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Surfactant and irrigation effects on wettable soils: runoff, erosion, and water retention responses

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Abstract:

Surfactants are chemical compounds that can change the contact angle of a water drop on solid surfaces and are commonly used to increase infiltration into water repellent soil. Since production fields with water repellent soil often contain areas of wettable soil, surfactants applied to such fields worldwide will likely be applied to wettable soil, with unknown consequences for irrigation-induced erosion, runoff, or soil water relations. We evaluated surfactant and simulated sprinkler irrigation effects on these responses for three wettable, Pacific Northwest soils, Latahco and Rad silt loams, and Quincy sand. Along with an untreated control, we studied three surfactants: an alkyl polyglycoside (APG) in solution at a concentration of 18 g active ingredient (AI) kg^{-1}, a block copolymer at 26 g kg^{-1}, and a blend of the two at 43 g kg^{-1}. From 2005 to 2009 in the laboratory, each surfactant was sprayed at a rate of 46·8 l ha^{-1} onto each soil packed by tamping into 1·2- by 1·5-m steel boxes. Thereafter, each treated soil was irrigated twice at 88 mm h^{-1} with surfactant-free well water. After each irrigation, runoff and sediment loss were measured and soil samples were collected. While measured properties differed among soils and irrigations, surfactants had no effect on runoff, sediment loss, splash loss, or tension infiltration, compared to the control. Across all soils, however, the APG increased volumetric water contents by about 3% (significant at $p \leq 0{\cdot}08$) at matric potentials from 0 to −20 kPa compared to the control. With a decrease in the liquid–solid contact angle on treated soil surfaces, surfactant-free water appeared able to enter, and be retained in pores with diameters ≥15 µm. All told, surfactants applied at economic rates to these wettable Pacific Northwest soils posed little risk of increasing either runoff or erosion or harming soil water relations. Moreover, by increasing water retention at high potentials, surfactants applied to wettable soils may allow water containing pesticides or other agricultural chemicals to better penetrate soil pores, thereby increasing the efficacy of the co-applied materials. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS soil loss; water repellent soil; infiltration; overland flow; hydrological response; soil water relations; water content; available water; water potential; sediment loss

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INTRODUCTION

Soil water repellency is a phenomenon that reduces the affinity of soils for water so that they resist wetting for periods ranging from seconds to weeks (Doerr *et al.*, 2000). By definition, a water repellent soil has a water–solid (hereafter termed a 'liquid–solid') contact angle >50–60° (Shirtcliffe *et al.*, 2006) and/or a surface tension $<0{\cdot}073$ J m^{-2} (Doerr *et al.*, 2000). Since soft organic solids (e.g. waxes, organic polymers, etc.) can exhibit surface tension (or surface-free energies) $<0{\cdot}073$ J m^{-2}, they are frequently hydrophobic (Zisman, 1964). One such hydrophobic organic compound, the recalcitrant glycoprotein glomalin exuded by arbuscular mycorrhizal fungi was postulated to increase the water repellency of soil aggregates, thereby minimizing aggregate breakdown due to slaking (Wright and Upadhyaya, 1996). Feeney *et al.* (2004) could find no relation, however, between glomalin and water repellency in the sandy soil they studied in growth chambers. Severe water repellency is thought to be due to the coating of soil mineral particle surfaces with various hydrophobic organic compounds (Wallis *et al.*, 1991; Bisdom *et al.*, 1993). Compared to finer-textured soils, sands are more susceptible to water repellency because of their much smaller specific surface area that, in turn, requires a smaller mass of organic compounds to effectively coat their mineral surfaces (Ma'shum *et al.*, 1989). Soil water repellency affects soil structure and varies spatially and temporally depending, in part, upon land use (Mataix-Solera and Doerr, 2004; Zavala *et al.*, 2009). Because water repellency affects a host of soil properties as well as crop responses, it has often been reviewed (Wallis and Horne, 1992; Bauters *et al.*, 2000; Doerr *et al.*, 2000; Shakesby *et al.*, 2000) with an extensive bibliography recently published (Dekker *et al.*, 2005).

Surfactants or wetting agents, at times termed surface-active agents, are amphiphilic molecules that reduce

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Manufacturer or trade names are included for the readers' benefit. By including names, the USDA-ARS implies no endorsement, recommendation, or exclusion.

the surface tension of water and increase the solubility of hydrophobic organic compounds (Laha *et al.*, 2009). Surfactant molecules are amphiphilic because they possess both a strongly hydrophilic group and a strongly hydrophobic group. Surfactants, their properties, and their environmental effects have been reviewed recently (Haigh, 1996; Krogh *et al.*, 2003; Ying, 2006; Fernández Cirelli *et al.*, 2008; Laha *et al.*, 2009). By reducing surface tension, surfactants also decrease the liquid–solid contact angle (Letey, 2001) and thereby affect the size of pores that water will enter at a given matric potential. By altering these fundamental properties of water in soils, surfactants affect both soil structure and soil and water management (Wallis and Horne, 1992; Fullen *et al.*, 1993; Sutherland and Ziegler, 1998; Kostka, 2000; Arriaga *et al.*, 2009).

Surfactants applied to soil may increase infiltration or decrease infiltration. Kuhnt (1993) noted how a surfactant solution could infiltrate faster or slower than untreated water, depending upon the soil's wettability, how the surfactant was applied, and the surfactant's effects on surface tension and on liquid–solid contact angle. Where growing potato (*Solanum tuberosum* L.) in wettable, coarse-textured soils in the north central region of the United States, a dry zone commonly occurs in the centre of the planting bed about 0·25 m below the soil surface (Arriaga *et al.*, 2009). They and Lowery *et al.* (2002) found that a nonionic surfactant sprayed atop those beds increased both infiltration and water contents in the dry zone.

