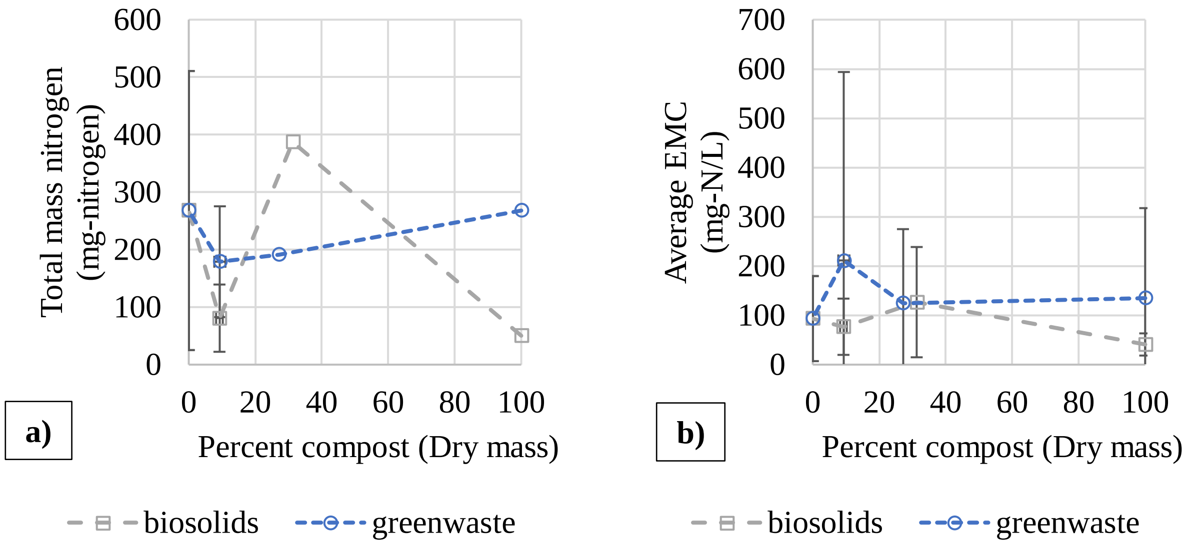

Figure 14: Dry mass compost effects on a) total mass export nitrogen and b) average nitrogen EMC.

The reduction in total mass export of nutrients from TS can be explained through volume reduction, as discussed previously. However, both B and TB also had the lowest EMCs (41 ± 22 mg-N/L and 77 ± 53 mg-N/L, respectively) compared to TS with (94 ± 37 mg-N/L), as shown in Figure 14b. Based on extraction data presented in Owen et al. (2020b) which showed increased extractable N with increased biosolids incorporation, runoff nitrogen concentrations would be expected to increase from TS with compost addition, which was seen in non-mulched media in that study. However, the extraction data presented in Owen et al. (2020b) does not account for the additional fertilizer applied at 2000 lbs/ac to the TS treatment. At a ratio of 20:16:12, applied at 2000 lbs/ac, and a bulk density of 0.94 ± 0.2 g/cm^3 calculated from the tested slopes this would result in an additional 190 mg-N/kg from the fertilizer. Combining extractable N from both TS and fertilizer the new extractable N value becomes 373 mg-N/kg which is greater than all extracted media (2-3-fold), except B. With the decrease in runoff and the adjusted extractable N for TS compared to composted extractions, finding comparable and improved N export from compost media was not surprising. From previous research, uncovered compost has been seen to reduce nitrogen mass export when compared to bare soil (Faucette et al., 2007; Muhktar et al., 2008; Hansen et al., 2012). The addition of straw to both the control and composted media produced similar results to the previous research.

