2017

Effects of Biochar Treatment of Municipal Biosolids and Horse Manure on Quality of Runoff from Fescue Plots

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EFFECTS OF BIOCHAR TREATMENT OF MUNICIPAL BIOSOLIDS AND HORSE MANURE ON QUALITY OF RUNOFF FROM FESCUE PLOTS

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ABSTRACT. *Land-applied horse manure and municipal biosolids can increase nutrient and bacteria concentrations in runoff. Biochar has been demonstrated to have beneficial impacts on nutrient retention and runoff quality when used to treat other land-applied organic soil amendments (e.g., poultry manure). The objective of this study was to evaluate the effects of biochar addition to horse manure and municipal biosolids on runoff concentrations of nutrients and fecal coliforms. Biochar was added at 5% to 8% (wet basis) to horse manure and biosolids that were applied to 2.4 m × 6.1 m fescue plots followed by application of simulated rainfall (102 mm h^{-1}). Analysis of runoff samples indicated that soil hydraulic characteristics, as reflected in the runoff curve number (CN), were a significant covariate for some analytical parameters. Analysis of covariance indicated that biochar addition decreased runoff concentrations of total Kjeldahl nitrogen (TKN) and ammonia nitrogen (NH_3-N) when added to municipal biosolids, with all effects more prominent at higher CN values. When added to horse manure, biochar decreased runoff concentrations of NH_3-N, total suspended solids, and fecal coliforms. Although runoff concentrations of total P and TKN increased with CN, there was no significant biochar effect on these parameters when added to horse manure. The findings indicate potential for biochar addition to improve runoff quality when added to these organic amendments, but the effects may be dependent on the receiving soil's runoff production characteristics.*

Keywords. *Biochar, Biosolids, Manure, Nutrients, Runoff.*

Kentucky's Inner Bluegrass physiographic region is well known for its numerous horse farms and its largest city, Lexington. According to most-current estimates, the Lexington-Fayette metropolitan statistical area (MSA, consisting of Bourbon, Clark, Fayette, Jessamine, Scott and Woodford counties) has a population of slightly more than 500,000 (U.S. Census Bureau, 2015). At the same time, there are nearly 2,000 horse farms in the MSA, with a horse inventory of just over 36,000 (USDA-NASS, 2012). In terms of relative biochemical oxygen demand production (Wadleigh, 1988), this horse inventory is equivalent to approximately 80% of the current human population. The area is an example of others in which population centers exist in geographic proximity to animal production enterprises in a mutually beneficial arrangement.

Though not practiced by all cities (e.g., Lexington), land application has historically been the most common fate of biosolids produced from municipal sewage treatment processes (Ozores-Hampton and Peach, 2002). Similar to other organic materials, biosolids have been demonstrated to have beneficial effects on crop production (e.g., Sigua, 2009; McFarland et al., 2010; Castillo et al., 2010) and soil properties in reclamation (Meyer et al., 2001; Cellier et al., 2014) and other contexts. In addition to concerns such as soil accumulation and mobility of metals (e.g., Islam et al., 2013; Antonious et al., 2008), land application of biosolids raises the possibility of runoff losses of plant nutrients, bacteria, and other constituents (Chen et al., 2011; Eldridge et al., 2009; Rostagno and Sosebee, 2001; Harris-Pierce et al., 1995). While not as thoroughly studied as other livestock manures, land application of stall-collected horse manure has a comparable potential to elevate runoff concentrations of nutrients and other manure constituents (Busheé et al., 1998; Edwards et al., 1999). Whether originating in biosolids or horse manure, runoff losses of nutrients, organic matter, solids, and metals can promote undesirable downstream impacts, including eutrophication (Chen et al., 2011; Smith et al., 1999; Busheé et al., 1998).

Biochar, the byproduct of biomass that has undergone pyrolysis (Mackie et al., 2015) preparatory to land application (Lehman and Joseph, 2015) has long been used as a soil amendment, as comprehensively reviewed by Mohan et al. (2014). Numerous researchers have found biochar effective in increasing retention of nutrients (Laird et al., 2010; Lehmann, 2007; Schnell et al., 2012; Zhai et al., 2015) and water (Beck et al., 2011; Novak et al., 2009, Ulyett et al., 2014) in soils, with water retention linked to increased pore space and surface area after biochar addition (Basso et al., 2013; Uzoma et al., 2011). Leaching of microbes such as *E. coli* decreased in response to biochar treatment (Abit et al., 2014;

Submitted for review in April 2016 as manuscript number NRES 11891; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in January 2016.

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Vol. 60(2): 409-417 ISSN 2151-0032 DOI 10.13031/trans.11891

Bolster and Abit, 2012; Mohanty et al., 2014). A similar effect on heavy metals has been documented (Park et al., 2011; Zhang et al., 2013), attributed to increased soil cation exchange capacity and sorption potential.

