RUNOFF, EROSION, AND SIZE DISTRIBUTION OF SEDIMENT FROM BEEF CATTLE FEEDLOTS

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Abstract. *The size distribution of sediment in runoff from feedlot surfaces influences erosion rates and settling velocity. The objectives of this study were to: (1) measure runoff, erosion, and size distribution of sediment in runoff from feedlot surfaces containing varying amounts of unconsolidated surface material (USM), and (2) determine the effects of varying runoff rate on erosion and sediment size distribution. Simulated rainfall was applied to 0.75 m wide by 2 m long plots located within feedlot pens. Sieve and pipette analyses were used to measure the diameters of the eroded materials. No significant differences in runoff and erosion were found among the treatments with varying amounts of USM. Values for D_{50}, the size for which 50% of the sediment is smaller, were 36 μm or less for each of the treatments containing varying amounts of USM. The surfaces containing 0 or 6.7 kg m^{-2} of USM had D_{50} values that were significantly greater than those with 13.5 or 26.9 kg m^{-2} of USM. An increase in runoff rate resulted in significantly greater erosion. The proportion of sediment fractions 31 μm and larger consistently increased as runoff rate became greater. No significant differences in D_{50} values were found for runoff rates varying from 0.5 to 9.7 kg min^{-1}. The D_{50} value of 310 μm obtained at a flow rate of 15.3 kg min^{-1} was significantly greater than measurements determined at the other runoff rates. Both erosion and size distribution of sediment in runoff from feedlot surfaces are significantly influenced by runoff rate.*

***Keywords*.** *Beef cattle, Feedlots, Manure management, Manure runoff, Overland flow, Runoff, Sediment size, Sediment transport, Sediment yield, Water quality.*

Environmental regulations have been established that define acceptable standards for runoff control from open-lot livestock production facilities. Runoff control systems prevent sediment from entering streams and lakes and store runoff until it can be land applied (*ASABE Standards*, 2009). Construction, operation, and maintenance requirements for feedlot runoff control structures have been established (Ham, 1999, 2002; Parker et al., 1999).

The size of settling and containment basins is influenced by the quantity of suspended material transported in runoff from the feedlot. Eroded material that accumulates within runoff control structures may substantially reduce storage capacity. As a result, sediment deposited within a runoff control system must be removed periodically to maintain required storage capacity.

Feedlot runoff control systems often include a solids settling basin located above a containment basin. The settling basin helps to prevent much of the eroded sediment from the feedlot from entering and filling the containment basin by allowing the suspended solids to be deposited before the accumulated runoff is discharged. If runoff within a settling basin is discharged before most of the suspended solids have been removed, the conveyance structure to the containment basin may become plugged. The amount of time required for sediment to be deposited within the settling basin is influenced by the size distribution of the sediment.

Vegetative treatment systems (VTS) have been proposed as an alternative to traditional containment structures. A VTS uses forage or grass species to filter contaminants and consume runoff (Koelsch et al., 2006). The reduction in pollutants from a VTS results from sedimentation and infiltration of runoff into the soil profile. A settling basin located upslope from a vegetative infiltration area is a critical component of a VTS. Critical management factors related to VTS operation include maintenance of a dense vegetative stand, sheet flow of runoff across the vegetative infiltration area, and minimization of nutrient accumulation.

Beef cattle feedlots contain USM and consolidated subsurface materials (CSM) (compacted manure and underlying layers) (Woodbury et al., 2001). Manure is removed from the feedlot between cattle production cycles, usually once or twice a year. Manure enrichment, compaction, and moisture content, which depend upon the location of feed and water sources, may vary across the pen surface with time during the production cycle. Pen location has been found to significantly influence feedlot soil characteristics (Gilley et al., 2008).

Submitted for review in May 2009 as manuscript number SW 8014; approved for publication by the Soil & Water Division of ASABE in February 2011.

This article is a contribution from the USDA-ARS in cooperation with the Agricultural Research Division, University of Nebraska, Lincoln.

