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Soil Detachment by Single and Multiple Waterdrops

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Abstract: Single-drop splash/detachment studies and multiple-drop splash/detachment experiments were carried out to measure detachment by single and multiple drops. A raindrop tower 7.0 m in height was used to study soil splash by single drop raindrop impact over time on repacked soil samples in containers 76.2 mm in diameter. The waterdrop diameter and kinetic energy were 4.1 mm and 1.22×10^{-3} J $drop^{-1}$, respectively. The samples consisted of five agricultural topsoils sieved to <2 mm, varying from sandy loam to clay loam in texture. The average weight of splashed soil particles after 75 drops did not show any significant difference between the five soils. The average weight of particles splashed by the first 15 drops showed that the sandy Pelham soil splashed to a greater degree than the others, and was therefore more detachable ($p=0.05$) than the other soils. The average weight of particles splashed by the last 15 drops also showed that the Pelham soil was the most detachable, with Cecil, Appling, Dyke, and Worsham soils being progressively less detachable. The effect of multiple drops on detachment was studied under a nozzle-type rainfall simulator at 74.9 mm h^{-1} intensity for 85 min using the same soils as the single drop experiments. The total soil splash value for 85 min on Appling, Cecil, Dyke, Pelham, and Worsham soils were 6121, 6206, 4183, 5160, and 3247 g m^{-2}, respectively. There were no obvious relationships between soil loss measured from the different experiments (single drop and multiple drop splash) (Received April 6, 1995; accepted April 27, 1995).

Introduction

In the 1940's, soil erosion was defined as a process of detachment and transportation of soil materials by erosive agents. Ellison[1,2] considered soil erosion as two principal sequential events: the detachment of soil particles from the soil mass and the transport of these particles. Soil erosion of the area between rills (interrill erosion) is a function of detachment by raindrop impact and transport by overland flow.[3] For the Barnes loam, Crofton silt loam, and Central sandy loam soils, Young and Wiersma[4] found that 11.3, 10.7 and 6.7%, respectively, of the detached particles from the interrill area were splashed directly into the rills. From these data, they concluded that most of the soil movement to the rills was by overland flow. However, depths and velocities of overland flow alone were so low that it was evident that the ability of the surface flow to transport the detached particles was greatly enhanced by drop impact-imparted velocities.

For a better understanding of interrill erosion, quantitative measurement of soil detachment by raindrop impact was necessary. Since Ellison's[5] pioneering research, many researchers have studied soil detachment by raindrop impact using different devices and techniques. Some researchers used single drops, while others used multiple raindrops for their experiments.[6-9] The horizontal drift of a waterdrop at its terminal velocity and the difficulty in collecting soil splash were two problems in measuring the amount of soil splash from a single raindrop directly.[6] Since the kinetic energy of a raindrop depends upon drop height, this parameter is critical in raindrop studies. The drift of falling water drops due to the height to the drop tower creates a serious problem. As both the target area and the splash angle with the horizon increase, the possibility of collecting all the splash from a single drop is reduced. Because of the problems from single drop experiments, much of the work has been done using multiple drop experiments, but the use of relatively large soil containers and multiple drops limit the collection of all detached particles.

As it is necessary to treat soil detachment and transport as independent variables in expressing the final results, it is also necessary to carry this same breakdown into the detailed studies. A number of soil and raindrop parameters have been proposed as indices of soil detachment by raindrop impact and transport by overland flow. Raindrop parameters such as drop size, velocity, kinetic energy, momentum, water viscosity and surface tension and intensity have been used for the interrill

Key words: erosion, interrill, detachment, splash, rainfall simulator.
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soil detachment studies.[10-14] Organic matter content,[15] aggregate stability,[15-16] percent clay,[11] soil type and size of structural aggregates,[17] soil shear strength,[6,8] infiltration rate[13] and surface water content[18] were some of the soil parameters which were used for the interrill soil detachment studies.

