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A comparative analysis of the changes in soil detachability with texture and rainfall intensity

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Abstract

The study involved monitoring the energy load and splash erosion (detachability) of two soil textures. This analysis was done in the laboratory using Ellison's splash cups and a rainfall simulator. Laboratory sand and Woburn soil (sandy loam) were subjected to simulated rainfall at intensities of 25 mm/hr and 120 mm/hr for 30 minutes at a time. The median drop size for the two rainfall intensities was measured using the flour pellet method. The median drop diameters were 2.26 mm and 0.73 mm for simulated rainfall intensities of 25 mm/hr and 120 mm/hr respectively. Overall, higher rates of soil loss were observed from the laboratory sand than from the Woburn soil although the difference in detachment was not statistically significant when a T-test was applied to the means . Higher levels of soil detachment were observed on laboratory sand at lower simulated rainfall intensity (25 mm/hr) than at higher simulated rainfall intensity (120 mm/hr), although again, the difference was not statistically significant. The rain drop mass as well as kinetic energy could have accounted for the nominally higher detachment of soil aggregates from the laboratory sand. For the Woburn soil, higher rates of detachment were experienced at 120 mm/hr than at the lower intensity of 25 mm/hr. The kinetic energy was less effective in dislodging Woburn soil particles as this was overcome by a higher drag coefficient at 120 mm/ hr than at 25 mm/hr. The higher soil losses from laboratory sand as compared to Woburn soil are in resonance with the fact that higher rates of soil losses are associated with soils of lower clay content and lower organic matter. However, the results also show that at some point, and in some soil type, the drag co-efficient can be used to explain an increase in soil loss when this is related to higher detachment rates.

Key Words: Detachability, Splash Erosion, Drag Coefficient, Soil Erodibility

Objective

To assess the relative erodibility of a Cottenham soil (sandy loam) from Woburn (UK) compared to standard laboratory sand under two different rainfall intensities using a pressurized rainfall simulator.

Introduction

The erodibility of a soil refers to that soils susceptibility to erosion (Lal, 1998). Different soils, respond differently to the identical kinetic energy of raindrops. This difference in resistance is attributable to the different mechanical makeup and chemical compositions of the different soil materials (Lal, 1998). Soil erodibility could also be a function of the grain size and shape of the soil particles, the aggregate size and strength, cohesiveness, organic matter content, the chemical status and active biomass composition and the physical treatment of the soil like tillage (Kent and Bubenzer, 1980).

The soil erosion process is often described as a three phase system. In most cases, detachment of soil particles precedes transportation which is then followed by deposition. Soil detachment sets the stage for the erosion process and therefore is crucial in the quality and quantity of material that is lost through erosion. It is prudent to relate soil erosion to the rate and amount of its detachment. A number of techniques are used to determine the erodibility of a soil in terms of its detachability or of its resistance to detachment. These techniques can be applied in the field as well as in the laboratory. The use of splash boards and splash cups is quite common. The approaches make it possible for erodibility indexes to be determined for different soils. A comparative analysis can thus be drawn for different soils. The instability index of De Leenheer and De Boodt and the Henin index (De Leenheer and De Boodt, 1959; Henin et al., 1958) are among the indices that are used in predicting soil erosion risks for a wide range of soils. Another index, the kinetic energy index, gives a measure of erosivity of raindrop impact and is relevant to splash erosion (Lal, 1998). These mathematical models were primarily developed from laboratory studies. Another predictive and useful tool that was developed provides that detachment is a function of soil resistance to rainfall energy. Morgan et al. (1998) established that detachment by splash is expressed as:

$D\ (g/m^2) = KKE^b$ **Equation 1**

WhereD = detachment in grammes per m^2

K = an index of soil erodibility
KE = Kinetic energy of the stom using KE> 10 index and
b H” 1.0
(Morgan, 2005)

Lal (1998) also came up with another predictive equation in which the rate of rainfall detachment is given as;

$$e\ (\text{kg/m}^2\text{/s}) = aCe\ P. \qquad \textbf{Equation 2}$$

Where a is a measure of the detachability of the soil by rainfall

P, the rainfall rate and

Ce, the fraction of the soil surface exposed to raindrops.