Pyrolysis temperature and type of biomass play significant roles in the chemical and physical properties of the biochar (Abit et al., 2012; Singh et al., 2010). For example, biochars produced from woody feedstocks tend to have a relatively high C content and low nutrient content (Gaskin et al., 2008; Singh et al., 2010), while manures have a lower C content but greater total Kjeldahl N (TKN) and higher cation exchange capacity (Singh et al., 2010). Biochars produced at high pyrolysis temperatures (400°C to 700°C) tend to have relatively high specific surface area, pH, and micronutrient composition but lower N content (Bolster and Abit, 2012; Gaskin et al., 2008). Biochars thus vary, and the effects of such differences on their performance as runoff quality-enhancing amendments have not been widely reported. With the exception of Sheng et al. (2014), who reported that biochar addition to land-applied poultry litter improved the quality of runoff in a greenhouse study, there is very little to indicate the runoff quality effects of biochar addition to land-applied biosolids or animal manures. Our objective was to evaluate the effects of biochar addition to horse manure and municipal biosolids on runoff concentrations of TKN, ammonia-nitrogen (NH_3-N), nitrate (NO_3-N), total phosphorus (TP), total suspended solids (TSS), chemical oxygen demand (COD), and fecal coliforms (FC).

METHODS

RAINFALL-RUNOFF PLOTS

The study was performed in fall of 2015 at the Maine Chance Research Farm of the University of Kentucky (38.12° N, 84.48° W). The soil at the site is uniformly mapped as a Maury silt loam (fine, mixed, active, mesic Typic Paleudalf) (NRCS, 2017), which is classified as a hydrologic soil group B soil (NRCS, 1986).The vegetation at the site is primarily tall fescue (*Festuca arundinacea* Schreb.) with an average height of approximately 10 cm at the time of the study. The site contains 30 rainfall-runoff plots that were constructed in 1995, each measuring 2.4 m × 6.1 m with a slope of 3% along the major axis. Each plot is surrounded on three sides by rustproof metal borders with an aluminum gutter at the bottom to collect the runoff. The runoff is then diverted from the gutter through a PVC pipe to facilitate sample collection.

The study was conceived as two separate completely randomized designs with three replications of the treatment as primary factor. The treatments for the first design were municipal biosolids application with (MB) and without (M) biochar addition and control (C, nothing applied). For the design involving horse manure, the treatments were horse manure application with (HB) and without (H) biochar addition and control (C). The control plots were common to both designs, requiring a total of 15 rainfall-runoff plots. Treatment assignments to the rainfall-runoff plots were random and are indicated in figure 1. The plots had been used in prior rainfall-runoff studies involving herbicides and soil amendments

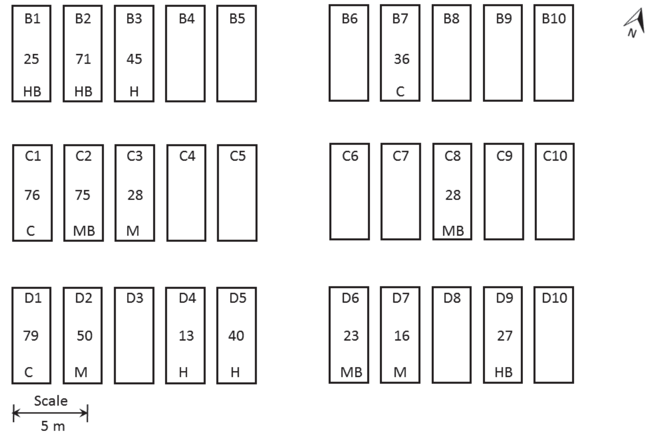

Figure 1. Study site schematic indicating plot identifiers (top characters), experimentally derived NRCS (1986) curve number values (middle characters), and treatments (bottom characters). H, M, and C indicate horse manure, municipal biosolids, and control, respectively, and B indicates the addition of biochar. Plots without treatments were not used in this study but are included to more fully illustrate the study layout.

(organic and inorganic) applied at agronomic rates, but none had been used in the two years prior to the present study. The physical impacts of the previous studies on the plots were negligible, and other than regular mowing, the plots experienced no anthropogenic activity (foot traffic, plowing, etc.).

AMENDMENTS

Fresh (2 to 3 days post-deposition) horse (*Equus caballus* L.) manure mixed with pine chip bedding material was collected from the Maine Chance Research Farm's equine research facility on 13 July 2015 and stored in doubled plastic bags at 4°C prior to analysis by the University of Kentucky Regulatory Services laboratory for water content, TKN, and extractable P (Mehlich III; Mehlich, 1984). Municipal biosolids produced at Lexington's Town Branch Wastewater Treatment Plant (38.06° N, 84.53° W) were collected on 15 July 2015. The biosolids material was taken from the end of a conveyor belt leading to disposal vehicles and stored in doubled plastic bags at 4°C prior to analysis by McCoy and McCoy Laboratories, Inc. (Madisonville, Kentucky, with a branch office in Lexington, Kentucky) for water content, TKN, and TP (inductively coupled plasma - atomic emission spectrometry).