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The amount of USM on a feedlot surface may influence the quantity and characteristics of sediment transported in runoff. One management alternative that has been proposed to improve pen conditions is the periodic removal of USM from feedlot surfaces. Equipment used for feedlot manure removal following a feeding cycle could also be used to remove USM. A skid loader could be especially useful in removing USM. The objectives of this study were to: (1) measure runoff, erosion, and size distribution of sediment in runoff from feedlot surfaces containing varying amounts of USM, and (2) determine the effects of varying runoff rate on erosion and sediment size distribution.

Materials and Methods

Study Site Description

This study was conducted at the U.S. Meat Animal Research Center near Clay Center, Nebraska, during the summer of 2008. Average long-term annual precipitation at the study site is approximately 728 mm. Steer calves born during the spring of 2007 were placed in the feedlot in September 2007 at a rate of 36 head per pen and were fed a corn-based diet. The 30 m × 60 m feedlot pens were constructed on a Hastings silt loam soil (fine, smectitic, mesic Pachic Argiustolls). The central mound was built with soil excavated from the C-horizon of a Hastings soil obtained from an off-site location. The C-horizon of the Hastings soil typically contains free carbonates. The experimental plots were located in upslope pen locations within areas with a mean slope gradient of 10.5% that allowed overland flow to drain uniformly from the feedlot surfaces.

Experimental Design

Four feedlot pens were used for this study, and four adjoining 0.75 m wide × 2 m long plots, in turn, were established within each of the pens. Thus, experimental tests were conducted on a total of 16 plots (four pens × four plots per pen). The surface of each of the four plots within a feedlot pen contained varying amounts of USM.

The quantity of USM contained on a specific plot was assigned randomly. The USM on the surface of one of the plots within each pen was left undisturbed. The undisturbed experimental plots contained an average of 6.7 kg m^{-2} of USM (the standard deviation was 1.8 kg m^{-2}). Unconsolidated surface material was completely removed from one of the four adjoining plots, and the plot surface was then left undisturbed. The USM was also completely removed from two other plots within each pen and then replaced at rates of either 13.5 or 26.9 kg m^{-2}. These rates were selected to provide USM values approximately 2 or 4 times greater than the amounts found on the undisturbed plot and provided a range of USM useful for comparison. The USM returned to the plots was obtained from an immediately adjoining undisturbed area at a similar downslope location.

Livestock from an individual pen were removed just prior to plot establishment, and the pen remained unstocked for the duration of the testing period. Livestock remained in the adjoining pens until initiation of testing within a particular pen. By using this procedure, the length of time that expired following removal of cattle among individual feedlot pens remained constant.

Rainfall Simulation Procedures

Water used in the rainfall simulation tests was obtained from a hydrant near the feedlot complex and stored in a 3800 L trailer-mounted plastic tank. Rainfall simulation procedures adopted by the National Phosphorus Research Project (NPRP) were employed in this study (Sharpley and Kleinman, 2003). Plot borders consisted of prefabricated sheet metal boundaries enclosing three sides of each plot and a sheet metal lip located at the bottom that emptied into a collection trough. The trough extended across the plot and diverted runoff into plastic drums. Two rain gauges were placed along the outer edge of each plot, and one rain gauge was located between the paired plots.

A portable rainfall simulator based on the design by Humphry et al. (2002) was used to apply rainfall simultaneously to paired plots. The rainfall simulator operated for 30 min at an intensity of approximately 70 mm h^{-1}. A storm in this area with this intensity and duration has approximately a five-year recurrence interval (Hershfield, 1961). Two additional rainfall simulation runs were conducted for the same duration and intensity at approximately 24 h intervals.

Members of the NPRP jointly selected a rainfall intensity of 70 mm h^{-1} as a standard. Rainfall simulation tests conducted at this intensity allowed runoff to occur from experimental sites with varying infiltration characteristics. By using the same design intensity, researchers at different locations were able to better compare and contrast their experimental results.

The plastic drums were weighed to determine total runoff volume after completion of each of the three rainfall simulation runs. A runoff sample was then obtained for analysis of size distribution of sediment, which was performed within a few hours following sample collection. An additional sample obtained for sediment analysis was dried in an oven at 105°C and then weighed to determine sediment concentration.

