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Biosolids Applications Affect Runoff Water Quality following Forest Fire

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ABSTRACT

Soil erosion and nutrient losses are great concerns following forest wildfires. Biosolids application might enhance revegetation efforts while reducing soil erodibility. Consequently, we applied Denver Metro Wastewater District composted biosolids at rates of 0, 40, and 80 Mg ha^{-1} to a severely burned, previously forested site near Buffalo Creek, CO to increase plant cover and growth. Soils were classified as Ustorthents, Ustochrepts, and Haploborols. Simulated rainfall was applied for 30 min at a rate of 100 mm h^{-1} to 3- × 10-m paired plots. Biosolids application rates did not significantly affect mean total runoff ($p < 0.05$). Sediment concentrations were significantly greater ($p < 0.05$) from the control plots compared with the plots that had received the 80 Mg biosolids ha^{-1} rate. Biosolids application rate had mixed effects on water-quality constituents; however, concentrations of all runoff constituents for all treatment rates were below levels recommended for drinking water standards, except Pb. Biosolids application to this site increased plant cover, which should provide erosion control.

High-intensity wildfires can cause significant adverse effects on vegetation and soil physical and chemical properties. Fire can remove surface litter and herbaceous cover, thus leaving the remaining substrate susceptible to erosion, and can volatilize nutrients and oxidize soil organic matter, which may result in an impervious hydrophobic layer in the soil profile (Wells et al., 1979). This condition generally exacerbates the potential for severe soil erosion with increased runoff, especially on relatively steep slopes. The application of biosolids (sewage sludge) might improve soil chemical and physical properties and mitigate the potential for severe erosion; however, biosolids addition requires judicious management to avoid some environmental risks such as overapplication of N and P and excessive accumulation of toxic elements in plants and soils.

Land application of biosolids will probably increase in the future as disposal practices such as landfilling, incineration, and ocean dumping are banned or become too expensive (Pierzynski, 1994). Because biosolids contain both macronutrients and micronutrients that are essential for plant growth, the application of biosolids to degraded soils may be an economical alternative to inorganic fertilizers (Fresquez et al., 1990).

Biosolids application can improve soil fertility, ultimately increasing vegetative cover and production. Cole et al. (1986) found that biosolids significantly increased total forest production in the Seattle, WA area. Other studies have shown that biosolids can improve semi-arid shrublands and rangelands (Pierce et al., 1998; Harris-Pierce et al., 1995). Denis and Fresquez (1989) found that soil chemical properties as well as the soil microbial community improved with increasing application rates of biosolids. The increase in plant cover after biosolids addition can result in significantly greater ground cover, thereby reducing the impact of raindrops and detachment of soil particles (Thurow et al., 1987).

The relatively high amount of organic matter in biosolids can improve the physical properties of soil (e.g., increased infiltration rates) (Bruggeman and Mostaghimi, 1989). Tester (1990) found that organic matter introduced to the soil from biosolids application reduced runoff and soil erosion. Results from other studies indicate that biosolids are a useful means to improve production and achieve ecological stability. Restoration of ecosystems through the use of biosolids is common. Research has been conducted on the effects of municipal biosolids application as fertilizer and soil amendment on forest lands since the 1970s. Cole et al. (1986) found that biosolids significantly increased total forest production. Other studies have shown that biosolids can improve overgrazed rangelands and semi-arid shrublands (Pierce et al., 1998, Harris-Pierce et al., 1995). Denis and Fresquez (1989) found that soil chemical properties as well as the soil microbial community improved with increasing application rates of biosolids. At the same time, it was found that semiarid plant productivity increased with increasing biosolids application rates (Fresquez et al., 1990). However, there is no available research that has focused on the biosolids application following forest fire and subsequent erosion remediation.

The objectives of this study were to (i) determine runoff quantity and (ii) determine runoff quality from a burned site as affected by biosolids application rate. Our hypotheses are that application of biosolids to forest-fire sites will (i) decrease runoff, (ii) decrease sediment concentration because plant canopy cover will increase, and (iii) increase the runoff-water concentration of NH_4–N, NO_3–N, total N, P, Ba, Ca, Cd, Cr, Cu, Pb, and Zn since these are common biosolids constituents.

