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THE ENERGIES OF SOIL DISPERSION UNDER RAINFALL.

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The wetting and kinetic energies applied by rainfall were quantified for two soils with contrasting stabilities. Breakdown of aggregates to <2 μm and <20 μm material by the application of both high and low energy rainfall to initially air-dry and capillary wetted soil was measured throughout simulated rainfall events. The energies associated with aggregate disruption during the rainfall were calculated from the soil dispersion characteristic for each soil. In each case, the wetting energy associated with rainfall was dominant with up to 0.39 J g^{-1} and 2.50 J g^{-1} of energy consumed by dispersion of the unstable and stable soils, respectively. Dispersive energy attributed to drop impact accounted for only 0.12 and 0.70 J g^{-1}, respectively.

INTRODUCTION

Seal and crust formation in soils has been attributed to both spontaneous dispersion and the physical disruption and compaction of soil aggregates (Agassi *et al.*, 1981). One of the most common causes of seal formation in the field is water drop impact associated with either rainfall or spray irrigation. The effect of rainfall on aggregate breakdown has been attributed to both the wetting action of the rain and pressure applied to the aggregate by drop impact. The importance of each process appears dependent on soil physical and chemical properties and the rainfall intensity applied. Although some empirical work has been conducted to determine the relative importance of these mechanisms under different conditions, the absence of a quantitative method of measuring soil dispersibility (including both <2 μm and <20 μm material) and the energies associated with this dispersion has limited progress.

Raine and So (1993) described a technique of measuring the energy applied to a soil-water suspension and the component of that energy consumed by aggregate dispersion. Although the dispersive efficiency of the applied mechanical force may vary under different conditions, it seems reasonable to assume that the same amount of dispersive energy will be required to produce an equivalent dispersion under any condition. In this case, the amount of energy consumed by dispersion will be dependent on the strength of the bonding mechanisms present and the efficiency of the applied energy in overcoming these bonds. Thus, the dispersive efficiency of the water drop impact should provide a quantitative measure of the interaction between water drop energy and aggregation mechanisms. This paper investigates the potential of the Raine and So (1993) technique to measure the energies associated with the dispersion of silt- and clay-sized material by rainfall. Differences due to rainfall kinetic energy and initial soil moisture content are investigated for two vertisols with contrasting stabilities.

MATERIALS AND METHODS

Soils

Two soils were used in this study, a Delvin Grey Clay (Ug5.24, Chromic Vertisol; Yates, 1972) from the Gwydir Valley, New South Wales and a Lawes Black Earth (Ug5.15, Udic Pellustert; Schafer *et al.*, 1984) from the Lockyer Valley, Queensland. These soils have similar clay contents but the Delvin was observed to be substantially less stable under field conditions. Both soils were collected from a single bulk surface sampling, air dried under glasshouse conditions and crushed to pass through a 2 mm sieve. Particle size analyses were conducted using the method of Gee and Bauder (1986).

Dispersion by rainfall

Effects of two rainfall impact energies and two initial soil moisture contents on the dispersion produced and the dispersive energy of the rainfall were investigated. Treatment plots were prepared by packing fine washed sand to a depth of 10 cm in wooden trays (80 cm x 60 cm x 15 cm). Soil was then packed above the sand until level with the tray surface. For the moist soil treatments, the trays were placed in a water bath allowing the soil to wet from the bottom. The height of the water was such that the soil at the surface of the trays was under a -3 cm tension. Samples were allowed to equilibrate over a period of 48 hours.

