Soil Detachment from Clods by Simulated Rain and Hail

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MUCH fallow land in the Great Plains is regularly subjected to low energy hailfall during thunderstorms. The effects of hail on soil cloddiness are generally unknown, but on fallow a high degree of soil cloddiness is essential to control wind and water erosion. We examined the effects of hail size and kinetic energy on soil detachment from clods during simulated rain under various windspeeds and amounts of surface mulch. Amount of soil detachment depended on size and energy of hail, windspeed, and surface cover as well as on interactions among these variables. A hail energy of 0.53 cm-newtons cm^{-2} increased soil detachment from clods more than 50 percent, and an energy of 5.3 cm-newtons cm^{-2} more than doubled soil detachment as compared with no hail. Small hail caused some damage to clods but quickly covered the surface to form a protective cover against subsequent wind, rain, and hail damage. Thus, a hail diameter exceeding about 0.75 cm was necessary to increase soil detachment above the no-hail level. Both seeding clouds to reduce hail size, if successful, and maintaining a 50 percent or greater mulch cover could reduce soil detachment from clods during hailstorms.

INTRODUCTION

Although hail occurs over most of the United States, it is especially severe near a line extending from northern Texas to western North Dakota. Here much fallow land, in addition to cropland, is subjected to hail because it is common practice to fallow nearly one-half of the cropland each year. While the devastating effect of hail on crops is well documented (Changnon 1972), little, if any research has been done on how hail affects fallow land, though it is often prone to both wind and water erosion. A high degree of soil cloddiness helps control erosion (Chepil 1957, Ellison 1947). It seemed likely that hail on fallow would increase clod breakdown and thus erosion. Therefore, we examined the effects of the most frequent hail sizes and energies on soil detachment from clods during rain under various windspeeds and amounts of vegetative mulch.

Estimates of the most frequent hail energies and sizes were obtained from the literature. Butchbaker's (1969) summary of 3 yr data from a large network of hailpads in southwestern North Dakota showed 60 to 80 percent of the damaged hailpads received hail energies less than 1.5 cm-newtons cm^{-2}, 14-33 percent received 1.5 to 5.8, and only 3 to 6 percent received more than 5.8. Average annual hailfall energies over the area ranged from 0.06 to 2.0 cm-newtons cm^{-2}. In Illinois and North Dakota, hailpad data also showed that 80 percent of all hailstones were less than 0.5 cm in diameter and 99 percent were less than 2 cm (Changnon 1971, Hagen and Butchbaker 1967).

TABLE 1. IDENTIFICATION AND LEVEL OF EXPERIMENTAL VARIABLES.

Variable	Test I values	Test II values
Windspeed (U), m sec^{-1}	11.2	0
		11.2
Mulch cover (C), percent	0	0
	50	50
	90	90
Hail diameter (S), cm	0.51	0.87
		1.64
Hail energy (I), cm-newtons cm^{-2}	0	0
	0.8	0.53
	3.2	2.10
		5.26

METHODS AND MATERIALS

Trays of clods were subjected to simulated rain and hail in the laboratory at levels that frequently occur in the field. Statistically, the study consisted of two factorial experiments in completely random designs with each treatment combination replicated three times. In the first experiment, small simulated hail (tapioca) was used; in the second, two larger sizes (marbles) were used. The treatment levels for each variable are summarized in Table 1. The effects of

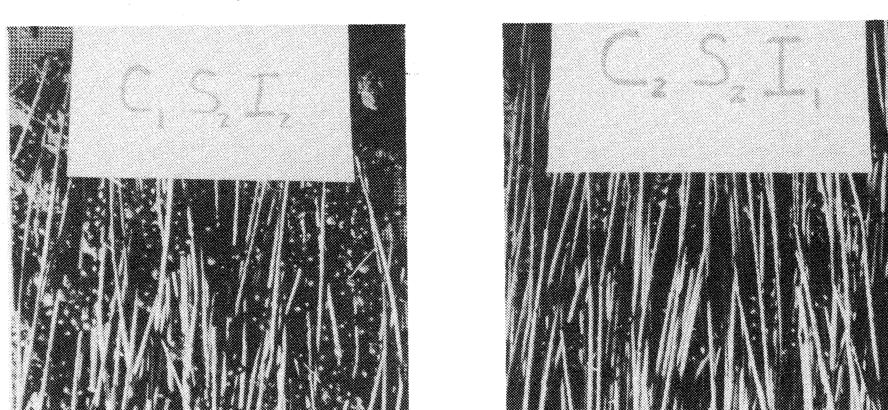

FIG. 1 Trays of Clods after Treatment and drying. Variables shown are: straw cover, 50 (C_1) and 90 (C_2) percent; hail diameter, 1.64 cm (S_2); and hail energy, 0.53 (I_1) and 2.10 (I_2) cm-newtons cm^{-2}.