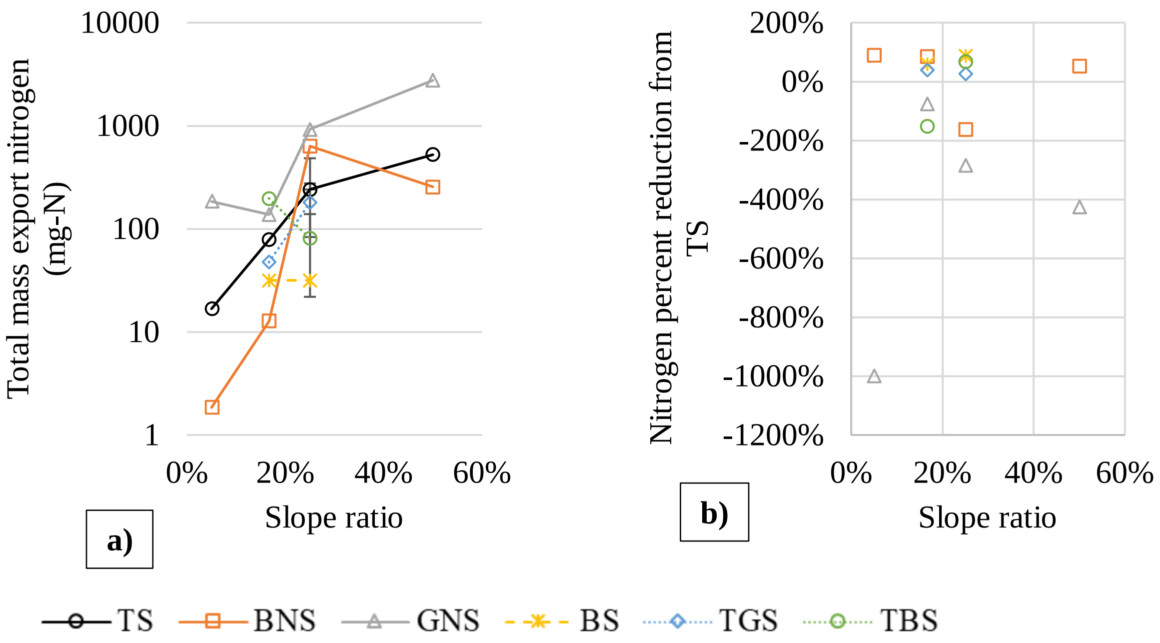

Figure 15: (a) nitrogen total mass export and (b) percent reduction from TS for all media applications at each slope ratio tested.

Total exported nitrogen and nitrogen percent reduction from TS can be seen in Figure 15 for all media at the tested slope ratios. TS and BNS had statistically decreasing nitrogen export from 25-5% ($p \leq 0.02$ and $p \leq 0.008$, respectively). Both GNS and TGS only had statistically declining nitrogen export from 25% to 17% ($p = 0.02$ and $p = 0.05$, respectively). No other treatment media or slope ratio change showed statistical significance. Based on Figure 15a and the statistical analysis, nitrogen export was strongly correlated to slope ratio change. However, unlike both the volume and sediment, Figure 15b does not show a strong correlation between percent reduction from TS and slope ratio for nitrogen which indicates that the effectiveness or ineffectiveness of the soil medium to reduce nitrogen from TS may be independent of slope ratio.

Nitrogen increase with slope ratio was a function of plant uptake and immobilization, runoff volume increase, and sediment export. At steeper slopes GV was seen to decline, runoff volume increase, and sediment export increased which translated directly to increases in nitrogen export. At the 50% slope TS had significant increase in sediment export (30-fold from the 25% slope), with that export came an increase in organic N (particulate) and ammonium (which readily adsorbs to clay and fine particles) of (12% and 6%, respectively) (Sparks, 2003).

PHOSPHORUS

All media showed statistically significant reductions in both mass export and EMC phosphorus with straw mulching, shown in Figures 16. Reduction in total mass export of phosphorus with straw mulching was the greatest for both TB (99.4%) and TG (99.0%), both of which showed evidence of surface sealing in Owen et al. (2020b) without straw mulching which increased runoff volume and sediment transport, discussed previously. Both materials also had statistically lower EMC values (TB: 44% on average, p = 0.045 and TG: 57% on average, p = 0.001) with the addition of straw mulching. The greater phosphorus export from the non-mulched TB and TG was likely due to release of particulate P attached to sediment. Strong bonding between particulate P and soil particles was seen by Fu et al. (2009) which suggests that, with the increased sediment export from both TB and TG, higher concentrations of phosphorus would be seen. Further evidence for this was found in the increased speciation percentage of particulate P in both non-mulched media (particulate P increase of 28% TB and 36% TG).

