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ABSTRACT. *Manure has been used effectively to improve crop production and soil properties because it contains nutrients and organic matter. While it is generally accepted that the improved soil properties associated with manure application lead to changes in runoff and soil erosion, few studies have quantified these impacts. Water quality models used to assess watershed management and estimate total maximum daily load must accurately predict loading rates from fields where manure has been applied. This study was conducted to assemble and summarize information quantifying the effects of manure application on runoff and soil loss resulting from natural precipitation events, and to develop regression equations relating runoff and soil loss to annual manure application rates. For selected locations at which manure was added annually, runoff was reduced from 2 to 62%, and soil loss decreased from 15 to 65% compared to non-manured sites. Measured runoff and soil loss values were reduced substantially as manure application rates increased. Regression equations were developed relating runoff and soil loss to manure application for rates ranging from 11 to 45 Mg ha^{-1}, and slope lengths varying from 21 to 24 m. The equations can be used in estimating environmental impacts or to account for manure applications in water quality modeling efforts.*
Keywords. *Animal Waste, Erosion, Land application, Manure application, Runoff, Runoff volume, Soil loss.*

Manure has been used effectively for crop production and soil improvement primarily because it contains nutrients and organic matter (Eghball and Power, 1994). The organic matter content of some soils has been found to increase substantially as a result of the addition of beef cattle manure (Vitosh et al., 1973; Tiarks et al., 1974; Fraser et al., 1988). Soil physical properties such as infiltration, aggregation, and bulk density can be influenced by manure application (Mielke and Mazurak, 1976; Sommerfeldt and Chang, 1985). Improved crop production resulting from land application of manure can also affect soil erosion. These changes in soil properties can have a substantial impact on runoff and soil loss from fields where manure has been applied.

Recently, increased emphasis has been placed on water quality models to help manage water resources. These models are being used to both assess water quality and quantify non-point source loads. Often these models account for land application of manure through increased nutrient loads but adjustments to runoff or soil erosion are rarely made. If adjustments are not made, these models may not accurately represent the impacts of manure application on pollutant loads.

Runoff and erosion rates have been found to be influenced by manure characteristics, loading rates, incorporation, and the time between application and the first rainfall (Mitchell and Gunther, 1976; Westerman et al., 1983; Edwards et al., 1994; Sauer et al., 1999). The addition of either cattle, poultry or swine manure reduced runoff and soil loss (Giddens and Barnett, 1980; Mueller et al., 1984; Bushee et al., 1999). The effects of manure addition on soil erosion have been shown to be influenced by the time required for organic matter in manure to become incorporated in the soil and impact soil properties (Chandra and De, 1982). These results suggest that longer term experiments under field conditions may be necessary to determine the impacts of manure application on runoff and soil loss.

Field plots established to collect runoff from natural precipitation events are well suited for identifying the effects of manure application on annual runoff and soil loss. However, monitoring soil and water losses from natural precipitation events is labor intensive and expensive. As a result, few studies have recently been initiated in which runoff and soil loss have been measured from land application areas. Long et al. (1975) did not report erosion values but did measure significantly less runoff over three years from natural runoff plots (0.04 ha) that were treated with 45 Mg ha^{-1} of dairy manure. Wood et al. (1999) conducted a study on 33 × 33 m plots planted to corn and rye on a silty clay soil with two rates of broiler litter and a fertilized control. They observed a nonsignificant trend toward reduced runoff on the broiler litter treated plots and significantly lower flow-weighted sediment losses than the fertilized control in the second year of the study. Vories et al. (1999) found similar results on 0.6 ha cotton fields where treatments that received poultry litter exhibited

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significantly less total runoff and sediment loss than treatments of commercial fertilizer. However, they noted that sediment concentrations tended to increase on the litter treated plots for rainfall events occurring immediately following application. The objectives of the present study were to assemble and summarize information quantifying the effects of manure application on runoff and soil loss resulting from natural precipitation events, and to develop regression equations relating reductions in runoff and soil loss to annual manure application rates.

Manure Application Studies

In 1928, plans were developed for establishing 10 soil conservation experiment stations at selected locations throughout the United States (United States Congress, 1928). The soil erosion monitoring network was soon expanded to include 35 sites (Wischmeier, 1955). Research programs were initiated at each of these locations to investigate the causes of erosion and to identify practical and effective methods for controlling soil and water losses. At a few of these sites, manure applications were examined as a possible erosion control treatment. The plots described above are the primary data source for this study. A brief description of the locations containing data used in this study is provided below. Additional information on the physical and chemical characteristics of the soils from the soil conservation experiment stations is provided by Middleton et al. (1932, 1934).