The difficulty in developing a universally applicable relationship between detachment and transport processes and soil and raindrop parameters lies in the lack of joint consideration of both soil and raindrop parameters, the lack of understanding of dynamic soil properties with time, the limited spectrum of soil materials in use, and the lack of standard methods. The objectives of this study were i) to measure soil detachment by single and multiple waterdrops, ii) to find out splash erosion patterns of different soils, and iii) to determine particles size distribution of the detached particles.

Materials and Methods

Five Georgia soils were selected for study as typical materials representing major physiographic regions of the state (Table 1). Bulk samples from the Ap horizons were air-dried and sieved to <2 mm for single- or multiple-drop splash experiments and laboratory characterization.

Soil analyses

Organic matter was determined by dichromate oxidation,[19] cation exchange capacity by sum of the cations,[20] particle-size analysis by the micro-pipette method[21] and pH in water and 1N KCl using a combination pH electrode (1 : 2 ratio).

Soil dispersibility was measured by a method similar to that of Miller and Baharuddin.[22] Three five-gram soil replicates were placed in 50 m*l* centrifuge tubes with 40 m*l* deionized water and shaken end-over-end at 50 revolutions per minute (rpm) for 16 hrs. After sieving sand-sized particles, dispersed clay and silt plus clay were determined by pipetting a 5 m*l* sample from a depth of 25 mm after allowing coarser particles to settle.[23] The percentages of total size fraction of clay and silt plus clay that were water-dispersible were calculated.

The Universal Soil Loss Equation (USLE) K (soil erodibility) factors were obtained using the soil erodibility nomograph by Wischmeier and Smith (1978)[24] which requires characteristics of soils such as (% silt + % very fine sand), % sand, % O.M., soil structures, and soil permeability.

Single drop experiment

Soil samples were prepared by evenly packing air-dried, <2 mm soil into splash cups (Fig. 1). A sheet of Whatman No. 1 filter paper was placed on the bottom of the device to support the soil, which was then added and compacted by gentle tapping. The soil surface was smoothed to reduce microtopographic effects. Five replicate splash cups were prepared for each soil. Soil was wetted to saturation from the bottom overnight.

Fig. 1 also shows the design of the raindrop tower. The wind shield was constructed using PVC pipe, 101.6 mm diameter by 7.0 m height, supported by attaching to a 9.0 m tall telephone pole. Drifting was further controlled by a device, which was used to eliminate the no-

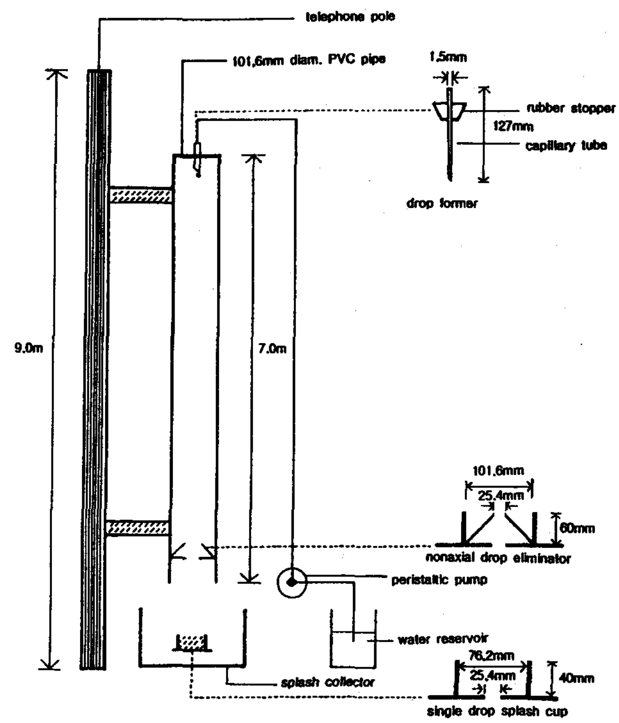

Fig. 1. Schematic diagram of a raindrop tower.

Table 1. Classification and sampling location of soils.