MATERIALS AND METHODS

We initiated this study in spring 1997 at the 1996 Buffalo Creek fire site in Pike National Forest, approximately 22 km southeast of Pine Junction, CO. The site is located at 39°22′4.4″N, 105°14′26.5″W at an average elevation of 2235 m.

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Abbreviations: TKN, total Kjeldahl nitrogen.

Table 1. Seeded grasses, species cover, and total canopy cover at the Buffalo Creek study site, June 1999.

Species	Common name	Biosolids rate, Mg ha^{-1}		
		0	40	80
		% cover		
Elymus macrourus (Turcz.) Tzvelev	thickspike wheatgrass	18	25	24
Elymus lanceolatus (Scribn. & J. G. Sm.) Gould subsp. *lanceolatus*	streambank wheatgrass	23	28	39
Nassella viridula (Trin.) Barkworth	green needlegrass	2	14	5
Bromus marginatus Nees ex Steud.	mountain brome	–	–	–
Poa secunda J. Presl	Sandberg bluegrass	–	–	–
Festuca idahoensis Elmer	Idaho fescue	–	–	–
Festuca arizonica Vasey	Arizona fescue	–	–	–
Total		47	69	71

Mean annual precipitation at the site is 520 mm and mean annual temperature is 8°C. Nearly 75% of the annual precipitation occurs in spring or summer, while fall and winter months are comparatively dry. Ponderosa pine (*Pinus ponderosa* P. Lawson & C. Lawson) and Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] dominated the site before the wildfire. The U.S. Forest Service broadcast-seeded the plots with a grass mixture at the rate of 34 kg ha^{-1} (Table 1) following biosolids application and discing in May 1997. We conducted rainfall simulations in June 1999, approximately 3 yr following the fire and about 2 yr after biosolids incorporation and grass seeding.

Two grasses, thickspike wheatgrass [*Elymus macrourus* (Turcz.) Tzvelev] and streambank wheatgrass [*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould subsp. *lanceolatus*], dominated the study site in 1999 (Table 1). Canopy cover was determined by the point method (Bonham, 1989). We recorded cover for 100 points along two randomly placed transects in each rainfall plot.

Soils at the study site are loamy-skeletal, mixed Typic Ustorthents; loamy-skeletal, mixed Typic Ustochrepts; and loamy-skeletal, mixed Typic Haploborols. These soils are 25 to 50 cm deep and have developed from Pike's Peak granite. Surface textures of these soils are gravelly clay-loam to gravelly sandy-loam. We found inclusions of each soil in every plot.

Simulated rainfall plots were established in pairs on slopes ranging from 10 to 16%. We assumed that slope would not affect runoff, since Harris-Pierce et al. (1995) found no differences between runoff on plots with approximately 8 or 15% slopes used in a rainfall-simulation study on a grassland site near Fort Collins, CO. Bulldozers were used to clear trees and to smooth the surface so that a dump truck could safely apply the biosolids. Plots either received no biosolids (control) or composted biosolids (40 or 80 dry Mg ha^{-1}) from Denver Metro Wastewater District in Spring 1997 (Table 2). Compost application was accomplished using calibrated broadcasting with a dump truck fitted with rear discharge manure-spreading capabilities. Controls and biosolids treatments were randomly located and replicated four times for a total of 12 experimental plots in a randomized complete block design. Biosolids were incorporated in the soil to a depth of 10 to 20 cm with a commercial disc. Control plots were also disced to a depth of 10 to 20 cm. The disc was large enough to work through tree stumps and roots remaining on the soil surface after the bulldozing operation. After biosolids application, discing, and then seeding, a chain-link fence was dragged on the surface to cover the seed and smooth the soil.

Table 2. Nutrient and trace mental composition (dry weight basis) of Denver Metro composted biosolids applied to the Buffalo Creek site, May 1997.