Bethany, Missouri

The soil at the Missouri Soil Conservation Experiment Station in Bethany is a Shelby silt loam and the subsoil consists of sandy clay material which contains coarse sand and gravel. At the time the station was established, the area had been cultivated for approximately 35 to 40 years (Smith et al., 1945). Runoff and soil loss from manured and non-manured plots planted to corn were measured over a seven-year period at this station. The manured plots received an annual application of barnyard manure. Both the manured and non-manured plots were tilled by hand using a spade. Runoff and soil loss were also measured over a three-year period on manured and non-manured plots planted to corn, on an area where topsoil was removed. The manure was applied and spaded under each year before corn was planted.

Clarinda, Iowa

The soil at the Clarinda, Iowa, Soil Conservation Experiment Station is a Marshall silt loam. Both surface and subsoil materials are calcareous, having a structure that is loose and friable. The study area had been cultivated for approximately 75 years at the time the station was established (Musgrave and Norton, 1937; Browning et al., 1948). Only data collected on plots where 0.3 m of topsoil was removed were used in this investigation. Manure was applied at rates of 18 and 36 Mg ha^{-1} on fallow plots. Runoff and soil loss were monitored over a three-year period.

La Crosse, Wisconsin

The La Crosse, Wisconsin, Soil Conservation Experiment Station has a Clinton silt loam soil. Subsoils from this series are compact but not highly calcareous. The farm had been cultivated for approximately 70 to 75 years at the time the station was established (Hays et al., 1949). Runoff and soil loss were measured over a six-year period on manured and non-manured plots maintained in a fallow condition. The plots were spaded in the fall and hoed as needed to maintain weed control. Barnyard manure was applied each spring at a rate of 11 Mg ha^{-1}.

Marlboro, New Jersey

The Marlboro, New Jersey, Soil Conservation Experiment Station has a Freehold loamy sand soil. Replicated plots with slope lengths of 21, 43, and 64 m were established at this location. Runoff and soil loss were measured over a five-year period on manured (45 Mg ha^{-1}) and non-manured plots planted to vegetables.

Morris, Minnesota

The Morris, Minnesota, location was not part of the original soil conservation experiment station network. The studies initiated by Young and Holt (1977) and Ginting et al. (1998) were both conducted at the West Central Experiment Station near Morris, Minnesota, on a loam soil from a Forman-Buse complex. Young and Holt (1977) conducted a three-year study in which runoff and soil loss were measured on manured and non-manured plots planted to corn. Solid dairy manure (45 Mg ha^{-1}) was either surface applied in the winter or added in the fall. Both manured and non-manured plots were fall-plowed and smoothed with a harrow. A three-year study on plots planted to corn, with and without the addition of manure, was conducted by Ginting et al. (1998). Both ridge till and moldboard plow tillage systems were selected to represent different intensities of soil disturbance and manure incorporation. Manure was applied at a rate of 56 Mg ha^{-1} at the initiation of the study.

Moscow, Idaho

The Idaho Agricultural Experiment Station near Moscow, Idaho, contains Palouse silt loam soil. The study area had been cropped to winter wheat for 21 years preceding station establishment (Horner et al., 1944). During the investigation, three of the plots received an annual application of 34 Mg ha^{-1} of manure every third year, while no manure was applied to three other plots. All the equipment except the collection tanks were removed during the harvesting and seeding periods to allow farming operations to be conducted with field-scale machinery.

State College, Pennsylvania

The soil on the State College, Pennsylvania, Soil Conservation Experiment Station is a Hagerstown silty clay loam formed in residuum weathered from limestone. At this study site, runoff and soil loss were measured over a three-year period on manured and non-manured plots planted to corn. Manure was applied in the spring to one plot at a rate of 31 Mg ha^{-1}. Both manured and non-manured plots were spaded in the spring prior to planting.

Effect of Manure Application on Runoff and Soil Loss

Runoff and soil loss ratios for the selected sites are shown in tables 1 and 2. To determine the respective ratios, measurements of total runoff or soil loss during the entire study period from a plot on which manure was added were divided by corresponding values from a plot which received no manure. If a soil received no benefit from the addition of manure, runoff and soil loss ratios would be 1.00. Thus, a smaller ratio indicates greater protection against runoff or soil loss.