Soil series	Classification	Topsoil texture	Sampling location	Physiographic region
Appling	Kaolinitic Typic Hapludults	SL	Oconee Co.	Piedmont
Cecil	Kaolinitic Typic Hapludults	SL	Oconee Co.	Piedmont
Dyke	Oxidic Typic Rhodudults	CL	Union Co.	Blue Ridge Mountain
Pelham	Thermic Arenic Paleaquults	SL	Tift Co.	Southern Coastal Plain
Worsham	Mixed Typic Ochraquults	SL	Oconee Co.	Piedmont

naxial water drops, located at the bottom of the wind shield, directly above the sample. This consisted of a sharp-edged cone with an upper and lower diameter of 25.4 mm. All drops which fell outside the 25.4 mm diameter opening were eliminated. The drop former, which was a 1.5 mm inner diameter capillary tube with a sharpened tip, was inserted into a rubber stopper located at the top of the wind shield. This drop former produced 4.1 mm diameter drops. Deionized water was pumped from the ground up to the drop former by a Rabbittm peristaltic pump (RAININ INSTRUMENT Co., Boston, MA) through polyethylene tubing (1.4 mm I.D.× 3.2 mm O.D.). The pump was adjusted to produce 10 drops per min. The temperature of the deionized water used ranged from 25 to 30℃.

A twenty liter bucket was used as the splash collector, with the splash cup being placed inside the bucket during splash measurements. During splash measurements, soil water content was kept near saturation. After a drop struck the soil surface, the splash cup was moved so that the next drop did not hit the same spot. After fifteen drops had hit the soil surface, the soil in the splash cup was wetted to saturation again before it was used for the next 15 drops. The splashed particles inside the splash collector were washed into a previously weighed beaker, dried at 105℃ and reweighed to measure the weight of detached soil. Five consecutive fifteen-drop-measurements were made on each splash cup.

Multiple drop experiment

For the multiple drop experiment, separate sets of splash cups were prepared in the same manner as for the single drop experiment, except for the design of the splash cups. In this experiment, double-ringed splash cups were used to exclude collection of runoff, which accumulated in the outer ring. Several small notches on the lip of the inner ring were made to allow water to drain and to reduce the build-up of surface water on the soil. Two replicate splash cups were prepared for each soil. The soil was wetted to saturation from the bottom overnight before use.

Five liter buckets were used as splash collectors. The splash cups were placed in the splash collectors, and splash measurements were made by placing the splash collector with the splash cup under a nozzle-type rainfall simulator.[25] A wide square-spray 30 WSQ nozzle (Spraying Systems, Inc. Wheaton, IL)[26] located over the splash collector at a height of 3.5 m applied simulated rainfall at a rate of 74.9 mm h^{-1} with a kinetic energy of 22 KJ $m^{-2}\,mm^{-1}$. The splashed particles were collected at different intervals for 85 min. At each collection, the splash collector was changed instantly and the suspension between the inner and the outer ring was removed by pouring. The splashed particles inside the splash collector were washed into smaller containers with deionized water. Particle size distribution of the splashed particles was determined by sieving sand sized particles on a 53 μm screen, followed by drying and weighing. Silt-plus clay-sized particles were determined by drying and weighing the suspension after sieving.

Results and Discussion

Selected properties of the soils used for the experiments are presented in Table 2. The Appling and Pelham

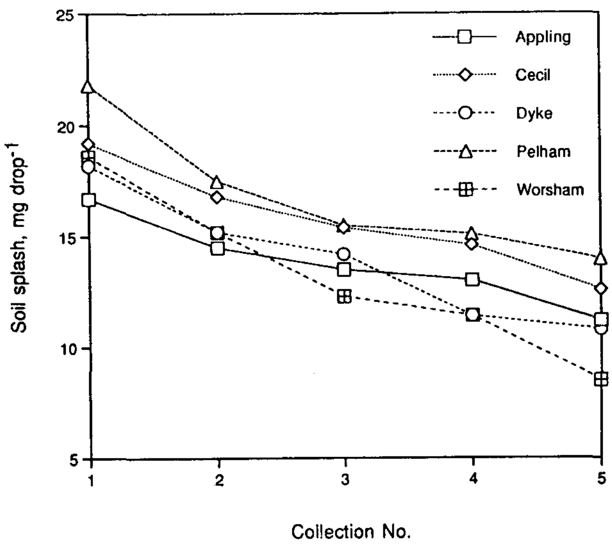

Fig. 2. Relationship between average splash weight of the fifiteen-drop collections and the collection number.