These empirical relationships were established after a model was developed by Bisal (1960) in which soil loss was expressed as a function of the product of raindrop diameter and a detachability constant. In this study, Bisal (1960) had noted that there was a linear relationship between the amount of sand splashed and the raindrop size.

Methodology

The approach used involved monitoring the energy load and splash erosion simultaneously, and is often referred to as the Ellison's Splash Cup Method because of its use of splash cups. A Complete Randomised Design (CRD) was used for this study since it is the one appropriate for homogeneous experimental units usually carried out in a laboratory (FAO, 1999). The study had 2 treatments (a laboratory sand and Woburn soil) subjected to 2 rainfall intensities and replicated 5 times. The Woburn soil samples were extracted from the upper 25 cm soil layers of randomly selected spots on a field in which tillage using heavy machinery had been undertaken for more than a century. The soil exhibited a loose, sandy consistency and showed a general lack of cohesion when moistened.

Ellison's Splash Cups, each measuring 8.9 cm in diameter and 5 cm deep in which moist filter paper was placed at the base were used in the study. At any one time, five cups were filled to the brim with standard laboratory sand and weighed. The other five were filled with soil from Woburn (UK) in the same manner. The purpose of the filter paper was to retain soil in the cups whilst at the same time facilitating water movement within the soil. The cups were reweighed and then randomly placed on a tray under a rainfall simulator and then subjected to a rainfall intensity of 25 mm/hour for 30 minutes at a time. The soil in the cups was then oven dried for more than 48 hours and reweighed after cooling.

Similarly, simulated rainfall intensity of 120 mm/hour was applied for 20 minutes at a time to an equal number of splash cups containing samples of the two soil types and subjected to the same procedure as the first batch. Moisture content measurement for the two samples was carried out.

Before and during the rainfall simulation, catching cans were used in determining the quantity, rate of fall and distribution of the simulated rainfall over the tray. The flour pellet method was used to determine the median drop size for the two rainfall intensities.

This square grid depicting the layout of the cups under simulator was used to determine Christiansen's uniformity coefficient (Equation 3) as well as the energy parameters of the simulated rain fall.

$Cu = 100 * (1.0 - (\text{"}X)/nm)$. **Equation 3**

Cu = Christiansen's coefficient of uniformity
Z = amount of water measured/collected in each catch can (mm)
X = z-m = total absolute value of deviations from average amount of water
m = average amount of water (mm)
n = the number of catch cans

The splash erosion caused in each event was correlated to the simultaneously monitored parameters, namely, kinetic energy (Equation 4), median drop size, momentum, intensity and drag force (Equation 5).

$KE = \frac{1}{2} mv^2$ **Equation 4**

Where KE is kinetic energy (joules/ m^2),
m = mass (g)
v = fall velocity (ms^{-1})

(Morgan, 2005)

$Cd = 2fd/A\tilde{n}v^2$ **Equation 5**

Where Cd = Drag coefficient (dimensionless)
fd is the drag force
A is the area of raindrop (m^2)
V is the fall velocity (ms^{-1})
ñ is the density of air (assumed 1.293 kg m^{-3})

The mean soil losses at each simulated rainfall event were computed and a T test to compare the mean losses was applied at 95 % confidence level (á=0.05).

Justification for Methodology

The choice of air dry soil samples instead of wetting the soil samples was to prevent the slacking of the soil mass which would otherwise be introduced and distort the effect of simulated rainfall. Oven dry samples on one hand or saturated soil sample on the other could have been used. If however, a research is studying the effect of different rainfall intensities, it is apt to apply simulated rainfall at each intensity to each of the moisture conditions of interest (Lal, 1998).