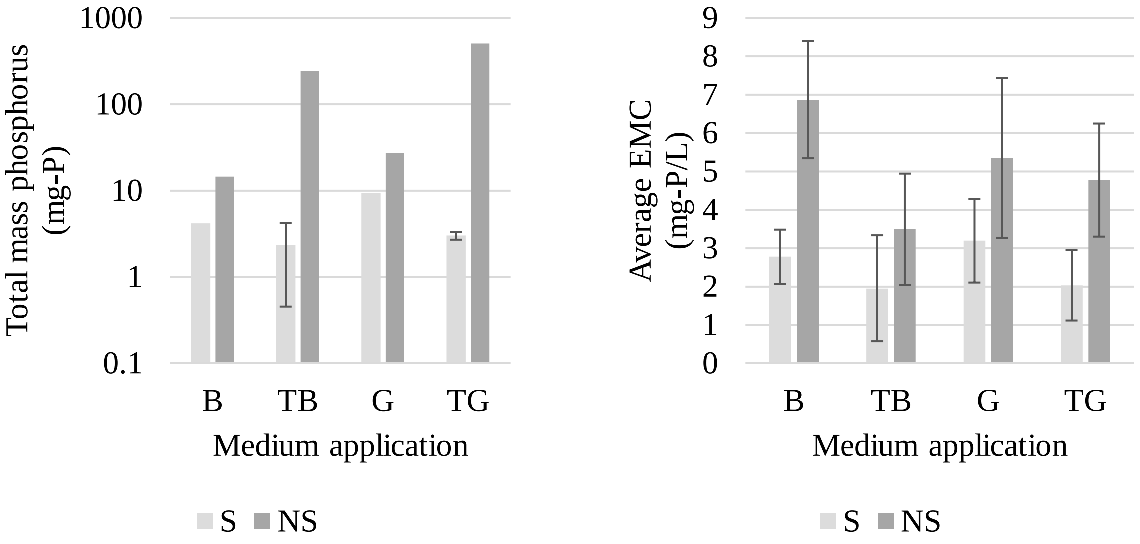

Figure 16: Straw mulching effects based on a) total phosphorus mass export after 30 cm. of applied rainfall and b) average phosphorus EMC.

Pure compost treatments also saw reductions in total mass P export of 71% for B and 66% for G and EMC reductions of 60% (p = 0.001) for B and 40% (p = 0.066) for G. Unlike TB and TG, pure compost did not show evidence of surface sealing (Owen et al., 2020b). The reduction in EMC for these materials was more likely due to dilution of runoff concentration from water flowing through and over the straw mulched layer which would have had a lower concentration of phosphorus, discussed previously (Figure 7). Although TB and TG saw changes in phosphorus speciation, the straw layer addition did not observably affect the phosphorus speciation of B or G.

The addition of compost compared to TS can be seen in Figures 17. Apart from the BTS treatment, which had an increase in total mass export of 15% (significance of EMC p = 0.4), export of phosphorus was reduced with compost addition from the TS standard. Based on EMCs, these reductions were not statistically significant as all treatments had statistically similar values, with GTS having the largest significance of p = 0.11. However, based on mass export per applied rainfall event, BS (p = 0.022), TBS (p = 0.001), TGS (p = 0.002), and GTS (p = 0.047) all had statistically reduced mass export. TGS and TBS reduced phosphorus export the most from TS with reductions of 76% and 69%, respectively. Percent compost addition did not appear to be correlated to mass export or average EMC for biosolids but did show strong positive correlation (correlation coefficient of 0.97) with mass export for greenwaste.

