

Surfactant effects on the water-stable aggregation of wettable soils from the continental USA

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Abstract:

Surfactants may affect soil structure differently depending upon the soil or the quality of rainfall or irrigation water. This study examined whether the water-stable aggregation of 11 wettable soils was affected by surfactants and the water in which the soils were sieved. The study also examined whether the wettable soils' water drop penetration time (WDPT) was affected by surfactants, water drop quality, and elapsed time since the surfactants were applied. Two nonionic surfactants and a surfactant-free water control were sprayed (by misting) upon air-dry soil, then WDPT was measured 1 and 72 h thereafter. Subsequently, this treated soil was slowly wetted with an aerosol to its water content at a matric potential of -3 kPa, then immediately sieved for 600 s in water that contained either appreciable or few electrolytes. Water-stable aggregation, quantified as mean weight diameter (MWD), varied widely among soils, ranging from 0.10 to 1.36 mm. The MWDs were affected (at $p = 0.06$) by surfactant treatments, depending upon the soil but not sieving water quality. Surfactants affected the MWD of an Adkins loamy sand and Feltham sand, two of the three coarsest-textured soils. Although WDPTs never exceeded 5 s, depending upon the soil WDPTs were affected by surfactant treatments but not by water drop quality. After surfactant application, WDPTs generally decreased with time for three soils but increased with time for one soil. Findings suggested that surfactants interacted (1) with clay mineralogy to affect MWD and (2) with soluble calcium to affect WDPT for certain soils. Surfactant treatments but not water quality affected both MWD and WDPT for some but not all of 11 wettable, US soils. Published 2012. This article is a US Government work and is in the public domain in the USA.

KEY WORDS water quality; wetting agent; water-stable aggregation; aggregate stability; mean weight diameter; MWD; water drop penetration time; WDPT

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INTRODUCTION

Surfactants are organic molecules that serve as wetting agents to reduce the surface tension of water (Laha *et al.*, 2009). They are used to improve the water relations and increase nutrient use efficiencies of water repellent soils in highly managed environments, like golf courses, horticultural facilities, and agricultural production areas (Kostka, 2000; Lowery *et al.*, 2002; Arriaga *et al.*, 2009). Because soil water repellency is highly variable in both space and time (Crockford *et al.*, 1991; Mataix-Solera and Doerr, 2004; Zavala *et al.*, 2009), surfactants are and will be inadvertently applied to wettable soil (that with WDPTs ≤ 5 s, Bisdom *et al.*, 1993) as they amend co-located water repellent soil (Lehrs *et al.*, 2011).

Soil water repellency frequently improves soil structure (Mataix-Solera and Doerr, 2004) and generally increases aggregate stability by slowing or preventing water entry into aggregates (von Lützwow *et al.*, 2006). Surfactant effects on soil structure and water-stable aggregation of wettable soils, however, are less well established. On the

one hand, by reducing surface tension, surfactants allow water to more easily and quickly enter fine pores in soil aggregates (Fernández Cirelli *et al.*, 2008; Laha *et al.*, 2009), potentially leading to the damaging effects of slaking and aggregate breakdown (von Lützwow *et al.*, 2006; Hallett, 2007). On the other hand, surfactants added to wettable soil particles may be positioned such that their nonpolar hydrophobic ends extend into the soil solution, thus decreasing wettability to reduce slaking, leading to increased aggregate stability (Mustafa and Letey, 1969).

To date, researchers studying surfactant effects on wettable soil structure have reached different conclusions. Lehrs *et al.* (2011) found no effect of nonionic surfactants on runoff or sediment loss from three wettable, Inland Pacific Northwest soils (two silt loams and a sand). Lack of a runoff effect suggests little or no surfactant impact upon surface aggregate breakdown or surface seal formation. Absence of an effect on sediment loss implies no surfactant effect on water-stable aggregation or aggregate stability. Mustafa and Letey (1969) studied the aggregate stability of wettable soils pretreated with nonionic surfactant solutions and concluded that surfactants generally did not improve soil structure in wettable soils. In contrast, Law *et al.* (1966) reported that nonionic surfactants increased the geometric mean diameter (Gardner, 1956) of a montmorillonitic vertisol, whereas Mbagwu *et al.* (1993) reported that nonionic surfactants increased the percentage of water-stable aggregates in two coarse-textured acidic soils. All in all,

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net effects of surfactants on soil structure are difficult to assess and to predict. In a review of hydraulic conductivity changes caused by surfactant interactions with soil structure, Tumeo (1997) speculated that the difficulty may be due (1) to one or more of ten possible mechanisms opposing others and (2) to multiple mechanisms operating simultaneously. Additional research on surfactant effects on structural stability has been recommended (Hallett, 2007). In a similar vein, surfactant effects upon water drop penetration time (WDPT) are well known for water repellent soils but essentially unknown for wettable or barely wettable soils. Soils that are barely wettable are termed subcritically water repellent and, by definition, exhibit WDPTs >1 but ≤ 5 s (Cerdà and Doerr, 2007).

Water quality differences may affect the responses of both subcritically water repellent and wettable soils to surfactants. Lehrsche and Sojka (2011) found that irrigation water containing modest amounts of electrolytes or salts, particularly those of Ca^{2+} , greatly reduced the WDPT of a subcritically water repellent Quincy sand in both the presence and the absence of a nonionic surfactant, IrrigAid Gold[®] (IGG), marketed commercially by Aquatrols Corporation of America, Paulsboro, NJ, USA. Calcium ions may have served as effective bridges between clay particle surfaces and the soil's hydrophobic organic compounds (Edwards and Bremner, 1967), lessening the latter's coverage of the sand grains and thereby reducing both WDPTs and water repellency (Ward and Oades, 1993). As solution ionic strength increases, sorption of surfactants onto soil likewise increases (Rao and He, 2006; Laha *et al.*, 2009). Increasing ionic strength increases a surfactant's critical micelle concentration (CMC), the minimum concentration at which the surfactant monomers start to form self-assemblies called micelles (Laha *et al.*, 2009). As surfactant is continually added to a soil sample, the sorption of the surfactant increases until its CMC is reached (Liu *et al.*, 1992). Thus, increasing solution ionic strength increases surfactant sorption onto soil. As solution strength increases, cations tend to move closer to particle surfaces, thus compressing the diffuse double layer, leading to clay flocculation (Tumeo, 1997). If soil solution electrolyte concentrations become less than some critical value, the double layer becomes more diffuse, clays swell, and dispersion occurs (Quirk and Murray, 1991). Surfactant sorption onto soil depends upon the surfactant's properties (especially its net charge) as well as the soil's clay mineralogy and, less so, total clay content (Rodríguez-Cruz *et al.*, 2005).