Since there was no intention to directly compare the runoff quality characteristics of horse manure and municipal biosolids, there was no attempt to adjust the plot application rates to N or P equivalent rates. Rather, horse manure and biosolids were applied on an equivalent gross-weight basis of 12 Mg ha^{-1}, a rate selected to supply N at an approximately agronomic rate, to better reflect practical operational considerations. The compositions of the horse manure and biochar as well as the resulting N application rates are given in table 1.

Bison Biochar (Bison Soil Solutions, Buffalo, S.D.) was used as the biochar additive to the biosolids and manure. This brand of biochar was selected due to its ready commercial availability and its guarantee of consistency of quality, materials, and manufacturing procedure. Bison Biochar uses

Table 1. Composition of horse manure and municipal biosolids and nitrogen application rates.[a]

Sample	H_2O (% wet basis)	Total N (% dry basis)	Total P (% dry basis)	Application Rate (kg N ha^{-1})
Horse manure	35 ±1.3	0.89 ±0.13	0.26 ±0.05	66.6 ±8.8
Municipal biosolids	84 ±1.11	5.03 ±0.31	1.46 ±0.11	93.0 ±0.98

[a] Values are means ± standard deviations (means of six samples for horse manure, and means of three samples for municipal biosolids).

Table 2. Biochar characteristics.[a]

Parameter	Mean
pH	9.9 ±0.0
Conductivity (dS m^{-1})	2.2 ±0.1
Total C (% dry basis)	88.5 ±3.8
Total N (% dry basis)	0.4 ±0.0
NO_3-N (mg kg^{-1})	2.0 ±0.6
P (mg kg^{-1})	12.4 ±1.0

[a] Values are means ± standard deviations (means of three samples).

California Department of Food and Agriculture certified organic feedstock (yellow pine, *Pinus* sp.) pyrolyzed at 600°C and then cooled slowly to produce large interior pore space within the product (D. Lemm, personal communication, 4 February 2016). Three samples from a single 0.03 m^3 commercially obtained package of Bison Biochar were analyzed by the University of Kentucky Regulatory Services laboratory for pH, conductivity, total C, total N, and plant-available (Mehlich III) P, and NO_3-N (table 2). The average pH was 9.9, somewhat higher than the results for pine chip biochar reported by Gaskin et al. (2008), perhaps related to those researchers' use of a lower pyrolysis temperature. The average C content of this biochar is comparable to results of Rajkovich et al. (2011), while the N content is slightly higher (Gaskin et al., 2008; Rajkovich et al., 2011), resulting in a smaller C:N ratio (250:1) in this study.

Previous studies indicated that biochar was added to organic amendments at rates ranging from 0.5% to 10% on a w/w basis (Abit et al., 2012, 2014; Beck et al., 2011; Bolster et al., 2012; Laird et al., 2010; Mohanty et al., 2014; Zhai et al., 2015). We selected the near-median biochar addition rate of 5% (w/w) for the horse manure and, in anticipation of a higher nutrient content, 8% (w/w) for the municipal biosolids. The associated gross application rates for biochar were 0.6 and 1.0 Mg ha^{-1} for the horse manure (HB) and municipal biosolids (MB) treatments, respectively. A comparison of tables 1 and 2 indicates that the nutrients added via biochar were very small proportions of those contained in the horse manure and municipal biosolids. Appropriate masses of biochar were added to the manure and biosolids followed by manual mixing to the greatest practical degree. The organic amendments were then transferred to the corresponding plots, manually applied, and spread as evenly as possible using rakes.

RUNOFF SAMPLING AND ANALYSIS

All plots were pre-wetted via sprinkler irrigation for a minimum of 24 h prior to simulated rainfall application to minimize between-plot soil moisture variability (and thus runoff variability). Rainfall simulators (Busheé et al., 1998) were used to produce runoff. Tarps were placed on the four sides of the simulators to minimize draft due to wind, and the gutters were covered during simulated rainfall to eliminate the direct entry of simulated rainfall into the gutters. Simulated rainfall intensity began within 0.1 h of organic amendment application (when applicable) at 102 mm h^{-1} for each plot and continued until 0.5 h of continuous runoff had occurred. This intensity was chosen to reliably produce runoff in a practical period of time. However, for nearly half of the plots, no runoff had occurred after an hour of simulated rainfall application at this very high intensity. In these cases, the intensity was increased to approximately 135 mm h^{-1} so that runoff would be available for sampling. As a result of operational limitations, the rainfall simulations were conducted on two days: 23 September 2015 (plots B7, C8, D1, D2, D4, D5, D6, D7, and D9) and 8 October 2015 (plots B1, B2, B3, C1, C2, and C3), over which period 103 mm of natural rainfall was observed at the Spindletop weather station (UK Ag Weather Center, 2016) located roughly 1.7 km from the study site.