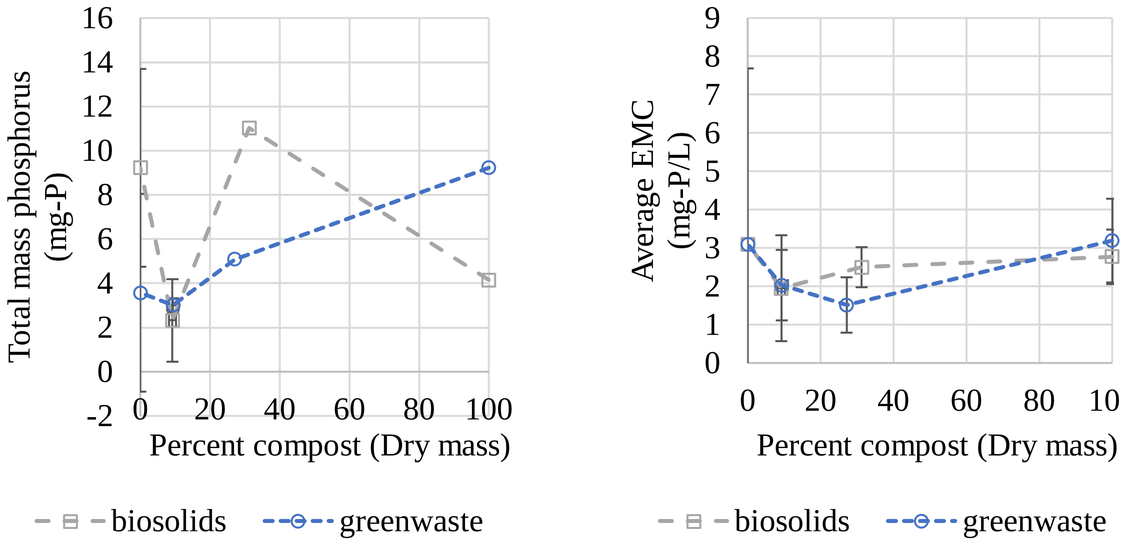

Figure 17: Dry mass compost effects on a) total mass export nitrogen and b) average nitrogen EMC.

Owen et al. (2020b) showed increased Mehlich-3 extractable P with increased compost percent for both B and G medium. The mehlich-3 extraction is a strong acid method that has been shown to strip orthophosphate as well as organic P from the soil medium (Cade-Menun et al. (2018) found up to 50% of mehlich-3 extractable phosphorus was organic P). Compost is often considered a slow release fertilizer because most nutrients held within compost are in the form of inaccessible organic matter which is held tightly in the soil structure and is decomposed into more mobile forms over time. As such, values from the extraction will largely overpredict the available phosphorus from highly organic rich soil, like pure compost (47% for B and 39% for G). Additionally, the topsoil extraction measurement does not include the applied fertilizer which, at a fertilizer ratio of 20: 16: 12, loading rate of 2000 lbs/ac, and bulk density of 0.94 ± 0.2 g/cm^3 would have an adjusted extractable P value of 343 mg-P/kg.

Excluding the results from BS, both compost treatments showed increased phosphorus export with increased compost application. However, all these treatments produced statistically similar EMC, presented earlier. By adjusting the topsoil extraction value for the additional fertilizer addition to 343 mg-P/kg and assuming the organic matter percent in each soil is initially inaccessible organic phosphorus measured in the mehlich-3 extraction (Cade-Menun et al., 2018), extractible phosphorus measurements for all treatments approach similar values (average of 370 ± 100 mg-P/kg) and may explain the statistically similar EMCs.

In Figure 18 the effects of slope ratio change on total mass phosphorus export and phosphorus percent reduction from TS can be seen for the tested media. For both TS and GNS all media at the various slopes were statistically similar, except the 50% slope which was greater than all other slopes ($p \leq 0.002$) for TS and only greater than the 5% slope ($p = 0.01$) for GNS. BNS had the only other statistical difference in phosphorus runoff 5-17% were different from 25-50% slopes ($p = 0.002$). BS, TBS, and TGS were not found to be statistically different between 17% and 25% slopes.