The rainfall simulation protocols established by the NPRP were followed during each of the three rainfall simulation runs (Sharpley and Kleinman, 2003). Additional testing was then conducted on the experimental plots to identify the effects of varying flow rate on size distribution of sediment. Overland flow discharge within individual pens increases with downslope distance. If the flow rate from a plot of a given length is known, then the effective plot length for other discharge rates can be estimated.

The addition of inflow to the test plots to simulate greater slope length is a well established experimental procedure (Monke et al., 1977; Laflen et al., 1991). When adding additional inflow, it is assumed that the test section is of sufficient length to allow soil erosion variables to become fully developed. Since the water introduced at the top of the test plot did not contain sediment, it was assumed that the test section was long enough to allow representative detachment and transport processes to become established. Feedlot surface materials removed by raindrop impact appeared to have been of sufficient quantity to meet the transport capacity requirements of the overland flow contained within the test plot (Gilley et al., 1985a, 1985b).

After rainfall had been applied for 30 min during the third simulation run, runoff was diverted into a 0.18 m HS flume on which a stage recorder was mounted to measure discharge rate (fig. 1). Inflow was then added in four successive increments at the top of the plots to produce average runoff rates of 5.0, 8.4, 9.7, and 15.3 kg min^{-1}. The flow rates employed

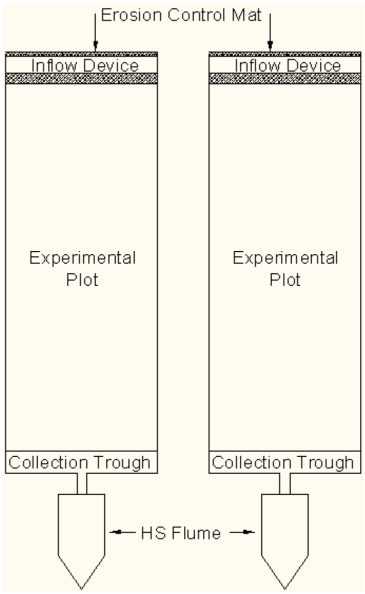

Figure 1. Schematic showing a pair of experimental plots, inflow devices, collection troughs, and HS flumes.

in the study provided a range of runoff values useful for comparison. Runoff and erosion measurements obtained during the 30 min before the addition of inflow were included in the analyses.

A mean runoff rate of 0.5 kg min^{-1} was measured without the addition of inflow. The largest mean runoff rate resulting from inflow addition was 15.3 kg min^{-1} or approximately 31 times the smallest value. The use of runoff quantities substantially larger than 15.3 kg min^{-1} did not seem justified for the size of the plots used in this study. Three additional inflow quantities were selected to provide intermediate runoff rates useful for comparison.

A 2.5 cm diameter plastic tube that extended across the top of the plot served as an inflow device. Several holes were drilled into the plastic tube to allow water to be introduced uniformly across the plot surface. A gate valve and associated pressure gauge located on the inflow device was adjusted to provide the desired flow rate.

A narrow mat was placed on the soil surface beneath the inflow device to prevent scouring and distribute flow more uniformly across the plot. Flow addition for each inflow increment usually occurred for approximately 8 min. This was the period of time typically required for steady-state flow conditions to become established and samples for nutrient and sediment analyses to be collected.

A single tube was used to provide two inflow quantities. Two larger inflow quantities were introduced using a second inflow tube with larger outlet holes. There was not a large difference in discharge rate between inflow rates two and three due to the sizes of outlet holes used in the pipes and the pressure supplied by the pump located on the storage tank.

Particle Size Analyses

The runoff samples were wet sieved within a few hours after collection, as suggested by Meyer and Scott (1983). Sand-sized fractions were determined by washing the runoff samples through sieves with 1000, 500, 250, 125, and 63 μm openings. Each sieve was gently and thoroughly washed. The material passing through the 63 μm sieve was used for pipette analyses.

Sediment sizes of 31, 16, 8, and 4 μm were determined using the pipette withdrawal procedures proposed by Guy (1969) and a special 25 mL pipette (Day, 1965) to facilitate withdrawing and dispensing the sample. Guy (1969) suggested that particles greater than 62 μm be classified as sand, that silt-sized particles vary from 4 to 62 μm, and that particles less than 4 μm be classified as clay.

