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The influence of the soil conditioner ‘Agri-SC’ on splash detachment and aggregate stability

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Abstract

The influence of the soil conditioner ‘Agri-SC’ on splash detachment and water-stable aggregation of an erodible clay Vertisol from Oahu, HI, was assessed. Laboratory rainfall simulation was used to assess splash detachment from soil treated with 0 (untreated control), 0.3, 3.0, 30, and 300 l ha^{-1} of Agri-SC. Results indicated that the quantity of sediment splashed was significantly lower for Agri-SC application rates of 0.3 and 3.0 l ha^{-1} (rates are equivalent to 1 and 10 times the manufacturer’s recommended rates, respectively), than for the control, or for Agri-SC applied at 30 and 300 l ha^{-1} (100 and 1000 ×, respectively). A second experiment was designed to test the influence of Agri-SC on water-stable aggregation of the Vertisol. Aggregates were subjected to rapid immersion in solution, shaken and washed through a series of sieves. Data indicated that there were no statistically significant differences in geometric mean aggregate diameter between the untreated and treated aggregates. The effect of the active ingredient, ammonium laureth sulfate (an anionic surface active agent) on splash and erodibility are discussed. These preliminary results indicate that further testing of Agri-SC is warranted on a variety of soils with different textures and mineralogies. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Erodibility; Rainsplash; Water-stable aggregation; Anionic surfactant; Rainfall simulation

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1. Introduction

Soil conditioners have been shown to alter the fundamental processes that influence erosion, e.g., increase pore space in soils, increase infiltration, enhance soil aggregation, reduce soil sealing, reduce soil crusting, decrease wind erosion, reduce rainsplash

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detachment, and reduce soil erosion by concentrated or unconcentrated overland flow (c.f., Martin, 1953; Chepil, 1954; Wallace and Nelson, 1986; Fox and Bryan, 1992; Sojka and Lentz, 1994; Nadler et al., 1996). The benefits of soil conditioners include an improved soil moisture balance, improved nutrient storage, reduced erodibility by wind or water processes, and the creation of an environment more conducive to biomass production.

Despite the voluminous literature on soil conditioners, their widespread application on arable lands has been limited, primarily because of economic considerations. With new technological advances and the identification of chemicals that can be applied at low, cost-effective concentrations, interest has been renewed. One such soil conditioner is Agri-SC (manufactured by Four Star Services, Bluffton, IN, USA), and it has been found to decrease the erodibility of a sandy loam Entisol (Fullen et al., 1993, 1995). However, this success was not achieved previously on a silt loam Alfisol (Fitch et al., 1989). Because Agri-SC is currently hailed as an effective soil amendment (e.g., Northcutt, 1996), and because it is very inexpensive when applied at manufacturer-recommended rates, the contradictory results on the two different soil types call for further research on the general effectiveness of this product before it is recommended for widespread use.

The objective of this study is to test the effectiveness of Agri-SC in decreasing the ‘erodibility’ of a soil not previously tested. In particular, we (1) examine the rainsplash response of an erodible clay Vertisol treated with different concentrations of Agri-SC; (2) examine the influence of Agri-SC concentrations on the water stability of aggregates (WSA) of the same soil; and (3) briefly examine the previous research on anionic surfactants, the general class to which the main ingredient in Agri-SC belongs.

2. Background

2.1. Previous research on Agri-SC

Fullen et al. (1993, 1995) investigated the influence of Agri-SC on runoff, erosion rates, and soil erodibility of a loamy sand Entisol in England. Their data, although not always statistically replicated, indicated that Agri-SC was an effective soil conditioner since treated aggregates were more stable to raindrop impact than the untreated aggregates. Additionally, although the 2-, 3-, and 4-times recommended rates produced significantly more stable aggregates than the recommended application rate ($0.30\ \mathrm{l\ ha^{-1}}$, $1\times$), there was no difference in aggregate stability between the three higher application rates. These WSA data support that Agri-SC decreases the erodibility of the Entisol, as aggregate stability is generally thought to be correlated with increased infiltration, decreased runoff, and therefore, decreased surface erosion (c.f., Bryan, 1968, 1971; Bryan et al., 1989).

The above test results contradict an earlier statistically designed field study (Fitch et al., 1989), in which a silt loam Alfisol was treated with three application rates of Agri-SC, $0.15\ \mathrm{l\ ha^{-1}}$ ($0.5\times$), $0.30\ \mathrm{l\ ha^{-1}}$ ($1\times$), and $0.60\ \mathrm{l\ ha^{-1}}$ ($2\times$). Agri-SC was applied twice, once in 1986 and again in 1987. During each year, soil cores from the treated plots and an untreated control were analyzed for organic matter, mean aggregate diameter, porosity, saturated hydraulic conductivity and Atterberg limits. Analysis of variance (ANOVA) indicated no significant differences between any of the treatments for any of the properties measured during either of the two years.