Runoff samples were collected in plastic, autoclaved 1 L bottles at 2, 4, 8, 14, 22, and 30 min after continuous runoff began. Each sample was collected for 1 min or until the bottle was full, whichever occurred first, with stopwatches used to measure collection durations for flow rate calculations. Volumes were measured for each runoff sample and, together with the respective collection times, enabled calculation of runoff flow rates and a runoff hydrograph. The runoff hydrograph was numerically integrated to calculate total runoff volume, after which the sub-volumes represented by each of the individual runoff samples were evaluated. A single, flow-weighted composite sample was then formed from the six individual samples by (1) specifying a composite sample volume of 1 L and (2) setting each individual sample's volumetric proportion of the composite sample equal to its proportion of sub-volume of runoff to total volume of runoff.

The composite runoff samples were stored at 4°C until analyzed for TKN, NH_3-N, NO_3-N, TP, TSS, COD, and FC. The persulfate digestion method (Rice et al., 2012) was used in TKN and TP analyses. Analyses of NH_3-N, NO_3-N, and COD followed U.S. Environmental Protection Agency (EPA) methods 350.1 revision 2 (EPA, 1993a), 353.2 revision 2 (EPA, 1993b), 365.1 revision 2 (EPA, 1993c), and 410.4 revision 2 (EPA, 1993d), respectively. Fecal coliforms were analyzed by membrane filtration per EPA method 1603 (EPA, 2006). Laser diffraction (ISO method 13320) was used in TSS analysis (ISO, 2009). Consistent with EPA (2003) guidelines, FC analyses commenced no more than 6 h following sample collection, and COD analyses occurred no more than 24 h following sample collection. Holding times for other analysis parameters did not exceed recommended values (EPA, 1983).

DATA ANALYSIS

Data were initially analyzed as two distinct experiments (with C plot data common to both) using one-way analysis of variance (ANOVA) since, as noted earlier, there was no intent to directly compare the horse manure findings to the municipal biosolids findings. For reasons to be discussed later, it was deemed beneficial to instead use analysis of covariance (ANCOVA) with the NRCS (1986) curve number (CN) as covariate to serve as a lumped surrogate for soil hydraulic properties. In doing so, values of S were first calculated for each plot by rearranging the NRCS rainfall-runoff relationship as (Haan and Edwards, 1988):

$$S = 5R + 10Q - 10\sqrt{Q^2 + 1.25RQ} \quad (1)$$

where R is total applied rainfall (mm), and Q is runoff (mm). Each value of S was then converted to its corresponding value of curve number (CN) through:

$$\text{CN} = \frac{25{,}400}{S + 254} \quad (2)$$

The ANOVA and ANCOVA were conducted with SAS (ver. 9.4, SAS Institute, Inc., Cary, N.C.) using the PROC ANOVA and PROC MIXED procedures, respectively. All tests of significance were conducted at the $p \leq 0.05$ level of significance.

Results and Discussion

One-Way ANOVA

Analysis of variance indicated that biochar addition had no significant effect on runoff quality for either horse manure or municipal biosolids. Furthermore, the runoff quality for the plots treated with manure or biosolids did not differ significantly from the control plots (which received no organic amendment). Mean runoff concentrations of the analysis parameters are given in table 3. Mean mass transport of analysis parameters is given in table 4; a comparison to table 1 reveals that mass transport of N and P was agronomically insignificant in comparison to the amounts applied via biosolids and horse manure (<1%).

The ANOVA results (especially with regard to runoff concentrations) being unexpected, CN values were calculated as described earlier in an attempt to account for some of the variability in the concentration results. For the given hydrologic soil group and land use, a range of 37 to 76 (depending on antecedent rainfall) in CN values was anticipated, with the higher values judged more likely due to the pre-wetting and natural rainfall. The resulting CN values were highly variable, with a range of 13 to 79 (fig. 1) and a mean of 42 ±23, indicating high variability in the soil hydraulic characteristics, which were implicitly assumed to be uniform in one-way ANOVA. While the observed variability in CN values was unwelcome, it was not unexpected; previous studies at this location have also reported a high range in calculated CN values. For example, Moss et al. (1999) reported that CN values at this site ranged from 29 to 66, and Edwards et al. (2000) reported a range of mean (of three replications) CN values of 32 to 79. Researchers working at other locations have also found high variation in CN values. In a plot-scale study in Australia reported by Cao et al. (2011), overall mean CN values for pasture plots had a coefficient of variation of 1.00 for CN values calculated by the method most compatible with that used in this study. In another example, Huang et al. (2007) reported that measured CN values for plots in the Loess Plateau of China varied from roughly 60 to 98 at the same antecedent moisture condition. Potentially high variability in runoff is thus not uncommon, even for plot-scale studies confined to a small study site. Hjelmfelt and Burwell (1984), who found significant plot-to-plot and within-plot variation in runoff characteristics for 40 plots in Missouri, indicated that the underlying reasons for variation might lie beyond the usual variables, such as surface variations and spatial soil textural variations, which suggests an influential role for subsurface characteristics, such as macropore structure and/or bioturbation. As a result of variation in plot runoff characteristics as quantified by CN values, ANCOVA was applied to the concentration data with CN considered as the covariate.