The pipette method of particle size analysis is based on Stokes' law. This procedure assumes that the particles are spherical, of uniform density, and settle independently of each other. In this study, it was assumed that the specific gravity of sediment was 2.65. The time of pipette withdrawal was adjusted to account for temperature-induced variations in viscosity.

Statistical Analyses

Analysis of variance (ANOVA) was performed to determine if runoff and erosion measurements were significantly affected by the amount of USM on the feedlot surface. The effects of USM and runoff rate on erosion values were also examined using ANOVA. The least significant difference (LSD) test was used to identify significant differences in erosion measurements among runoff rates. A probability level <0.05 was considered significant.

The Mixed Procedure of SAS (SAS, 2003) was used to determine the effects of varying amounts of USM on D_{50} values. The effects of varying runoff rate on D_{50} values were identified using the GLM procedure of SAS. Differences among experimental treatments were identified using the LSD test. A probability level <0.05 was considered significant.

Results and Discussion

Runoff and Erosion as Affected by USM

Runoff and erosion values, which ranged from 14 to 23 mm (approximately 35 mm of rainfall was applied) and from 0.45 to 0.65 Mg ha^{-1}, respectively, decreased as the amount of USM on the feedlot surface became larger (fig. 2). The reduction in erosion values with increasing amounts of USM is attributed to smaller runoff rates and associated decrease in sediment transport capacity. Although runoff and erosion measurements decreased with increasing amounts of USM, ANOVA indicated that differences among experimental treatments were not significant; p-values obtained for the

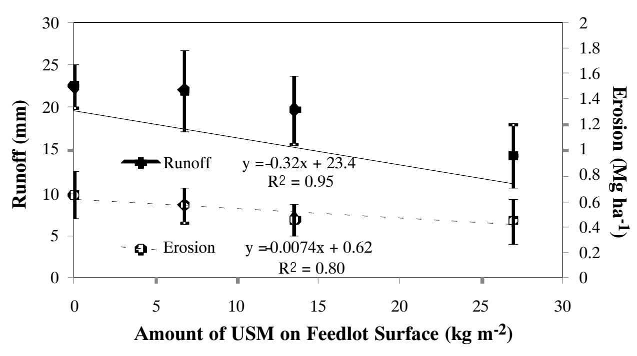

Figure 2. Runoff and erosion values for the feedlot surfaces containing selected amounts of unconsolidated surface material (USM). Vertical bars represent one standard deviation of the mean value.

runoff and erosion measurements were 0.46 and 0.74, respectively.

Gilley et al. (2007) measured runoff and erosion from a cropland site during the year following application of beef cattle manure. The Aksarben (formerly Sharpsburg) silty clay loam on which the field tests were performed in southeast Nebraska near Lincoln is classified as a fine, smectitic, mesic typic Argiudoll. Mean runoff and erosion values under tilled conditions were 23 mm and 0.52 Mg ha^{-1}, respectively (approximately 35 mm of rainfall was applied). Thus, little variation in runoff and erosion values was found between the tilled Arksarben silty clay loam soil and the feedlot site that was constructed from a Hastings silt loam soil. The runoff and erosion measurements may have been different if tests were conducted on sites with substantially different soil characteristics.

Both detachment and transport mechanisms influence erosion on interrill areas (Gilley et al., 1985a, 1985b). In the absence of concentrated flow, raindrop impact is the principal mechanism providing soil particles for transport by overland flow. A relatively large supply of highly erodible material can be assumed to be available for transport on feedlot surfaces containing USM. Therefore, it can be assumed that sediment transport capacity and not the availability of sediment is the constraint in this system.

Erosion measurements were greater from the plots containing CSM even though the surfaces were composed of compacted materials. The larger erosion values were thought to be caused by reduced infiltration and greater runoff volumes (fig. 2). More than enough materials to meet sediment transport capacity requirements appeared to be available on the feedlot surfaces containing both USM and CSM.

The erosion values obtained in this study can serve as an aid in the design of runoff collection ponds and containment structures. Sediment deposited within runoff control facilities must be removed periodically to restore storage capacity. If the quantity of USM on a beef cattle feedlot surface can be estimated, then figure 2 can be used to predict the amount of sediment delivered to the runoff control facilities for a rainfall input of 35 mm.