The reasons for the contradictory responses of Agri-SC on two different soils are not known, but may stem from variations in the availability of charged adsorption surfaces of the soils to the active ingredient in Agri-SC, ammonium laureth sulfate, an anionic surfactant. The disparate results are obviously a concern for the widespread application of this soil conditioner to arable soils of disturbed hillslopes; however, considering the relationships between the properties of surfactants and aggregate soil physics/chemistry, these differences are not surprising.

2.2. Anionic surfactants

Ammonium laureth sulfate is only one compound within a class of surfactants termed anionic. Surfactants are organic compounds composed of both hydrophobic (water-repellent) and hydrophilic (water-attracting) parts (Allred and Brown, 1994). As noted by Zartman and Bartsch (1990), surfactants reduce surface tension, thereby diminishing solid/liquid interfacial forces. Surface tension commonly falls to a minimum value at or above the critical micelle concentration (CMC), the concentration at which surfactant molecules form ‘aggregates’ called micelles (Allred and Brown, 1996). Surfactants are common components in detergents, cleaning agents, and agrochemicals (Bock and Stache, 1982; Tadros, 1995). The question that arises is how do surfactants affect aggregate stability or soil erodibility?

The literature on surfactants and their relationship with ‘erosion’ is limited, but what exists suggests that the relationship is dependent on both soil and surfactant type. Adsorption studies of Law and Kunze (1966) and Law et al. (1966) indicated that anionic surfactants were adsorbed in small amounts by kaolinite, and that none was adsorbed by montmorillonite. In contrast, significant quantities of cationic and nonionic surfactants were adsorbed by montmorillonite clays (Law and Kunze, 1966). Later, Fink et al. (1970) found that soils with high adsorption for anionic surfactants had high free iron oxide, high clay contents, and low cation exchange capacity (CEC); while low adsorbers, were typically sandy soils or soils with low free iron oxide, high clay contents, and high CEC.

Xu et al. (1991) found that anionic surfactant adsorption on kaolinite was consistent with an electrostatic adsorption mechanism, since both positive and negative sites coexist on kaolinite surfaces. They also found that the decrease in adsorption with increased pH (5 to 10) was also consistent with theory, since the number of positive sites on kaolinite decreases with increasing pH. Other mechanisms may also be present for anionic surfactant adsorption on basal faces of clay minerals, since a positive charge may develop from the precipitation of dissolved aluminum hydroxide complexes (Xu et al., 1991). This mechanism of anionic adsorption was also suggested by Wayman (1962, cited in Law and Kunze, 1966), when he found adsorption at pH 4 for kaolinite, illite and montmorillonite was consistently greater than that at pH 7 or 10. The $Al(OH)^{2+}$ and $Al(OH)_2^+$ complexes play a significant role in increased anionic adsorption at low pH

(Law and Kunze, 1966). Lagaly (1994) stated that anions (as in anionic surfactants) can replace hydroxyl groups at the edges (ligand exchange) and become directly coordinated to octahedral cations, mainly aluminum ions, and this exchange should predominate at pH 5–7. Anionic surfactants can be coadsorbed at negatively charged sites, via multivalent cations, such as Ca^{2+} and Mg^{2+}, that bridge surfactant anions and negatively charged soil particles (Allred and Brown, 1996).

The strength of aggregates in the presence of anionic surfactants is complex. Law et al. (1966) found that three anionic surfactants significantly decreased geometric mean aggregate diameter (GMAD) from a montmorillonitic Vertisol; while nonionic and cationic surfactants significantly increased the GMAD of the same soil. More recently, Piccolo and Mbagwu (1989) studied the water stability of 1.0–2.0 mm aggregates, separated from two soils, a sandy loam Entisol (pH = 6.9) and a clay Inceptisol (pH = 7.6) to various concentrations of an anionic surfactant. They found that low concentrations increased the percentage of WSA, while high concentrations reduced the percentage of WSA; intermediate concentrations had no effect on the aggregate stability of either soil. A follow-up study using a sandy clay loam Entisol (pH = 4.5) and a sandy loam Ultisol (pH = 5.2) investigated the influence of three anionic and two nonionic surfactants on WSAs (Mbagwu et al., 1993). This study confirmed that high concentrations of anionic surfactants decreased the percentage of aggregate stability for both soils. Conversely, the study also showed that high concentrations of nonionic surfactants had the opposite effect on aggregate stability, i.e., increased the percentage of WSA.

In summary, the relationship of anionic surfactants with aggregate stability and soil erodibility is a complex function of the cation or anion exchange of the soil, the pH of the soil system, competing ions, clay minerals present, sesquioxides present, and the concentration of surfactant applied. Therefore, the mixed results reported in the literature are probably not atypical, and demonstrate the need to rigorously test products containing anionic surfactants on different soil types before widespread application.