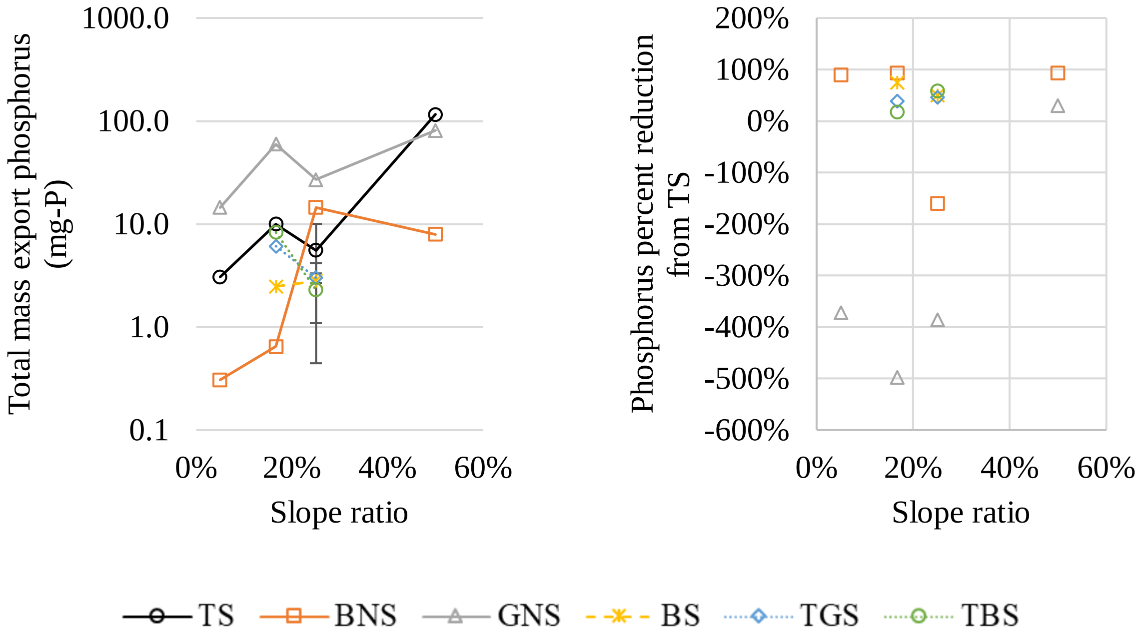

Figure 18: (a) phosphorus total mass export and (b) percent reduction from TS for all media applications at each slope ratio tested.

Like nitrogen, phosphorus percent reduction from TS did not appear to be correlated to slope. The increase of phosphorus export with increased slope ratio can be attributed to the decrease in GV, increase in runoff volume, and increase in sediment export associated with slope ratio increase. Additional evidence for sediment transport of phosphorus comes from increased percentages of particulate P in both TS and BNS, (24% and 17%, respectively) which is highly adsorbed to particulate matter.

RUNOFF TRENDS

Throughout the various experiments a few trends in the data were consistently seen and are demonstrated in Figure 19a and b. These figures show concentrations for nitrogen and phosphorus for various media applications at various slope ratios with and without straw mulching. In each figure, there is a clearly defined 'first flush' like the ones discussed in Owen et al. (2020) within each applied rainfall event. Also seen in Figure 19a and b is a gradual decline in concentration over the six applied rainfall events. These trends were present in all applications, with enough runoff volume for grab samples, regardless of slope, straw mulching, or compost mixture.

Sediment did not consistently yield statistically significant trending data. In Figure 19c the sporadic nature of the sediment concentrations can be seen for TS, BNS, and GNS. Only a few individual rainfall application events showed declining concentrations of TSS for BNS and GNS.

As rainfall was applied, the 'first flush' was seen to decrease for both nitrogen and phosphorus for most media applications in an asymptotic way. This would indicate a possible steady-state value at which each slope may be approaching but not reached. It was unclear in the current study if that steady-state was reached after the 30 cm of applied water. Similar first flush phenomenon were seen in Owen et al. (2020b) and Mukhtar et al. (2008).