Surfactant effects on sediment loss from wettable rather than water repellent soil have been studied by few researchers. Compared to an untreated but pre-wetted control, a nonionic surfactant applied with simulated rainfall to a wettable loamy sand increased runoff but had no effect on sediment loss, with findings attributed to seal formation (Sullivan *et al.*, 2009). Increased runoff, in turn, increases erosion risks (Lehrsch *et al.*, 2005). In contrast, Osborn *et al.* (1964) documented that sediment loss from a water repellent soil was 13 times greater than that from an initially water repellent soil rendered wettable by surfactant application prior to rainfall. Compared to wettable soils, greater sediment loss from water repellent soil may be due to the water repellent soil particles on its surface remaining dry, even beneath a water film, thus facilitating detachment by raindrop kinetic energy and transport in overland flow (Shakesby *et al.*, 2000). More sediment is lost from water repellent than wettable surfaces, despite commonly greater aggregate stability in water repellent than wettable portions of a soil (Wallis and Horne, 1992; Capriel *et al.*, 1995; Mataix-Solera and Doerr, 2004). Because aggregate stability of wettable soils pretreated with nonionic surfactant solutions was unaffected in two of three cases, Mustafa and Letey (1969) concluded that surfactants produced inconsistent results and thus did not reliably improve soil structure.

Many reports of nonionic surfactant effects on wettable soil physical properties are not representative of field situations where applications would be at cost-effective rates for production. Miller *et al.* (1975) packed soil into columns, then saturated the soil with surfactant, an event unlikely to occur in the field. Mingorance *et al.* (2007) continuously applied surfactants, in solution at concentrations far greater than those at which they affected surface tension, to three highly calcareous soils. Surfactants with different properties affect water flow differently, a point noted by Abu-Zreig *et al.* (2003) and Mingorance *et al.* (2007).

Characterizing surfactant effects on runoff and sediment loss from irrigation or simulated rainfall is a topic of current interest (Leighton-Boyce *et al.*, 2007; Arriaga *et al.*, 2009). A recently patented formulation of surfactant compounds, a blend of an ethylene oxide/propylene oxide (EO/PO) block copolymer (COP), and alkyl polyglycoside (APG) (Bially *et al.*, 2005), has potential to affordably alter water repellent soil hydraulic- and water-mediated solid phase properties at very low application rates (<47 l ha^{-1}) at the field scale, begging the question, 'How might wettable soil properties be affected?'. Since wettable soil horizons often occur above or below repellent horizons (Doerr *et al.*, 2000) and water repellency varies spatially, surfactant applied to fields with water repellent patches would likely also treat wettable areas within the field. Moreover, water repellent soils in the field commonly alternate between wettable and non-wettable states during or between seasons due to changing regimes of temperature, rainfall, or both (Crockford *et al.*, 1991; Dekker and Ritsema, 1994). Thus, wherever surfactants are applied worldwide they will likely be applied to wettable soil with unknown outcomes.

Surfactants may affect wettable soil properties such as erosion rates, infiltration rates, or water retention. To properly assess the response of wettable soil hydrologic properties (e.g. rates of erosion and infiltration) to applied surfactants, as Cerdà and Doerr (2007) recommended, we measured those rates directly rather than inferring their response from some surrogate measure such as water drop penetration time (WDPT). Thus, our first objective was to evaluate the effects of three surfactants and sprinkler irrigation on runoff and erosion from three selected, highly productive wettable soils in a laboratory setting. A second objective was to quantify the effects of the three surfactants applied at economic rates on selected physical properties of the three soils. For each soil, we measured surfactant and control effects on sediment loss, the soil displaced by splash, the proportion of applied water that ran off the soil surface (hereafter termed 'runoff'), tension infiltration, and water retention at high potentials.

METHODS

Study site/soil properties

The study was conducted at the United States Department of Agriculture, Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, Kimberly, ID, USA, between 2005 and 2009. We studied

Table I. Chemical and physical properties of surfactants used and amount applied

Property	Surfactant[a]		
	APG	COP	IGG[b]
Chemical components	Glucoethers	Alkoxylated polyols (ethylene oxide and propylene oxide)	Alkoxylated polyols (0·10 kg kg^{-1}) and glucoethers (0·07 kg kg^{-1})
Active ingredient (kg kg^{-1})	0·70	1·00	0·85
Specific gravity (kg l^{-1})	1·149	1·043	1·123
pH	4·3	3·2	4·2
Physical appearance	Amber to dark brown liquid	Clear to hazy viscous liquid	Clear, odourless, viscous brown liquid
Dilution factor (by wt)	1 : 26·31	1 : 26·13	1 : 11·70
Application rate[c] (kg AI ha^{-1})	3·35	4·80	8·09

[a] All surfactants were nonionic and miscible in water.

[b] Provided in concentrated form; properties shown are for the concentrate as received.

[c] The AI application rate corresponding to a whole product application rate of 46·8 l ha^{-1}.

three nonionic surfactants, each miscible in water, produced by Aquatrols Corporation of America, Paulsboro, NJ, USA (Table I). The commercially available surfactant IrrigAid Gold® (IGG) is a light brown, odourless liquid that contains 0·17 kg active ingredient (AI) kg^{-1} with the remainder being water. It has a specific gravity of 1·024 Mg m^{-3} as marketed. In addition to IGG, we studied the two components of IGG: an APG and a COP. The surfactant APG is a dark brown liquid that makes up 0·07 kg AI kg^{-1} of IGG while COP is a colourless liquid that makes up 0·10 kg AI kg^{-1} of IGG. In a supporting investigation designed to identify appropriate surfactant application rates for detailed study, we used the experimental protocol described in detail below to study the effects of three application rates of IGG on the runoff and sediment loss of a Quincy sand. The application rates were 0, 9·4, and 46·8 l ha^{-1} of whole product, equivalent to 0, 1, and 5 times the manufacturer's recommended rate. Rates $<$47 l ha^{-1} were economically viable for high value crops such as potato or turf. These rates were chosen with input from our industry cooperator to enable us to detect any here-to-fore unknown effects of surfactants on runoff and erosion of wettable soils. The Quincy soil was chosen for this supporting investigation for two reasons. First, it was the coarsest soil we studied and thus most susceptible to water repellency. Second, the Quincy, though wettable, approached a commonly used threshold for being classified as non-wettable and was thus most likely to respond to surfactant applied at a moderate rate (Bisdom *et al.*, 1993). Based upon this supporting investigation's findings (presented below), we used surfactant application rates of 0 and 46·8 l ha^{-1} for all three surfactants for all the remaining portions of our study.