3. Materials and methods

3.1. Agri-SC and the test soil

At the manufacturer’s recommended rate (0.30 l ha^{-1}) the cost of Agri-SC in solution form (excluding shipping and application costs) ranges from US$7.94 to US$10.42 (US) per ha, depending on volume purchased. The primary active ingredient in Agri-SC is ammonium laureth sulfate (48%):

$$CH_3(CH_2)_{10}CH_2(OCH_2CH_2)_n OSO_3NH_4$$

where n has a value of between 1 and 4 (Rieger, 1985). Ammonium laureth sulfate is an alkyl ether sulfate, a group of compounds widely used in shampoos because of their excellent cleansing and foaming properties (Nikitakis, 1988). Two other reported ingredients in Agri-SC are isopropanol (400 ppm) and ethanol (1000 ppm).

The Lualualei Vertisol (Typic Chromustert) from Oahu, HI was used in this study for several reasons: (1) we have previously conducted detailed erosion studies using this soil (e.g., Sutherland and Ziegler, 1996; Ziegler and Sutherland, in press), (2) its physical

Table 1
Chemical and physical characteristics of the Lualualei Vertisol, Oahu, HI

Soil characteristics	Units	Soil depth (cm)	Value(s)[a]
pH in water (1:1)	–	0–10	7.2
Organic carbon	$g\ kg^{-1}$	2–20	5.0
Total nitrogen	$g\ kg^{-1}$	0–10	1.8
CEC	$cmol\ (+)\ kg^{-1}$	2–20	47.5
Exchangeable Ca^{2+}	$cmol\ (+)\ kg^{-1}$	2–20	34.4
Exchangeable Mg^{2+}	$cmol\ (+)\ kg^{-1}$	2–20	18.4
Exchangeable K^{+}	$cmol\ (+)\ kg^{-1}$	2–20	0.6
Exchangeable Na^{+}	$cmol\ (+)\ kg^{-1}$	2–20	4.44[b]
ESP	%	2–20	9.3[b]
Smectite	$g\ kg^{-1}$	2–20	175
Kaolinite/halloysite	$g\ kg^{-1}$	2–20	110
Surface area ($< 2.0\ \mu m$)	$m^2\ g^{-1}$	2–20	743
Particle density	$Mg\ m^{-3}$	2–20	3.19
Field bulk density	$Mg\ m^{-3}$	0–10	1.08–1.22
Sand (63–2000 μm)	$g\ kg^{-1}$	0–10	28[c]
Silt (2–63 μm)	$g\ kg^{-1}$	0–10	372[c]
Clay ($< 2\ \mu m$)	$g\ kg^{-1}$	0–10	600[c]
Liquid limit	%	2–20	61.5
Plastic limit	%	2–20	36.8

[a] c.f. Ziegler et al. (1997) and the associated references.
[b] Malik (1990).
[c] Primary particle size determined using the hydrometer method after sonification and chemical dispersion.

and chemical characteristics are well documented (Table 1), and (3) for many regions of the world, Vertisols are important for agricultural production (Coulombe et al., 1996). Therefore, performance of Agri-SC on this soil should be of great interest to land managers and farmers in the tropics. Soil samples from the 0–10 cm portion of the A-horizon were collected from the US Lualualei Naval Magazine in western Oahu. In preparation for the experiment, the samples were sieved to pass a 4-mm screen, then air-dried to a gravimetric soil moisture content of about 10%.

3.2. Rainfall simulation and splash detachment

A laboratory drip-type simulator was used for this detailed splash investigation. Raindrop fall height was 2.0 m; and uniform drops with a median diameter of 3.2 mm were produced. Rainfall intensity, controlled by an inline pressure gauge, averaged $120 \pm 11\ mm\ h^{-1}$ (± 1 standard deviation) for all events. To produce a random distribution of raindrops at the soil surface, two opposing fans were used to generate turbulence.

The transparent splash containers used in this study had volumes of 2.5 l and surface areas of 166 cm^2. Prior to filling with soil, holes were punctured in the bottom of the splash cup then covered with 2 μm pieces of filter paper. To reduce wash over by rainflow, soil was gently packed (mean bulk density of 1.12 $Mg\ m^{-3}$) to within approximately 5 mm of the splash cup lip. The soil-filled container was set within a second container, forming a two-tiered system that allowed free drainage into the open space between the two cups, thus preventing the generation of saturation overland flow. Fresh presieved soil was used for each simulation to insure comparability in initial moisture contents and availability of material ≤ 4 mm in diameter.