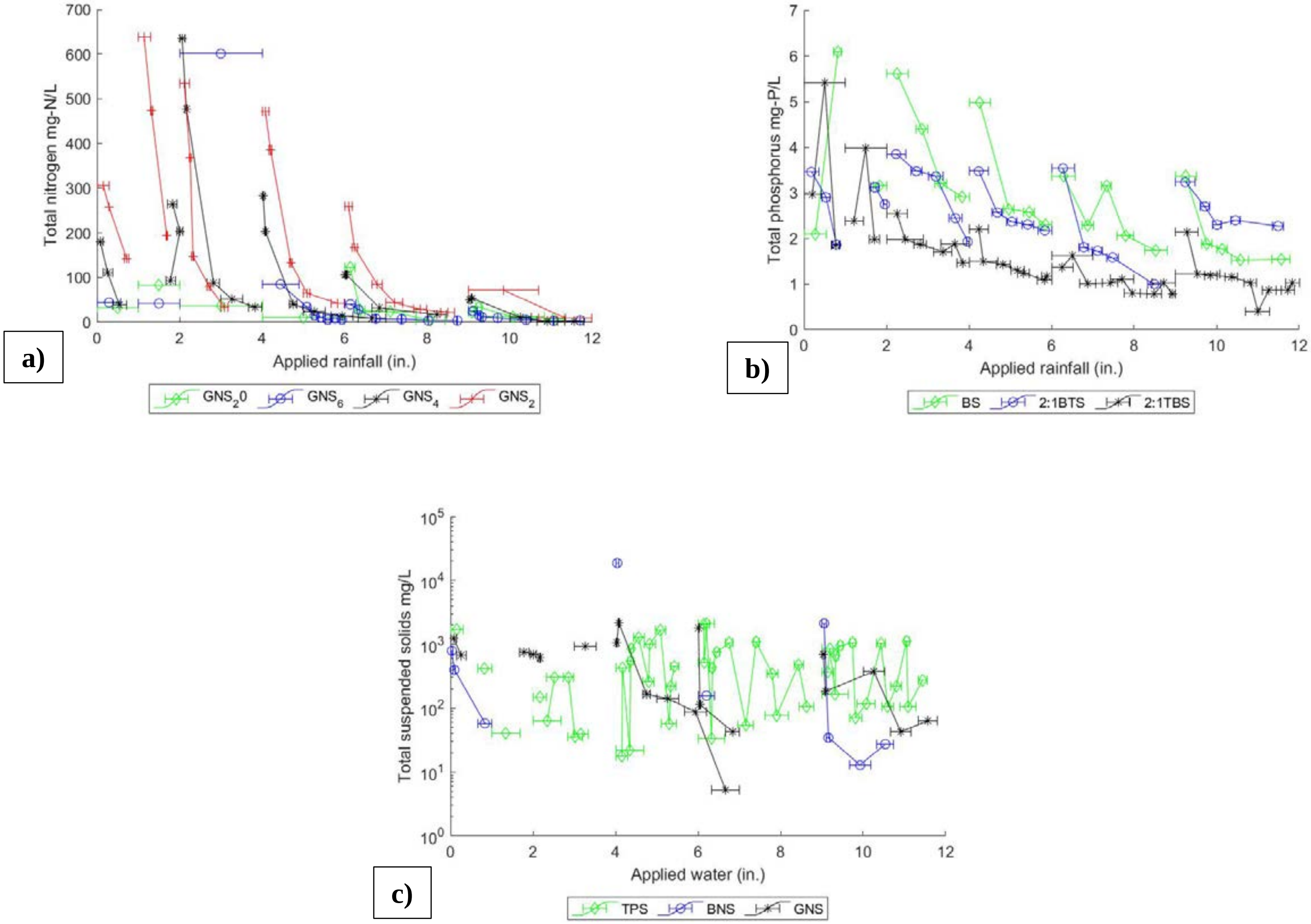

Figure 19: (a) Total nitrogen EMCs for GNS at all 4 slope angles, (b) total phosphorus EMCs for the three biosolids compost mixtures, and (c) TS, BNS, and GNS at the 25% slope for sediment

Conclusions

Three water quality parameters along with digital GV growth analysis were used to analyze the application of both biosolids- and greenwaste-derived composts for the purpose of slope stabilization along highway embankments. Straw mulching, percent compost with topsoil, and slope ratio were altered to further understand the effects of compost addition.

GV establishment was significantly greater for straw mulched medium applications (4-33-fold faster). This was most evident for the B and G treatments which, without straw mulching, failed to achieve more than 3% GV cover after 60 days. With straw mulching, there were no statistical differences between treatments with all reaching >95% GV coverage within 60 days. Although not statistically significant, all media applications (except BS which had a 6% reduced average GV establishment) had greater establishment rates than TS (3-30%). In general slope ratio increase negatively affected grass establishment, rates for TS, GNS, and BNS decreased by 60-99% from a 5% slope to a 50% slope.

Volume of runoff for all composted materials was reduced significantly with straw application by 64-99%, with the most successful reductions occurring for TB and TG. Compost addition, with straw mulching, to TS reduced runoff volume by 13-64% except for BTS which produced 13% more runoff. No statistical trends were seen with slope ratio change, however TS, BNS, and GNS showed a decrease in runoff generation from the 50% to 5% slopes of 96%, 91%, and 46%.

Both sediment mass export and runoff EMC were reduced with straw mulching compared to bare soil. This was most significant for both the topsoil: compost mixtures with EMC reductions of 92% for TB and 94% for TG and mass export reductions of 99.7% for TB and 99.9% for TG. Compost addition to TS also consistently reduced sediment mass export and EMC. The BS and TBS treatments had the greatest sediment reduction for both EMC (by 91% and 74%, respectively) and mass export (98% and 86%, respectively). Slope ratio changes did not show statistical trends in mass export of sediment, however, both TS and BNS showed positive correlation with slope ratio and had 4-140- fold increase in sediment yield from 5% to 50% slope.