Since all of the runoff and soil loss values shown in tables 1 and 2 were less than 1.00, the application of manure reduced runoff and soil loss at all of the sites. For the sites identified in table 1, manure was added at intervals greater than one year. Snowmelt would be expected to represent a significant percentage of the total annual runoff and soil loss at La Crosse, Wisconsin, Morris, Minnesota, and Pullman, Washington. At each of these three locations, substantial reductions in runoff and soil loss were found on those plots where manure was applied. Thus, a residual benefit resulting from previous manure additions appears to have been present during those years in which manure was not applied.

For those locations at which manure was added annually (table 2), runoff was reduced from 2 to 62%, and soil loss decreased from 15 to 65%. The incorporation of manure on recently exposed subsoil materials was especially effective in reducing runoff and soil loss. At the Bethany, Missouri, Soil Conservation Experiment Station, the annual application of manure at a rate of 18 Mg ha^{-1} to plots on which corn was planted reduced runoff and soil loss by 25% and 31%, respectively (table 2). Manure was applied at rates of 18 and 36 Mg ha^{-1} to fallow plots on which topsoil was removed at the Clarinda, Iowa, Soil Conservation Experiment Station. Increasing the manure application rate substantially reduced the amount of runoff

Table 1. Runoff and soil loss ratios* for selected sites resulting from intermittent manure application

Location	Reference	Soil Texture	Cropping Practice	Manure Application Rate (Mg/ha)	Manure Application Interval	Measurement Period	Annual Precipitation (cm)	Slope Gradient (%)	Slope Length (m)	Runoff Ratio	Soil Loss Ratio
La Crosse, Wis.†	Hays et al. (1949)	Silt loam	Hay, hay, corn, grain	18	Plowed under proceeding corn and grain	1940-1951	19 - 71	16	22	0.92	0.73
La Crosse, Wis.†	Hays et al. (1949)	Silt loam	Hay, hay, corn, grain	18	Surface applied preceding corn and grain	1940-1951	19 - 71	16	22	0.88	0.75
Morris, Minn.	Ginting et al. (1998)	Loam	Corn	56	Once, at initiation of study under ridge till conditions	1992-1994	54 - 86	12	21	0.85	0.33
Morris, Minn.	Ginting et al. (1998)	Loam	Corn	56	Once, at initiation of study followed by moldboard plowing	1992-1994	54 - 86	12	21	0.89	0.50
Moscow, Idaho†	Horner et al. (1944)	Silt loam	Winter wheat	34	Every third year	1936-1941	42 - 77	8	28	0.55	0.60

* To determine runoff and soil loss ratios, measurements from a plot on which manure was added were divided by corresponding values from a plot which received no manure.
† Values obtained from replicated plots.

Table 2. Runoff and soil loss ratios* for selected sites resulting from annual manure application

Location	Reference	Soil Texture	Cropping Practice	Manure Application Rate (Mg/ha)	Measurement Period	Annual Precipitation (cm)	Slope Gradient (%)	Slope Length (m)	Runoff Ratio	Soil Loss Ratio
Bethany, Mo.	D.D. Smith et al. (1945)	Silt loam	Corn	36	1933-1939	44 - 75	8	39	0.62	0.66
Bethany, Mo.	D.D. Smith et al. (1945)	Silt loam†	Corn	18	1933-1935	65 - 75	8	24	0.75	0.69
Clarinda, Iowa	Musgrave and Norton (1937)	Silt loam†	Fallow	18	1932-1935	54 - 83	9	22	0.88	0.79
Clarinda, Iowa	Musgrave and Norton (1937)	Silt loam†	Fallow	36	1932-1935	54 - 83	9	22	0.68	0.63
State College, Pa.	Wischmeier (1955)	Silty clay loam	Corn	31	1939-1941	69 - 76	13	22	0.47	0.51
La Crosse, Wis.	Hays et al. (1949)	Silt loam	Fallow	11	1933-1938	68 - 110	16	22	0.98	0.85
Marlboro, N.J.‡	Wischmeier (1955)	Loamy sand	Vegetables	45	1938-1942	63 - 79	4	21	0.51	0.35
Marlboro, N.J.‡	Wishmeier (1955)	Loamy sand	Vegetables	45	1938-1942	63 - 79	4	43	0.77	0.70
Marlboro, N.J.‡	Wischmeier (1955)	Loamy sand	Vegetables	45	1938-1942	63 - 79	4	64	0.62	0.83
Morris, Minn.	Young and Holt (1977)	Loam	Corn-manure plowed under	45	1972-1974	52 - 68	9	23	0.40	0.59
Morris, Minn.	Young and Holt (1977)	Loam	Corn-manure surface applied	45	1972-1974	52 - 68	9	23	0.38	0.51

