

The effect of soil characteristics on erosion and nutrient loss

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ABSTRACT Soil properties which exert a significant influence in the type of erosion occurring, interrill or rill, were compared. Those characteristics most influential in determining a soil's susceptibility to interrill erosion are the degree of aggregation of the surface soil, the stability of soil aggregates to breakdown under raindrop impact, and the type and amount of clay in the soil. The characteristics influencing susceptibility to rill erosion are organic matter content, aggregate density, bulk density of the surface soil, and the dispersion ratio. Some factors affecting the transportability of detached particles were also examined along with their possible effects on nutrient enrichment of sediment.

INTRODUCTION

Concern over water quality associated with runoff and erosion from agricultural lands has emphasized the need for developing improved methods of predicting amounts of sediment and chemicals leaving an area during runoff events. Effects of runoff and erosion are twofold; firstly, sediment and chemicals carried off agricultural areas contribute to nonpoint source pollution and, secondly, loss of soil and plant nutrients resulting from erosion can significantly affect soil productivity. These effects on soil productivity, while acknowledged to exist, are not well defined. An understanding of how these effects relate to productivity is necessary in the development of comprehensive systems for achieving and maintaining maximum long term productivity on the nation's cropland.

Soil erosion from a field is the end result of two physical processes, namely, soil detachment and soil transport. There are generally two types of erosion, that occurring in small channels or rills and that occurring in the nearly level areas between these rills. The type of erosion affects sediment physical characteristics and subsequent detachment and transport of eroded soil particles.

Sediment source is also significant because of the effect on associated nutrient losses and sediment delivery ratios, and subsequent reductions in soil productivity. Whether an eroded soil particle originates from the tilled layer within a rill, or from the surface of the interrill area has significance in estimating the

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potential soil adsorbed chemical yield from a field. This paper attempts to separate some of the factors affecting soil resistance to rill and interrill erosion as they relate to sediment source.

SEDIMENT SOURCE

Interrill detachment

Recently developed sediment detachment equations based on the fundamental mechanics of erosion, attempt to represent the erosion process more realistically by expressing total erosion as the sum of the two separate processes of rill and interrill erosion. One such equation developed by Foster *et al.* (1977) divides the total sediment load into these two components as follows:

$$G = K_i I (bS + c)x + K_r (aS^e) \sigma x^2 \quad (1)$$

where

- G sediment load;
- K_i soil erodibility factor for interrill erosion;
- I a measure of the combined potential of raindrop impact and interrill flow to detach and transport soil particles;
- S slope steepness;
- K_r soil erodibility factor for rill erosion;
- σ excess rainfall rate;
- x distance downslope;
- a, b, c and e are constants.

The rate of detachment by interrill erosion is expressed as a function of rainfall, topography, and a soil factor. The rate of detachment by rill erosion is expressed as a function of runoff characteristics and a different soil factor. Measured interrill flow velocities and depths are generally so low that flow in these areas accounts for an insignificant portion of interrill soil particle detachment (Young & Wiersma, 1973; Lattanzi *et al.*, 1974; Meyer *et al.*, 1975). Thus, the effect of rainfall characteristics on interrill erosion lies primarily in the degree to which they represent the erosive potential of falling raindrops.

Impacting raindrops impart energy and momentum to the soil surface. These forces degrade soil aggregates and detach soil particles, clogging the soil surface and forming a surface seal which results in decreased infiltration and increased runoff. Raindrop impact pressures, while in themselves high, are accompanied by lateral and tangential shear stresses when drops impact at an angle or on rough or irregular surfaces and these may equal or exceed the impact pressures (Bowden & Brunton, 1961; Thomas & Brunton, 1970). The impact pressure under a relatively small water drop, approximately 2.3 mm in diameter, falling at terminal velocity has been calculated to be approximately 3×10^6 Pa on a dry soil and 7×10^6 Pa on a wet soil (Rogowski & Kirkham, 1976). These impact pressures and associated shear stresses are sufficiently large to cause soil rupturing and detachment. When raindrops are accompanied by wind, the pressures and shear stresses can be even greater causing increased soil detachment.