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TABLE 2. CALCULATED PARAMETERS OF REAL AND SIMULATED HAILSTONES.

Hail diameter, cm	Hailstones: Terminal velocity, cm sec^{-1}	Hailstones: Kinetic energies, cm-newtons	Simulated hailstones: Impact velocity, cm sec^{-1}	Simulated hailstones: Drop height, cm	Simulated hailstones: Density, g cm^{-3}
0.51	901.9	0.25	668.1	255	1.64
0.87	1,175.3	2.11	705.2	265	2.50
1.64	1,617.9	27.26	970.7	505	2.50

TABLE 3. THE EFFECT OF 0.51-CM DIAMETER HAIL AND 11.2-M-SEC^{-1} WIND ON AVERAGE SOIL DETACHMENT FROM 12.7- TO 38-MM DIAMETER CLODS.

Amount of cover, percent	Hail energy, cm-newtons cm^{-2}: 0	0.8	3.2
	Soil detached, g		
0	572 d*	341 c	197 ab
50	317 c	196 ab	154 ab
90	223 b	114 a	117 a

*Means followed by the same letter do not differ statistically ($P < 0.05$).

rainfall alone are represented by treatments in which hail energy approached zero; rainfall intensity was 4.5 cm hr^{-1}. Some typical treatments are shown in Fig. 1.

The soil clods (bulk density of 1.45 g cm^{-3}) were formed by chisel tilling silty clay loam soil. The clods were air dried to less than 1 percent moisture and sieved to retain only those 12.7 to 38 mm in diameter. Clod samples of 1 500 g were then placed on 38.1- x 45.7-cm trays of 2-mm screens and covered with various amounts of wheat straw mulch which was anchored with a wide-mesh netting and oriented parallel to the wind direction in a rain-tower-wind tunnel previously described (Disrud et al. 1969, Lyles et al. 1969).

The order of treatment events was 10 min of rainfall, then hailfall, and finally an additional 20 min of rainfall, which is similar to the sequence of events in Great Plains hailstorms. Weighed amounts of simulated hail were dropped uniformly onto the trays from an overhead feeder. Groups of three trays (replications) were treated simultaneously. After treatment, the materials were oven dried (60-65 C) and reweighed to determine the amount of soil that was detached and passed through the screens.

Kinetic energies (KE) of simulated hailstones were matched to those of real hailstones in still air by this procedure: first, the terminal velocities and KE of real hailstones (density 0.9 g cm^{-3} and drag coefficient 0.6) were calculated using standard formulas, the results from which are shown in Table 2. According to Macklin and Ludlam (1961), a drag coefficient of 0.6 is typical of hailstones with minor surface irregularities. The impact velocity of the simulated hail was then calculated so its KE would equal the KE of real hail. The required impact velocity of the simulated hail was determined from a numerical function of fall veloctiy vs. fall height. This function was obtained by numerically integrating the equation of motion of a free falling sphere in still air. Numerical integration was necessary because the drag coefficient varies with Reynolds number so that analytical integration of the equation of motion is difficult. The velocity from the preceding time step was used to compute successive drag coefficients, and time steps of 0.001-sec were used to compute successive velocities. Calculated impact velocities and drop heights along with densities of the three sizes of simulated hail are also shown in Table 2.

Reference windspeed was measured in the center of the wind tunnel immediately upwind from the test samples with a pitot-static tube and associated recording equipment.

EXPERIMENTAL RESULTS AND DISCUSSION

An analysis of variance of soil detached by the 0.51-cm hailstones (treatment variables as shown in Test I of Table 1) indicated that main effects of cover and energy as well as the CI-interaction all were significant ($P < 0.01$). Duncan's new multiple range test (Steel and Torrie 1960) was then used to test for differences between individual treatment means (Table 3).

Apparently, the KE of the individual small hailstones was too small to detach more soil from clods than rain alone. However, the small hail was an effective mulch cover during the last 20 min of rain. At an I of 0.8 cm-newtons cm^{-2} where 64 percent of the surface was covered by small hail, soil detachment was similar to the 50 percent mulch cover with no hail (Table 3). Results were similar at the highest cover and intensity. Thus, small hail did not increase the erosion hazard. There also is evidence that small hail causes little crop loss. Changnon and Staggs (1969) reported that total number of stones showed no relation to crop loss; only the number larger than 0.64 cm was related to crop loss.