Rainfall (80 mm h^{-1}) was applied to all treatments using a rainfall simulator designed with a fall height of 2.2 m and fitted with Veejet 80100 nozzles. The kinetic energy applied by waterdrop impact using a similar system was calculated on the basis of measured drop size and velocity as 29.5 J m^{-2} mm^{-1} (Duncan, 1972). For the low energy rainfall treatment, a 0.2 mm wire mesh was placed 0.2 m above the plots to reduce the impact energy without reducing intensity. The kinetic energy applied to the soil surface by impact was reported to be negligible for a similar system (Loch, 1989) and no significant ($P<0.05$) reduction in rainfall intensity was observed due to the wire mesh. In each case, rainfall was applied for various periods up to 140 minutes. Trays were placed on a two percent slope within the simulator to allow some run-off and reduce the effect of ponded water on raindrop impact energy. After each period of rainfall, two samples of the surface 5 mm of soil were removed from each treatment plot and placed on a tension table at -3 cm to prevent drying out and possible re-aggregation of the sample. To determine the effective particle and aggregate size distribution produced by the treatment, sub-samples were removed from the tension table and immersed in 200 cm^3 water. The suspension was then gently hand stirred for 10 s to ensure uniform mixing while minimising additional dispersion. After the appropriate settling period, the amount of <20 μm and <2 μm equivalent spherical diameter material present was determined using a pipette withdrawal technique.

Determination of the dispersive energy

The relationship between the quantity of dispersed material produced by sonification and the energy consumed by dispersion has been described as the soil dispersion characteristic (*SDC*) (North, 1976; Raine and So, 1993). To obtain the *SDC* for both soils, the air dried equivalent of 5 g oven dried soil was capillary wetted under -3 cm tension for 24 hours. Samples were then immersed in 30 g deionised water within a 40 cm^3 glass vial. Ultrasonic energy was applied to the suspensions using a probe type sonifier producing

8.9 (± 0.3) W (measured calorimetrically at 27.5 °C) with the energy application and dispersive energy consumption throughout the period of sonification determined using the method of Raine and So (1993). The effect of sonification on dispersion was determined by measuring the quantity of $<20\ \mu m$ and $<2\ \mu m$ equivalent spherical diameter material produced by periods of sonification up to 900 s. The energy consumed by dispersion due to the rainfall treatments was then calculated from the *SDC* for each soil.

RESULTS

The physical characteristics of the experimental soils are presented in Table 1. Table 2 shows the period of rainfall observed to induce surface runoff in each treatment. For the stable Lawes soil, large differences were found due to the initial moisture content of the soil, with the air-dry treatments producing runoff after 15 minutes of rainfall irrespective of rainfall energy. However, for the capillary wetted treatments, much larger periods of rainfall were required to induce runoff with differences observed due to rainfall energy. For the relatively unstable Delvin soil, runoff was observed earlier in the high energy rainfall treatments than in the low energy rainfall treatments. However, differences between air-dry and capillary wetted treatments were smaller than observed for the Lawes soil with all Delvin treatments producing runoff after 20 minutes.

Table 1. Particle size distributions and dispersion produced by immersion wetting of the experimental soils.

Soil	Particle size distribution			Dispersion produced by immersion wetting		
	$<2\ \mu m$ ($g\ g^{-1}$)	2-20 μm ($g\ g^{-1}$)	$>20\ \mu m$ ($g\ g^{-1}$)	$<2\ \mu m$ ($g\ g^{-1}$)	2-20 μm ($g\ g^{-1}$)	$>20\ \mu m$ ($g\ g^{-1}$)
Lawes	0.53	0.22	0.25	0.01	0.12	0.87
Delvin	0.53	0.15	0.32	0.03	0.15	0.82

Table 2. Periods of rainfall required to induce surface runoff on the experimental soils.

Soil	Air-dry soil		Capillary wetted soil	
	High energy rainfall	Low energy rainfall	High energy rainfall	Low energy rainfall
Lawes	15 min	15 min	90 min	>140 min
Delvin	3 min	10 min	14 min	20 min

Negative exponential functions relating the period of rainfall applied and dispersion of $<20\ \mu m$ and $<2\ \mu m$ sized material were found to be significant at $P<0.05$ for each treatment (Table 3). Where D is the amount of $<20\ \mu m$ or $<2\ \mu m$ dispersed material and t is the period of rainfall applied:

$$D = c + b(1\text{-exp}^{(-at)}) \qquad \text{Eqn (1)}$$

In this equation, c is the amount of $<20\ \mu m$ or $<2\ \mu m$ material that is spontaneously dispersed by capillary wetting; $(c + b)$ is the maximum dispersion produced by the treatment and a is a fitted parameter indicating the rate of dispersion.