Soil detachment resistance to the forces of drop impact and splash are represented by the soil factor in the interrill portion of equation (1). This factor is generally related to the size and strength of exposed soil aggregates. Aggregate strength is primarily due to the clay and organic matter content and other agents which act to cement or bind the soil aggregates together. High aggregate strength results in a resistance to dispersion and breakdown under waterdrop impact. Past studies have shown that aggregate strength increases and splash losses decrease as the clay content of aggregates increases (Rogowski *et al.*, 1968; Romkens *et al.*, 1975). Soils high in clay are generally more aggregated and have aggregates larger than soils high in silt or sand (Young, 1980). Eroded soil particles from high clay soils are also larger than eroded particles from more coarse textured soils. Table 1 illustrates the aggregate size distribution of matrix soil and eroded soil from two typical Midwest agricultural soils, a loam and a clay loam, under identical cropping and topographic conditions.

TABLE 1 Aggregate size distribution of soil and sediment from two upper Midwest soils

	Particle diameter (mm):			
	<0.5	0.5-1.0	1.0-2.0	>2.0
<i>Barnes loam:</i>				
Matrix	17	10	12	61
Sediment	76	17	5	2
<i>Forman clay loam:</i>				
Matrix	8	11	15	66
Sediment	68	19	9	4

Differences in the type of binding agent can account for differences in strength between soil aggregates. For instance, clay content affects aggregate strength not only due to total amount of clay present but also to the type of clay. As an example, the tensile strength of a film of Na-montmorillonite measured at a vapour pressure ratio of 0.32 was approximately 12×10^6 Pa (Dowdy & Larson, 1971). This is high compared to many soil aggregates ($<2 \times 10^6$ Pa) (Rogowski *et al.*, 1968) and can account for differences in resistance to breakdown under raindrop impact between soil aggregates containing similar total amounts of clay but of different types.

Generally, aggregate strength decreases as the size of the aggregate becomes very large. Moldenhauer & Koswara (1968) found that, under equilibrium conditions, aggregates 8-30 mm in diameter in both the A and B horizons of a silty clay loam from continuous corn resulted in the highest splash and wash loss rates from soil pans subjected to simulated rainfall. As aggregate size decreased below this range, aggregates did not break down as readily, resulting in a subsequent decrease in rainfall detachment. Final infiltration rates were also greater on the plots with smaller aggregates than with larger aggregates (Moldenhauer & Kemper, 1969).

Particle size alone also affects soil detachment. In a study by Mazurak & Moser (1968), as particle size decreased from 4 to 0.15 mm in diameter, rainfall detachment increased, then as the particles continued to decrease from 0.2 to 0.002 mm, rainfall detachment decreased. While these were single grain particles rather than soil aggregates, this study did indicate a possible optimum size range for the degree of aggregation.

Another force facilitating soil particle detachment under drop impact is that of rupture due to rapid wetting (Quirk & Panabokke, 1962). Rupture pressures, P_r , due to rapid wetting, or the excess trapped air pressure, is approximately equal to

$$P_r = 2N/R \quad (2)$$

where N is the surface tension of water, or 7.3 Pa, and R is the radius of the particle (Kirkham & Powers, 1972). For a clay-sized aggregate with a radius of 1 μm , trapped air pressure is approximately equal to 15×10^4 Pa. This is large enough to cause some soil aggregates to rupture.

Thus, an effective soil factor indicating susceptibility to interrill erosion should include the effects of the following: the degree of aggregation, reflecting an optimum aggregate size for resistance to raindrop impact forces; aggregate stability, indicating resistance to impact and rupture forces and subsequent aggregate breakdown; and the amount and type of clay present in the soil, relating to aggregate strength and, thus, affecting aggregate stability. Of these, resistance to drop impact is the parameter least well defined. Aggregate stability is commonly measured using a wet sieving procedure (Russell, 1949) which more closely approximates the forces exerted by flowing runoff water on soil particles rather than raindrop impact forces. A reliable index characterizing the ability of soil aggregates to withstand the forces exerted by falling waterdrops would be very useful in refining the soil factors in the interrill and rill portions of equation (1).