Five treatments were examined, one untreated control (0 ×), and four application rates of Agri-SC, 0.3 l ha^{-1} (recommended, 1 ×) 3.0 l ha^{-1} (10 ×), 30 l ha^{-1} (100 ×), and 300 l ha^{-1} (1000 ×). Each treatment, consisting of 100 ml of tap water or mixture of tap water and Agri-SC, was applied to the soil surface then left to cure for a minimum of 11 days. The pH of the applied solutions ranged from 6.8 to 7.8; and the electrical conductivities at 25°C ranged from 340 to 1 160 μS cm^{-1}.

Five 1-h rainfall events were simulated on each of the treatments; 10 events on an untreated control surface. Based on previous splash research (Sutherland et al., 1996a,b), we determined that 1-h experiments were sufficient to examine the temporal patterns of rainsplash detachment. During each run, four randomly chosen splash containers were subjected to rainfall. Adjustments were made to the random design to insure that each of the treatments was tested at least once in each of the four simulator locations. Every 5 min, a tarp was stretched above the treatments and the 45-l containers were removed from beneath the simulator. The two-tiered splash cups were then placed within 'clean' 45 l containers and immediately placed under the simulator for another 5-min period. Each 5-min sediment sample was oven-dried at 105°C for a minimum of 24 h, then massed to ±0.001 g. This procedure allowed the temporal response of splash detachment for each treatment to be determined from twelve 5-min samples.

3.3. Fractionation of splashed aggregates

The influence of Agri-SC on size of splashed aggregates was examined because the preferential production of fine aggregates would result in increased transport by unconcentrated or concentrated overland flow. Following mass determinations, splashed sediment for each 5-min time increment, all replicates, were combined to produce a single Agri-SC 1 × sample and a single Agri-SC 10 × sample. Two replicates of the control treatment were composited in the same fashion. Compositing was necessary because of small aggregate mass fractions in some of the time increment samples. These samples were dry-sieved using a standard Ro-tap® (W.S. Tyler, OH, USA) sieve shaker with a nest of sieves to quantify the following aggregate size fractions, 2.00–4.00, 1.00–2.00, 0.50–1.00, 0.25–0.50, 0.13–0.25, 0.063–0.13, and < 0.063 mm. These data were used to determine the temporal variation in GMAD. Following mass determinations, splashed sediment from the 100 and 1000 × Agri-SC treatments were combined for each replicate to form a 1-h cumulative splash sample for each concentration (100 and 1000 ×). These were then dry-sieved using the same procedures discussed previously.

3.4. Water stable aggregate analysis

A new approach to characterizing the stability of aggregates was employed in this study (Sutherland and Ziegler, 1997). Soil samples were dry-sieved to isolate the

2.0–4.0 mm aggregate fraction, and individual 10-g samples were treated with 7.5 ml of tap water or Agri-SC and tap water. A pipette was used to carefully apply water along the rim of the container to minimize slaking during the curing phase. The same Agri-SC treatments used in the rainfall simulation experiment were used in the water-stable aggregate experiment. Samples were left to cure at room temperature for 48 h, then transferred to 250 ml Erlenmeyer flasks containing 100 ml of tap water. Application of water to the flasks was rapid, and thus caused slaking, which is the disruption of aggregates arising from the escape of entrapped compressed air (Angers and Mehuys, 1993). The slaking mechanism was considered to be important in this laboratory study because it simulates conditions similar to those typically experienced in the field. Additionally, the work of Farres (1980) showed that slaking was the prime mechanism in aggregate breakdown.

Agri-SC treatments were replicated 8 times; the untreated control was replicated 24 times. Eight randomly selected flasks were shaken simultaneously with a Burrell Wrist Action® laboratory shaker (Burrell, Pittsburgh, PA, USA) for 10 min. Samples were then washed through a nest of sieves using a low-velocity water jet. The aggregate fractions isolated included, 2.00–4.00, 1.00–2.00, 0.25–1.00, and 0.063–0.25 mm. Aggregate fractions on each sieve were oven-dried at 105°C for a minimum of 24 h; then mass determinations made to ± 0.001 g. The less than 0.063 mm aggregate fraction was determined by residual following corrections for initial air-dry water content and mass of dissolved solids in solution. From these data, the multisieve GMAD was calculated.

3.5. Statistical analysis and curve fitting

Variation in total splash and GMAD were examined using one-way ANOVA. If a significant F-ratio ($P \leq 0.05$) was observed, Fisher's protected least significant difference test was used to assess whether pairwise differences were significantly different at the $\alpha = 0.05$ significance level. To examine research questions associated with temporal splash detachment, repeated measures ANOVA was used. Curve-fitting using best-fit polynomials was used to characterize the temporal splash response for the untreated soil control and the different application rates of Agri-SC.