* To determine runoff and soil loss ratios, measurements from a plot on which manure was added were divided by corresponding values from a plot which received no manure.
† Topsoil removed prior to initiation of investigation.
‡ Values obtained from replicated plots.

and soil loss (table 2). The application of manure at a rate of 36 Mg ha^{-1} reduced runoff and soil loss by 32% and 37%, respectively, when compared to similar fallow plots where manure was not applied.

The effects of slope length on runoff and soil loss were examined at the Marlboro, New Jersey, Soil Conservation Experiment Station. Vegetables were planted on loamy sand plots having variable slope lengths (table 2). For slope lengths of 21, 43, and 64 m, soil loss ratios of 0.35, 0.70, and 0.83, respectively, were obtained. Thus, as slope length increased, the effectiveness of manure in reducing soil loss consistently decreased. Since the runoff ratios did not exhibit this same trend, it could indicate that manure is more effective at reducing interrill erosion than rill erosion.

Derivation and Use of Predictive Equations

Varying soil textures, cropping practices, manure application rates, slope gradients and slope lengths were used at the experimental sites shown in tables 1 and 2. With the limited data available and the interrelationship between variables, development of empirical equations covering all of these experimental conditions is not possible. From a review of the available data (tables 1 and 2), runoff and soil loss ratios appear to be strongly influenced by manure application rate.

Since sufficient data were not available to adequately characterize the effects of intermittent manure addition on runoff and soil loss (table 1), only data from sites where manure was applied annually were used in the derivation of the predictive equations (table 2). Slope length has been shown to substantially influence soil loss ratios. Data collected from Bethany, Missouri, Clarinda, Iowa, State College, Pennsylvania, La Crosse, Wisconsin, Marlboro, New Jersey, and Morris, Minnesota (table 2) were used to obtain the predictive equations. However, only data obtained from plots with slope lengths varying from 21 to 24 m were used in the regression analyses.

Plots of runoff and soil loss ratios versus manure application rate for the six sites are shown in figures 1 and 2, respectively. For annual manure application rates ranging from 11 to 45 Mg ha^{-1} it can be seen from figures 1 and 2 that runoff and soil loss ratios consistently decreased as manure application rate increased. It is apparent from figures 1 and 2 that a linear relationship can be used to represent the effects of manure application on runoff and soil loss ratios. However, the runoff and soil loss ratios could have an asymptotic behavior beyond a threshold annual manure application rate. Additional data from plots on which larger amounts of manure were applied would be required to verify and parameterize the asymptotic relationship.

Results of linear regression analyses are presented in figures 1 and 2. It is important that the regression relationships are robust. Thus, the intercepts of the regression equations were forced to equal 1.00. If no manure was applied, the runoff and soil loss ratios would equal 1.00. Linear regression analyses yielded the following relationships:

$$\text{Runoff Ratio} = -0.0123 \text{ Manure Application Rate} + 1 \quad (1)$$

$$\text{Soil Loss Ratio} = -0.0120 \text{ Manure Application Rate} + 1 \quad (2)$$

for manure application rate given in Mg ha^{-1}. The coefficient of determination (r^2) values for equations 1 and 2 were 0.800 and 0.683, respectively.

Cumulative runoff and soil loss values determined from both rainfall and snowmelt events occurring over the entire