Methods of examining soil erodibility by drop impact have been attempted in the past with limited success (McCalla, 1944; Bruce-Okine & Lal, 1975). Using a technique based partly on the method of DeLeenheer & DeBoodt (1959) and the mean weight diameter of soil aggregates as suggested by Van Bavel (1949), Young (unpublished) developed a method to divide the stability of soil aggregates into their relative susceptibility to breakdown by interrill erosive forces and rill erosive forces. The ratio of the rate of interrill erosion to rill erosion of five soils varying widely in texture, geographic location, and erodibility (Onstad & Young, in press) correlated well with the stability of aggregates to interrill forces of erosion as determined by this method. The method is still preliminary but shows promise of being useful in characterizing the nature of a soil's erodibility.

Rill detachment

The soil factor in the rill erosion portion of equation (1) is dependent on parameters other than those influencing interrill erosion since it must represent properties which are resistant to a

different set of forces.

For a rill to develop normally in the field, there must be a concentration of surface runoff caused by some irregularity which results in a convergence of flow, such as a pebble, a stem, a cavity, or a hole. For example, bulk densities of the surface soil usually vary in a field after a tillage operation and those areas of lowest bulk density may tend to settle or collapse when wetted, forming a depression which acts as a starting point of a rill. A loose seedbed will have many areas of high and low density soil and consequently can be quite susceptible to rill initiation in this manner (Rogowski & Kirkham, 1976).

Seepage forces occurring along the side and through the bottom of rills may cause considerable sloughing of soil particles and breakup of aggregates on the surface of the rill itself. This is the result of water moving into the aggregates, weakening the bonds holding the aggregate together to the point where the critical shear strength is sufficiently low that the effect of shear along the soil/water boundary is able to detach the particle.

Shear forces along the soil/water interface in themselves are relatively minor as far as the soil detachment is concerned (Young & Wiersma, 1973). The critical shear stress, or that stress which causes general movement of soil particles along the channel bed, can be expressed as

$$\tau_c = \gamma R S \quad (3)$$

(Henderson, 1966), where γ is the specific weight of the water, R is the hydraulic radius of the rill, and S is the slope of the channel bed. For example, on a 9% slope, if a rill has a bottom width of 3.8 cm, a depth of 3.8 cm, and side slopes of 1:3, the critical shear stress can be calculated to be equal to 15 Pa. This value is low as far as soil detachment is concerned. The critical shear strength for a typical Midwest soil, a Storden sandy loam, has been measured at approximately 12×10^4 Pa and this value increases for heavier textured soils (Rogowski & Kirkham, 1976).

Resistance of a soil to shearing stresses has been shown to be directly related to the amount and type of clay in the soil and inversely related to the mean size of the soil aggregates and to the dispersion ratio of the soil (Smerdon & Beasley, 1959). Laboratory tests on three Minnesota soils of widely varying texture show that the greatest rill erosion occurred on a loamy sand as compared to a loam soil (Table 2) (Young & Wiersma, 1973). The loamy sand had the highest dispersion ratio while the loam had the lowest. Resistance to the shear forces was apparently also affected by organic matter content. A low organic matter content allows aggregates in direct contact with water to wet up faster (Quirk & Panabokke, 1962), lowers their intra-aggregate strength, making them more susceptible to breakdown and detachment.

An effective soil factor indicating susceptibility to rill erosion should include the effects of the following: organic matter content, relating to the ease of wetting of soil aggregates and, hence, their resistance to breakdown under immersion; aggregate density, also relating to particle size within the soil aggregates and to aggregate strength; bulk density, possibly affecting rill initiation; and

TABLE 2 Soil properties and rill erosion rates of three upper Midwest soils

	Organic matter (%)	Dispersion ratio (%)	Rate of rill erosion ($\text{mg cm}^{-2} \text{min}^{-1}$)
Barnes loam	5.86	10.75	1.50
Crofton silt loam	0.50	10.29	2.80
Sverdrup loamy sand	1.73	16.74	3.70

dispersion ratio, a factor relating to the particle size distribution of the soil and reflecting the ease with which a soil tends to disperse. The dispersion ratio has an effect on both interrill and rill erosion, but its effect on rilling is probably greater because of the manner in which it is usually measured (slaking).