Constituent	Amount	Constituent	Amount
	g kg^{-1}		mg kg^{-1}
Organic N	51.0	Ag	22.2
NH_4–N	5.22	As	3.1
NO_3–N	0.45	Hg	1.6
Na	0.90	Se	1.6
K	3.6	Pb	74.5
P	32.0	V	14.3
Al	14.0	Cu	386
Fe	10.0	Zn	490
		Ni	63.9
		Mo	15.9
		Cd	3.9
		Cr	134
		Sr	211
		B	33.5
		Ba	338

In June 1999 before the rainfall simulations, we determined in the top 5 cm of soil at two locations within each plot the bulk density using a core sampler, antecedent volumetric moisture content, and the sorptivity (measure of instantaneous infiltration rate; Smith, 1999). As suggested by Smith (1999), we determined sorptivity using a 10-cm-diameter by 10.5-cm-high ring, pushed approximately 1 cm into the surface, and a 1-cm head of water. After determining the time required for the 1 cm of water to infiltrate, we calculated sorptivity (Smith, 1999) as:

$$S = I/t^{0.5} \qquad [1]$$

where S = sorptivity, cm s$^{-0.5}$; I = cumulative infiltrated depth, cm (I = 1 cm for our tests); and t = time for infiltration of 1-cm head, s.

A border consisting of 15-cm-high galvanized metal edging was installed to a depth of 6 cm around each of the twelve 3- × 10-m plots to exclude runon and to prevent runoff loss before measurement. We collected runoff in each plot in troughs at the lower edge of each plot after directing flow through critical-depth flumes. A bubble flow meter was used to measure the depth of the water flowing through the flumes. We recorded flow measurements at 2-min intervals.

In June 1999, we used a rainfall simulator from the U.S. Geological Survey to apply water to the plots. The simulator consisted of 18 revolving sprinkler heads mounted on 3-m standpipes (Lusby and Lichty, 1983). Water was applied simultaneously to two plots and covered the entire area of the plots plus overlap of the plot borders. We collected samples to determine antecedent moisture conditions to a depth of 7.5 cm immediately preceding each rainfall simulation. We applied simulated rainfall to each pair of plots for 30 min at the rate of approximately 100 mm h^{-1}. Harris-Pierce et al. (1995) and Aguillar and Loftin (1992) used this same rate for rainfall simulations on grasslands in Colorado and New Mexico, respectively. Total rainfall and application rate were measured by 12 plastic gauges in each pair of plots. We conducted only one rainfall simulation on each pair of plots.

We divided runoff quantity by the total amount of applied simulated rainfall to calculate the amount of runoff for the amount of rainfall input (Harris-Pierce et al., 1995). Runoff percentages [(runoff × 100)/rainfall] were computed for each treatment (Ward and Bolin, 1989).

We collected runoff samples in 0.5-L plastic bottles at 5-min intervals during the single rainfall simulation conducted on each pair of plots. Samples were immediately placed in ice chests and held at 4°C (Stednick, 1991). We then transported the samples to the lab in an ice chest for subsequent analyses

Table 3. Bulk density, volumetric moisture content in the top 7.5 cm of soil, and sorptivity (a measure of instantaneous infiltration rate) of runoff plots at the Buffalo Creek study site, June 1999.

Biosolids rate	Bulk density†	Volumetric H_2O content†	Sorptivity†
Mg ha^{-1}	g cm^{-3}	cm^3 cm^{-3}	cm s$^{-0.5}$
0	1.45	0.0073	0.152
40	1.25	0.0080	0.125
80	1.35	0.0171	0.158
Standard error	0.12	0.0066	0.036

† All statistical results showed nonsignificant effects of biosolids application rate at $p = 0.05$.

for Na, K, B, P, Al, Fe, Cu, Ni, Mo, Pb, Cd, Cr, Ba, Mn, and Zn. Samples analyzed for total metal concentrations were preserved with concentrated nitric acid (5 mL HNO_3 L^{-1} of water sample). We collected separate samples for total Kjeldahl nitrogen (TKN), NH_4–N, and NO_3–N. We obtained sediment samples on each plot at each 5-min interval in 0.5-L plastic bottles and subsequently dried the unfiltered samples at 105°C to determine sediment mass.