Table 2. Selected properties of solis.

Series	sand	silt	clay	WDC[1]	WDSC[2]	O.M.	pH_w[3]	pH_k[4]	CEC	exch.-Al	ESP[5]
				%					cmol(+)kg^{-1}		%
Appling	75	17	7	81	98	2.61	5.16	4.06	2.44	1.33	2.04
Cecil	66	18	16	84	100	1.78	6.20	5.25	5.01	0.12	1.00
Dyke	28	33	39	4	76	2.08	6.44	5.43	8.11	0.04	0.74
Pelham	76	15	9	74	96	1.97	5.90	4.76	5.06	0.31	0.79
Worsham	55	29	16	75	97	3.02	5.24	4.37	5.45	0.74	0.73

[1]Water-dispersible clay, expressed as % of total clay. [2]Water-dispersible silt plus clay, expressed as % of total silt plus clay. [3]pH in water(1:2). [4]pH in 1 N KCl(1:2). [5]Exchangeable sodium percentage.

soils were very sandy with less than 10% clay, while the Cecil and Worsham soils had approximately 15% clay content, with the Dyke being highest in clay content. All the soils except Dyke were very dispersible. All the soils had 2~3% O.M., and were low in sodium, which is typical of southeastern U.S. cultivated soils. The bulk densities of soil in the splash cups for the Appling, Cecil, Dyke, Pelham, and Worsham soils were 1.64, 1.57, 1.49, 1.78 and 1.42 Mg m^{-3}, respectively.

Single drop experiment

Fig. 2 shows the relationship between the average splash weight of the fifteen-drop-collections and the collection number. As was expected, all soils behaved in a similar manner; initially the weight of splashed particles was high, but as soils became crusted and consolidated with time, the weight decreased. Using 20 soils ranging in texture from sand to clay, Bradford et al. (1986) found that the three soils with a high sand content gave significantly greater soil splash with no significant differences ($p=0.05$) among the 11 soils having the lowest amounts of splash. According to the least significant difference (LSD) test, the average weight of splashed soil particles (mg $drop^{-1}$) after 75 drops did not show very much difference between the five soils used here. But the average weight of particles splashed by the first 15 drops was higher for the Pelham soil than the others ($p=0.05$). Since most soil was detached by raindrop impact, this suggested that the Pelham was more easily detachable than the other soils. The average weight of particles splashed by the last 15 drops also showed that the sandy Pelham soil again was the most detachable, with Cecil, Appling, Dyke, and Worsham soils being progressively less detachable. In a single drop experiment with 3 drop sizes and 3 bulk densities, Al-Durrah and Bradford[6] reported that for all drop sizes, the weight of soil splash was reduced as bulk density increased. In the present experiment, although the bulk densities of the soils were varied only by varying soils, the average splash weight from the last 15 drops increased significantly with increasing bulk density. It did not seem like the chemical and physical properties of soils affected splash loss much.

Multiple drop experiment

Fig. 3 shows soil loss rates for the five soils as a function of time in the multiple drop experiments performed under the rainfall simulator and the USLE K factors for the soils.

In this experiment, the soil surface was much more prone to crusting due to more drops falling over the entire sample surface compared to the single drop experiment. There appear to be some differences here in the "initial" splash rates (first sampling) and in the "steady state" splash rates (average of last 4 to 5 collections) between soils, but not really the ones which were expected. The USLE K factors, which are indicators of erodibility in the absence of actual data, for the soils also did not match up well. The initial soil loss rate for the Appling soil was the highest and then decreased significantly (160 to 60 g m^{-2} min^{-1}) over the 85 min. It took about 60 min for the Appling soil to reach its steady state. The Cecil and Pelham soils showed a trend similar to that of the Appling soil, but with lower splash loss rate initially: the initial soil loss rates for both soils were approximately 100 g m^{-2} min^{-1}, decreasing to about 60 g m^{-2} min^{-1} after 30 to 45 min. The Worsham soil had a very high initial soil loss rate, but because of rapid consolidation, the value decreased to about 30 g m^{-2} min^{-1} after 30 min which is supported by a runoff pan study with 15 Georgia soils,[22] in which the Worsham soil was very prone to crusting and was highly erodible. It was clear that detachment by raindrop impact only with no transport by overland flow did not result in high erosion rate no matter what the soils' erodibility were. The stable and well-structured Dyke soil showed an intermediate, fairly constant splash loss rate.