Because data for low intensity rainfall and very high intensity rainfall are usually insignificant, researchers generally simulate storm intensities in the range that cause significant erosion and hydrological events. Thus for Bedfordshire, it was sensible to choose between 25 and 130 mm per hour. The amount and rate of rainfall are important in the interpretation of rainfall data. As such, rain simulators need to be calibrated for the conditions on which they are used or the applied rain needs to be measured during the simulated storm (Morgan *et al*, 1998 and Lal, 1998).

The duration of a rainfall simulation test is often less critical than other decisions. If rainfall intensity – frequency – duration data are available for the area, they may be considered in selecting the duration period (Lal, 1998).

The choice of splash cups provided the opportunity for the detachment process to be studied in detail. It is easier to control the parameters of soil erosion more closely than say using Splash boards or running the experiment in the field (Mutchler et al., 1990).

Results and Discussion

From the results, it can be noted that there was a higher loss of material from the laboratory sand than from the Woburn soil (Figure 1 and 2). A sandy loam soil such as the Woburn soil, has between 15 % and 45 % clay content (Evans, 2005), whereas a sandy soil would have less than 10 %. Evans after Bryan (1971) pointed out that the amount of clay in a soil is important in controlling the stability of the soil aggregates and hence erodibility. The higher soil loss from the laboratory sand than from the Woburn soil is a reflection of lower clay content. Even at the higher intensity, as shown in Figure 2, the laboratory sand lost more soil than the Woburn soil.

Related to the foregoing is the difference in the dispersion ratio of the two soils. The two soils differ in the way the particles disperse after the raindrop impact. A soil that exhibits a high splash detachment has a high dispersion ratio and this could primarily be due to the inherent low clay or silt content in the soil. It therefore follows that a sandy soil is likely to lose more soil through detachment than a sandy loam (Lal, 1990).

The difference in response to splash detachment could also be attributed to the difference in organic matter content. Although there is no indication of actual content, one can safely say there was more organic matter in the Woburn sandy loam because the laboratory sand was acid treated after sieving, thus making it devoid of any binding material and making it more prone to splash detachment. In general, a soil with more organic matter has more binding material to keep the soil particles together during a rainfall event (Morgan, 2005).

The subtle differences in soil loss (Figure 1 and Figure 2) could be linked to different antecedent soil moisture contents in the two soils. Antecedent soil water contents differed in the two soil types. The laboratory sand had moisture content of 0.7% whereas the Woburn soil had about 2% as shown in Table 1. Antecedent soil moisture conditions influence soil susceptibility to erosion by affecting cohesion, shear strength, consistency and plasticity (Lal, 1990). Although soil consistency relates to soils which exhibit cohesion, it is important to note that consistency – the resistance/adhesion of the soil deformation or the degree of the soil mass has an important effect on the processes governing soil erosion. Consistency limits, which range from the cohesion limit when the soil is relatively dry, to the liquid limit when the soil is fluid due to high moisture content and the soil behaves like a viscous liquid, depend on soil type. A higher antecedent moisture content of the Woburn soil could have meant that the soil required only a small amount of additional water through the simulated rainfall, for it to exhibit some measure of cohesion (Lal, 1990).

Table 1: Antecedent Soil Moisture Content

Texture	Moisture Content
Lab sand	0.7 %
Woburn soil	2 %

Table 2: Median Drop Diameter (D5o) at different rainfall intensities – as determined by flour pellet method

Intensity	Diameter (mm)
25 mm/hr	2.26
120 mm/hr	0.73

In the Woburn soil, there was a relatively high increase in the amount of soil detached when the rainfall was increased from 25 mm/hour to 120 mm/hour (Figure 3). This, from an energy point of view, was unusual and could have been a direct response by the soil to the rain fall drag coefficient. The bombardment of the soil surface by the raindrops changed the surface of the soil and may have accounted for more detachment in the case of a higher intensity. In the case of the Woburn soil, where higher rates of detachment were experienced at 120 mm/hour, there was less energy imparted by the median drop but this was overcome by a higher drag coefficient (Table 3 and Table 4 and Figure 3) at 120 mm/hour than at 25 mm/hour. According to Evans (1980), kinetic energy explains most of the soil loss measured in the field plots. Such an explanation may not be valid because higher losses were experienced when the energy levels were low.