4. Results

4.1. Total splash output

Results indicated that 1× and 10× Agri-SC treatments reduced splash output significantly compared to the control; however, there was no difference in splash between the two treatments (Table 2). Splash from the 100× and 1000× treatments was statistically similar to that of the control, although 100× treatment produced less splash output than the control; the 1000× treatment produced more. Variability in total splash output within and between the treatments is shown in Fig. 1. For the four Agri-SC treatments, the total splash values for each run were ranked from low (Rank 1)

Table 2
Variation in average splash detachment from 1-h rainfall events for five surface treatments

Treatment	Application rate (l ha^{-1})	No. of samples	Mean splash detachment (g)
Agri-SC	0.30 (1×)†	5	21.21†,‡
Agri-SC	3.0 (10×)	5	21.63†
Agri-SC	30 (100×)	5	36.48‡
Untreated (control)	–	12	46.32‡
Agri-SC	300 (1000×)	5	62.25‡

†Values in parentheses represents the factor by which the application rate of Agri-SC exceeds the manufacturers recommended rate.

‡Mean splash values followed by the same letter are not significantly different at $\alpha = 0.05$.

to high (Rank 5), and plotted from left to right. The 10 replications on the untreated sample were ranked, then the average of each ranked pair, (e.g., 1 and 2, 3 and 4, ... to 9 and 10) were plotted for comparative purposes. These data suggest that for reducing splash detachment on this soil, the optimal application rate for Agri-SC is less than or equal to that recommended by the manufacturer.

4.2. Temporal splash response

Repeated measures ANOVA results indicated: (i) a highly significant difference ($P = 0.0036$) in mean splash detachment existed between the five treatments over the twelve 5-min periods; (ii) splash detachment (averaged over treatments) varied significantly with time ($P = 0.0004$), indicating that throughout the 1-h events, there were

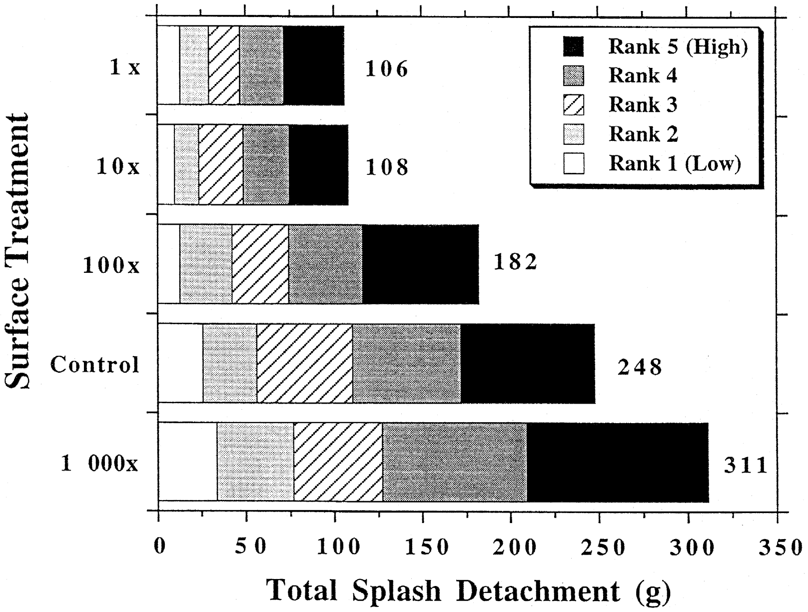

Fig. 1. A ranked stack graph indicating the splash detachment for each replicate of a treatment. Cumulative values for all five events are shown.

phases when splash was significantly higher or lower than at other times; and (iii) there was a highly significant ($P = 0.0003$) interaction between time and surface treatment, suggesting that the patterns of splash detachment over time differed depending on surface treatment. These results served as a basis from which we direct further temporal-based analyses.

Mean splash values, for five treatments, are plotted against time in Fig. 2. Temporal splash response on the control was characterized by a peak at 20 min, followed by a gradual decline to the end of the event. This pattern, similar to that reported in other detailed splash studies (e.g., Farres, 1987), can be described by an initial preparation period (0–20 min) when soil strength is decreased, and aggregates are destroyed, filling the pore space with fine sediment. A thin muddy layer forms and splash peaks. This period is followed by an increase in water layer depth and a depletion of readily available sediment.

High application rates of Agri-SC (100 and 1000 ×) produced a temporal splash pattern similar to that of the control, with the exception being the response from the 100 × application was slightly dampened; and the response from the 1000 × application was somewhat enhanced. Again, the 0 ×, 100 ×, and 1000 × treatments were determined to be statistically indistinguishable. In contrast, the low application rates (1 and 10 ×) produced a splash detachment response very different from the control and the higher rates. For instance, the maximum output occurred during the first 5 min, suggesting that the initial preparation and breakdown processes did not occur, or occurred before 5 min. Observations during the simulations, suggest the rapid formation of a soil seal produced a thick, protective water layer that shortened the period of direct raindrop impact.