Table II. Selected properties of the three soils

Soil property	Latahco	Rad	Quincy
Textural classification	Silt loam	Silt loam	Sand
Particle size distribution (g kg^{-1})			
Sand (0·05–2 mm)	190	250	950
Silt (0·002–0·05 mm)	610	610	10
Clay ($<$0·002 mm)	200	140	40
Organic C (g kg^{-1})	19·3	12·1	4·6
pH (saturated paste)	5·5	7·8	6·4
CEC (cmol(+) kg^{-1})	24·3	16·2	12·6
Base saturation (%)	49	97	45
EC (dS m^{-1})	0·76	3·57	1·66
SAR (meq l^{-1})$^{0.5}$	0·32	1·27	0·32

We chose three agriculturally important soils from the Pacific Northwest region of the United States (Table II). The Latahco silt loam (fine silty, mixed, superactive, frigid Argiaquic Xeric Argialboll; Soil Survey Staff, 2010), a soil from the Palouse region of northern Idaho, is found on nearly 11 000 ha (NRCS, 2009). The Rad silt loam (coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocambid) is found on nearly 26 100 ha throughout south-central Idaho and northern Nevada. The Quincy sand (mixed, mesic Xeric Torripsamment) is present on nearly 280 000 ha, primarily in the Columbia River Basin region of Washington, Oregon, and Idaho, though also in California. The soils' particle size distribution, organic C content, and mineralogy are typical for Pacific Northwest soils. Particle size was determined using the pipette method (Gee and Or, 2002), organic C using the Walkley–Black method (Nelson and Sommers, 1996), and pH using a combination electrode in a saturated paste (Robbins and Wiegand, 1990). Cation exchange capacity (CEC) and base saturation (both at a ratio of 2 g of soil to 20 ml of extractant) were determined following the guidelines of Sumner and Miller (1996) for soils containing carbonates. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were calculated as the difference between those extracted by 1 N NH_4OAc and by deionized water. Base saturation was then calculated as the ratio of the sum of the exchangeable bases to CEC. Electrical conductivity (EC) and sodium adsorption ratio (SAR) were determined using a saturated paste extract (Robbins and Wiegand, 1990). The Rad soil was collected in May 2005 and again in June 2006 at soil depths of 0–0·2 m from a furrow-irrigated field (42°31′N, 114°22′W) in fallow near Kimberly, ID, USA. At sampling, the Rad's water content was 0·14 kg kg^{-1}. The Latahco soil was collected in October of both 2005 and 2006 at soil depths of 0–0·15 m from a fallow area (46°42′N, 117°00′W) near Moscow, ID, USA. When sampled, the Latahco contained 0·11 kg water kg^{-1}. The Quincy soil was collected in February 2007 at soil depths of 0–0·3 m from a field (45°45′N, 119°32′W) near Hermiston, OR, USA. The Quincy's water content was about 0·16 kg kg^{-1} as sampled. After collection, each soil was transported to Kimberly, ID, USA, and stored in a field-moist condition at ambient temperatures in covered metal bins.

All three soils were wettable with each soil's mean WDPT <5 s (Bisdom *et al.*, 1993). The WDPT measured periodically at the soil surface prior to irrigation was essentially 0 (being too short to measure) for the Latahco and Rad silt loams (data not shown). Measured WDPTs were often <1 s for the Quincy sand, a soil that *in situ* is often water repellent during summer and early fall (Horneck D, 2009, personal communication). Only once in 80 measurements was the Quincy's WDPT >5 s, being 6·9 s in that lone instance. Though the Quincy soil is water repellent at times, the mixing that occurred when it was collected, handled, and packed into steel boxes (described below), being processes akin to deep ploughing, rendered the mixed Quincy soil wettable, much as noted by Shakesby *et al.* (1993).

A portion of each soil was taken from its bulk storage container, well mixed, then sieved through a 10-mm screen into a steel box, 1·22 m wide by 1·52 m long by 0·20 m deep, maintained in the laboratory. Each box contained a 76-mm-deep layer of fine gravel overlaid by a 76-mm-deep layer of packed soil. The soil was packed by tamping in three to four lifts to bulk densities representative of field conditions, nominally 1·1 Mg m^{-3} for the two silt loam soils and 1·3 Mg m^{-3} for the Quincy sand. A screed was then used to level the soil surface. The upslope end of each box filled with either Rad or Latahco soil was elevated so that each soil's surface was at a 2·5% slope. In a similar manner, Quincy soil surfaces were positioned at a 5% slope to obtain measurable amounts of runoff (described below).

Surfactant application

Before irrigation, each surfactant was applied directly to the soil surface by hand using a backpack sprayer and a 1·52-m long, hand-held spray boom equipped with five nozzles (Spraying Systems Co. TeeJet® Model 1 100 050V) operated at a nozzle pressure of 172 kPa. At a calibrated rate, we moved the boom across each box twice in a cross-slope direction, once moving left to right and once right to left. Tracks were placed 0·36 m above the soil surface to support the boom and to help distribute the surfactant evenly (Christiansen's Uniformity Coefficient of 0·93; Christiansen, 1942; Smajstrla *et al.*, 1997). Nominal surfactant application rate was 46·8 l ha^{-1} mixed with well water, taken from a tap, to obtain the dilutions shown in Table I. Well water, drawn from Idaho's upper Snake River Plain aquifer, had a pH of 7·6, EC of 0·7 dS m^{-1}, and SAR of 1·7 (meq $l^{-1})^{0·5}$. It contained 55 mg Ca^{2+} l^{-1}, 32 mg Mg^{2+} l^{-1}, and 67 mg Na^{+} l^{-1}. The control spray solution was also well water. We applied 34·8 ml (equivalent to a depth of $<0·02$ mm) of either diluted surfactant or well water to the soil in each box.