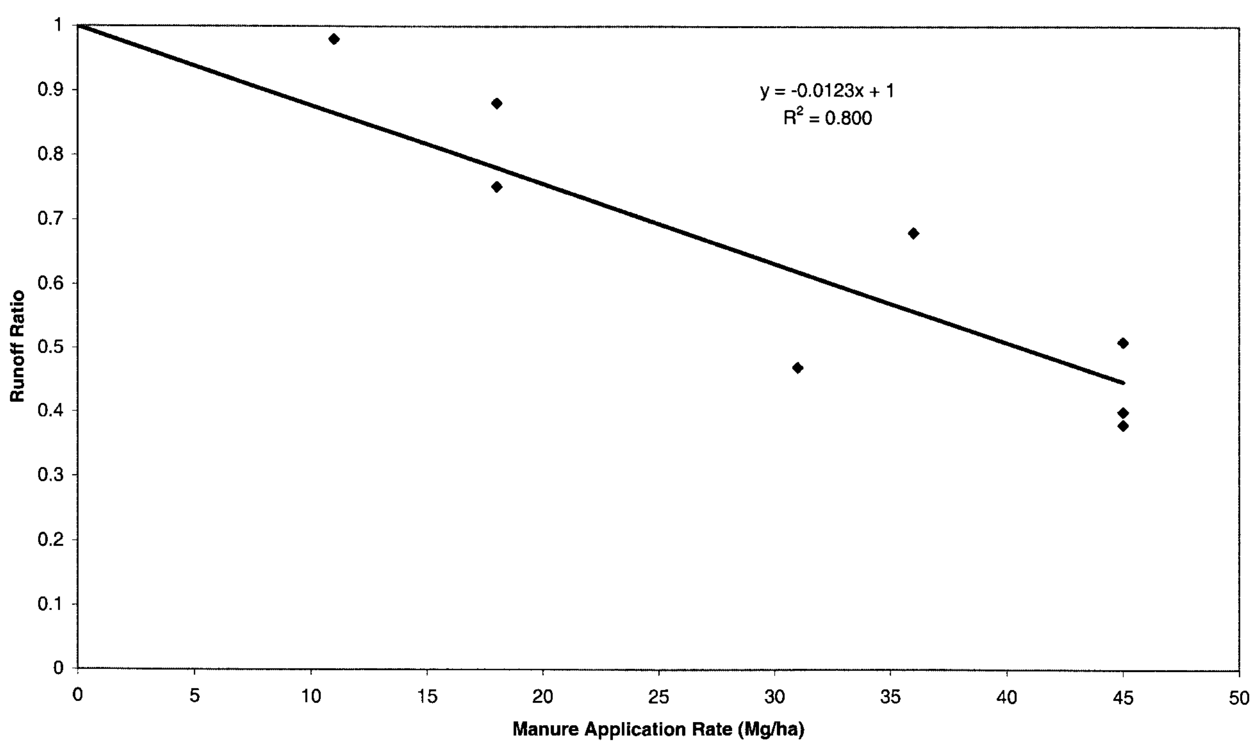

Figure 1–Runoff ratio versus manure application rate.