Nitrate in water samples was determined by ion chromatography, USEPA Method 300.0 (USEPA, 1983). Ammonium content was determined by the automated phenolate colorimetric method, USEPA Method 350.1 (USEPA, 1983). We used Bremner's (1996) procedure for determining TKN (organic N plus NH_4–N). Concentrations of metals were determined by inductively coupled plasma emission spectroscopy (ICP), USEPA Method 200.0 (USEPA, 1983).

We conducted statistical analyses on all data using analyses of variance mean separation tests, which we performed when significant treatment effects were detected using least significance difference (LSD) at $p = 0.05$.

RESULTS AND DISCUSSION

Analyses completed in June 1999 within 2 wk prior to rainfall simulation showed that biosolids application did not significantly affect ($p = 0.05$) bulk density, soil moisture content, or sorptivity (Table 3). The relatively high standard errors for each parameter indicate that these measurements exhibited a great deal of variability. Mean antecedent volumetric moisture contents taken the same day as the rainfall simulations were 0.056, 0.048, and 0.069 cm^3 cm^{-3} for the control and 40 and 80 Mg ha^{-1} biosolids rates, respectively.

Even though mean runoff values were smaller on the biosolids treatments, biosolids application rate did not statistically affect runoff ($p = 0.05$; Table 4), thus we cannot accept our first hypothesis concerning runoff reduction with biosolids addition. Control plots had a range of 18 to 53% of rainfall input lost as runoff, whereas the plots that had received the 40 Mg ha^{-1} rate ranged from 1 to 12% and those that received the 80 Mg ha^{-1} biosolids rate ranged from 0.5 to 22%. Harris-Pierce et al. (1995), in their work in a shortgrass steppe community, reported ranges of 28 to 65% of rainfall input lost as runoff on control plots while their biosolids plots ranged from 8 to 55%. The proportion of simulated rainfall lost as runoff varied widely on all treatments, which is common on many watersheds. Because of variation in soil surface sealing, bulk density, soil wetability, soil texture, and moisture holding capacity, areas within the same plots may exhibit large differences in infiltration rates. Adding to this complexity are the hydrophobic conditions caused by variability in fire intensity (Pyne et al., 1996). In areas where vegetation biomass is limited prior to a burn, hydrophobicity is usually less. Conversely, where fire consumes large quantities of biomass, hydrophobicity can be quite severe, resulting in low rates of infiltration. Kladivko and Nelson (1979), in their study of biosolids effects on soil properties of an undisturbed area, reported that one application of biosolids had no significant effect on infiltration on two silt loams and a sandy loam in Indiana at the end of the first growing season. They concluded that as the result of spatial heterogeneity in infiltration characteristics a large number of replicates (>10) would be needed to obtain statistically significant infiltration data.

Table 5. Runoff water quality for three rates of Denver Metro composted biosolids at Buffalo Creek, June 1999. Means with different letters within a row are significantly different according to the least significant test at $p = 0.05$.

Constituent	Biosolids rate, Mg ha^{-1} 0 (control)	40	80
Sediment, g L^{-1}	2.37a	1.11b	0.98b
NH_4–N, mg L^{-1}	0.02a	0.13a	0.13a
NO_3–N, mg L^{-1}	0.47a	0.42a	0.73a
TKN, mg L^{-1}†	2.01b	2.22ab	2.60a
P, mg L^{-1}	1.08b	1.24b	2.11a
Ba, mg L^{-1}	0.70a	0.31b	0.32b
Ca, mg L^{-1}	37a	28b	28b
Cd, mg L^{-1}	<0.01a	<0.01a	<0.01a
Cr, mg L^{-1}	0.02a	0.02a	0.03a
Cu, mg L^{-1}	0.02b	0.03b	0.04a
Pb, mg L^{-1}	0.07a	0.07a	0.04b
Zn, mg L^{-1}	0.37a	0.48a	0.46a

† Total Kjeldahl nitrogen.