Irrigations

Within 48 h of surfactant application, the first of two irrigations took place. We used a calibrated sprinkler simulator to irrigate the soil in each box at a rate of 88 mm h^{-1} twice, first for 0·33 h to apply 29 mm of water, then 7–10 days later for 0·25 h to apply 22 mm of water. Our second irrigation was about 1 week after the first to allow surface soil to dry, thus simulating our region's field environment prior to irrigation. Compared to our first irrigation, our second irrigation was shorter because (1) we expected more runoff due to wetter subsoil and (2) we did not wish to exceed either the volume of our runoff collection vessel or the capacity of our platform scale. In addition, we wanted to ensure that our soils' hydrological and erosion responses to Irrigation 2 were not affected by the possible presence of a water table. The water applied in the irrigation was surfactant-free well water. The irrigation water was applied using a single, oscillating Spraying Systems Co. VeeJet® Model 8070, flat-fan type nozzle mounted about 3 m above the soil surface. The sprinkler, similar in design to one described by Meyer and Harmon (1979), was operated at a nozzle pressure of 76 kPa to simulate irrigation with a median drop diameter of 1·2 mm and sprinkler droplet kinetic energy of 26·0 J kg^{-1} (Kincaid, 1996; Aase *et al.*, 1998). The simulator, which wet the entire soil surface of each box throughout the irrigation, was operated to apply water as uniformly as possible achieving a Christiansen Uniformity Coefficient of 0·90 (Smajstrla *et al.*, 1997; Figure 1). During the irrigation, runoff from the downslope edge of each box was collected with a covered, triangular-shaped flume that directed all sediment-laden runoff into a catch basin positioned atop a continuously weighed platform scale. Data from this scale enabled us to prepare curves of sediment-laden runoff with time. No runoff or sediment subsamples were collected periodically throughout the irrigation. The additional sediment that was splashed from the soil in each box during the irrigation was collected on the cover of the flume and in three 0·25 m wide by 1·60 m long troughs positioned along both sides and the upslope edge of the box. After each irrigation, we collected the splashed sediment by rinsing it from the cover and each of the troughs. We measured splashed sediment because it is a significant component of total sediment loss from water repellent soils (Doerr *et al.*, 2000).

Runoff, in total for the irrigation, and the water containing the splashed sediment were each allowed to stand undisturbed for 24 h. Thereafter, we decanted

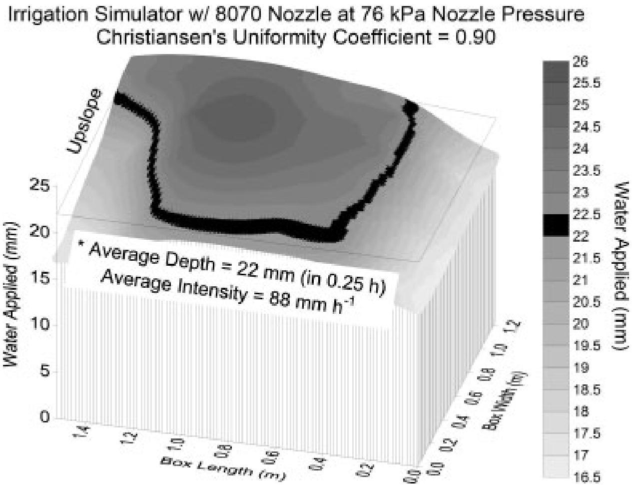

Figure 1. Water distribution pattern from the sprinkler irrigation simulator (Christiansen's Uniformity Coefficient = 0·90)

and then discarded the supernatant. We recovered the sediment from the remaining runoff and splash water by passing the water through a filter under vacuum. The sediment so obtained was dried at 105 °C for 24 h and weighed. Sediment loss, also as a total for the irrigation, was calculated as the mass of oven-dried sediment per unit area of the box (1·85 m^2). Splash loss was calculated as the mass of oven-dried, splashed sediment per unit area of the box. By collecting the irrigation's entire runoff (with its suspended sediment), we were able to determine the total runoff as a per cent of applied water. To do so, we first subtracted the oven-dry weight of the runoff's sediment from the net weight of the sediment-laden runoff, and then divided the remaining weight of runoff by the weight of the water applied to the box, expressing the quotient as a per cent.

After the first irrigation, steady-state tension infiltration at -60 mm water potential was measured *in situ* twice in each box using the procedure of Ankeny (1992) as modified by Lehrsch and Kincaid (2010). Tension infiltration at the soil surface was measured 0·4 m from each box edge, once at one upslope corner and once at the diagonally opposite downslope corner of each box. For the Rad and Latahco soils, tension infiltration was determined 3–5 days after the irrigation, at which time the surface soil in each box had dried to a water content of about 0·10 kg kg^{-1}. For the Quincy sand, tension infiltration was measured 1 day after irrigation. Software described by Ankeny *et al.* (1993) was used to determine the unconfined (three-dimensional) tension infiltration rate.

Between irrigations of each silt loam, box fans were used to dry the surface soil in the boxes by moving air horizontally across the soil surface. A few days before the first and before the second irrigation of the Quincy, the soil in each box was dried to a nominal water content $\leq$0·04 kg kg^{-1} using one ceramic heater (Holmes Model HCH4051) positioned along the upslope edge of a custom-made, insulated cover that provided 0·27 m of headspace above the soil surface. During drying, the surface soil temperature was about 50 °C, less than the temperatures found by Dekker *et al.* (1998) and by Doerr *et al.* (2005) to alter soil water repellency. After heating, the soil in each box was untouched for about 24 h, found by Doerr *et al.* (2005) to be adequate for soil to reach equilibrium with a laboratory's atmosphere.

About 7–10 days after we had first irrigated, we irrigated a second time as we had done earlier. After this second irrigation, we collected soil cores at three locations in each box to determine bulk density, water content, and water retention. Bulk density from the soil surface to the 34-mm depth was measured (Grossman and Reinsch, 2002) on cores with 50-mm diameters. Additional cores 49 mm in diameter and 19 mm deep were collected from the soil surface for the measurement of volumetric water contents. Using these cores, we measured water contents at sampling and at saturation, as well as water retention at matric potentials of -10, -20, -33, and -100 kPa (Topp *et al.*, 1993; Dane and Hopmans, 2002). Water contents at specific potentials were measured in a constant temperature room to minimize fluctuating temperature effects on soil water characteristics (Bachmann *et al.*, 2002).

Statistical analysis

We conducted the experiment by analysing the three soils in sequence having been constrained by both logistics and time. All told, measurements were taken from 48 soil-filled boxes: three soils × four surfactant treatments × four replications. The four surfactant treatments were the three surfactants (Table I), each applied at 46·8 l ha^{-1}, and an untreated control, being surfactant-free well water, also applied at 46·8 l ha^{-1}. For each soil, the experimental design was a split-plot with surfactant treatments as main plots arranged in randomized complete blocks (RCBs) and irrigations being subplots in time. For those measurements only taken after the second irrigation of each soil, surfactant treatments were arranged in RCBs. In every case, treatments were replicated four times.