Negligible amounts of Ca^{2+} in the soil, soil solution, irrigation water, or the water used for wet sieving may affect surfactant performance, water-stable aggregation, or both. For example, differing Ca^{2+} concentrations in water used for irrigation or rainfall simulation might cause surfactants to affect soil structure differently. High quality water such as rainfall or snowmelt water contains few divalent salts and thus exhibits a relatively low electrical conductivity (EC). Applying this water to

certain soils can reduce aggregate stability and, thereby, decrease water-stable aggregation (Kemper and Rosenau, 1986; Quirk and Murray, 1991). The effects of calcium, as lime or gypsum, have been studied on water repellent soils (Roper, 2005; Cerdà and Doerr, 2007; Mataix-Solera *et al.*, 2008). In contrast, calcium effects on the structure and WDPTs of surfactant-treated wettable soils are yet to be studied. Another research need is the study of short-term (1 to 72 h) temporal variation in WDPT under controlled conditions, particularly for surfactant-treated soil (Doerr *et al.*, 2000; Shakesby *et al.*, 2000).

Sullivan *et al.* (2009) and Lehrsche *et al.* (2011) reported different runoff responses of wettable soils treated with the same nonionic surfactant, IGG. This discrepancy could be due to differences in each soil's structural response to surfactant application, the quality of the applied irrigation water, or both. The surfactant may affect the soils' aggregate stability differently, thereby altering the size distribution of water-stable aggregates. In so doing, the surfactant may also disperse clays, depending upon the amount and type of clay present. Clay dispersion and aggregate disruption seal soil surfaces, increasing runoff. Indeed, Sullivan *et al.* (2009) attributed runoff differences between treated and control plots to surface seals that formed quicker on surfactant-treated soil. Such a finding suggests that an interaction occurred between the soil's structure and the applied surfactant. Also, application of the same surfactant may affect runoff differently from soil to soil depending upon soil mineralogy, specific surface area, organic C content, texture, or aggregate size distribution. As noted earlier, differences in chemical characteristics of applied water (i.e. the water quality of the simulated rainfall or irrigation) also affect soil water repellency (Lehrsche and Sojka, 2011). It is conceivable that water quality can interact with surfactants to alter other soil properties, such as organic C as well. This study was conducted partly to explain the conflicting findings of Sullivan *et al.* (2009) and Lehrsche *et al.* (2011).

This investigation of wettable soils had primary and secondary objectives. The primary objective was to determine if the soils' water-stable aggregation was affected by surfactants or the water in which the soils were sieved. The secondary objective was to determine if the soils' WDPT was affected by surfactants, water drop quality, or elapsed time since surfactant application. It was hypothesized that waters differing primarily in Ca^{2+} concentration would affect subsequent measurements of water-stable aggregation and might affect WDPT.

METHODS

Surfactants and soils

The study was conducted at the United States Department of Agriculture (USDA), Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, Kimberly, ID, USA. Two nonionic surfactants, each miscible in water, produced by Aquatrols Corporation of

America, Paulsboro, NJ, were chosen for study, based upon input from my industry partner. One was a colourless liquid composed of an ethylene oxide/propylene oxide block copolymer (COP), not marketed commercially but whose responses were of interest to Aquatrols personnel, and the other was a light brown, odourless liquid commercially available as IrrigAid Gold[®] (IGG) (Bially *et al.*, 2005). Of the 0.17 kg of active ingredients kg⁻¹ in IGG, 0.10 kg alkoxylated polyols kg⁻¹ were supplied by COP and 0.07 kg glucoethers kg⁻¹ were supplied by an alkyl polyglycoside not included in this study but described by Lehrs *et al.* (2011). The COP surfactant has a pH of 3.2 and a specific gravity of 1.04 kg l⁻¹, whereas IGG, as marketed, has a pH of 6.4 and a specific gravity of 1.02 kg l⁻¹. Other surfactant properties were given by Lehrs *et al.* (2011).

Eleven soils from the continental USA were studied, representing a broad cross section of those important to agriculture (Table I). Six major soil orders (Soil Survey Staff, 2010) were represented with textures ranging from sands to silty clay loams. The sampling sites' global positioning system (GPS) coordinates and cropping histories are also given. In the year sampled, all sites were in fallow or were planted to a small grain or row crop, never to a forage or pasture grass. Properties of the Ap horizons of the soils are given in Table II. Particle size was determined with the pipette method (Gee and Or, 2002), and pH was measured using a combination electrode in a 1:1 soil-water slurry (Thomas, 1996). Inorganic C was calculated from the CaCO₃ equivalent, measured using the pressure-calculator method of Sherrod *et al.* (2002). Organic C was calculated as the difference between inorganic C and total C, with the latter (as well as total N) measured (Nelson and Sommers, 1996) by the combustion of a 50-mg sample in a Thermo-Finnigan FlashEA1112 CNS analyzer (CE Elantech Inc., Lakewood, NJ). Soluble Ca²⁺ in an aqueous saturated paste extract (Rhoades, 1996; Horneck *et al.*, 2007) was quantified with

inductively coupled plasma optical emission spectroscopy (ICP-OES) using an Optima Model 4300 DV spectrometer (Perkin Elmer Instruments, Waltham, MA). Cation exchange capacity (CEC) and clay mineralogy were measured or obtained from the USDA Natural Resources Conservation Service Soil Characterization Database (National Cooperative Soil Survey, 2012) or from published sources (Johnson and Makinson, 1988; Lewis *et al.*, 1991; Sullivan *et al.*, 2009; McDaniel and Hipple, 2010). The advancing contact angle was measured using the Wilhelmy plate method (Lamparter *et al.*, 2006). Specific surface area was determined using the ethylene glycol monoethyl ether retention method (Pennell, 2002). About 15 kg of each soil were collected in the 2008 or 2009 growing season (April through October), in general, from the Ap horizon (nominally the uppermost 0.10 m, if necessary to 0.15 or 0.20 m) of agricultural production fields. After being collected, each of the field-moist soils was sealed in three, 19-l plastic buckets, then over-night mailed or transported to the Laboratory at Kimberly. Upon arrival, a subsample was taken for gravimetric water content (Topp and Ferré, 2002) with the remaining field-moist soil stored in air-tight containers at 4 °C for less than 100 d, on average, until analyzed. In general, water contents upon arrival ranged from 0.04 to 0.19 kg kg⁻¹ and averaged 0.11 kg kg⁻¹.