Soil and nutrient transport

Once soil particles have been detached, most are delivered short distances by splash erosion and interrill flow to rills where they are transported downslope (Young & Wiersma, 1973; Swanson & Dedrick, 1967). The amount and distance these particles are transported depend on the size and density of the eroded particles, the critical tractive force, and the capacity of the rill flow to carry them (Foster & Meyer, 1972). The general characteristics of eroded material transported from a field as summarized by Young (1980) indicate that most sediment can be classified into two general size categories depending on the textural classification of the soil from which the sediment originates. These are particles from 50 to 250 μm for soils high in either sand or clay and particles 20 to 35 μm for soils high in silt. However, particle size generally increases as land slope increases and decreases with the amount of vegetative cover present. Also, in most cases the larger the total erosion from an event, the more closely the sediment particle size distribution approaches the particle size distribution of the matrix soil. Thus, the percentage of finer sized particles being transported usually increases as the amount of total erosion decreases.

Once a soil particle becomes detached, either by drop impact or surface flow, particle density becomes an important factor in the transport of the particle downslope. The lower the density, the more easily the particle can be transported. Most sediment transport relationships are quite sensitive to variations in particle or aggregate density. Young (1980) reported that aggregate density averages only about two-thirds or less than that of primary particles and varies inversely with aggregate size. Aggregate density also varies inversely with the amount of silt in the soil. As a result, significant enrichment of silt in large eroded aggregates (>2 mm) compared to matrix soil aggregates can occur. Smaller eroded aggregates less than 2 mm are usually enriched in sand

and clay.

The physical characteristics of sediment significantly affects the movement of agricultural chemicals from an area during an erosive event. Since the physical adsorption of chemicals depends on soil specific surface area, any chemical enrichment generally accompanies a physical enrichment of finer sized soil materials such as clay or fine silt. Thus, nutrient enrichment is closely related to sediment size and concentration (Monke *et al.*, 1976). The amount of nutrients being transported from a field can also be strongly affected by the type of erosion occurring such as rill or interrill erosion. For example, considering the method of fertilizer application, an incorporated chemical would have a different contribution to nutrient loss than a surface applied chemical depending upon whether rill or interrill erosion predominated.

While in the past most nutrient enrichment studies have dealt primarily with total nitrogen and total phosphorus, of possibly greater significance is the amount of readily available nitrogen and phosphorus lost from fields due to erosion. Olness *et al.* (1981), in a study to determine the enrichment of available nitrogen in eroded sediment compared with the soil from which the sediment originated, found significant increases in available nitrogen from cropped soil, with enrichment ratios approximating those of organic carbon, cation exchange capacity and total Kjeldahl nitrogen in the same soil. Enrichment ratios of nitrogen mineralization potentials as determined by a biological method, which would be more closely related to a natural environment, were greater than 2 for cropped plots and 30-100% higher than the relative enrichments of organic carbon, cation exchange capacity, or total Kjeldahl nitrogen (Table 3). Aggregate size distribution of the sediment had little or no influence on N enrichment.

In a similar study of available phosphorus (unpublished data from J.J.Latterell, Univ. of Minnesota, Morris), enrichment ratios of aggregate phosphorus were found to be close to 1.7 for eroded aggregates less than 63 μm in size but only slightly greater than 1 for composite samples comprising all aggregate sizes.

Thus, it can be seen that nutrient enrichments of sediment are complex and vary considerably with suspended sediment size and

TABLE 3 Nutrient enrichment ratios of eroded sediment

	Mineral- izable N*	N mineral- ization potential†	Organic carbon	Cation exchange capacity	Total Kjeldahl N
Continuous fallow	1.37	1.47	1.19	1.03	1.13
1st year corn	1.23	2.01	1.61	1.49	1.58
2nd year corn	1.44	2.76	1.39	1.25	1.19
Soybeans	1.25	2.26	1.56	1.48	1.49

* Autoclave method (Smith & Stanford, 1971).

† Incubation method (Stanford *et al.*, 1974).

concentration. Agricultural chemical transport equations and sediment delivery equations to be useful must take into consideration the type of erosion occurring to be able to estimate the amount of soil and nutrients coming from the soil surface and from deeper within the tillage layer.

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