Before performing an analysis of variance (ANOVA), we examined each response variable's error variance by treatment using the relationship between the variable's treatment means and corresponding treatment standard deviations (Box *et al.*, 1978). If a response variable's error variance was not constant, we transformed that variable's raw data using a common log, reciprocal square root, reciprocal square, or arcsine square root transformation. We then conducted a Bartlett's test (Steel and Torrie, 1960) to ensure that the treatment variances were homogeneous. As needed, ANOVA grouping options were used to account for heterogeneous variances among treatments for each response variable. We then used SAS (SAS Institute Inc., 2008) to perform an ANOVA using mixed-model procedures (PROC MIXED) and a significance probability (p) of 0.05, unless otherwise noted. We separated least-squares means using t-tests of pairwise differences. Where needed, means were back-transformed into original units for presentation.

RESULTS

Surfactant rate study

Surfactant application rates of 0, 9·4, and 46·8 l ha^{-1} did not differ significantly in their effects on runoff or sediment loss at each irrigation (Table III). Neither runoff in Irrigation 2 nor sediment loss in Irrigation 1 monotonically increased or decreased with increasing application rates. Runoff from Irrigation 1 tended to increase with surfactant rates but a 500% increase in rate from 9·4 to 46·8 l ha^{-1} increased runoff less than 16% (not significant). Similarly, sediment loss from Irrigation 2 tended to increase with surfactant rates but a fivefold increase in rate increased sediment loss less than 5% (also not significant). All told, increasing surfactant application rates had inconsistent and statistically insignificant effects on runoff and sediment loss from the Quincy sand, the soil most likely to show a response. Consequently, surfactant rates of 0 and 46·8 l ha^{-1} were used for the remainder of our study.

Runoff, sediment loss, and splash loss measured after each irrigation

Compared to the control, none of the surfactants, applied at economic rates to soil surfaces prior to irrigation, had any significant effect on runoff or, by extension, infiltration when analysed by soil and irrigation (Figure 2A). Within each soil, there were only small differences, and none statistically significant, in runoff within an irrigation among the control and the three surfactants. Runoff from the Quincy was minimal due to its very high sand content (Table II). When averaged across the four surfactant treatments, however, runoff from each soil varied from one irrigation to the next (Figure 2B). For the Latahco and Rad, runoff increased by four percentage points, despite 24% less water being applied at Irrigation 2 than 1. Though the runoff increases were slight, they were still highly significant, with $p < 0.001$ for the Latahco and for the Rad. The Quincy's runoff, in contrast, for Irrigation 2 was only one-third of that from Irrigation 1. Antecedent water contents (0–76 mm) measured prior to Irrigations 1 and 2 were similar within each soil. The water contents, all in kg kg^{-1}, for Irrigations 1 and 2 were 0·09 and 0·10, respectively, for the Latahco, 0·10 and 0·12 for the Rad, and 0·02 and 0·04 for the Quincy. The fact that Quincy's antecedent water content was greater prior to Irrigation 2 than 1 provides no explanation for this threefold runoff decrease. Runoff was far less for the coarse-textured Quincy than for either of the two silt loams, regardless of irrigation. Runoff within an irrigation differed between the Latahco and Rad (Figure 2B). Runoff was 50% greater ($p < 0.002$) from the Latahco than the Rad for each irrigation.

Table III. Surfactant application rate effects on runoff and sediment loss from Quincy sand

Application rate[a] (l ha^{-1})	Runoff[b]		Sediment loss[c]	
	Irrigation		Irrigation	
	1 (% of applied)	2 (% of applied)	1 (kg ha^{-1})	2 (kg ha^{-1})
0	7·8 a[d]	1·6 a	301 a	155 a
9·4	8·3 a	3·5 a	375 a	161 a
46·8	9·6 a	1·8 a	231 a	169 a

[a] Surfactant was IGG. Rates shown are for the whole product.
[b] Neither the rate nor the rate by irrigation interaction was significant ($p > 0.883$ and $p > 0.869$, respectively).
[c] Neither the rate nor the rate by irrigation interaction was significant ($p > 0.677$ and $p > 0.440$, respectively).
[d] Within a column, means ($n = 4$) followed by a common letter are not significantly different according to t-tests of pairwise differences at $p = 0.05$.

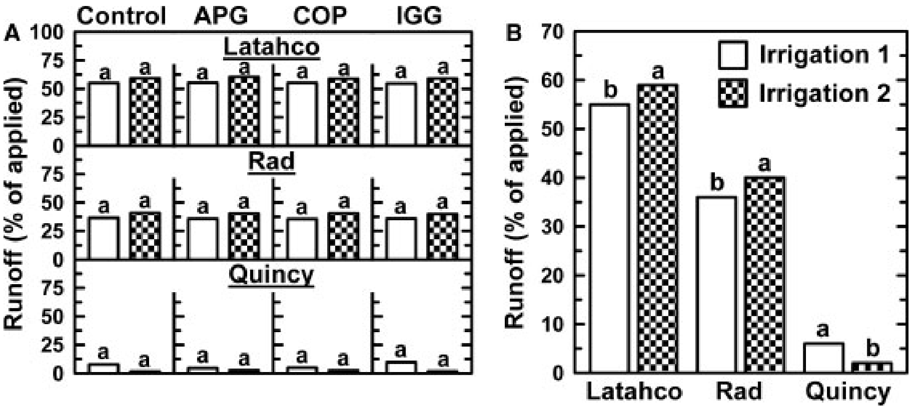

Figure 2. Runoff (as per cent of applied water) by irrigation for each of three soils. Runoff is shown by surfactant treatment (A) and averaged across surfactant treatments (B). Within a soil and an irrigation in (A), means ($n = 4$) with a common letter are not significantly different according to t-tests of pairwise differences at $p = 0.05$. Within a soil in (B), means ($n = 16$) with a common letter (a or b) are not significantly different according to t-tests of pairwise differences at $p = 0.05$