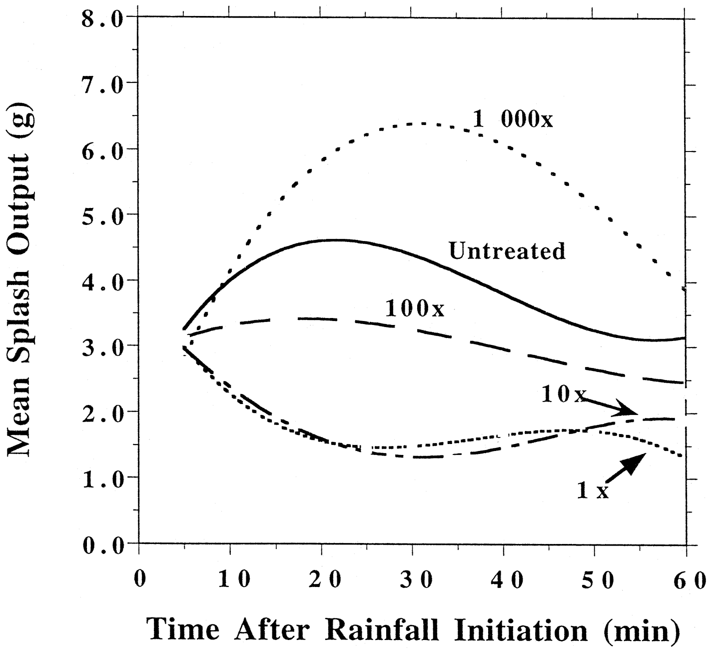

Fig. 2. Temporal variation in mean splash detachment for the untreated soil (bare) and the soil treated with four application rates of Agri-SC.

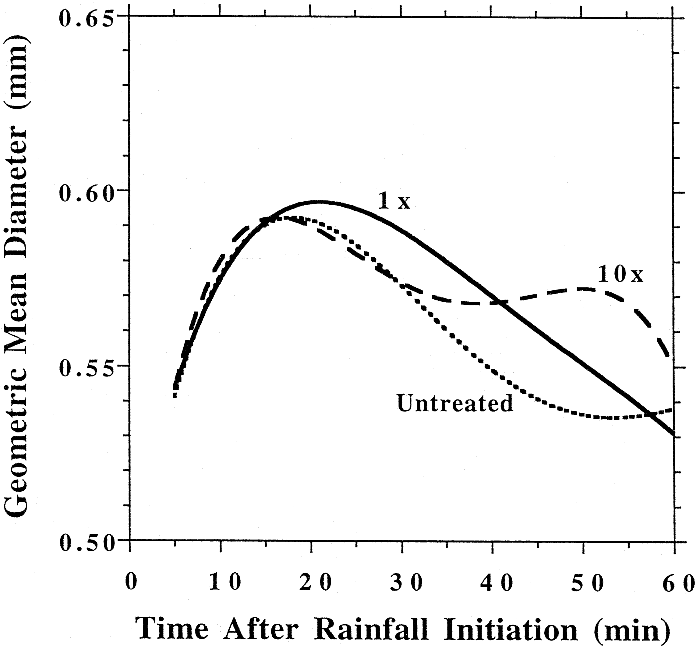

Fig. 3. Temporal variation in geometric mean aggregate diameter for the untreated soil (bare), and the soil treated with Agri-SC at 1 and 10 times the recommended rates.

In an attempt to understand how 1 and 10 × concentrations of Agri-SC reduced splash, we examined the GMAD of splash sediment over time. Time trend GMAD data for the composited 1 and 10 × Agri-SC treated samples, and the untreated sample are shown in Fig. 3. GMAD values for the three treatments increased minimally from 540 μm at 5 min to a peak between 590 and 600 μm at 15 to 20 min. This was followed by general decreases in GMAD to values similar to the first 5 min. Statistical differences could not be established due to compositing; nonetheless, the diagram suggests the two low application rates of Agri-SC did not influence the size of aggregates transported.

Table 3
Variation in geometric mean aggregate diameter (GMAD) for splash sediments from an untreated Vertisol and a treated Vertisol with four application rates of Agri-SC

Treatment	Application rate (l ha^{-1})	No. of samples	GMAD (μm)
Agri-SC	0.30 (1 ×)[a]	1[b]	568
Agri-SC	3.0 (10 ×)	1[b]	569
Agri-SC	30 (100 ×)	5[c]	566
Agri-SC	300 (1000 ×)	5[c]	553
Untreated (control)	–	1[b]	558
Untreated (control)	–	5[c]	558

[a] Values in parentheses represents the factor by which the application rate of Agri-SC exceeds the manufacturer's recommended rate.

[b] Samples were composited per 5 min time increment for five replicates for Agri-SC treated aggregates and twice for untreated (control) aggregates.