Analysis of variance of soil detached by the largest hailstones (variables in Test II, Table 1) indicated that all main effects, all two-way interactions, and one three-way interaction (U x S x I) were statistically significant ($P < 0.01$). Wind drag probably caused the strong interactions involving windspeed because wind sharply increases the amount of soil detached from clods, as previously observed by Lyles et al. (1969). Disrud and Krauss (1971) concluded that wind drag on saturated clod surfaces caused an increased flow rate of soil and water from clods. Thus, a mulch cover, whether straw or hail, shields the surface from the kinetic energy of

TABLE 4. EFFECTS OF HAIL SIZE AND ENERGY ON SOIL DETACHMENT FROM 12.7- TO 38-MM DIAMETER CLODS AVERAGED OVER WINDSPEEDS AND MULCH COVERS.

Hail energy, cm-newtons cm^{-2}	Hail diameter, cm: 0.87	1.64	Mean
	Soil detached, g		
0	252	252	252 a
0.53	396	446	421 b
2.10	412	546	479 bc
5.26	423	685	554 c
Mean	371 a*	482 b	

*Means followed by the same letter do not differ statistically ($P < 0.05$)

TABLE 5. EFFECT OF MULCH COVER AND WINDSPEED ON SOIL DETACHMENT FROM 12.7- TO 38-MM DIAMETER CLODS AVERAGED OVER HAIL SIZES AND ENERGIES.

Amount of cover,	U_0 0 m sec^{-1}	U_1 11.4 m sec^{-1}	Mean
	Soil detached, g		
0	268	967	618 a
50	181	608	395 b
90	161	524	343 b
Mean	203 a*	700 b	

*Means followed by the same letter do not differ statistically ($P < 0.05$).

TABLE 6. EFFECTS OF INCLUDING ADDITIONAL VARIABLES ON SOIL DETACHMENT VARIANCE.

Variable added	R^2	ΔR^2, percent
SU	0.71	-
ln (C + 1)	0.84	13
SI	0.86	2
U	0.89	3
CU	0.93	4

$\hat{SD} = 14.47 + 1.61\ SU - 1.91\ \ln(C + 1) + 1.58\ SI + 2.22\ U - 0.021\ CU$

$\hat{SD}$ – soil detachment, percent
C – mulch cover, percent
U – windspeed, m sec^{-1}
S – hail diameter, cm
I – hail energy, cm-newtons cm^{-2}

impact and also reduces wind drag on the clods.

The significance of the interactions somewhat restricts interpretation of main effects, but the trends are meaningful. A multiple range test was again used to test for differences between means of main effects, and the results are summarized in Tables 4 and 5. Compared with no hail, an intensity of 5.26 cm-newtons cm^{-2} more than doubled soil detached from clods. Surprisingly, even 0.53 cm-newtons cm^{-2} increased soil detachment 67 percent as compared with no hail. As expected, soil detachment increased as hail diameter increased. Calculated rainfall KE was 5.9 cm-newtons cm^{-2} in each treatment.

The significant interaction between size and energy is apparent in Table 4. Only the largest hail significantly increased soil detachment at the highest energies because small hail quickly covered the surface and prevented subsequent stones from striking unprotected soil clods. There also was a larger mulch effect by the small hail during the final wind-rain period. For example, at an I of 2.1 cm-newtons cm^{-2}, the soil was 59 percent covered by 0.87-cm hail but only 16 percent covered by 1.64-cm hail.

A 50-percent-mulch cover on the surface effectively reduced soil detachment, especially under high windspeeds (Table 5). The 90- and 50-percent covers did not differ significantly because the first hailstones tended to lodge in open spaces between straws and to quickly increase total surface cover.

Lyles et al. (1974) have shown that percentage of cover, not kind of cover, controls soil detachment from clods. They also showed that mulch oriented parallel to wind direction, as in this study, permits more soil detachment than mulch oriented perpendicular to wind direction. Although small grain crops usually provide enough straw to give 100 percent soil cover, successive tillage operations on fallow with some implements can quickly reduce cover to less than 50 percent (Woodruff et al. 1972). Thus, tillage operations should be designed to leave a maximum amount of residue on the surface and to orient it perpendicular to the prevailing wind direction.

The hail did not break the wheat straw but at high energies tended to push it into the clods. The initial 10 min of rain apparently made the straw resilient enough to withstand breakage, but pushing the straw into the clods will likely enhance the decomposition rate. It also decreases the straw's ability to shield the surface from impact but may increase its resistance to water flow under the mulch. However, Young and Wiersma (1973) showed that raindrop impact energy was the major force initiating soil detachment.

Stepwise, multiple-curvilinear-regression procedures were applied to the soil detachment data (Table 1, Test II) to determine an estimating equation, variance accounted for, and the importance of various variables (Table 6). While the estimating equation provides a good fit of the data, $R^2 = 0.93$, it should not be used to predict soil detachment at variable levels far from those studied. This is particularly true of windspeed which has a large effect on percentage soil detached but where only two levels of the variable were studied. The regression coefficients shown in the estimating equation were all significantly different from zero ($P < 0.01$).