Runoff curve numbers (CN) are used to estimate runoff quantities from feedlot areas (Koelliker et al., 1975). The CN incorporates the effects of soil type, land use, treatment practices, and hydrologic conditions on runoff (Wensink and Miner, 1975). A mean CN of 89 was calculated for the wet feedlot surfaces examined in this study. This value is similar to the CN of 90 recommended by Sweeten (1991) for unsurfaced feedlots. Annual runoff estimates for unsurfaced feedlots were reported to vary from 15% of mean annual precipitation in central North Dakota to approximately 30% in central Texas (USDA-NRCS, 1992).

Size Distribution of Sediment as Affected by USM

For each of the experimental treatments, D_{50} values were 36 µm or less. Smaller-sized sediment materials remain in suspension for greater periods of time and are more easily transported by overland flow. A p-value of 0.04 was obtained for D_{50} values on the feedlot surfaces containing varying amounts of USM, which indicated that significant differences existed among experimental treatments.

The D_{50} values for the feedlot surfaces containing 0 or 6.7 kg m^{-2} of USM were significantly greater than those

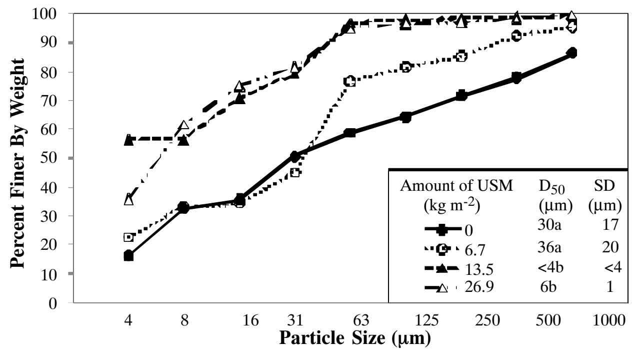

Figure 3. Size distribution of material eroded from feedlot surfaces containing selected amounts of unconsolidated surface material (USM). Differences in D_{50} values, the size for which 50% of the sediment is smaller, are significant at the 5% level (least significant difference test), if the same letter does not appear. Standard deviation values are designated as SD.

measured for feedlot surfaces containing 13.5 or 26.9 kg m^{-2} of USM (fig. 3). No significant difference in D_{50} values was found between the surfaces containing 13.5 or 26.9 kg m^{-2} of USM. A decrease in runoff rate on the feedlot surfaces with greater amounts of USM may have reduced the ability of overland flow to transport sediment materials with larger particle diameters.

Since unconsolidated materials were absent on the surfaces containing CSM, suspended materials transported by overland flow can be assumed to be detached by raindrop impact. In contrast, a relatively large quantity of material was available for transport by overland flow on the feedlot surfaces containing USM. Some of the aggregated materials on the feedlot surfaces with USM may have been broken down into smaller-sized particles as a result of raindrop impact. Thus, an increased number of silt and sand sized materials may have been present on the surfaces containing USM and those materials are more easily transported by overland flow.

Gilley et al. (1986) measured the effects of varying amounts of corn residue on the size distribution of sediment eroded from a Monona soil (fine-silty, mixed mesic typic Hapludolls) located in southwestern Iowa near Treynor. On a recently tilled soil with varying amounts of corn residue, D_{50} values for the eroded sediment varied from 10 to 29 µm. In the present study, the D_{50} values for sediment eroded from the feedlot surfaces constructed from a Hastings silt loam soil ranged from <4 to 36 µm (fig. 3). Thus, little variation in D_{50} values was found between the cropland and the feedlot site. Again, as was true for the soil measurements, D_{50} values may have been different if tests were conducted on sites with substantially different soil characteristics.

The diameter of materials transported in runoff from feedlot surfaces influences the amount of time required for suspended materials to be deposited within a settling basin. Ideally, most of the suspended material within a runoff storage facility should be deposited before the accumulated runoff is discharged.