[c] Each replicate was analyzed separately, and not composited per time increment.

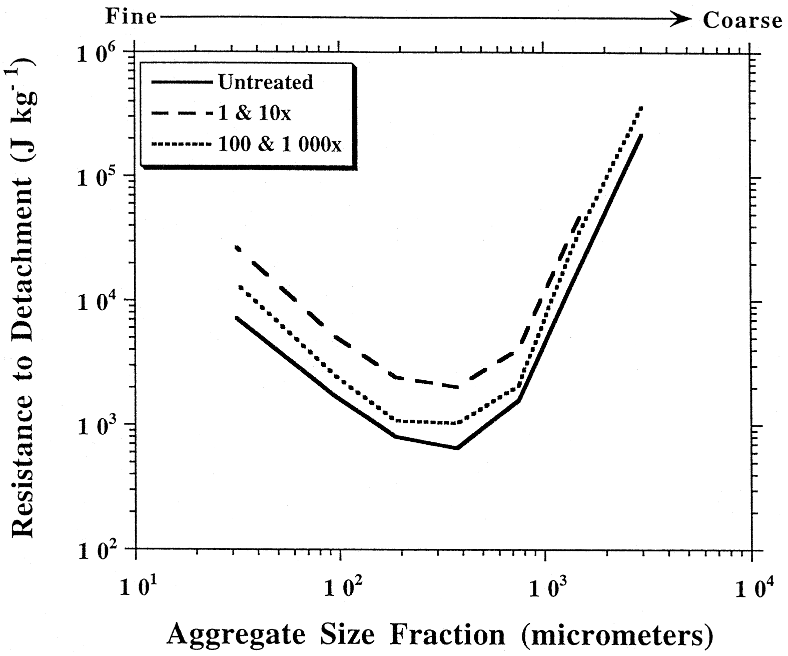

Fig. 4. Splash resistance to detachment for the bare control soil and two groups of data, Agri-SC applied at 1 and 10 times recommended, and 100 and 1000 times recommended.

Comparisons of all available GMAD values indicates that there were only minor differences in the size of aggregates transported from all treatments (Table 3).

4.3. Resistance to splash transport

Splash resistance of soils, previously examined by De Ploey and Poesen (1985) and Sutherland et al. (1996b), allows for the identification of the most easily detached particles or aggregate size fractions; and alternately, allows the most resistant sizes to be isolated. We used the aggregate size data to examine the influence of treatment groups on splash resistance. Splash data for the 1 and 10 × treatments and the 100 and 1000 × Agri-SC treatments were combined into two groups as defined by ANOVA. The untreated soil was isolated for comparison purposes. Data in Fig. 4 indicate that more energy (J = joules) was required to splash 1 kg of the largest (2.00–4.00 mm and 1.00–2.00 mm) and smallest (< 0.063 mm) aggregates from all treatments. The most easily detached aggregate sizes were 0.25–0.50 mm, followed by 0.13–0.25 mm. Note that no 2.00–4.00 mm aggregates were detached from the low Agri-SC treatments. Treated aggregates tended to be more resistant to splash transport than the untreated aggregates; and the lower treatment concentrations produced the greatest resistance to splash detachment.

4.4. Water-stable aggregates

Variation in the water-stable aggregate GMADs for the untreated soil and the aggregates treated with Agri-SC are shown in Fig. 5. Error bars represent 95% confidence bands about the average GMAD. As all lower 95% confidence limits of the

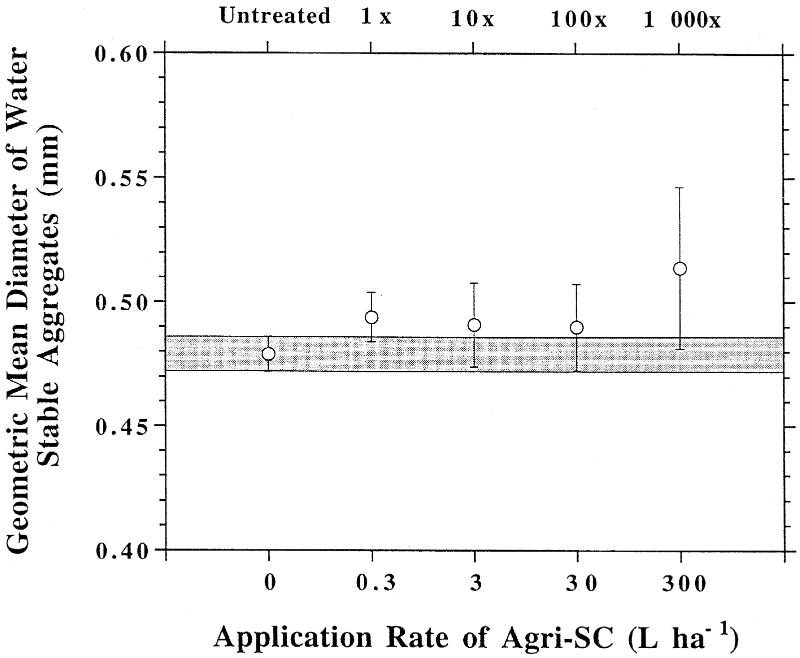

Fig. 5. Variation in the geometric mean aggregate diameter of water stable aggregates after slaking and shaking. Note the error bars reflect 95% confidence bands about the mean for each of the application rates of Agri-SC, and the stippled zone represents the confidence band about the untreated (control) soil.