Table 3. Mean runoff concentrations of analysis parameters for plots treated with municipal biosolids (M+MB), both with and without biochar addition, plots treated with horse manure (H+HB), both with and without biochar addition, and untreated plots (C).[a]

	Treatment		
Parameter[b]	M+MB	H+HB	C
TKN (mg L^{-1})	4.93 ±3.81	6.55 ±5.08	2.35 ±1.28
NH_3-N (mg L^{-1})	2.85 ±2.36	2.5 ±1.73	0.68 ±0.10
NO_3-N (mg L^{-1})	0.51 ±0.50	0.70 ±0.31	0.57 ±0.43
TP (mg L^{-1})	0.76 ±0.21	2.13 ±1.47	0.68 ±0.11
COD (g L^{-1})	2.54 ±0.18	2.44 ±0.24	2.57 ±0.22
TSS (mg L^{-1})	116.8 ±104.0	108.8 ±82.0	28.7 ±4.6
FC (MPN per 100 mL)	18.5 ±5.6	155 ±211	2.47 ±3.58

[a] Values are means ± standard deviations (means of six values for M+MB and H+HB, and means of three values for C).
[b] For FC, values are geometric means and standard deviations.

Table 4. Mean runoff mass transport (kg ha^{-1}) of analysis parameters for plots treated with municipal biosolids (M+MB), both with and without biochar addition, plots treated with horse manure (H+HB), both with and without biochar addition, and untreated plots (C).[a]

	Treatment		
Parameter	M+MB	H+HB	C
TKN	0.28 ±0.12	0.36 ±0.20	0.24 ±0.12
NH_3-N	0.16 ±0.07	0.19 ±0.13	0.09 ±0.06
NO_3-N	0.07 ±0.09	0.11 ±0.17	0.07 ±0.09
TP	0.06 ±0.05	0.14 ±0.09	0.09 ±0.07
COD	257 ±298	415 ±561	343 ±231
TSS	5.94 ±3.52	7.51 ±3.39	3.94 ±2.94

[a] Values are means ± standard deviations (means of six values for M+MB and H+HB, and means of three values for C).

Municipal Biosolids

ANCOVA indicated a significant ($p < 0.05$) relationship between the covariate (CN) and runoff concentrations of TKN, NH_3-N, and TSS. For the M and MB treatments, runoff concentrations of these analysis parameters increased in proportion to plot CN with no significant difference between line slopes. This finding is consistent with results reported by Pote et al. (2001), who reported that, for some analysis parameters, concentrations in runoff varied with infiltration rate and thus soil hydraulic characteristics. This interaction is demonstrated in figure 2 for runoff TKN and in figure 3 for NH_3-N, in which concentrations for the C treatments (which did not demonstrate a significant dependence on plot CN) are also indicated. Controlling for the effect of plot CN enabled the identification of treatment effects that generally increased with CN. In the case of TKN (fig. 2), there were no consistent differences among any of the treatments, including the C treatment, for plot CN < 50. However, at CN

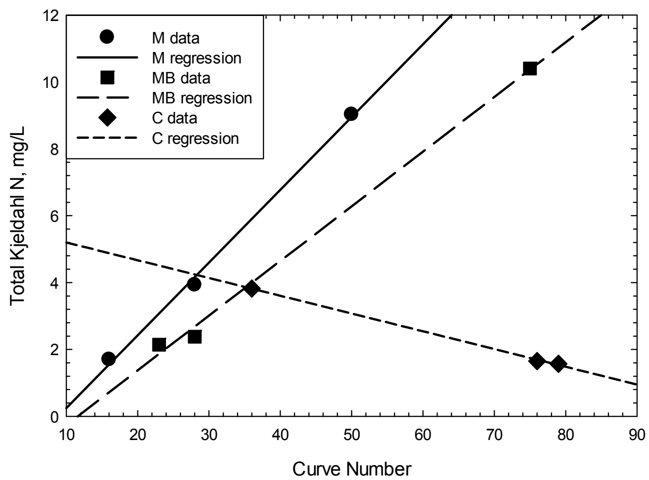

Figure 2. Runoff concentration of total Kjeldahl N in relation to plot curve number and treatment (M = municipal biosolids, MB = municipal biosolids with biochar addition, and C= control).