Gilbertson et al. (1972) found in laboratory tests that 40% of total solids transported in runoff settled in 16 to 18 min. Debris basins were found by Gilbertson and Nienaber (1973) to remove 71% of the suspended solids transported from feedlot surfaces. Lott et al. (1994) recommended use of a settling velocity of 0.003 m s^{-1} for feedlot manure.

Table 1. Erosion measurements as affected by USM and runoff rate.

Variable		Erosion[a] ($kg\ ha^{-1}\ min^{-1}$)
USM ($kg\ m^{-2}$)[b]	0	75.7
	6.7	34.9
	13.5	38.7
	26.9	47.3
Runoff rate ($kg\ min^{-1}$)	0.5	2.0 d
	5.0	31.6 c
	8.4	62.2 b
	9.7	61.6 b
	15.3	88.5 a
Analysis of variance	(PR > F)	
	USM	0.12
	Runoff rate	0.01
	USM × runoff rate	0.49

[a] Erosion measurements followed by different letters are significantly different at the 0.05 probability level based on the LSD test.
[b] USM = unconsolidated surface material.

Erosion as Affected by Runoff Rate

Runoff rate was found to significantly influence erosion measurements (p = 0.01) (table 1). However, sediment transport was not significantly influenced by varying amounts of USM (p = 0.12). Erosion measurements increased from 2.0 to 88.5 kg ha^{-1} min^{-1} as runoff rate varied from 0.5 to 15.3 kg min^{-1}.

Erosion measurements in this study did not change significantly as runoff rates increased from 8.4 to 9.7 kg min^{-1} (table 1). For the existing plot conditions, a small increase in flow rate did not result in significantly greater sediment transport. However, erosion values became much larger when flow rate was increased to 15.3 kg min^{-1}.

The regression equation shown in figure 4 can be used to estimate sediment transport from feedlot surfaces as affected by runoff rate. The equation was derived for runoff rates varying from 0.5 to 15.3 kg min^{-1}. The equation may not provide reliable estimates for feedlot conditions substantially different from those existing in this study.

Greater sediment transport capacity results from increased flow rate (Gilley et al., 1985a). Increased sediment transport capacity, in turn, can result in greater erosion if a sufficient amount of material is available for transport by overland flow (Gilley et al., 1985b). For the flow conditions examined in this investigation, it appears that transport capacity may be the variable limiting sediment transport from feedlot surfaces.

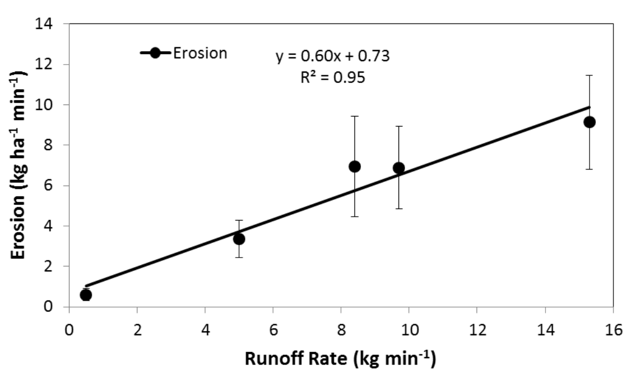

Figure 4. Erosion values as affected by runoff rate for the feedlot surfaces. Vertical bars represent one standard deviation of the mean value.

Gilley et al. (2007) measured runoff and erosion from an Aksarben silty clay loam soil in southeast Nebraska near Lincoln with varying amounts of corn residue. Erosion values increased from 8.2 to 103 kg ha^{-1} min^{-1} as runoff rate varied from 1.1 to 15.3 kg min^{-1}. In this study, erosion values on the feedlot pens constructed from a Hastings silt loam soil increased from 2.0 to 88.5 kg ha^{-1} min^{-1} as runoff rate varied from 0.5 to 15.3 kg min^{-1}. Thus, little difference in erosion measurements was found between the selected beef cattle feedlot and cropland sites.

Erosion values were found in this study to increase significantly as runoff rates became greater. Runoff rates can be expected to increase as the upslope contributing area becomes larger. A feedlot design that reduces the upslope contributing area should serve to decrease sediment transport. However, additional pens would be required to maintain total feedlot capacity.