Surfactant application

Each surfactant was applied at the manufacturer's recommended rate of 9.41 ha⁻¹ of product containing either 0.10 kg active ingredient (a.i.) kg⁻¹ for COP or 0.17 kg a.i. kg⁻¹ for IGG. The surfactant solution was assumed to wet the uppermost 10 mm of soil when applied in the field. The surfactant application rate, on an a.i. per unit mass oven-dry soil basis, was then calculated based upon a 10-mm depth of soil at an assumed dry bulk density of (a) 1.1 Mg m⁻³ for soils with <520 g kg⁻¹ sand or (b) 1.4 Mg m⁻³ for sandier soils. The resulting application

Table I. Soils studied

Soil series	Surface texture ^a	Taxonomic classification ^a	State	GPS coordinates	Cropping history ^b	
					Previous year	Year sampled
Adkins	Loamy sand	Xeric Haplocalcid	OR	45°49.01'N 119°17.38'W	Wh	Wh
Aksarben	Silty clay loam	Typic Argiudoll	NE	40°51.27'N 96°28.34'W	So	So
Bolfar	Loam	Cumulic Endoaquoll	CA	37°04.40'N 120°35.77'W	Ma	To
Chino	Sandy loam	Aquic Haploxeroll	CA	34°02.39'N 117°48.99'W	Ma	Ma
Faceville	Sandy loam	Typic Kandiodult	GA	31°46.56'N 84°31.79'W	Pe	Co
Feltham	Sand	Xeric Torriorthent	ID	42°48.34'N 112°53.68'W	Po	Ba
Grenada	Silt loam	Oxyaquic Fraglossudalf	MS	34°25.87'N 89°37.75'W	So	So
Latahco	Silt loam	Xeric Argialboll	ID	46°42.68'N 117°00.21'W	Fa	Fa
Oxford ^c	Silty clay loam	Vertic Haploxerept	ID	42°08.71'N 111°52.36'W	Ba	Ba
Quincy	Sand	Xeric Torripsamment	OR	45°45.66'N 119°32.40'W	Fa	Fa
Rad	Silt loam	Xeric Haplocambid	ID	42°31.08'N 114°22.40'W	Lu	Ma

^a Soil Survey Staff (2010).

^b Ba was barley (*Hordeum vulgare* L.); Co was cotton (*Gossypium hirsutum* L.); Fa was fallow; Lu was lucerne (alfalfa; *Medicago sativa* L.); Ma was maize (corn; *Zea mays* L.); Pe was peanut (*Arachis hypogaea* L.); Po was potato (*Solanum tuberosum* L.); So was soybean (*Glycine max* Merr.); To was tomato (*Solanum lycopersicum* L.); Wh was wheat (*Triticum aestivum* L.).

^c Soil was an Oxford-Banida complex; hereafter referred to as Oxford.

Table II. Properties of the Ap horizon^a of 11 soils

Soil property	Soil series										
	Adkins	Aksarben	Bolfar	Chino	Faceville	Feltham	Grenada	Latahco	Oxford	Quincy	Rad
Particle size distribution, g kg ⁻¹											
Sand (0.05 to 2 mm)	840	50	340	610	750	940	70	90	180	950	250
Silt (0.002 to 0.05 mm)	110	610	400	270	80	20	740	650	430	10	610
Clay (<0.002 mm)	50	340	260	120	170	40	190	260	390	40	140
pH (1:1, water)	6.3	6.3	6.8	7.8	6.3	7.9	4.7	5.5	6.8	6.4	7.8
Inorganic C, g kg ⁻¹	0.4	0.8	0.5	5.9	0.5	0.5	0.2	0.3	1.4	0.4	12.4
Organic C, g kg ⁻¹	7.5	23.9	11.7	27.1	5.8	3.9	15.9	19.7	14.6	6.1	10.2
Total N, g kg ⁻¹	0.7	2.0	1.4	2.2	0.4	0.4	1.2	1.5	1.3	0.6	1.0
Soluble Ca ²⁺ , mg kg ⁻¹	9.7	66.5	196	73.4	26.8	18.5	6.0	35.5	49.3	43.8	164
Cation exchange capacity (CEC), cmol(+) kg ⁻¹	10.1	31.2	20.2	27.6	4.2	7.4	13.3	24.3	NA ^b	12.6	16.2
Advancing contact angle, degrees	5.9	21	0	7	0	9	46	34	9.3	35.6	1.0
Specific surface area, × 10 ³ m ² kg ⁻¹	28.6	186	80.1	85.5	25.9	11.4	48.7	110.4	104.1	17.7	119
Dominant clay mineral(s) ^b	MT/MI	MT	NA	NA	KK	MT	KK/MI/MT	MI	MI	KK/MI/MT/VR-CH	IL

^a Samples were collected from each profile's uppermost 0.10 m in general; the uppermost 0.15 or 0.20 m if necessary.

^b NA, not available; IL, illite; KK, kaolinite; MI, mica; MT, montmorillonite; VR-CH, a vermiculite-chlorite intergrade.

rate for finer-textured soils was 8.9 mg a.i. kg⁻¹ soil for COP and 14.9 for IGG, whereas for sandier soils, it was 7.0 mg a.i. kg⁻¹ for COP and 11.7 for IGG. The appropriate volume of surfactant was then diluted to a final volume of 70 ml using double deionized water (DDI). The pH of the DDI was 4.9, measured according to Thomas (1996), and the EC was 2.4×10^{-3} dS m⁻¹, determined per Rhoades (1996). Soluble cations (including Ca²⁺, Mg²⁺, K⁺, and Na⁺) in the DDI were measured using ICP-OES. Using the resulting cation concentrations, the DDI's sodium adsorption ratio (SAR; Horneck *et al.*, 2007) was 0 because it contained no measurable Na⁺. The pH of the dilute solution of COP was 4.6 and that of IGG was 6.0.

Before applying surfactants, soil was air-dried at about 22 °C and 26% relative humidity for at least 72 h then passed through an 8-mm sieve. For each of the three surfactant treatments (COP, IGG, and control), approximately 0.7 kg of soil was placed on a 0.6-m by 0.6-m piece of plastic sheeting and spread smoothly into an approximate 10-mm-thick circular layer using a clean spatula moving horizontally. About 15 ml of the 70 ml of dilute surfactant solution was then sprayed by hand as evenly as possible onto the soil. The volume of solution applied was determined by weighing the spray bottle before and after applying the surfactant solution. Thereafter, the soil was gently mixed by lifting alternate corners of the sheeting. Then, the soil was again spread on the sheeting. This spraying and mixing protocol was repeated another 4 to 5 times until the entire 70 ml of the dilute solution had been applied. In like manner, 70 ml of reverse osmosis water (RW, Table III) was applied to the control treatment. The pH, soluble cations, EC, and SAR were measured for RW as for DDI. Treated soil samples and the control (still on the sheeting) were permitted to dry at ambient temperature (ca 22 °C) and relative humidity (ca 26%) for 1 h. The soil sample was then representatively split using the edge of a clean spatula, as recommended by Angers *et al.* (2007), into four pie piece-shaped lots, one of about 250 g for an ancillary soil aggregate tensile strength measurement (not reported) and three other 150-g lots, one for each of the three waters used to measure WDPT (described in the succeeding text).