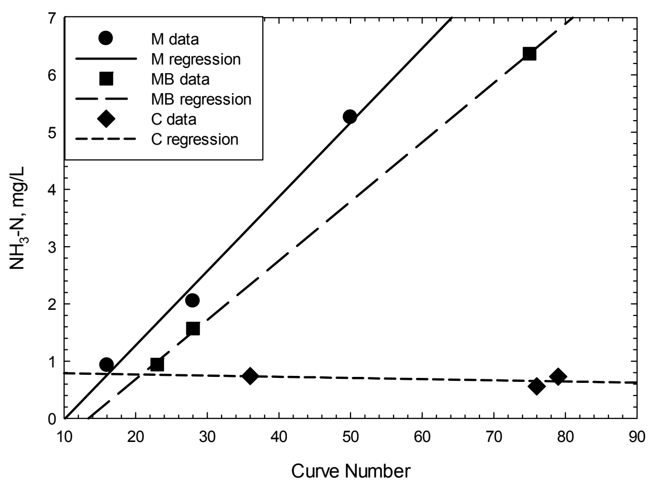

Figure 3. Runoff concentration of NH_3-N in relation to plot curve number and treatment (M = municipal biosolids, MB = municipal biosolids with biochar addition, and C = control).

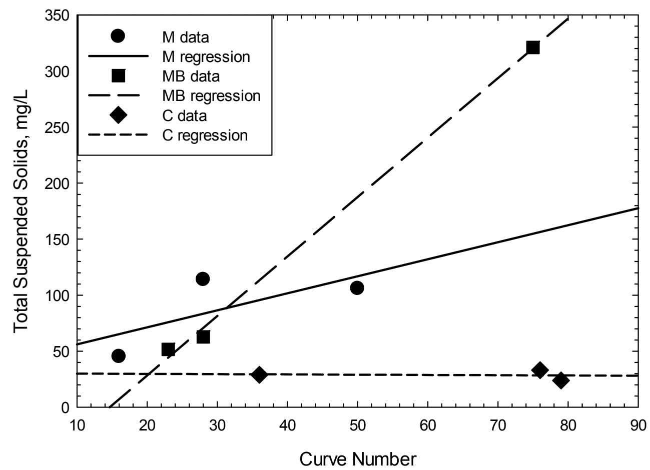

Figure 4. Runoff concentration of total suspended solids in relation to plot curve number and treatment (M = municipal biosolids, MB = municipal biosolids with biochar addition, and C = control).

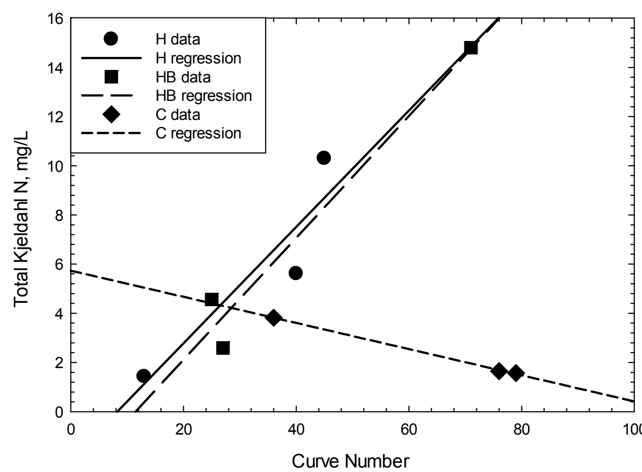

Figure 5. Runoff concentration of total Kjeldahl N in relation to plot curve number and treatment (H = horse manure, HB = horse manure with biochar addition, and C = control).

≥ 50, runoff TKN concentrations for the MB treatment were significantly ($p < 0.05$) less than those for the M treatment, although both were greater than for the C treatment. An analogous effect is present for runoff NH_3-N concentrations (fig. 3), with MB treatments having significantly lower concentration than M at plot CN ≥ 30. Results with regard to TSS were mixed; at plot CN ≥ 50, the MB treatment differed significantly from the C treatment but not the M treatment (fig. 4).