Differences between maximum and minimum splash loss rates might be used to represent the degree of surface sealing. With 20 soils ranging in texture from sand to clay, Bradford *et al.*[27] reported that all the soils showed large differences in splash amounts over time, with larger differences for medium textured soils, and smaller differences for the finest and coarsest textured soils. To compare splash erodibility of each soil, the percent decrease in splash loss rate was defined:

$$\% \text{ decrease in splash loss rate} = \frac{\text{highest splash loss rate-lowest splash loss rate}}{\text{highest splash loss rate}} \times 100\%$$

The percent decreases in splash loss rate were large for the Worsham (80%) and Appling (72%) soils which form crusts, medium for the Cecil (63%), and low for the Dyke (54%) and Pelham (48%) soils.

Most of the splash was composed of sand-sized particles, especially for the Appling and Pelham soils, which are more sandy in texture than the other soils. During the 85 min rainfall event, the splash loss percentage of fine (silt- plus clay-sized) particles for the Appling, Cecil, and Pelham soils averaged 5~10%, whereas for the Worsham soil, which is finer, the percentage of fine particles in the splash was the highest. The extremely low water-dispersible-clay percentage (Table 2) for the Dyke soil could explain the large difference between the percentage of sand in the splashed particles and that in the original soil, suggesting that the sand-sized fraction was composed of many small aggregates. The