Water drop penetration time measurement

Soil water repellency was then quantified by measuring WDPT on each of the three lots of treated and untreated soil (van't Woudt, 1959). In this study, three different waters were used to measure WDPT (Table III). They were (1) a control consisting of reverse osmosis water (RW), (2) well water from Dawson, GA, used by Sullivan *et al.* (2009) to simulate rainfall, and (3) well water from Kimberly, ID, used by Lehrsch *et al.* (2011) for irrigation (WW). For each water quality, 10 drops (0.06 ml per drop) were randomly placed atop the 10 mm-thick layer of unpacked soil on sheeting in the laboratory where the surfactants were applied and the time recorded for each drop to fully infiltrate into the soil surface. In many cases, the short time required for a drop to penetrate the sample's surface approached the limits of one's ability to

Table III. Water drop quality for the WDPT measurements: reverse osmosis water (RW) and well water from Georgia and Idaho (WW)^a

Water quality parameter	Reverse osmosis water (RW)	Water from Georgia	Water from Idaho (WW)
pH	5.7	7.5	7.6
Soluble Ca ²⁺ , mg l ⁻¹	0.07	6.66	54.9
Soluble Mg ²⁺ , mg l ⁻¹	0.02	0.83	32.0
Soluble K ⁺ , mg l ⁻¹	0.21	0.52	5.21
Soluble Na ⁺ , mg l ⁻¹	2.37	5.39	67.2
Electrical conductivity (EC), dS m ⁻¹	7.2 x 10 ⁻³	0.18	0.7
Sodium adsorption ratio (SAR), (meq l ⁻¹) ^{0.5}	2.1	0.5	1.7

^a Water-stable aggregation, reported as mean weight diameter (MWD), was measured by sieving in RW and WW only.

quickly operate a timer. When WDPT was measured, an approximate 5-g soil sample was collected to determine gravimetric water content (Table IV), as recommended by Goebel *et al.* (2004) who showed that soil water repellency was a function of water content (or water potential). Matric potentials were known from a pressure

plate measurement (Reynolds and Topp, 2007) or were estimated from the van Genuchten (1980) water retention function fitted using the pedotransfer functions of the ROSETTA model (Schaap *et al.*, 2001). The model inputs were the water contents in Table IV, the sand, silt, and clay proportions in Table II, and assumed bulk densities

Table IV. Water contents and matric potentials of the samples when water drop penetration time (WDPT) and mean weight diameter (MWD) were measured

Soil	Property ^a	Water content (kg kg ⁻¹)	Matric potential ^b (kPa)	pF ^c
Adkins	WDPT ₁	0.083	-14	2.2
	WDPT ₇₂	0.008	NA	NA
	MWD	0.311	-3	1.5
Aksarben	WDPT ₁	0.114	-3100	4.5
	WDPT ₇₂	0.034	NA	NA
	MWD	0.461	-3	1.5
Bolfar	WDPT ₁	0.086	-6900	4.8
	WDPT ₇₂	0.017	NA	NA
	MWD	0.295	-3	1.5
Chino	WDPT ₁	0.102	-76	2.9
	WDPT ₇₂	0.017	NA	NA
	MWD	0.379	-3	1.5
Faceville	WDPT ₁	0.080	-160	3.2
	WDPT ₇₂	0.009	NA	NA
	MWD	0.174	-3	1.5
Feltham	WDPT ₁	0.078	-7	1.9
	WDPT ₇₂	0.004	NA	NA
	MWD	0.151	-3	1.5
Grenada	WDPT ₁	0.107	-810	3.9
	WDPT ₇₂	0.018	NA	NA
	MWD	0.400	-3	1.5
Latahco	WDPT ₁	0.082	-13000	5.1
	WDPT ₇₂	0.021	NA	NA
	MWD	0.433	-3	1.5
Oxford	WDPT ₁	0.107	-14000	5.2
	WDPT ₇₂	0.033	NA	NA
	MWD	0.371	-3	1.5
Quincy	WDPT ₁	0.075	-7	1.9
	WDPT ₇₂	0.006	NA	NA
	MWD	0.233	-3	1.5
Rad	WDPT ₁	0.073	-2100	4.3
	WDPT ₇₂	0.021	NA	NA
	MWD	0.421	-3	1.5

^a WDPT₁ and WDPT₇₂ were the water drop penetration times measured 1 and 72 h, respectively, after surfactant application. MWD was the mean weight diameter of water-stable aggregates.

^b Matric potential was known to be -3 kPa (Reynolds and Topp, 2007) or else was estimated using the measured water contents with the pedotransfer functions of the ROSETTA model (Schaap *et al.*, 2001).

NA is not available. Where NA is shown, the matric potential could not be estimated using the ROSETTA model because the measured (i.e., air-dry) water content was less than the residual water content of the fitted van Genuchten (1980) water retention function.

^c pF was the common log of the matric suction in cm H₂O.

(1.1 Mg m⁻³ for soils with <520 g sand kg⁻¹ or 1.4 Mg m⁻³ for sandier soils) for all except the Latahco, Quincy, and Rad soils. For those three soils, I used the aforementioned data and the water contents at -33 kPa matric potential given by Lehrsch *et al.* (2011). The sample's pF , the common log of the matric suction in cm H₂O, was calculated from the matric potential. Because the estimated matric potentials were model-derived, their values and the pF values in Table IV were rounded as shown.