By comparison, the opposite was true for laboratory sand. It was observed that there was a higher level of detachment at lower simulated rainfall intensity (Figure 4). The median drop diameter for the two intensities as inferred from the flour pellet method used decreased from 25 mm/ hour rainfall to the 120 mm/ hour rainfall. From this perspective, higher energy values were expected in the lower rainfall intensity. The kinetic energy is directly derived from the distribution of raindrop size for a given intensity (Table2 and 3). It is said that at intensities between 50 and 100 mm/hour and above 200 mm/hour per hour, the drop size distribution includes a very large proportion of drops larger than 4 mm. Since momentum and kinetic energy of raindrops increase with drop size, rainfall is more aggressive at between 50 mm/hour and 100 mm/hour, and above 200 mm/hour. At rainfall intensity of 25 mm/hour, the median drop diameter was 2.26 mm but at about 120 mm/hour, the median drop diameter was 0.73 mm. The high pressure for 120 mm/hour discharge resulted in smaller drop formation and from kinetic energy and momentum calculations (Table 3) there was a decline in energy when rainfall increased from 25 to 120 mm/ hour. The smaller median drop diameter at higher intensity may have resulted in a lower detachment rate in this case. The mass, hence the kinetic energy, of the median raindrop was more effective in detaching soil aggregates than at 120 mm/hour.

The weak inverse to an increase in rainfall intensity within the same soil type in some instances could be explained by the development of a water layer on the soil surface and this layer possibly served as a cushion for soil against further bombardment by the raindrops. In a case where the soil detachment rate increases, the turbulence set up during the bombardment could magnify the effect of the rain drops (Morgan, 2005). This view is corroborated by Palmer (1963) and Kirkby (1980) who observed that raindrop impact increased until the water layer was about 85 % of the drop diameter and then declined. In the field it was observed on that a crust formed on clayey soils during rainfall. The formation of a soil crust leading to water ponding on the surface indicates, somewhat, a change in the soil's erodibility, making the soil less erodible as the storm progresses.

Conclusion and Recommendations

Although the effect of soil type on splash detachment is important when considering the resistance of a soil to the energy of raindrops, the role of other factors such as tillage may also be important. The study revealed slightly higher rates of soil loss on laboratory sand than the Woburn soil, and this could be attributed to the inherently poor resistance of a sandy soil on one hand and tillage practices implemented over a long period of time which could have weakened the structure of the Woburn soil on the other hand. In other words, the Woburn soil, being generally considered to be more coherent in structure and therefore more resistant to detachment than a sandy soil, became more erodible due to tillage.

Another important explanation is based on the rainfall and the temporal changes that would be occurring on the sol properties. The quality and quantity can bring about different responces. In general, soil detachment is a result of interaction of the rainfall in terms of its intensity and duration and the nature of the soil in terms of its resistance. However, as the rainfall intensity and duration change, so does the condition on the soil surface and the resulting different soil detachment rates which depends on the soil type. It is possible to argue that during a rain storm, soil erosion from a bare surface increases until a layer of water sufficiently deep enough to protect the soil beneath it develops. So, where infiltration exceeds precipitation, this will not occur and for as long as there is enough energy to dislodge soil particles, soil erosion will occur.

In principle therefore, management practices that reduce cover for soil, for instance conventional residue-free practices, expose the soil and may magnify the raindrop impact by impeding infiltration and inhibiting temporary storage of rainfall whilst some tillage will weaken the soil structure and render it more erodible.