To illustrate the range of soil detachment caused by the variables, some predictions of the estimating equation are plotted in Fig. 2. The dashed lines for hail less than 0.75 cm indicate linear projection back to no hail. In reality, soil detached in this region may be more than offset by the additional mulch effect provided by hailstones. Clearly, estimating soil detachment from clods is a complicated process, but estimating crop loss from hailfall parameters is probably more complicated. Changnon and Staggs (1969) discuss some of the additional variables involved in estimating crop losses.

The estimating equation can be used to determine changes in soil detachment which hail suppression might cause. For example, Schleusener (1968) suggested that hail suppression might reduce hail size without decreasing volume of ice. Thus, if we start with the condition $C_0I_2U_1$ (Fig. 2), and S equal 1.64 cm, then a reduction in hail size to 0.866 cm reduces soil detachment from 83 to about 62 percent. If the lower KE of the 0.866-cm hail is also accounted for, soil detachment drops to 59 percent. Similar calculations for $C_1I_2U_1$ show soil detachment is reduced from

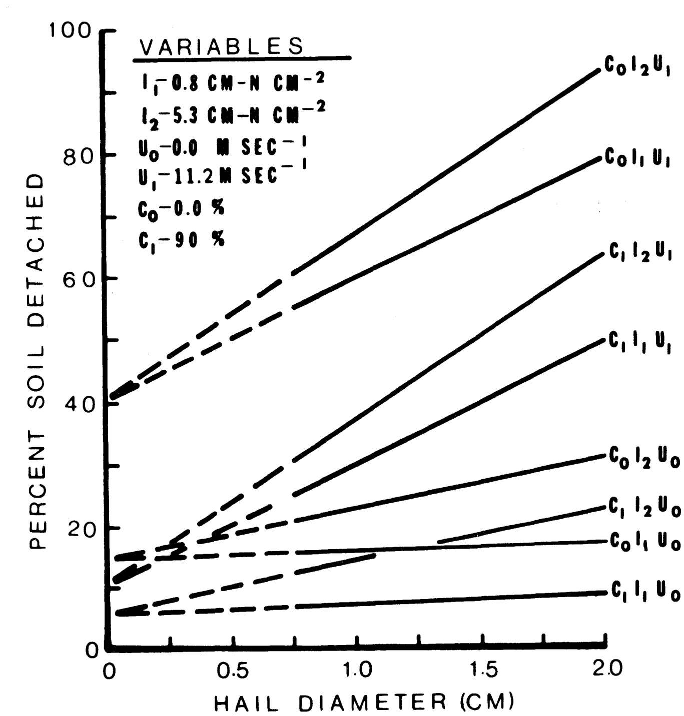

FIG. 2 Plot of estimating equation showing percentages of soil detached from 12.7 to 38 mm clods under various levels of indicated variables.

53 to 29 percent when hail size is reduced from 1.64 to 0.866.

In addition to the variables noted, wind imparts horizontal momentum to both raindrops and hailstones, but that cannot be easily simulated in the wind tunnel-raintower facility. Caldwell and Elliot (1972) have calculated that the horizontal momentum of a raindrop is only slightly decreased in the surface layer and thus arrives with the horizontal momentum of the wind well above the surface. However, the rain may impart enough momentum to the air to slightly increase the surface wind shear. Both mechanisms increase soil detachment from clods, and their effects have been reported (Disrud and Krauss 1971). The probability of winds associated with rains in Kansas also has been reported (Disrud 1970).

With hail, horizontal velocity causes the hailstones to strike the surface at an angle and dissipate their energy over an increased area as evidenced by the streak marks left on hailpads. If the horizontal velocity of a hailstone equals the terminal vertical velocity, the KE is doubled. The estimating equation shows that this results in an 8 percent increase in soil detachment for 1 cm hailstones at I_2 which is slightly conservative, however, because the added energy is not accompanied by an increase in surface cover of hailstones.

CONCLUSIONS

Low energy hailfall, which commonly occurs in thunderstorms, can easily increase soil detachment from clods by 50 percent; at moderate intensities, it can double soil detachment over no hail. Increased soil detachment occurs when hail diameter exceeds about 0.75 cm. Hail less than 0.75 cm may slightly damage clods but it quickly covers the surface and protects against subsequent rain, wind, and hail damage. The process of soil detachment is complicated and depends on size and intensity of hail, windspeed, and surface cover as well as on interactions among these factors. Both seeding clouds to reduce hail size, if successful, and maintaining a mulch cover of at least 50 percent could substantially reduce soil detachment from clods.

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