Seventy-two hours after the surfactant solutions were applied, WDPTs were again measured using this protocol. After 72 h in the same environment as before, the samples were air-dry. Each soil's air-dry water content, measured in preliminary testing, is given in Table IV. For these water contents, neither the matric potential nor the pF could be estimated because the air-dry water contents were less than the van Genuchten water retention model's residual water contents, θ_r (van Genuchten, 1980), fitted by the ROSETTA model (Schaap *et al.*, 2001). Water drop penetration time was thus measured under controlled conditions twice in a three-day period. The sample's WDPT for each water drop quality was calculated as the arithmetic mean of the 10 observations taken, thus yielding the best estimate of that sample's response (Horn and Dexter, 1989). That resulting value was the WDPT response variable subjected to subsequent statistical analysis as described in the succeeding text. In this investigation, a soil sample was classified as wettable if its WDPT was ≤ 5 s (Bisdorn *et al.*, 1993) and subcritically water repellent (Cerdà and Doerr, 2007) if its WDPT was > 1 but ≤ 5 s. After measuring WDPT for the last time, each of the 150-g lots of soil on which WDPT had been measured using either RW or WW was enclosed in a labelled, vapour-proof plastic bag and stored without overburden pressure at about 4 °C for less than 100 d, in general, until its water-stable aggregation could be measured. Only 1.2 ml of water, in total, were added to each 150-g lot of soil in the WDPT measurement protocol. This small volume of water, reduced even more by evaporation after application, likely had little or no effect upon subsequent analyses of water-stable aggregates.

Water-stable aggregation measurement

Water-stable aggregate size distribution (WASD) was measured on surfactant-treated and control (that receiving only surfactant-free RW) soil samples by sieving in either RW or WW, two waters that differed nearly 800-fold in Ca²⁺ concentration (Table III). The sample sieved in RW was the same sample on which WDPT had been measured using RW, whereas the sample sieved in WW was that on which WDPT had been measured using WW. The WASD technique of Nimmo and Perkins (2002) was modified so that duplicate, 25-g samples were taken from each lot in a representative manner per Angers *et al.* (2007). In the technique, each duplicate was slowly wetted with a cool aerosol produced by a non-heating vaporizer (Vicks Humidifier Model VN5100NS) to its gravimetric water content at a matric potential of -3 kPa

(Haynes, 1993). These water contents, ranging from 0.15 to 0.46 kg kg⁻¹ (Table IV), had been measured earlier using a pressure plate extractor (Dane and Hopmans, 2002; Reynolds and Topp, 2007). Soon after wetting, the sample was sieved in either low Ca²⁺ water (RW) or high Ca²⁺ water (WW) through a nest of 203-mm-diameter sieves with openings of 4.75, 2.0, 1.0, and 0.25 mm moving vertically through an 38-mm amplitude at 0.5 times s⁻¹ for 600 s. Each resulting size distribution was expressed as a mean weight diameter, MWD (van Bavel, 1949), calculated per Angers *et al.* (2007). Each sample's duplicate MWDs were then arithmetically averaged before the resulting mean was analyzed statistically.

Statistical analysis

The experimental design for WDPT was a split split plot in three blocks, with 11 soils, three surfactant treatments, three water drop qualities, and two measurement times, along with their interactions, as fixed effects in a mixed-model analysis of variance (ANOVA). Soils, as the main plot treatment, were arranged in randomized complete blocks. Before performing the ANOVA, the WDPT's error variance by treatment was examined using the relationship between treatment means and corresponding treatment standard deviations (Box *et al.*, 1978; Lehrsch and Sojka, 2011). To stabilize its error variance, WDPT means were transformed using a reciprocal square root before further analysis. The design for MWD was a split split plot in three blocks, with 11 soils, three surfactant treatments, and two sieving water qualities, as well as their interactions, as fixed effects. The MWD means were also transformed with a reciprocal square root before further analysis.

The PROC Mixed procedure in SAS (SAS Institute Inc., 2009) was used to perform a mixed-model ANOVA with a significance probability (p) of 0.05, unless otherwise noted. As needed, ANOVA grouping options were used to account for heterogeneous variances in the response variables. For all fixed effects found significant, least-squares means were separated with the Tukey-Kramer test at $p=0.05$. All means presented were back-transformed into original units.

RESULTS

Water drop penetration time

Surfactant treatments affected WDPT at $p < 0.01$, depending upon the soil and when WDPT was measured, but not upon water drop quality. The greatest effects on WDPT were detected for two coarse-textured, subcritically water repellent soils (Figure 1). The Chino soil's WDPT measured 1 h after surfactant application was similar among surfactant treatments (Figure 1A). Measured 72 h later, however, WDPT had decreased fourfold, to less than 1 s for each treatment. At that time, the Chino's WDPTs were slightly greater if surfactant-treated than not.

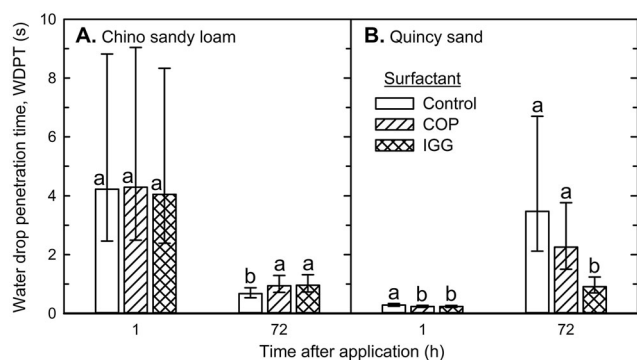


Figure 1. Water drop penetration time (WDPT) of the Chino sandy loam (A) and Quincy sand (B) measured 1 and 72 h after applying reverse osmosis water (RW) to the control and two nonionic surfactants: a copolymer (COP) and IrrigAid Gold® (IGG). Data have been averaged across water drop quality (interactions not significantly different, NS, at $p=0.84$). Within a soil and time, surfactant means ($n=9$, shown with 95% confidence limits) with a common letter are NS at $p=0.05$.

The Quincy sand, however, reacted differently than the Chino sandy loam. One hour after surfactant application, the Quincy's WDPTs were <0.3 s, statistically shorter, although not practically shorter, if surfactant-treated (Figure 1B). Seventy-two hours after treatment, in contrast, Quincy's WDPTs were much longer, ranging from 0.91 to 3.47 s. As the soil dried in the laboratory (Table IV), WDPTs increased with time, common for drying soil (Doerr *et al.*, 2000). Compared with the 1-h measurement, WDPT measured after 72 h increased by 12-fold for the control and nearly tenfold for COP but less than fourfold for IGG. After 72 h, Quincy's IGG-treatment WDPT was 40% of the COP treatment and only 26% of the control, with both comparisons significantly different at $p < 0.01$ (Figure 1B).