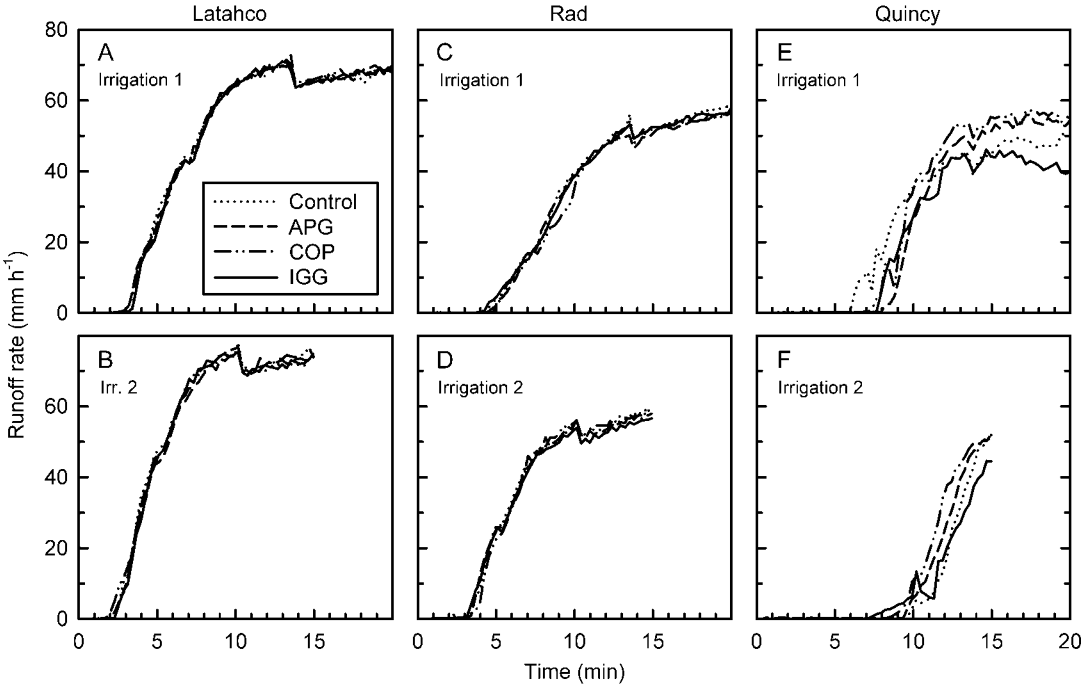

Figure 3. Runoff rate with time by surfactant treatment from each soil at each irrigation. Each curve is an average of four runs for the Latahco and Rad soils and two for the Quincy. Data for two runs of the Quincy were lost due to equipment malfunction

Runoff from the Latahco began about 3 min after the start of the first irrigation and rose at a moderate rate, reaching a quasi-steady-state (or peak runoff) rate of about 69 mm h^{-1} about 13 min into the irrigation (Figure 3A). Quite remarkable is the similarity in runoff curves between the control and the three surfactants. This runoff similarity among surfactant treatments was illustrated earlier when Latahco's runoff was expressed as per cent of applied water (Figure 2A). Comparing Latahco's second irrigation to its first, runoff began about 1 min earlier, increased faster, and reached its higher peak runoff rate of ~75 mm h^{-1} about 3 min earlier (Figure 3B), in part because the Latahco was slightly wetter prior to Irrigation 2 than 1. These runoff changes suggest that, during the first irrigation, a surface seal may have formed that decreased infiltration and increased runoff from Irrigation 2 compared to 1 (Figure 3A and 3B).

Runoff from the Rad soil started between 4 and 5 min into the first simulated irrigation, increased at a slow but consistent rate for another 8 min, then changed little, reaching a peak runoff rate of about 58 mm h^{-1} (Figure 3C). As noted for the Latahco, the runoff curves for the control and the three surfactants were very similar throughout the entire irrigation. In contrast to its first irrigation, runoff from Rad's second started 1 min earlier, increased quickly, then changed only slightly until it attained its peak, also about 58 mm h^{-1}, at the end of the irrigation (Figure 3D). Again, throughout the simulation, runoff curves for the four surfactant treatments crossed one another frequently, with no one curve consistently above or below the remaining three, revealing no surfactant effects on runoff.

Runoff from Quincy's first irrigation, compared to Latahco's and Rad's first, varied more among surfactants, likely because valid runoff data were available for only two of the four replications (Figure 3E). Runoff began from the control about 6 min into the run but from the remaining three surfactants about 1·5 min later. Runoff increased from the four surfactant treatments in a similar manner, with each reaching its peak runoff rate about 15 min into the irrigation. After 20 min, the peak runoff rates for APG and COP were similar, ~54 mm h^{-1}. The final rate for the control was about 50 mm h^{-1} while that for IGG was least, about 40 mm h^{-1}. Though the Quincy was wettable, its runoff rate after 20 min nonetheless seemed to be decreased somewhat from its peak runoff rate (i.e. infiltration rate increased) when treated with IGG (Figure 3E). Compared to Quincy's first irrigation, runoff from its second started about 2 min later (Figure 3F) and increased at a rate similar to that of Irrigation 1 (Figure 3E). At the conclusion of the second irrigation, runoff rates were ranked COP $\approx$ APG $\approx$ Control $>$ IGG (Figure 3F). Runoff from the Quincy began later after Irrigation 2 than 1, likely because the surface was more hydrophilic, with hydrophobic organic compounds likely having been leached downwards by infiltrating water (Lehrsch *et al.*, 2010, unpublished).

Compared to the control, none of the surfactants significantly affected sediment loss when analysed by soil and irrigation (Figure 4A). Within a surfactant treatment, Quincy's sediment loss was least because it contained by far the least silt (Table II), the soil separate most susceptible to erosion by water. Sediment loss averaged across surfactant treatments did vary, however, from one irrigation to the next for each soil (Figure 4B). Sediment

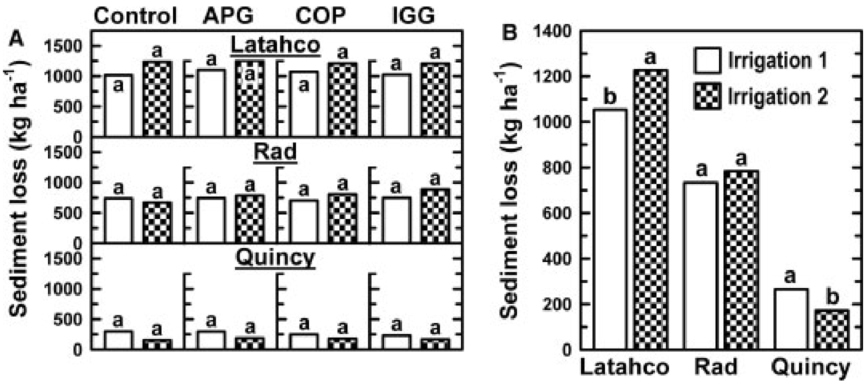

Figure 4. Sediment loss by irrigation for each of three soils. Sediment loss is shown by surfactant treatment (A) and averaged across surfactant treatments (B). Within a soil and an irrigation in (A), means ($n = 4$) with a common letter are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$. Within a soil in (B), means ($n = 16$) with a common letter (a or b) are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$