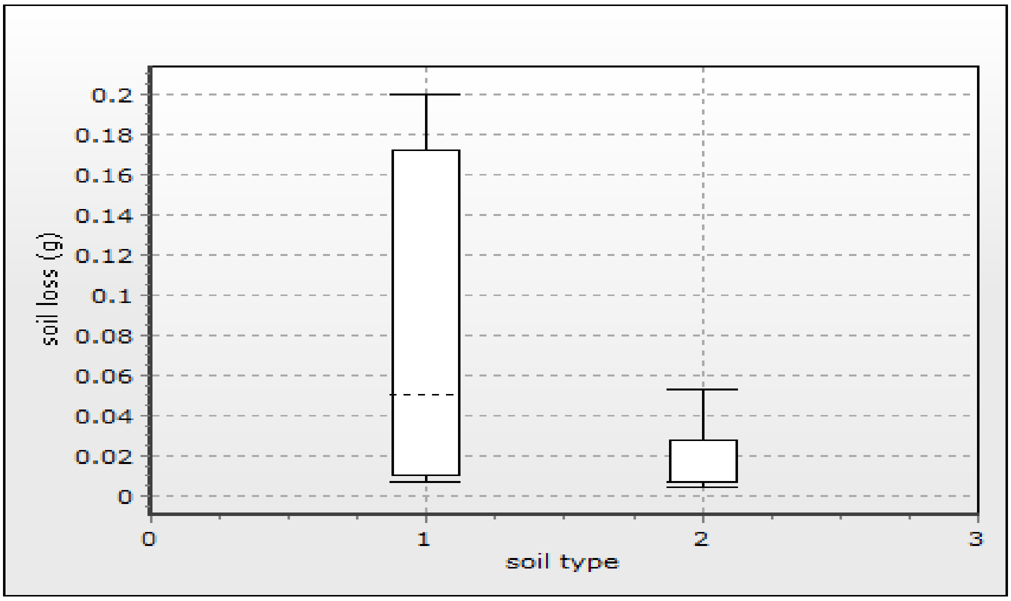

Figure 1: Comparison of mean soil losses between Lab Sand (1) and Woburn soil (2) at rainfall intensity of 25mm/hr

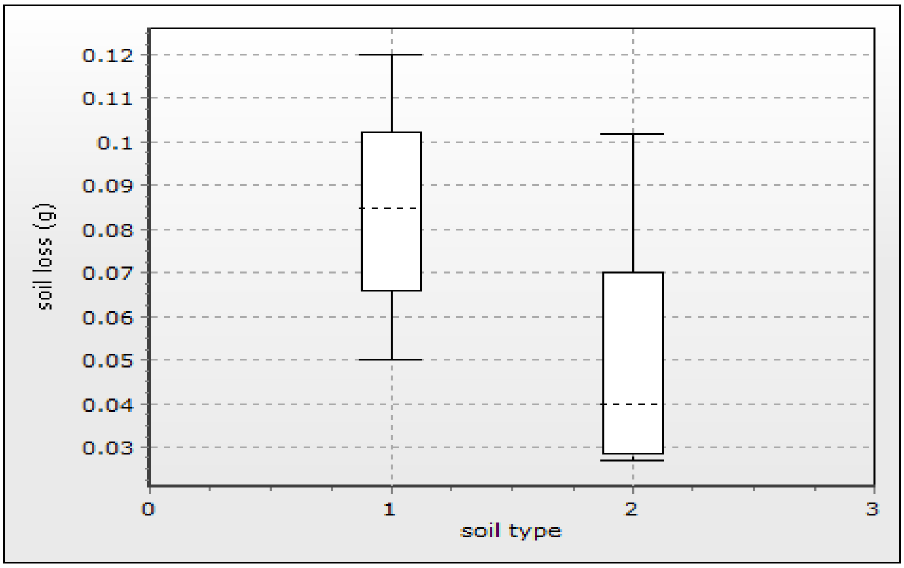

Figure 2: Comparison of mean soil losses between Lab Sand (1) and Woburn soil (2) at rainfall intensity of 120 mm/hr