The remaining nine soils had WDPTs that never exceeded 0.43 s (Table V) and were thus wettable, not even exhibiting subcritical water repellency. The WDPTs of two of the soils did vary, however, among surfactant treatments, measurement times, or both. Regardless of surfactant treatment, the WDPTs after 1 h of the Aksarben silty clay loam were the longest of the nine soils. Those WDPTs decreased significantly, however, from 1 to 72 h after application, also regardless of surfactant treatment (Table V). The WDPT of the Latahco treated with COP also decreased from 1 to 72 h. Overall, however, with the notable exceptions of the Chino sandy loam and Quincy sand (Figure 1) and the Aksarben silty clay loam (Table V), WDPTs were commonly similar whether measured 1 or 72 h after surfactant application (Table V). Where differences among surfactant treatments within a measurement time were detected for a particular soil, the WDPT of COP-treated soil was generally greatest or among the greatest WDPTs of all surfactant treatments. For example, after 1 h, the WDPT of the COP-treated Aksarben exceeded that of the untreated Aksarben by 23% (Table V).

Mean weight diameter

Surfactant effects on MWD, significant at $p=0.06$, were deemed worthy of presenting in detail. Mean weight

Table V. Water drop penetration time (WDPT) for each of the nine soils measured 1 and 72 h after applying reverse osmosis water (RW) to the control and two nonionic surfactants: a copolymer and IrrigAid Gold® (IGG)

Time after application (h)	Water drop penetration time, WDPT ^a (s)		
	Surfactant		
	Control (RW)	Copolymer	IrrigAid Gold
		<u>Adkins</u>	
1	0.23	0.24	0.25
72	0.24	0.25	0.25
		<u>Aksarben</u>	
1	0.35 a ^b y ^c	0.43 a x	0.39 a xy
72	0.24 b x	0.24 b x	0.24 b x
		<u>Bolfar</u>	
1	0.23	0.22	0.22
72	0.21	0.23	0.21
		<u>Faceville</u>	
1	0.21	0.22	0.21
72	0.22	0.22	0.21
		<u>Feltham</u>	
1	0.23	0.22	0.22
72	0.22	0.22	0.22
		<u>Grenada</u>	
1	0.22	0.22	0.23
72	0.22	0.21	0.22
		<u>Latahco</u>	
1	0.27 a x	0.28 a x	0.27 a x
72	0.26 a x	0.25 b x	0.27 a x
		<u>Oxford</u>	
1	0.20	0.21	0.21
72	0.20	0.21	0.21
		<u>Rad</u>	
1	0.24	0.24	0.24
72	0.22	0.23	0.24

^a Data have been averaged across water drop quality (interactions not significantly different, NS, at $p=0.84$).

^b Within a column for each soil, means ($n=9$) followed by a common letter (a or b) are NS at $p=0.05$. Letters are not displayed if means did not differ.

^c Within a row for each soil, means followed by a common letter (x or y) are NS at $p=0.05$. Letters are not displayed if means did not differ.

diameter differed among surfactant treatments, depending upon the soil but not upon sieving water quality (Table VI). Surfactants affected the MWD of two of the 11 soils. For both the Adkins loamy sand and Feltham sand, their MWDs were consistently greater where treated with COP than IGG. The MWD was similar between the COP and the control for the Adkins, but for the Feltham, the MWD of the COP exceeded that of the control. Compared with the controls, Adkins' MWD where IGG-treated was 29% less (significant at $p < 0.01$), and Feltham's MWD was 9% less (not significantly different, NS).

For the nine remaining soils, MWD did not differ among surfactant treatments (Table VI) or between sieving water qualities (data not shown in tabular form). When averaged across 11 soils and two sieving water qualities, MWD was 0.44 mm for the control, 0.45 mm for COP, and 0.43 mm for IGG (NS at $p=0.31$). When averaged across 11 soils and three surfactant treatments, MWD was 0.43 mm for RW as sieving water and 0.44 mm for WW (NS at $p=0.30$). Water with low EC (RW, Table III), commonly

Table VI. Mean weight diameter (MWD) via the wet sieving method for each of the 11 soils after applying reverse osmosis water (RW) to the control and two nonionic surfactants: a copolymer and IrrigAid Gold® (IGG)

Soil	Mean weight diameter, MWD ^a (mm)		
	Control (RW)	Copolymer (COP)	IrrigAid Gold (IGG)
Adkins	0.28 d ^b x ^c	0.25 d x	0.20 e y
Aksarben	1.20 a	1.17 a	1.36 a
Bolfar	0.90 ab	1.08 ab	1.04 ab
Chino	0.90 ab	1.05 ab	0.96 ab
Faceville	0.77 b	0.74 b	0.66 cd
Feltham	0.11 e y	0.12 e x	0.10 f y
Grenada	0.95 ab	0.92 ab	0.76 bc
Latahco	0.96 ab	0.82 ab	1.02 ab
Oxford	1.04 ab	0.93 ab	1.01 ab
Quincy	0.12 e	0.12 e	0.12 f
Rad	0.44 c	0.45 c	0.52 d

^a Data have been averaged across sieving water quality (interactions not significantly different, NS, at $p=0.10$).

^b Within a column, means ($n=6$) followed by a common letter are NS at $p=0.05$.

^c Within a row, means followed by a common letter (x or y) are NS at $p=0.05$. Letters x and y are not displayed if means did not differ.

causes aggregates to be less stable or to slake. Thus, the slightly lower MWD for RW compared with WW is as expected. For nine of the 11 wettable soils (Table VI), I found, as did Mbagwu *et al.* (1993), that nonionic surfactants applied at low rates had little or no effect on soil structural stability. The MWDs of the Adkins, Feltham, Quincy, and Rad soils were the lowest of the 11, indicative of unstable aggregates and, for the Rad silt loam, a highly erodible soil (Le Bissonnais, 2006).

The MWDs of the 11 soils were ranked similarly whether untreated or treated with COP. Although the Aksarben's MWD exceeded that of Faceville, otherwise the MWDs of the Aksarben, Bolfar, Chino, Faceville, Grenada, Latahco, and Oxford were statistically similar. As a group, their MWD was greater than that of the Rad, whose MWD was greater than the Adkins. The Adkins' MWD, in turn, exceeded that of the Feltham and Quincy, whose MWDs were similar (Table VI).

The IGG surfactant, in contrast, affected the Faceville soil's MWD differently (Table VI). When ranked, the Faceville's MWD was statistically similar to the more stable Grenada and the less stable Rad. The Faceville was, however, less stable than the Aksarben, Bolfar, Chino, Latahco, and Oxford. The Faceville soil, classified as an ultisol in the USA (Soil Survey Staff, 2010; Table I), was the most weathered soil in the study. Although not significant at $p=0.05$, the MWD of Faceville soil was 14% less for IGG-treated than untreated soil (Table VI).