The findings with regard to TKN and NH_3-N are consistent with the earlier-cited reports of biochar's ability to increase N retention in leaching and soil column studies (e.g., Zheng et al., 2013) and greenroof tray runoff studies (Beck et al., 2011). Biochar's tendency to increase cation exchange capacity and thus promote sorption has been credited for nutrient retention (Laird et al., 2010; Mackie et al., 2015). Given the high pH of the biochar and the fact that high pH drives the $NH_3 \leftrightarrow NH_4$ equilibrium in the direction of NH_3 (e.g., Ndegwa et al., 2008; Moore et al., 2000), the biochar might have reduced the presence of NH_3 (and thus TKN) through rapid volatilization. The TSS results are suggestive of direct runoff of biochar particles. The pyrolysis temperature of the biochar used in this study would have produced a relatively large proportion of fine particles (Kim et al., 2012) susceptible to runoff transport. Given that the MB treatment differed only from the C treatment and not the M treatment in terms of runoff TSS concentrations, the degree to which this might have occurred is unclear.

Horse Manure

The covariate CN significantly ($p < 0.05$) influenced runoff concentrations of the same parameters for horse manure as for municipal biosolids (TKN, NH_3-N, and TSS), but also TP and FC. As was the case with the M and MB treatments, runoff concentrations of the affected parameters increased with CN for the H and HB treatments. Contrary to the M and MB results, biochar addition did not lead to significant differences between runoff TKN concentrations for the H and HB treatments (fig. 5). For plot CN ≥ 71, runoff TKN concentrations for the HB treatments were significantly ($p < 0.05$) different from those for the C treatments, but no other significant differences were found. Runoff TP demonstrated

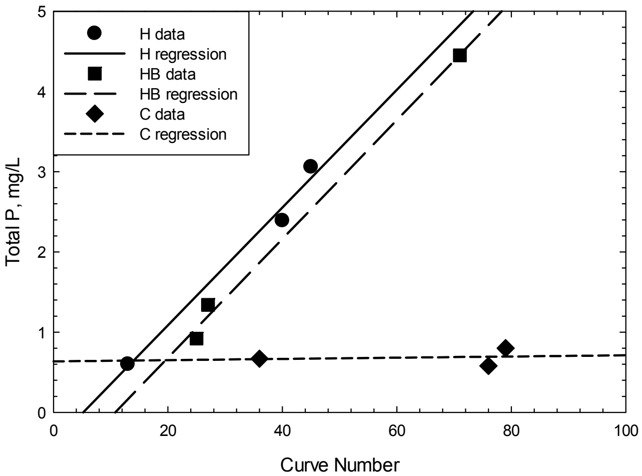

Figure 6. Runoff concentration of total P in relation to plot curve number and treatment (H = horse manure, HB = horse manure with biochar addition, and C = control).

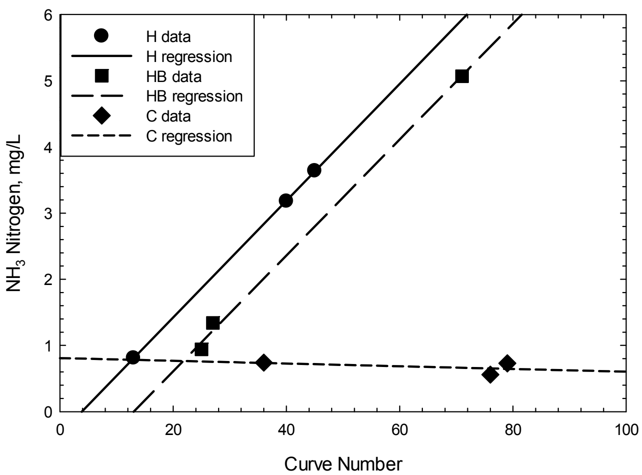

Figure 7. Runoff concentration of NH_3-N in relation to plot curve number and treatment (H = horse manure, HB = horse manure with biochar addition, and C = control).

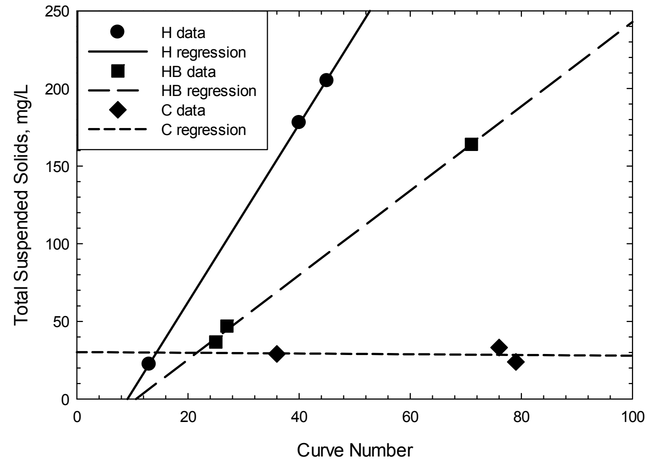

Figure 8. Runoff concentration of total suspended solids in relation to plot curve number and treatment (H = horse manure, HB = horse manure with biochar addition, and C = control).