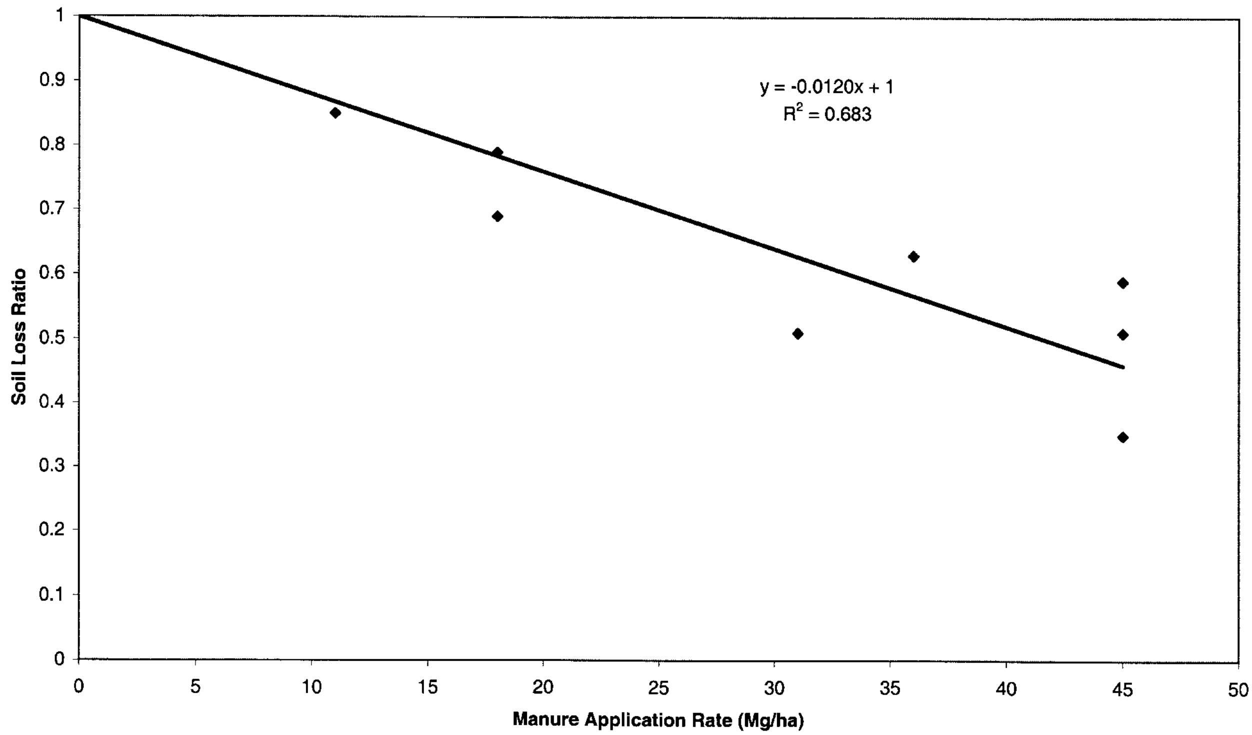

Figure 2–Soil loss ratio versus manure application rate.

study period were used to obtain the runoff and soil loss ratios presented in table 2. For each of the study sites, runoff and soil loss measurements were collected for at least three years. During this extended period, runoff was generated from storms having widely variable intensities and duration. As a result, runoff and soil loss ratios for an individual rainfall or snowmelt event should not be estimated using the information obtained from tables 1 and 2, or equations 1 or 2.

The soil textures of the sites used in the regression analyses included loam, loamy sand, silt loam, and silty clay loam materials. Because of the limited number of study locations, it was not possible to identify the effects of textural characteristics on calculated runoff and soil loss ratios. The runoff and soil loss ratios obtained from the regression equations may not be applicable to sites having textural characteristics substantially different from those identified in this study.

Producers are currently encouraged to apply manure at rates necessary to meet crop nutrient requirements (Eghball and Power, 1999). Applying manure at rates in excess of crop requirements could result in an accumulation of nutrients in the soil. By knowing the nutrient content of the soil at the land application site, the nutrient content of manure, and nutrient availability, the amount of manure required to meet a specific production goal can be predicted. Due to the residual effect of previous manure applications, smaller annual application rates would be required in subsequent years (Eghball and Power, 1999).

The application of manure to cropland areas has been shown in this study to substantially reduce runoff and soil loss. However, water quality concerns must be addressed on areas receiving manure. Phosphorous (P) from manure application may move deep into the soil (Eghball et al., 1996). Ammonia loss into surface waters can result in poisoning of aquatic organisms if the concentration is greater than 2.5 mg L^{-1} (USEPA, 1986). Nitrate in runoff from fields receiving manure can be carried to streams, rivers, and lakes (Eghball and Gilley, 1999). The elevated nitrate concentration of water entering the Gulf of Mexico contributes to the extent of a hypoxia zone which is depleted of oxygen and marine life. Filter strips and grass hedges have been used to substantially reduce the transport of nutrients from cultivated agricultural areas (Eghball et al., 2000). Best management practices should be implemented on cropland areas where manure is applied to control the transport of nutrients to both surface and groundwater.

Conclusions

The application of manure reduced runoff and soil loss on each of the sites on which it was added, even when manure was not applied annually. A residual benefit from previous manure additions appears to have been present during those years in which manure was not applied. For those locations on which manure was added annually, runoff was reduced from 2 to 62%, and soil loss decreased from 15 to 65%. The incorporation of manure on recently exposed subsoil materials was effective in reducing runoff and soil loss. As slope length increased, the effectiveness of manure in reducing soil loss from plots planted to vegetables near Marlboro, New Jersey, consistently decreased. For slope lengths of 21, 43, and 64 m, soil loss ratios of 0.35, 0.70, and 0.83, respectively, were obtained.

The quantity of applied manure strongly influenced measured runoff and soil loss rates. Regression relationships were derived which related runoff and soil loss ratios to annual manure application rates. While these relationships would only be applicable to conditions similar to those under which they were developed, they do represent a first step at attempting to quantify the reductions in runoff and soil loss caused by the application of manure. The regression relationships can be used to estimate the long-term reduction in runoff and soil loss caused by varying manure application rates.

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