DISCUSSION

Water drop penetration time

The Chino and Quincy, two soils that exhibited subcritical water repellency (Figure 1), had three

properties that distinguished themselves from the remaining nine soils. As a group, the two soils contained much sand ($\geq 610 \text{ g kg}^{-1}$), little clay ($\leq 120 \text{ g kg}^{-1}$), and much soluble Ca^{2+} ($\geq 43.8 \text{ mg kg}^{-1}$, Table II). These properties, in total, suggest that soluble Ca^{2+} played a role in the wetting of clay-poor soils with low to moderate surface area (van't Woudt, 1959; Lehrsch and Sojka, 2011). What that role may have been is an open question, but it was likely related to Ca^{2+} effects on the diffuse double layers of clay particle surfaces. Suppression of double layer thicknesses by Ca^{2+} may have led to clay flocculation that, after drying, decreased the WDPT of some soils (Figure 1A) while increasing the WDPT of others (Figure 1B), regardless of surfactant treatment. Lichner *et al.* (2006) reported that WDPT increased with increasing amounts of exchangeable Ca^{2+} on clay mineral surfaces but McKissock *et al.* (2000) found no such relationship for western Australian soils.

Chino's fourfold decrease in WDPT from 1 to 72 h is logical, at least where surfactants were applied (Figure 1A). During the intervening 71 h, the surfactant molecules likely became oriented with their nonpolar hydrophobic ends positioned on the Chino's water repellent surfaces and their polar hydrophilic ends extending outward, thus rendering those surfaces wettable. The control's fourfold WDPT decrease cannot be explained as easily. Once the soil was wetted, bonds between hydrophobic substances and particle surfaces may have weakened sufficiently to be broken, allowing those surfaces to become wettable (Doerr *et al.*, 2000).

The WDPT of the Quincy increased rather than decreased with time like the Chino (Figure 1) and Aksarben (Table V). This anomalous response could be because the Quincy, compared with the Chino, contained only 33% as much clay and 23% as much organic C (Table II). Moreover, considering all soils, the Quincy was one least in both clay and organic C (Table II). Clay-poor soils are commonly more water repellent than clay-rich ones, particularly after drying (Doerr *et al.*, 2000; Roper, 2005). Also, the Quincy's specific surface area was only 21% of the Chino's and 9.5% of the Aksarben's (Table II). Coarse-textured soils with little surface area often exhibit water repellency to some degree (Doerr *et al.*, 2000). In addition, hydrophobic organic compounds, known to be present in untreated Quincy sand (Lehrsch and Sojka, 2011) and revealed by Quincy's relatively large contact angle in Table II, impart water repellency to this field soil during drier portions of the year. Water content decreases of only a few percentage points can increase water repellency in some relatively dry soils (Goebel *et al.*, 2004). As the Quincy sand dried from 0.075 to 0.006 kg kg^{-1} in the laboratory (Table IV), those amphiphilic hydrophobic compounds likely rearranged on particle surfaces, rendering them water repellent (Ma'shum and Farmer, 1985). Reorientation of hydrophobic functional groups may be minimal, however, as water contents change in low-organic matter, subcritically water repellent silt loams (Goebel *et al.*, 2004). In the Quincy sand, though, this likely rearrangement is supported by the data shown in Figure 1B. Where untreated, Quincy's WDPT increased

12-fold from 1 to 72 h. Where surfactant-treated in contrast, Quincy's WDPT increased much less, in general, from 1 to 72 h, suggesting that the application of surfactants, IGG in particular, should improve this soil's wetting. The surfactant molecules' nonpolar hydrophobic groups likely attached to the hydrophobic organic compounds on the Quincy's surface, thus limiting or preventing the compounds' rearrangement with time and thereby reducing the 72-h WDPTs compared with the control (Figure 1B).

The WDPTs after 1 h were greater for the Chino than the Quincy soil (Figure 1). Surface area and soil textural differences were likely responsible because the Chino's surface area was nearly five times greater and its clay content three times greater than the Quincy's (Table II). The water repellent portions of the clay surfaces may have been effectively coated with surfactant within 1 h in the low-surface area Quincy but not in the high-surface area Chino. This mechanism could explain why the treated soil WDPTs at 1 h were much greater for the Chino than Quincy. For the untreated Chino that received calcium-poor RW (Table III) in lieu of surfactant, 1 h was surely too short a time for slightly soluble CaCO_3 to sufficiently dissociate to solubilize a significant amount of Ca^{2+} ions. More Ca^{2+} ions in the soil solution increase the solution's ionic strength and decrease a soil's WDPT (Lehrsch and Sojka, 2011).

After 72 h, WDPTs were, on average, greater for the Quincy than Chino. Water content differences were likely responsible, at least in part. After 72 h, the water content of the Quincy was only a third of the Chino (Table IV). WDPTs generally increase as water contents decrease (Zwolinski, 1971; Doerr *et al.*, 2000). Moreover, the 1.7-fold greater soluble Ca^{2+} concentration of the Chino than Quincy (Table II) may have increased the Chino's soil solution ionic strength more than the Quincy, decreasing the Chino's WDPT as noted earlier. For the treated soil, the possibly greater solution strength in the Chino than Quincy may have increased surfactant sorption onto the Chino more than the Quincy, thereby decreasing the WDPT of the Chino more than the Quincy (Liu *et al.*, 1992). Clearly, more research is needed on the wettability of soils similar to the Chino and Quincy.

Quincy's WDPT was always <1 s after IGG application (Figure 1B). A prophylactic application of IGG may well help alleviate water repellency in this low-surface area soil, often water repellent *in situ* in summer and early fall (D. Horneck, personal communication).

Of the remaining nine soils, the Faceville was texturally similar to but contained 51% less soluble Ca^{2+} , on average, than the Chino and Quincy (Table II). As reported by Sullivan *et al.* (2009), runoff from the Faceville was greater where IGG-treated than untreated. Increased runoff from the Faceville could have been a consequence of increased WDPTs after IGG treatment. In this study, there was no evidence, however, that Faceville's WDPT increased either 1 or 72 h after IGG treatment, compared with the control (Table V).

As noted earlier, WDPTs were not affected by water drop quality, at least within the quality ranges studied in this investigation (Table III). This finding confirms the results of

Lehrsch and Sojka (2011) and extends the findings to a range of soils differing widely in characteristics (Table II).

Mean weight diameter

Using MWDs, soils were ranked similarly, in general, within each surfactant treatment (Table VI), as noted previously. The MWDs were largest for fine-textured and medium-textured soils and smallest for coarse-textured ones. This ranking was likely due to clay bridging between intra-aggregate particles (Kemper *et al.*, 1987; Kay and Dexter, 1992). The Rad soil's response was anomalous, however, among medium-textured soils. Of the three silt loams (Table I), the Rad's MWD was only about half that of the others, likely a consequence of the Rad's high sand content and relatively low organic C content (Table II), both of which are indicative of less stable soil structure (Le Bissonnais, 2006).