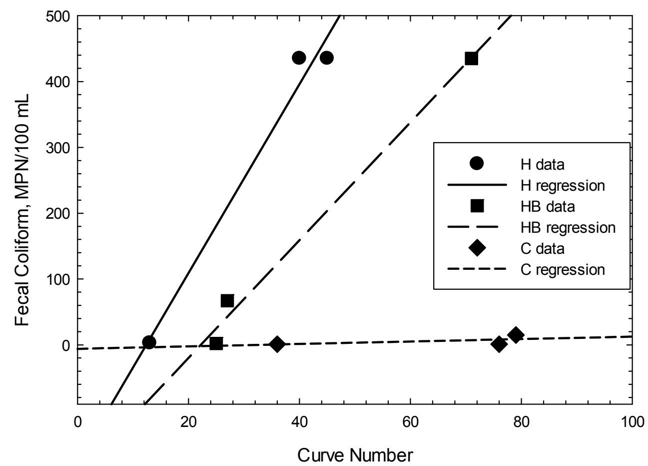

Figure 9. Runoff concentration of fecal coliform in relation to plot curve number and treatment (H = horse manure, HB = horse manure with biochar addition, and C = control).

similar behavior with regard to treatments (fig. 6), although significant ($p < 0.05$) differences between the C treatment and the H/HB treatments were detected at lower plot CN values (≥36). Runoff NH_3-N was greater ($p < 0.05$) for the H and HB treatments than for the C treatment for plot CN ≥ 36 (fig. 7). There were also significant differences between the H and HB treatments over the range of plot CNs encountered with biochar addition, leading to lower concentrations in runoff. Runoff concentrations of TSS (fig. 8) and FC (fig. 9) responded similarly to one another in response to treatments; in both cases, concentrations for the H and HB treatments were significantly ($p < 0.05$) different from one another for CN ≥ 25, and both were significantly different from the C treatment for CN ≥ 40.

The most consistent effects of biochar addition were associated with runoff concentrations of NH_3-N, TSS, and FC. The NH_3-N results may be attributed to the earlier-discussed processes of sorption and possibly volatilization. The FC findings are supportive of the leaching column results reported by Mohanty et al. (2014), who hypothesized that biochar addition increased both the availability of attraction sites and hydrophobic interactions. While the FC and TSS results might be related to the degree that similar mechanisms affect their transport, the underlying reasons for the TSS effects are unclear based on the results available. There were substantial differences in terms of the physical properties of the horse manure and municipal biosolids; the biosolids were wetter and more cohesive with a much greater tendency to form discrete aggregates on application. The biochar might have promoted the formation of relatively large, erosion-resistant aggregates in the horse manure but not the municipal biosolids owing to their differing properties. Little has been reported on biochar's effects on eroded sediment and associated material, and Wang et al. (2013) noted the need for additional work to better understand the operative mechanisms.

Conclusions

This experiment was conducted to evaluate the response of runoff concentrations of TKN, NH_3-N, NO_3-N, TP, FC, COD, and TSS to the addition of biochar to horse manure and municipal biosolids. Depending on the analysis parameter and the organic amendment to which the biochar was added, significant ($p < 0.05$) effects were observed. However, in such cases, the parameter concentrations also exhibited dependence on soil hydraulic characteristics, as reflected in plot values of the CN (NRCS, 1986). As a result, effects were generally detected only above threshold CN values that varied with parameter and organic amendment.

In the case of municipal biosolids, biochar addition decreased runoff concentrations of both TKN and NH_3-N for plot CN ≥ 28 (80% of the observed range). Relative to the control treatment, biochar addition significantly ($p < 0.05$) increased runoff TSS concentration at CN ≥ 50, but in no case was it significantly different from municipal biosolids without biochar. When added to horse manure, biochar significantly ($p < 0.05$) decreased runoff concentrations of NH_3-N, TSS, and FC throughout nearly the entire range of CN values observed. No biochar effect was found for runoff concentrations of TKN and TP, although the concentrations of these parameters were CN-dependent.

The findings of this study indicate that some of the beneficial effects of biochar addition (e.g., retention of N and microbes) found in column studies and small-scale runoff studies are transferrable to upscaled field plot studies. Future work involving biochar's effects on runoff of additional constituents (e.g., metals), the influence of biochar and organic amendment characteristics, mixing rates, and economic considerations can be helpful in more fully exploring biochar's potential as a runoff quality enhancement. Results from this study also indicate the direct influence of soil hydraulic properties on runoff quality; if future experimental designs do not effectively block for these properties, then the properties must be characterized to isolate their effects from the effects of biochar addition.

Acknowledgements

This is Publication No. 16-05-045 of the Kentucky Agricultural Experiment Station and is published with the approval of the Director. This work is supported by the USDA National Institute of Food and Agriculture (NIFA) Hatch Multistate Project under Grant No. 1006093.

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