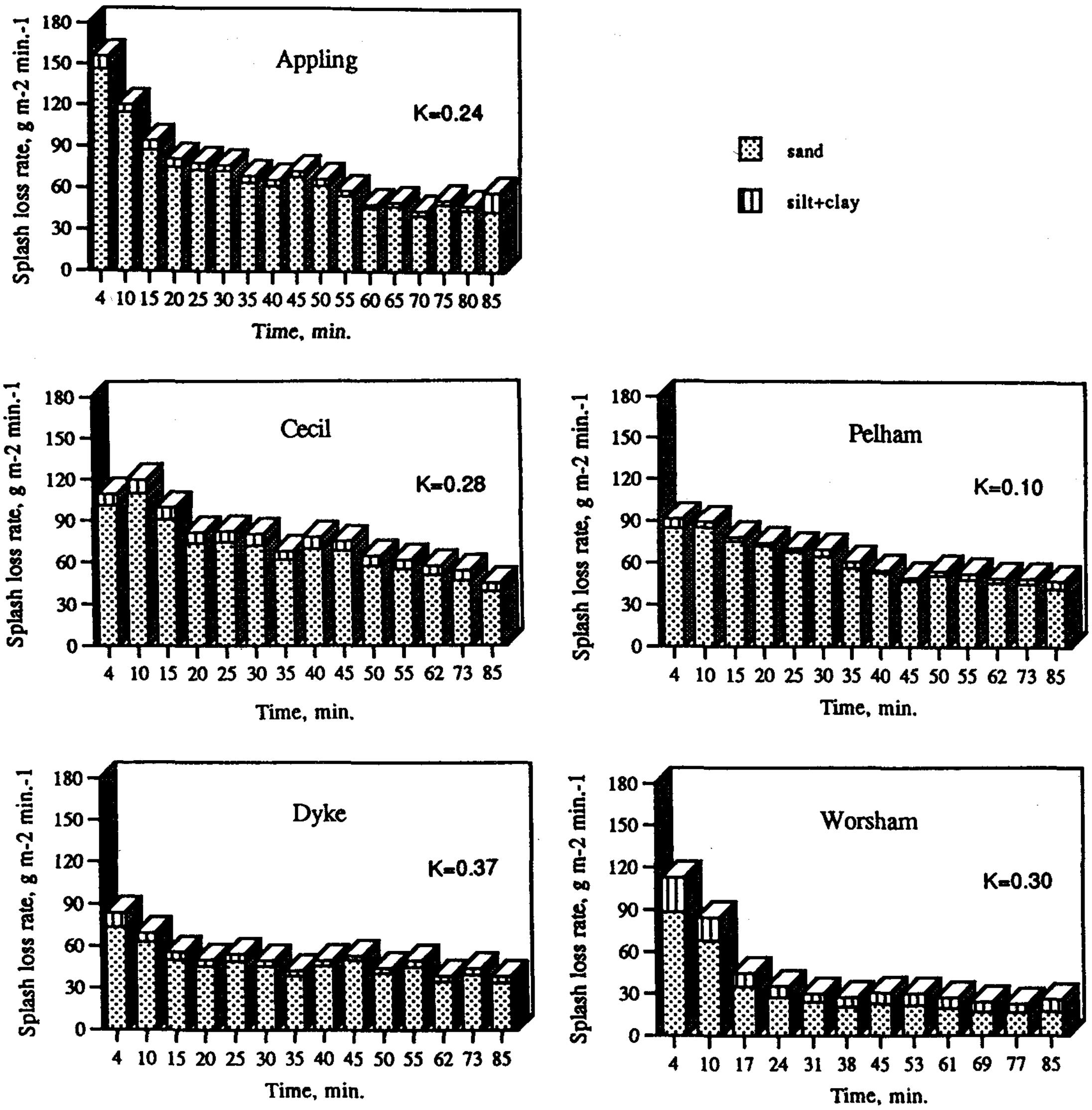

Fig. 3. Splash loss change over time for the solis (with USLE K factors).

much higher percentages of sand-sized particles in the splashed material relative to the original sand percentages (Table 2) agreed with the findings of Ellison,[5] which indicates that splash is non-selective, largely removing bulk soil from the cup, and is probably not affected at all by soil properties. Splash is really a measure to detachment in interrill erosion, and says nothing about transport, which is really a runoff-related parameter. Most of the soils used in the study were fairly easily detached (dispersible and relatively unstable), therefore, erosion was determined more by runoff rate than by detachment.

References

1. Ellison, W. D. (1947) Soil erosion studies - Part II. Soil detachment hazard by raindrop splash. *Agr. Eng.* **28**, 197-201.
2. Ellison, W. D., and O. T. Ellison (1947) Soil erosion studies-Part VII. Soil transportation by surface flow. *Agr. Eng.* **28**, 442-444, 450.
3. Meyer, L. D., G. R. Foster, and M. J. M. Romkens (1975) Source of soil eroded by water from upland slopes. p. 177-189. In Present and prospective technology for predicting sediment yields and sources. Proc. Sediment-Yield Workshop, USDA Sediment. Lab., Oxford, MS. 28-30 Nov. 1972. USDA-ARS, ARS-S-40, U.S. Department of Agriculture, Washington, DC.
4. Young, R. A., and J. L. Wiersma (1973) The role of rainfall impact in soil detachment and transport. Water Resources Research, **9**, 1629-1636.
5. Ellison, W. D. (1944) Studies of raindrop erosion. *Agr. Eng.* **25**, 131-136.
6. Al-Durrah, M. M., and J. M. Bradford (1981) New methods of studying soil detachment due to waterdrop impact. *Soil Sci. Soc. Am. J.* **45**, 949-953.
7. Bradford, J. M., P. A., Remley, J. E. Ferris, and J. B. Santini