For the capillary wetted Lawes soil, significant ($P<0.05$) differences in the rate of dispersion of both <20 μm and <2 μm sized material were observed due to rainfall impact energy (Table 3a). However, the maximum dispersion of <20 μm material produced was significantly ($P<0.05$) greater in the air-dry soil treatments than in the capillary wetted soil treatments. Where rainfall was applied to air-dry Lawes soil (Table 3a), dispersion of both <20 μm and <2 μm sized material occurred rapidly with no significant ($P<0.05$) difference in either maximum dispersion or rate of dispersion attributable to rainfall energy.

Maximum dispersion of <20 μm and <2 μm Delvin material was observed where the rain was applied to an initially air-dry soil (Table 3b). There was no significant ($P<0.05$) difference due to rainfall kinetic energy for the air-dry treatments. However, a significant reduction in the maximum amount of <20 μm material released was observed between the rainfall treatments applied to capillary wetted soil.

The maximum amount of <20 μm material released by each treatment and the corresponding dispersive energy requirements calculated from the *SDC* are shown in Table 4. Significant ($P<0.05$) differences in dispersive energy were observed between the soils and between rainfall energy treatments applied to capillary wetted soil.

DISCUSSION

Dispersion

The period of rainfall required to induce surface runoff (Table 2) provides a measure of the surface seal formation for each treatment. These results are consistent with previous

Table 3. Effects of initial soil moisture and rainfall impact energy on dispersion produced by application of 80 mm h^{-1} rainfall.

(a) Lawes soil

Initial soil moisture	Rainfall impact energy	<2 μm Regression Parameters [1]			<20 μm Regression Parameters [1]		
		a	*b*	r^2	*a*	*b*	r^2
Capillary Wetted	Low	0.3582^{a}	0.0101^{a}	0.750	0.3446^{a}	0.0416^{a}	0.812
	High	0.0361^{b}	0.0194^{ac}	0.698	0.0767^{b}	0.0686^{b}	0.767
Air-dry	Low	0.5698^{a}	0.0240^{b}	0.784	0.5602^{a}	0.0955^{c}	0.876
	High	0.2427^{ab}	0.0222^{bc}	0.804	0.2430^{ab}	0.0901^{c}	0.909

(b) Delvin soil

Capillary Wetted	Low	0.1462^{ab}	0.0384^{a}	0.835	0.2565^{a}	0.0764^{a}	0.913
	High	0.0771^{ab}	0.0490^{ab}	0.839	0.0779^{a}	0.1167^{b}	0.839
Air-dry	Low	0.0570^{a}	0.0528^{ab}	0.853	0.1912^{a}	0.1121^{b}	0.645
	High	0.0760^{ab}	0.0618^{b}	0.512	0.2761^{a}	0.1321^{b}	0.774

[1] Regression equation: $D = c + b(1\text{-}\exp^{(-at)})$ where D is the amount of <2 μm or <20 μm material released in g g^{-1}, t is the period of rainfall in minutes and $c = 0.0096$ (Lawes <2 μm); 0.0403 (Lawes <20 μm); 0.0188 (Delvin <2 μm); 0.0499 (Delvin <20 μm).
Superscripts represent T Groupings between treatments for each soil. Treatments with the same T grouping are not significantly different ($P<0.05$).

Table 4. The maximum dispersion of <20 μm material produced by 80 mm h^{-1} rainfall and the dispersive energy required to produce the dispersion.