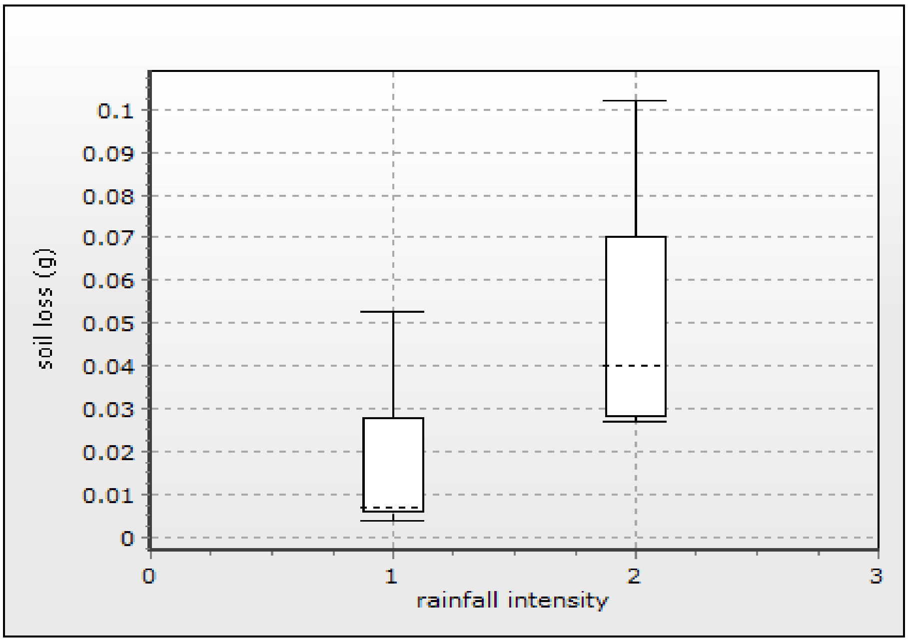

Figure 3: Comparison of mean Woburn soil losses at 25 mm/hr (1) and 120 mm/hr (2)

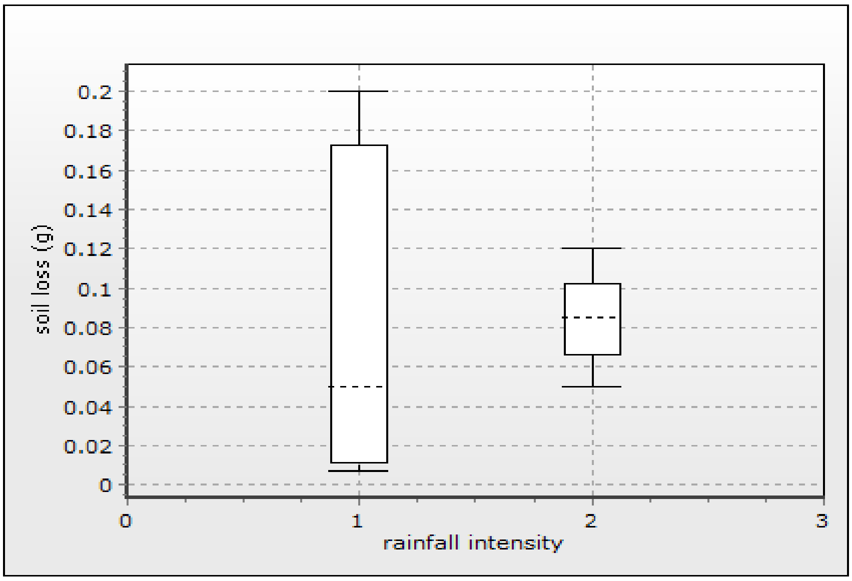

Figure 4: Comparison of mean Lab Sand losses at 25 mm/hr (1) and 120 mm/ hr (2)

Table 3: Summary of Energy Parameters at drop impact using Median Drop Diameter (D5o)

	Diam (mm)	**Fall h(m)**	**Vel(m/s)**	**A(m/5-2)**	**KE(J)**	**DRAG**
A	2.26	2.0044	5.1415	4.3665	7.97x10^{-5}	0.516

	Diam (m)	**Fall h(m)**	**Vel(m/s)**	**A(m/5^{-2})**	**KE(J)**	**DRAG**
B	0.73	2.0022	2.9034	0.2095	8.57x10^{-7}	0.924

A	Rainfall intensity 25 mm/hr
B	Rainfall Intensity 120 mm/ hr

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