Size Distribution of Sediment as Affected by Runoff Rate

Substantial variations in sediment size distribution existed among experimental treatments (fig. 5). In general, the proportion of larger-sized sediment fractions transported in runoff increased as runoff rate became greater. Significant differences in D_{50} values were found among the varying runoff rates (p = 0.01). More than 50% of the sediment transported by overland flow at runoff rates varying from 0.5 to 9.7 kg min^{-1} consisted of silt and clay size materials. The D_{50} value of 310 μm obtained at a flow rate of 15.3 kg min^{-1} was significantly larger than the other measurements.

It is possible that an increase in flow rate resulted in a greater sediment transport capacity for runoff rates varying from 0.5 to 9.7 kg min^{-1}. However, the hydraulic shear produced in this study at a runoff rate of 15.3 kg min^{-1} may have been large enough for overland flow to detach feedlot surface materials. As a result, much larger erosion values were measured at the highest flow rate. The amount of sediment transported from feedlot surfaces would increase substantially once critical shear stress values for USM are exceeded. As a result, the storage capacity of collection ponds and containment structures located below the feedlot would be reduced more rapidly.

Gilley et al. (1987) found that significant differences in size distribution of sediment occurred with downslope distance on cropland sites with varying amounts of crop residue.

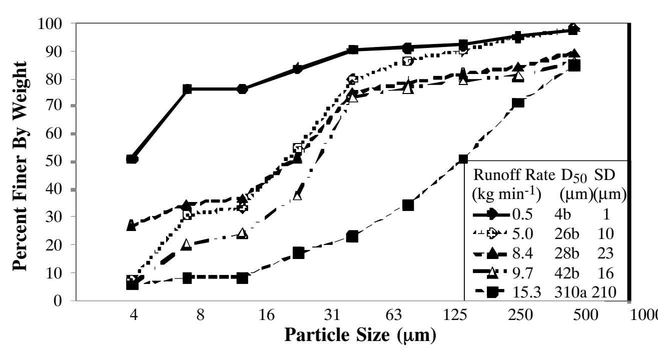

Figure 5. Size distribution of material eroded from feedlot surfaces as affected by selected runoff rates. Differences in D_{50} values, the size for which 50% of the sediment is smaller, are significant at the 5% level (least significant difference test), if the same letter does not appear. Standard deviation values are designated as SD.

The largest percentage of silt and sand sized material usually occurred at the greatest slope length. Differences in runoff rate, runoff velocity, and sediment concentration among experimental treatments were all found to influence the size distribution of sediment.

The data used in this study was collected from only one feedlot located in south central Nebraska. Since feedlot soil materials typically contain only 25% to 30% volatile solids, the texture of the soil on which the feedlot is constructed influences the size distribution of sediment. Thus, the results from this study, which was performed on a feedlot surface constructed from a Hastings silt loam soil, may not be directly applicable for open lots in other locations constructed from substantially different soil types.

Conclusions

Runoff measurements from the feedlot surfaces examined in this study varied from 14 to 23 mm (35 mm was applied), and erosion values ranged from 0.45 to 0.65 Mg ha^{-1}. Varying amounts of USM on the feedlot surface did not significantly affect runoff and erosion measurements. However, erosion measurements were significantly influenced by runoff rate. Rates of erosion increased from 2.0 to 88.5 kg ha^{-1} min^{-1} as runoff rate varied from 0.5 to 15.3 kg min^{-1}.

For each of the feedlot surfaces with varying amounts of USM, D_{50} values were 36 μm or less. The D_{50} values obtained for the feedlot surfaces containing 0 or 6.7 kg m^{-2} of USM were significantly greater than those for feedlot surfaces containing 13.5 or 26.9 kg m^{-2} of USM. Runoff rate was found to significantly influence D_{50} values. Values for D_{50} consistently increased from 4 μm at a runoff rate of 0.5 kg min^{-1} to 310 μm at a runoff rate of 15.3 kg min^{-1}.

Most of the sediment transported in runoff from feedlot surfaces should be deposited in runoff control structures before it is discharged. Runoff control structures should have a large enough storage volume to allow for deposition of suspended sediments. Information obtained in this field feedlot study can be used to aid in the design of runoff collection ponds and containment structures.

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