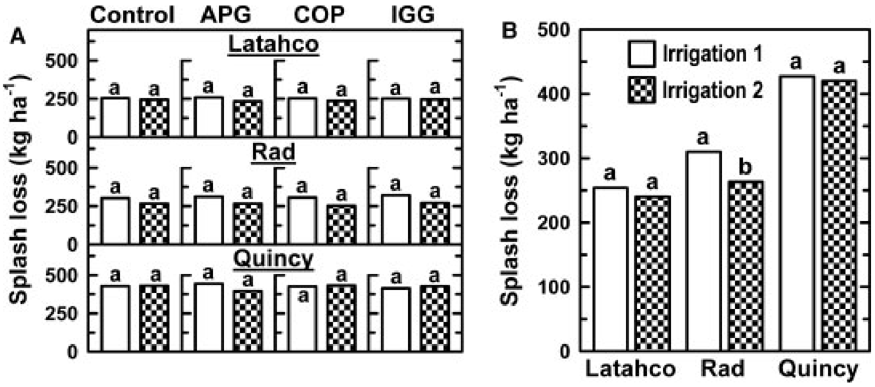

Figure 5. Splash loss by irrigation for each of three soils. Splash loss is shown by surfactant treatment (A) and averaged across surfactant treatments (B). Within a soil and an irrigation in (A), means ($n = 4$) with a common letter are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$. Within a soil in (B), means ($n = 16$) with a common letter (a or b) are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$

loss from Irrigation 1 to 2 increased for the Latahco but decreased for the Quincy. Despite the Latahco's high organic C content (Table II), generally correlated with stable aggregates (Lehrsch *et al*., 1991), its sediment loss increased ($p < 0{\cdot}002$) more than 16% from Irrigation 1 to 2. Since the Latahco's water content was greater, though only slightly, prior to Irrigation 2 than 1, surface soil aggregates were likely less stable, more easily fractured, and thus more easily transported in the greater overland flow from the Latahco's second irrigation (Figure 2B). In contrast, Quincy's sediment loss decreased by 35% from the first to the second irrigation, due in large part to the relatively low sediment carrying capacity of the minimal runoff from Quincy's second irrigation (Figure 2B). A crust may also have formed at the Quincy's surface when it dried after the first irrigation since Doerr *et al*. (2000) reported that simulated rainfall upon a coarse-textured, wettable soil compacted the soil surface and formed a crust. For each irrigation, sediment loss was ranked as Latahco > Rad > Quincy (Figure 4B). The Quincy's loss being least was expected because of its far greater sand content, 950 g kg^{-1}, compared to the other soils (Table II). The average 50% greater sediment loss for each irrigation from the Latahco than the Rad was not due to a greater silt content (Table II) but rather due to the corresponding 50% greater runoff from the Latahco than the Rad for each irrigation (Figure 2B). Due to differences in sediment carrying capacity, sediment loss is directly proportional to runoff (Kemper *et al*., 1985).

Splash loss for each soil did not differ among the control and surfactants when analysed within an irrigation (Figure 5A). Indeed, even for the Latahco and Quincy soils, splash loss varied little among irrigations within a surfactant. When splash loss was averaged across the four surfactant treatments, however, the soil by irrigation interaction on splash loss was significant at $p < 0{\cdot}001$ (Figure 5B). The Rad's splash loss decreased ($p < 0{\cdot}001$) by about 15% from Irrigation 1 to 2. The splash loss for the Latahco and Quincy also decreased from Irrigation 1 to 2 but not significantly.

Tension infiltration

The steady-state tension infiltration at −60 mm potential, hereafter termed 'tension infiltration', measures water entry through soil surface pores $\leq 0{\cdot}5$ mm in diameter. Tension infiltration measured after the first irrigation did not differ ($p = 0{\cdot}369$) among the control and surfactants (data not shown in tables). Averaged across soils and measurement positions, tension infiltration was $3{\cdot}80\ \mu\text{m s}^{-1}$ for the control, $4{\cdot}00\ \mu\text{m s}^{-1}$ for APG,

Table IV. Soil effects on water content after irrigation and water retention at specific potentials (data have been averaged across surfactants)

Soil	Water content after irrigation (m^3 m^{-3})	Water content (m^3 m^{-3}) at specified potential (kPa)				
		0	−10	−20	−33	−100
Latahco	0·067	0·563 a[a]	0·409 a	0·373 a	0·325 a	0·242 a
Rad	0·099	0·534 a	0·370 b	0·342 b	0·292 b	0·225 b
Quincy	0·231	0·396 b	0·115 c	0·097 c	0·082 c	0·065 c

[a] Within a column at each potential, means ($n = 16$) followed by a common letter (a, b, or c) are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$.

4·20 μm s^{-1} for COP, and 4·10 μm s^{-1} for IGG. Tension infiltration did differ, however, among soils. Quincy sand had the greatest infiltration rate, 9·92 μm s^{-1}. Although the Rad and Latahco soils were silt loams, the Rad's tension infiltration rate, 4·43 μm s^{-1}, was three times ($p = 0{\cdot}014$) the Latahco's rate, 1·48 μm s^{-1}. The lower infiltration rate for the Latahco, compared to the Rad, reveals that it had fewer flow-conducting, surface pores $\leq$0·5 mm. This finding suggests that there was more aggregate breakdown and pore occlusion (i.e. surface sealing) in the Latahco than Rad, despite the Latahco having more organic matter (organic C, Table II). Aggregate stability commonly increases with organic matter (Lehrsch *et al.*, 1991). Organic matter appears to be less important than droplet kinetic energy in affecting infiltration. More surface sealing in the Latahco than Rad is borne out by data in Figure 2A showing consistently more runoff from the Latahco than Rad.