With straw mulching to composted material, mass export of nitrogen was significantly reduced (71-92%), however, nitrogen average EMC increased for both compost mixtures (4-18-fold). Nitrogen also had consistent reduction in mass export (except for BTS which exported 36% more nitrogen) but not EMC for compost addition. Only the BS and TBS treatments showed reduced EMC from TS (56% and 18%, respectively). Greenwaste treatments and BTS increased nitrogen EMC by 33-126%. TBS and BS also had the lowest mass export of nitrogen and reduced total nitrogen export by 72% and 82% from TS. Nitrogen mass export increased with slope ratio for most tested slopes, this resulted in 14-140-fold increase in mass export. Comparisons between the treatments did not change greatly with slope change.

Phosphorus mass export and EMC were both reduced significantly with straw mulching for all tested materials. TB and TG showed the greatest phosphorus mass export reductions at 99.0% and 99.4% with straw mulching, respectively. Only the GS (which had 3% increase in average phosphorus EMC) and BTS (which increased mass export of phosphorus by 15%) treatments did not show reductions in mass export and EMC from the TS standard, all other treatments showed reductions. GTS and TBS had the greatest reductions in phosphorus EMC with 51% and 37% reductions. Phosphorus mass export was reduced by 76% and 69% for TBS and TGS, respectively. The export of phosphorus with respect to slope ratio was similar to volume runoff. GNS, TS, and BNS all had increasing phosphorus export with slope ratio (5-37-fold increase from 5% to 50%).

It is strongly recommended that straw mulching be used for all treatment applications regardless of compost percent; this treatment was shown to reduce total runoff volume and improve vegetation establishment for all tested media. The use of 50% compost: topsoil blends is not recommended based on the results obtained, this mix produced greater total export of nutrients (36% more nitrogen and 15% more phosphorus for BTS) and sediment (16% more sediment for GTS) than the current TS standard.

Overall, at a 25% slope, BS, GS, TBS and TGS showed similar or improved runoff generation, runoff quality, and vegetation establishment. Both BS and TBS showed the greatest improvement to the TS standard with 79% and 78% average reduction in mass export of sediment and nutrients and 56% and 59% reduction in runoff volume. TBS was also seen to improve GV establishment by 30%.

Slope ratio changes greatly affected the total mass export for each medium tested in inconsistent ways. In general, the runoff and vegetation establishment benefits displayed at the 25% slope are reduced at shallower slopes and enhanced at greater slopes.

RECOMMENDATIONS FOR FUTURE RESEARCH

The tested soil mixtures resulted in a range of runoff water quality based on compost fraction that could possibly be optimized for the specific composted material. Studies involving additional compost: topsoil mixtures may yield an optimal ratio for minimizing runoff volume and water quality. Only one additional SMP was used in this study (straw application) which showed a significant change in all media applications; using other SMPs may yield better results (eg. Geotextiles or silt fence). Water treatment residual and activated charcoal have been seen to reduce phosphorus and nitrogen concentrations in a variety of SMPs; investigation into compost amended with these or other materials may yield reduced nutrient export.

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Appendix

APPENDIX A: ANALYSIS CHEMICALS AND FILTERS

Test	Chemical	Formula	C.A.S No.	Company	Assay
TP, SRP	Ammonium molybdate tetrahydrate	(NH4)6Mo7O24* 4H2O	12054-85-2	Acros Organics	99+%
TP, SRP	Potassium antimonal tartrate trihydrate	C8H4K2O12Sb2* 3H2O	28300-74-5	Acros Organics	99+%
TP, SRP	Ascorbic acid	C6H8O6	50-81-7	Acros Organics	ACS grade
TP, SRP	Sulfuric acid	H2SO4	7664-93-9	VWR chemicals	95-98
TP	Potassium persulfate	K2S2O8	7727-21-1	Acros Organics	99+%
TP	Phenolphthalein	C20H14O4		Fisher Chemical	ACS grade
TP, NO2	Sodium hydroxide	NaOH	1310-73-2	Fisher Chemical	98.7%
TP, SRP, DP	Phosphate standard	PO4	LC18570	Lab Chem™	Certified
TN, NO3	Nitrogen standard	NO3	LC17900	Lab Chem™	Certified
NO2	N - (1-napthyl) - Ethylenediamine dihydrochloride	C12H14N2*2HCl	1465-25-4	Alfa Aesar	ACS grade
NO2	Phosphoric Acid	H3PO4	7664-38-2	Fisher Chemical	85%
NO2	Sodium Nitrite	NaNO2	7632-00-0	Fisher Chemical	ACS grade
NO2	Sulfanilamide	C6H8N2O2S	63-74-1	Fisher Chemical	98.9%
NH4	Ammonium chloride, anhydrous	NH4Cl	12125-02-9	Fisher Chemical	ACS grade
NH4	EDTA disodium salt dihydrate	C10H14N2Na2O8 * 2H2O	6381-92-6	Fisher Chemical	ACS grade
NH4	Phenol, crystalline	C6H5OH	108-95-2	Fisher Chemical	ACS grade
NH4	Sodium nitroferricyanide dihydrate	Na2{Fe(CN)5NO} * 2H2O	13755-38-9	Fisher Chemical	ACS grade
TSS	Glass fibre filters			MilliporeSigma™	
DP, SRP, NO3, NO2, NH4	Mixed Cellulose Ester Membranes: 0.22 um			MilliporeSigma™ MF-™	