Agri-SC treated aggregates overlap that of the untreated control (stippled area), the treated aggregates are not significantly different from those of the untreated soil.

5. Discussion

The varied splash response of the Vertisol to Agri-SC at low and high concentrations may be related to the adsorption of Agri-SC by the soil. Piccolo and Mbagwu (1989) indicate that anionic surfactants adsorb on particles of nonacidic soils only through weak Van der Waal's interactions and hydrophobic bonding with apolar soil constituents. Since the Vertisol studied has a significant proportion of smectite (Table 1), an expanding clay mineral, upon wetting, swelling pressures would develop and expand the particles to separation distances beyond the range of Van der Waal's forces (c.f., El-Swaify et al., 1970). However, the Vertisol also contains a significant proportion of kaolinite, a clay mineral with positive and negative sites. Thus, electrostatic bonds may form between the positively charged sites (primarily edges) and the anionic surfactant at low Agri-SC concentrations. Additionally, ligand exchange and coadsorption with multivalent cations, common in the test soil (Table 1), may also be significant mechanisms. Thus, predictions of water surface tension reduction and concomitant increases in infiltration into surface aggregates will be moderated. Slaking to some extent will be mitigated by bonds between ammonium laureth sulfate and kaolinite at low concentrations of Agri-SC. Splash increases found at higher concentrations of Agri-SC may reflect overloading of the available positively charges sites on kaolinite;

this may lead to a disruption of the electrical double layer and peptization. As the application rate of Agri-SC is increased, the pH of the added solution becomes increasingly alkaline; thus, there would be less adsorption of anionic complexes because the number of charged sites decreases with increased pH.

At low concentrations, splash detachment is reduced below that of the control soil and that of soil treated with higher concentrations of Agri-SC. One question that arises is what other soil variables related to erosion are altered by Agri-SC? Measurements of water percolated through the soil column (depth = 15 cm) were zero for all Agri-SC treatments and the untreated soil. Differences in water storage within the soil column were not measured. Regardless of treatment, surface water ponding, and thus sealing occurred within the first 20 min. Because more material was detached from the control and the soil treated with high ($\geq 100\times$) rates of Agri-SC, it is plausible that the aggregate stability, or the seal strength/continuity were different. However, the results from WSA analysis indicated negligible differences in stability for the untreated aggregates and those treated with Agri-SC at rates up to 1000 × recommended by the manufacturer. These results were unexpected, given the splash results shown in Figs. 1 and 4. Thus, the data would tend to support the alternate hypothesis, i.e., Agri-SC at low application rates influenced soil seal formation on the Vertisol in some fashion. This could be related with seal strength or continuity, with the latter effecting the development of a cushioning water layer.

6. Conclusions

Analyses of the splash data indicate that for the Lualualei Vertisol, low application rates of Agri-SC (≤ 3.0 l ha^{-1}) significantly reduced erodibility, but higher rates of Agri-SC (30–300 l ha^{-1}, i.e., 100 and 1000 × recommended) were ineffective in this capacity. Specifically, the following can be noted from the simulated rainsplash experiments: (1) only the 1 × and 10 × treatments of Agri-SC significantly reduced mean splash output; and (2) the 1 and 10 × treatments increased the resistance of aggregates to detachment. These data suggest that at low application rates, Agri-SC produced a less erodible surface and decreased the transportability of sediment. The reduced erodibility may reflect a preferential adsorption of the anionic surfactant, ammonium laureth sulfate, on the positively charged sites of kaolinite. However, at higher concentrations and concomitantly higher solution pH values, the availability of positively charged sites may have been reduced and the electrical double layer disrupted.

The WSA data does not support that the splash reduction achieved with the 1 × and 10 × treatments resulted from increased aggregate stability. Together, the splash and WSA data provide an initial indication that surface seal strength and/or continuity at low application rates of Agri-SC is different than at higher application rates. At lower application rates, the seal properties act to limit the amount of detachable material, but not the size. Further testing is required to examine the influence of Agri-SC on seal formation and strength. Additionally, field testing is also required to determine the persistence of Agri-SC in the environment, and to determine whether this soil conditioner influences crop production.

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