(1986) Effect of soil surface sealing on splash from a single waterdrop. *Soil Sci. Soc. Am. J.* **50**, 1547-1552.
8. Cruse, R. M., and W. E. Larson (1977) Effect of soil shear strength on soil detachment due to raindrop impact. *Soil Sci. Soc. Am. J.* **41**, 777-781.
9. Nearing, M. A., and J. M. Bradford (1985) Single waterdrop splash detachment and mechanical properties of soils. *Soil Sci. Soc. Am. J.* **49**, 547-552.
10. Bisal, F (1960) Effect of raindrop size and impact velocity on sand splash. Can. *J. Soil Sci.* **40**, 242-245.
11. Bubenzer, G. D., and B. A. Jones, Jr. (1971) Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Transactions of the ASAE **14**, 625-628.
12. Meyer, L. D. (1981) How rain intensity affects interrill erosion. Transactions of the ASAE **24**, 1472-1475.
13. Moldenhauer, W. C., and D. C. Long (1964) Influence of rainfall energy on soil loss and infiltration rates I. Effect over a range of textures. *Soil Sci. Soc. Am. Proc.* **28**, 813-817.
14. Rose, C. W. (1960) Soil detachment caused by rainfall. *Soil Sci.* **89**, 28-35.
15. Young, R. A., and C. A. Onstad (1978) Characterization of rill and interrill eroded soil. Transactions of the ASAE, **21**, 1126-1130.
16. Meyer, L. D. and W. C. Harmon (1984) Susceptibility of agricultural soils to interrill erosion. *Soil Sci. Soc. Am. J.* **48**, 1152-1157.
17. Rose, C. W. (1961) Rainfall and soil structure. *Soil Sci.* **91**, 49-54.
18. Poesen, J., and J. Savat (1981) Detachment and transportation of loose sediments by raindrop splash. II. Detachability and transportability measurements. Catena **8**, 19-41.
19. Nelson, D. W., and L. E. Sommers (1982) Total carbon, organic carbon, and organic matter. In A. L. Page (ed.) Methods of soil analysis, Part 2. 2nd ed. *Agronomy* **9**, 539-580.
20. Thomas, G. W. (1982) Exchangeable cations. In A. L. Page (ed) Methods of soil analysis, Part 2. 2nd ed. *Agronomy* **9**, 159-164.
21. Miller, W. P., and D. M. Miller (1987) A micro-pipette method for soil mechanical analysis, Commun. In soil science and plant analysis **18**, 1-15.
22. Miller, W. P., and M. K. Baharudin (1986) Relationship of soil dispersibility to infiltration and erosion of southeastern soils. *Soil Sci.* **142**, 235-240.
23. Jackson, M. L. (1972) Soil chemical analysis - Advanced course, 2nd ed. Published by author, Madison, WI.
24. Wischmeier, W. H., and D. D. Smith (1978) Predicting Rainfall Erosi on Losses, USDA, Agricultural Handbook 537.
25. Miller, W. P. (1987) A solenoid-operated, variable intensity rainfall simulation. *Soil Sci. Soc. Am. J.* **51**, 832-834.
26. Shelton, C. H., R. D. von Bernuth, and S. P. Rajbhandari (1985) A continuous- application rainfall simulation. Trans. ASAE **28**, 1115-1119.
27. Bradford, J. M., J. E. Ferris, and P. A. Remley (1987) Interrill soil erosion processes: II. Relationship of splash detachment to soil properties. *Soil Sci. Soc. Am. J.* **51**, 1571-1575.

雨滴에 의한 土壤 侵蝕

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초록 : 하나하나의 雨滴과 여러개의 雨滴에 의한 토양의 分離 (detachment)와 揮散 侵蝕 (splash erosion)을 연구하고자 미국 조지아주의 대표적인 농경지 토양 다섯 종류를 대상으로 雨滴塔 (raindrop tower)과 人工降雨機 (rainfall simulator)를 이용하여 分離 실험을 수행하였다. 공시토양에 대하여 하나하나의 雨滴과 여러개의 雨滴에 의하여 일어나는 分離는 대부분 모래 크기의 입자로 비선택적이며, 토양의 이화학적 특성의 영향을 거의 받지 않는 경향을 보였다. 본 실험에 이용된 다섯 종류의 토양은 대부분 분산이 잘 되며 비교적 불안정하여 물방울에 의한 分離가 매우 쉽게 일어났으므로, 이들 토양 interrill 지역에서의 侵蝕은 分離 보다는 유출율 (runoff rate)에 의하여 결정됨을 알 수 있었다.

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