Soil	Initial soil moisture	Rainfall energy	<20 μm material released ($g\ g^{-1}$)	Dispersive energy ($J\ g^{-1}$)
Lawes	Capillary wetted	Low	0.0819	1.09^{a}
		High	0.1089	1.79^{b}
	Air-dry	Low	0.1358	2.50^{c}
		High	0.1304	2.35^{c}
Delvin	Capillary wetted	Low	0.1263	0.22^{d}
		High	0.1666	0.34^{e}
	Air-dry	Low	0.1620	0.33^{e}
		High	0.1820	0.39^{e}

Superscripts represent T Groupings between treatments for each soil. Treatments with the same T grouping are not significantly different ($P<0.05$).

field observations of these soils and the dispersion of <20 μm sized material measured during rainfall application (Table 3). The large differences in the period of rainfall required to induce runoff observed between the initial soil moisture treatments of the Lawes soil indicates that rapid wetting plays an important role in surface seal formation for this soil.

The Delvin soil dispersed more readily under the influence of rainfall than the Lawes soil (Table 3). For this soil, the application of high energy rainfall to capillary wetted soil (Table 3) resulted in the same amount of dispersion as the application of rainfall to air-dry soil (Table 3) and immersion wetting (Table 1). The rapid development of surface runoff for the high energy rainfall treatments compared to the low energy rainfall treatments suggests that rainfall energy plays an important role in seal formation.

The negative exponential nature of the dispersion results supports Morin and Benyamini's (1977) observation that dispersion and sealing are related to cumulative drop impacts. The shape of the fitted functions also indicate that as aggregate breakdown continues, fewer bonds are available for dispersion and less dispersion occurs. Thus, where the individual impact energy applied by the water drop is insufficient to break the remaining aggregation bonds, additional dispersion does not occur and a maximum is reached.

Dispersive Energy

The Delvin soil disperses more readily than the Lawes soil and significantly less dispersive energy is required for this dispersion (Table 4). This is consistent with field observations for these soils and suggests that the Delvin soil has either weaker aggregate bonds or a smaller number of aggregate bonds than those found in the Lawes soil. In both soils, the dispersive energy measured for the capillary wetted, low energy rainfall treatment must be associated with spontaneous dispersion due to the additional wetting of the sample by the rain. This energy is most likely attributable to electrolyte effects or swelling pressures as the kinetic energy applied by the rainfall in this treatment is negligible. The dispersive energy measured for the air-dry soil treatments is associated with the rapid wetting of the sample (Table 3). Thus, the dispersive energies for these treatments provide a measure of the energies associated with rapid wetting. However, where high energy rainfall was applied to the capillary wetted soil, the difference in dispersive energy requirement between the high and low energy rainfall treatments must have been applied to the sample by the rainfall impact. For the Lawes soil, this energy was 0.70 J g^{-1} while for the Delvin it was 0.12 J g^{-1} (Table 4).

One method of confirming the accuracy of the dispersive energy values is to compare them to the actual energy applied by raindrop impact. Assuming a depth of 5 mm influence and a soil bulk density of 1 g cm^{-3}, the high energy rainfall treatment applied 0.0078 J g^{-1} min^{-1} of kinetic energy to the soil. For the capillary wetted treatments, ponding was induced by 90 minutes (0.702 J g^{-1}) and 14 minutes (0.109 J g^{-1}) of rainfall on the Lawes and Delvin soils, respectively. As these values are not significantly different to the measured dispersive energy component for either soil, this suggests that the *SDC* can be used to calculate dispersive energy requirements associated with rainfall. It also suggests that during the period of aggregate breakdown, the majority of the kinetic energy associated with waterdrop impact is effectively used by aggregate breakdown. However, where further dispersion does not occur, this energy is presumably associated with surface compaction or dissipated with no effect on dispersion.

This work has shown that it is possible to quantify structural stabilities using an energy based parameter. It has also shown that wetting energy associated with rainfall has a dominant effect on soil dispersion. However, where the soil is initially moist, the kinetic energy associated with raindrop impact also influences the dispersion of clay and silt sized material.

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