Biosolids application reduced runoff sediment concentrations (Table 5). Sediment concentrations were significantly reduced by application of 40 Mg ha^{-1} plots compared with the control plots at all sample times except 25 and 30 min, whereas the 80 Mg ha^{-1} significantly reduced sediment concentrations at all times (Fig. 1). Dadkhah and Gifford (1980) studied the influence of vegetation on infiltration rates and sediment production and found that as vegetative cover increased beyond 50%, sediment production decreased exponentially. Canopy cover on our control plots was 47% while can-

Table 4. Average precipitation and runoff produced by a single rainfall event with three Denver Metro composted biosolids application rates at the Buffalo Creek study site, June 1999.

Biosolids rate	Precipitation†	Standard error	Runoff†	Standard error	Runoff/precipitation†	Standard error
Mg ha^{-1}	mm					
0	52.1	3.1	12.4	4.4	0.24	0.10
40	56.4	4.4	2.8	1.6	0.05	0.03
80	49.8	1.5	7.0	2.4	0.14	0.05

† All statistical results showed nonsignificant effects of biosolids application rate at $p = 0.05$.

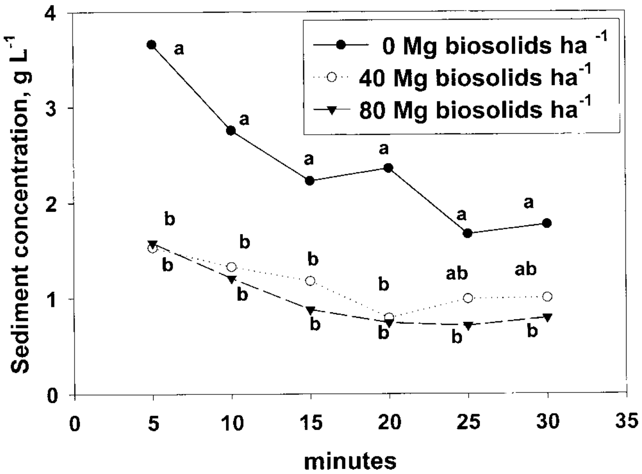

Fig. 1. Runoff sediment concentrations from biosolids treatments during a 30-min rainfall simulation (100 mm h^{-1}) at Buffalo Creek, June 1999. Lowercase letters at each data point represent mean-separation comparisons among the three biosolids application rate treatments at a given time.

opy cover on the 40 and 80 Mg ha^{-1} plots was 69 and 71%, respectively (Table 1). Vegetative cover not only reduces raindrop impact at the soil surface, but also slows overland flow, reducing soil particle transport. These results support our second hypothesis regarding reduction in runoff sediment concentration with biosolids application. Harris-Pierce et al. (1995) found that surface application (not incorporated into the soil) of City of Fort Collins, CO biosolids at rates of 22 and 41 dry Mg ha^{-1} increased sediment loads compared with their control. They postulated that transport of fine biosolids led to this increased sediment loading. They, however, had more than 75% canopy cover on all plots and their mean sediment loads ranged from 0.5 to 1.0 g L^{-1}, while we found mean sediment loads that ranged from 0.7 to 3.7 g L^{-1}. Aguilar and Loftin's (1992) rainfall simulations did not produce any runoff on biosolids-treated plots in New Mexico.