Surfactant treatments had no effect on the MWD of the Latahco, Quincy, and Rad soils (Table VI). Because water-stable aggregation is often inversely proportional to sediment loss (Barthès and Roose, 2002; Le Bissonnais, 2006), the lack of a surfactant effect upon these three soils' MWDs helps to explain the findings of Lehrsch *et al.* (2011) where surfactants had no effect on erosion from these same three wettable soils.

Whenever a soil's MWD differed among surfactant treatments, its MWD was greater when treated with COP rather than IGG (Table VI). This response could be a consequence of increased calcium ion concentrations in the soil solution. Aggregates can be strengthened as Ca^{2+} ions precipitate as cementing agents, such as CaCO_3 , upon drying (Dexter, 1988; Lehrsch *et al.*, 1993) or form bridges between clay surfaces and organic colloids (Edwards and Bremner, 1967). In my study, the relatively low pH of 4.6 in the added dilute COP solution likely led to increases in the soil solution Ca^{2+} concentrations as calcium ions were displaced from the soil's exchange complex. Additionally in calcareous soils, Ca^{2+} ions were likely released from the dissolution of lime, gypsum, or both.

Data reported for the Faceville soil (Table VI) is of interest given the findings of Sullivan *et al.* (2009). They reported increased runoff probably because of more surface sealing in IGG-treated than untreated Faceville soil. The fact that the MWD of Faceville soil tended to be less (by 14%, $p=0.26$) for IGG-treated than untreated soil suggests that the water droplet kinetic energy that Sullivan *et al.* (2009) applied could have hastened the breakdown of the less stable, treated Faceville aggregates on the soil surface (Lehrsch and Kincaid, 2006). Subsequent surface sealing would have decreased infiltration more into the treated than untreated Faceville soil. This sequence of events could have accounted for the greater runoff from IGG-treated than untreated soil found by Sullivan *et al.* (2009).

Even in the absence of surfactants, clay alters water repellency (Roper, 2005). On the one hand, the greater proportion of hydrophilic polar hydroxyl groups on kaolinitic rather than Ca-montmorillonitic clay surfaces

will preferentially adsorb water, likely limiting the sorption of hydrophobic organic compounds and thereby reducing water repellency (Bachmann and van der Ploeg, 2002; Dlapa *et al.*, 2004; Mataix-Solera *et al.*, 2008). Water repellent sandy soils wet easier when treated with clay mixtures containing kaolinite rather than illite or smectite (Ma'shum *et al.*, 1989; Mataix-Solera *et al.*, 2008). On the other hand, montmorillonitic clay with many platelets and much surface area should facilitate the sorption of hydrophobic organic compounds that would reduce the proportion of sand grains so covered and thereby decrease water repellency (Ward and Oades, 1993; Mataix-Solera *et al.*, 2008).

Clay mineralogy differences also may account for conflicting surfactant efficacy findings of Sullivan *et al.* (2009) for the Faceville soil and Lehrsch *et al.* (2011) for the Latahco, Quincy, and Rad soils. Laha *et al.* (2009) noted that clay interacts strongly with surfactants. Hydrophilic functional groups of the amphiphilic surfactant molecules might sorb to the hydrophilic hydroxyl groups on kaolinitic clay surfaces, resulting in the surfactant's hydrophobic groups extending into the soil solution, thereby increasing water repellency (Mustafa and Letey, 1969; Doerr *et al.*, 2000; Lehrsch and Sojka, 2011). This postulated mechanism would increase runoff from surfactant-treated, kaolinitic soils such as the wettable Faceville, as was reported by Sullivan *et al.* (2009). Kaolinite was the dominant clay mineral in the Faceville but absent or at most secondary in the wettable Latahco, Quincy, and Rad soils (Table II). Apparently, highly weathered, coarse-textured soils like the Faceville, respond to applied surfactants differently than do less weathered soils that contain appreciable illite, mica, and montmorillonite (Table II). Montmorillonite in less weathered soils also sorbs nonionic surfactants (Rodríguez-Cruz *et al.*, 2005), but owing to the soil's generally greater surface area, significant water repellency would be less likely to occur (Doerr *et al.*, 2000). Additional research is needed focusing upon clay mineralogy interactions with surfactants when applied to wettable soils.

As noted earlier, water-stable aggregation as MWD was not affected by water quality after this study's single sieving. In contrast, field soils have been exposed many times to water of a given quality for decades in the irrigated western USA and for millennia in the southeastern USA. Under such conditions, soils are known to reflect the influence of the quality of the water passing through them over such lengthy periods.

Should this experiment, or one similar to it, be repeated, some changes should be made. First, the wettability of treated, subcritically water repellent or wettable soils should be measured more precisely. Measuring the advancing contact angle using the Wilhelmy plate method (Lamparter *et al.*, 2006) or the capillary rise method (Goebel *et al.*, 2004) could be used in place of, or in addition to, measuring WDPT. Second, if WDPT is measured, it should be measured using water of only one quality because this study and that of Lehrsch and Sojka (2011) found no significant differences in WDPT when measured using

different water drop qualities. Water used to measure WDPT should be similar in quality to either rainfall or irrigation received by the field soil(s) under study. Also, the use of field-moist, rather than air-dry, soil samples for measuring water-stable aggregation should enable one to better differentiate subtle treatment effects on MWD (Lehrsch and Jolley, 1992).

CONCLUSIONS

1. Although WDPTs never exceeded 5 s, surfactant treatments affected WDPT, depending upon the soil and when WDPT was measured but not upon the quality of the water drops used to measure WDPT.
2. Surfactants altered the WDPT of three of 11 (27%) soils, increasing WDPT slightly for two soils while decreasing it for a third, compared with untreated soil.
3. WDPT decreased for three soils, in general, and increased for one soil, when measured 72 h, compared with 1 h, after application, regardless of surfactant treatment.
4. Water-stable aggregation (MWD) was affected by surfactant treatments, depending upon the soil but not upon the quality of the water used to sieve the aggregates. Surfactant effects were consistent upon the two affected soils. For the Adkins loamy sand and Feltham sand, MWD was greatest or among the greatest where COP treated, whereas MWD was least where IGG-treated. Surfactant treatments had no effect upon the MWDs of the remaining nine soils.
5. Using MWD, the soils were ranked similarly, in general, whether untreated or COP-treated. When the soils were treated with IGG, in contrast, the highly weathered Faceville soil was ranked among those less stable.

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