APPENDIX B: EQUATIONS

Equation 1: Particulate phosphorus

$$Particulate\ P = TP - DP;$$

Equation 2: Dissolved organic phosphorus

$$Dissolved\ organic\ P = DP - SRP;$$

Equation 3: Organic nitrogen

$$Organic\ N = TN - ([NO_3^- - N] + [NO_2^- - N] + [NH_3 - N])$$

Equation 4: Wilcoxan rank sum test

$$Rank\ all\ sample\ values\ in\ the\ sample\ sets\ from\ smallest\ to\ largest\ with\ ties\ equal\ to\ half$$

$$U_1 = W_1 - \frac{n_1(n_1+1)}{2};\ \begin{matrix} n_1\ is\ the\ sample\ size\ of\ sample\ 1 \\ W_1\ is\ the\ sum\ of\ the\ ranks\ of\ sample\ 1 \end{matrix}$$

$$or$$

$$U_2 = W_2 - \frac{n_2(n_2+1)}{2};\ \begin{matrix} n_2\ is\ the\ sample\ size\ of\ sample\ 2 \\ W_2\ is\ the\ sum\ of\ the\ ranks\ of\ sample\ 2 \end{matrix}$$

The smaller of the two is the U statistic used for significance

Equation 5: Mann-Kendall trend test

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)$$

$$\xi = \begin{cases} \frac{S-1}{v^{0.5}}; for\ S > 0 \\ 0; for\ S = 0 \\ \frac{S+1}{v^{0.5}}; for\ S < 0 \end{cases} ;\xi\ is\ the\ normal\ distribution\ N(0,1)$$

$$v = \frac{n(n-1)(2n+5) - \sum_{i=1}^{g} t_i(t_i-1)(2t_i+5)}{18};\ \begin{matrix} g\ is\ the\ number\ of\ ties \\ t\ is\ the\ number\ of\ groups\ of\ ties \end{matrix}$$

Equation 6: Modified thompson tau test

$$n = number\ of\ points;\ \overline{x_i} = is\ the\ mean\ of\ the\ current\ set\ of\ points\ being\ tested$$

$$\delta_i = |x_i - \overline{x}|$$

$$\tau = \frac{t_{\alpha/2} * (n-1)}{\sqrt{n} * \sqrt{n - 2 + t_{\alpha/2}^2}}$$

Equation 7: Kenetic Energy calculation from the Daily Morgan-Morgan Fenny model

$$KE = R_{eff} * \{(1 - CC) * U_{DT} + CC * U_{LD}\}$$

R_{eff}: effective rainfall (mm) based on slope ratio

U_{DT}: estimated KE of direct throughfall (rain that bypasses the coverage layer) based on the universal power law equation (Shin et al., 2016)

U_{LD}: leaf drainage KE based on plant height

CC: canopy cover

Equation 8: Manning's equation for velocity

$$v = \left(\frac{1}{n'}\right) d^{2/3} * \sqrt{\tan(S)}$$

Equation 9: Adjusted Manning's roughness coefficient

$$n' = \left(n^2 + \frac{D * NV * d^{4/3}}{2 * g}\right)^{1/2}$$

D: plant stem diameter
NV: number of stems per unit area
n: manning's roughness coefficient (based on soil surface roughness)
g: gravity
d: flow depth

Equation 10: Infiltration (i) based on the revised Green-Ampt model

$$i = K_s\left\{1 + (\theta_s - \theta_i) * \frac{S}{I}\right\}$$

K_s: saturated hydraulic conductivity

θ_s: saturated volumetric water content

θ_i: initial volumetric water content

S: soil suction

I: cumulative infiltration