Mean total runoff concentrations of NO_3–N and NH_4–N did not increase with increasing rates of biosolids application (Table 5). Total Kjeldahl nitrogen (TKN), however, was higher in runoff from the 80 Mg ha^{-1} biosolids treatment plots compared with the control plots. Runoff concentrations of these constituents, however, were below USEPA standards for drinking water (USEPA, 1992). We observed no consistent trends in runoff concentrations of NO_3–N, NH_4–N, or TKN over time within and between biosolids rates (data not shown). All NO_3–N levels were less than 2.4 mg L^{-1}, all NH_4–N concentrations were less than 0.4 mg L^{-1}, and all TKN were less than 3.2 mg L^{-1} (Meyer, 2000). Harris-Pierce et al. (1995) found significantly higher average NH_4–N and TKN concentrations in their surface-applied 22 and 41 Mg ha^{-1} biosolids treatments compared with the control. Their NH_4–N and TKN levels on the two biosolids treatments were more than an order of magnitude larger than our average concentrations. Since they conducted their rainfall simulations within 2 wk after biosolids application to their rangeland site, they did not observe detectable NO_3–N in the runoff samples. Nitrification of the NH_4–N in the biosolids did not have a chance to occur to a significant extent, since they had not incorporated the biosolids into the soil surface. Higher concentrations of N seem to occur with surface application (unincorporated) and when runoff happens within 2 wk compared with 2 yr after biosolids incorporation.

Mean total concentrations (mg L^{-1}) of nutrients and metals in runoff exhibited mixed results among the three treatments. Calcium, Mg, Al, Mn, Sr, Ba, and Si concentrations were higher in runoff from the control plots compared with either biosolids application rate (Table 5), probably because of the larger transport of mineral soil in the runoff from the control sites. Sodium, K, P, and Cu runoff concentrations were higher in runoff from plots with the highest biosolids application rate. These elements are significant constituents in the Denver Metro biosolids (Table 2). Total runoff concentrations of Fe, Ti, Zn, Ni, Mo, Cd, Cr, B, As, Se, and Hg did not differ among the three runoff treatments. Lead and V concentrations were significantly lower on the 80 Mg ha^{-1} treatment plots than either the 0 or 40 Mg ha^{-1} rates. As reported by Hooda and Alloway (1993), biosolids addition reduced plant availability of Pb in sandy soils, probably due to adsorption of the metals by the biosolids matrix. Corey et al. (1987) support this postulation. Harris-Pierce et al. (1995) found that their biosolids treatments (22 and 41 Mg ha^{-1}) significantly decreased average runoff concentrations of Al and Fe while biosolids application increased concentrations of Na, K, B, P, Cu, Ni, and Mo. Consequently, we not only have mixed results regarding acceptance of our third hypothesis, we find that a different study reported different results than ours. We attribute most of the inconsistencies between the two studies to the difference in biosolids incorporation and with the timing of simulated-rainfall tests after biosolids addition. Harris-Pierce et al. (1995) did their runoff tests within 2 wk after surface application (unincorporated) of biosolids while we had a lag of about 2 yr between the time we incorporated biosolids to when we conducted the rainfall simulations. Mean total runoff concentrations of potentially toxic substances at all treatment rates were less than the levels recommended for livestock drinking water reported by Soltanpour and Raley (1989; Table 6) and less than the USEPA drinking

Table 6. Recommended upper limit levels of potentially toxic substances in drinking water for livestock (Soltanpour and Raley, 1989) and according to USEPA (1992) drinking water standards for humans.

Constituent	Livestock drinking water	USEPA standards
	mg L^{-1}	
Al	5.0	–
B	5.0	–
Ba	–	2.0
Cd	0.05	0.005
Cr	1.0	0.1
Cu	0.5	1.3
Pb	0.05	0.01
Se	0.05	–
Zn	24	–
NO_3–N + NO_2–N	100	10

water standards (Table 6), except for the average Pb concentrations in the runoff water from the control and the 40 Mg ha^{-1} treatment (Table 5).

Biosolids application to the Buffalo Creek wildfire site has resulted in an increase in grass-vegetation cover, which in turn has reduced the potential for erosion by decreasing sediment loss. Although total runoff was unaffected by biosolids application, the decreases of sediment concentrations in runoff should help alleviate sedimentation of adjacent water bodies. Because all constituents, except Pb, were below recommended upper limit levels, contamination of surface water by biosolids application from Denver Metro Wastewater District does not constitute a threat to surface water supplies.

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