Tension infiltration, averaged across surfactant and soil, varied depending upon measurement location or position (data not shown in tables). Tension infiltration at the downslope position, 4·2 μm s^{-1}, was 8% greater ($p = 0{\cdot}060$) than that at the upslope position, 3·9 μm s^{-1}. This finding revealed that infiltration through pores with diameters $\leq$0·5 mm increased as runoff moved downslope. This pattern was similar from soil to soil regardless of surfactant treatment. This finding is somewhat surprising since one would expect more pores downslope than upslope to be occluded with sand or aggregate fragments from infiltrating runoff. It is likely that, since the irrigation system was moved progressively from downslope to upslope as the irrigation continued, soil near the runoff collection flume was saturated quickly, decreasing both the potential gradient and the resulting infiltration rate into the soil near the downslope edge of the box. With less infiltration and more runoff occurring in the downslope region, it may be that less sand and fewer aggregate fragments in runoff moved into surface pores there, obstructing them. When tension infiltration was later measured there, more pores with diameters $\leq$0·5 mm would thus be unobstructed and able to conduct flow.

Water content and water retention measured at study's end

A number of soil properties were determined using samples collected after the second (final) irrigation. Surfactants significantly affected the water contents of the Rad soil after the second irrigation, though the differences were slight (Figure 6). For each silt loam, water contents tended to be greater where surfactant-treated than untreated. The coarse-textured Quincy soil was unaffected by surfactant application, likely because it was initially wettable rather than water repellent.

We measured water content and water retention on volumetric soil samples collected after the second irrigation (Table IV). Water contents after irrigation decreased in the order Quincy > Rad > Latahco when averaged across surfactants. Water contents from saturation (0 kPa matric potential) to −100 kPa varied among soils, when averaged over surfactants (Table IV). As expected, the Quincy sand retained the least water at any measured potential. Also, at every potential ≤ -10 kPa, the Latahco soil, with its greater organic C content than the Rad (Table II), retained significantly more water than the Rad. Compared to the Quincy, the Rad retained three times and the Latahco four times as much water at each measured potential (Table IV).

Surfactants appeared to increase the volume of water held in pores with diameters $\geq$15 μm, that is, those pores that were water filled at potentials ≥ -20 kPa (Table V). For perspective, most bacteria have diameters of 1–2 μm and lengths of 4–6 μm. In general, water retention at potentials ≥ -20 kPa, averaged across soils, decreased in the order APG $\geq$ IGG $\geq$ COP $\approx$ Control. While others (Karkare and Fort, 1993; Karagunduz *et al.*, 2001) have reported the retention of surfactant-amended water by surfactant-treated soil, to our knowledge no

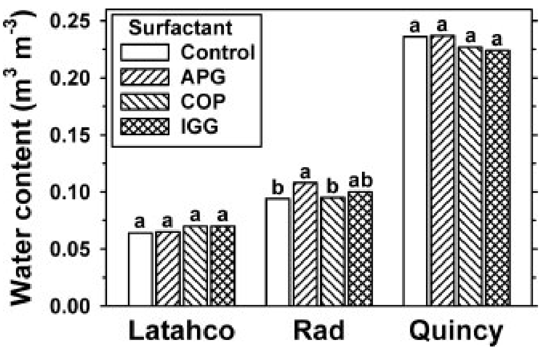

Figure 6. Surfactant effects on water content of three soils, with samples collected after the second irrigation. The surfactant by soil interaction was significant at $p = 0{\cdot}045$ for the Latahco and Rad data. Within a soil, means ($n = 4$) with a common letter (a or b) are not significantly different according to t-tests of pairwise differences at $p = 0{\cdot}05$

Table V. Surfactant effects on water retention at high potentials (data have been averaged across soils)

Surfactant treatment[a]	Water content ($m^3 m^{-3}$) at specified potential (kPa)		
	0	−10	−20
Control	0·484 b[b]	0·295 b	0·268 b
APG	0·495 a	0·304 a	0·276 a
COP	0·486 b	0·296 b	0·268 b
IGG	0·491 ab	0·297 b	0·270 ab

[a] Surfactant effects were significant at $p = 0.080$ at 0 kPa, at $p = 0.047$ at −10 kPa, and at $p = 0.065$ at −20 kPa.
[b] Within a column, means ($n = 12$) followed by a common letter (a or b) are not significantly different according to t-tests of pairwise differences at $p = 0.05$.

one has reported the retention of surfactant-free water by surfactant-treated soil. Our findings demonstrate that the retention of surfactant-free water at potentials from 0 to about −20 kPa in surfactant-treated soil is either greater than or equal to water retention in untreated soil depending upon surfactant properties.

Increased water retention in surfactant-treated soil (Table V) is important. We speculate that water content changes could be sufficient to increase the exposure of target organisms, 'hiding' in certain soil pores, to pesticides applied in conjunction with surfactants. Equally important, by increasing water retention at high potentials, surfactants applied to wettable soils may allow water containing NO_3–N or other agricultural chemicals to better penetrate soil pores, thereby increasing the efficacy of the co-applied materials. Water contents higher than those at field capacity (i.e. higher than those at a matric potential ≈−33 kPa) were greater in surfactant-treated than untreated soil (Table V). The amount of water taken up by plants growing in such relatively moist soils is important to producers, particularly under irrigated conditions (Hansen *et al.*, 1979). In addition, increased water retention after surfactant application (Table V) reveals that, with a likely decrease in the liquid–solid contact angle on treated soil surfaces, incoming surfactant-free water will enter, and be retained in, relatively large pores, possibly by allowing the escape of air otherwise entrapped within untreated pores.

These research findings are applicable to many relevant areas worldwide where irrigated coarse- and medium-textured soils are used to grow turf and produce row crops. In addition, these results provide evidence that surfactants applied jointly to wettable and water repellent soil produce no ill effects on the former while likely improving the water relations of both.

CONCLUSIONS

Compared to a control, these surfactants affected neither the physical properties nor the erosion responses of wettable soils, in general. At a probability level ≤8%, however, the volumetric water contents at potentials from saturation to −20 kPa, averaged across soils, were greater for APG-treated soils than for the control or soils treated with COP. At the same potentials, the water contents were similar, in general, for soils treated with either the APG or IGG (a blend of APG and COP). Increased water retention in larger pores of surfactant-treated soil could potentially improve the efficacy of pesticides that target organisms residing in certain-sized pores.

Although unaffected by surfactant treatment, the runoff and erosion responses frequently differed from soil to soil and from one irrigation to the next. Although similar in texture, the sediment loss for each irrigation was about 50% greater from the Latahco than Rad, likely a consequence of the 50% greater runoff from the Latahco than Rad. Runoff from the coarse-textured Quincy was 6% or less of the water applied. Runoff from the two silt loams, in contrast, ranged from 36 to 59%.

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