Will Wetter Water Make Fatter Wallets? Evaluating Soil Surfactants in Irrigation

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Abstract. *Growers concerned with drainage, runoff, and localized dry spots in the Pacific Northwest are considering adding soil surfactants during irrigation based on claims that these wetting agents improve infiltration, water distribution uniformity, and soil moisture retention. Growers are requesting independent studies on the cost effectiveness of these materials. Experiments are being conducted at Washington State University in uniformly prepared soil columns to investigate the effects of surfactants on soil-water properties of sandy and silt loam soils. The infiltration rate, water holding capacity, and unsaturated hydraulic conductivity were compared for soil columns irrigated with and without several types of soil surfactants. To date, no statistical differences between treatments have been found. Capillary rise experiments remain to be conducted, and some sand columns are still being processd. Researchers have concluded that new tests will need to be designed with problem-soil conditions before results can help advise the irrigation practices of regional growers of difficult-to-irrigate crops such as high-value vegetables and beans.*

Keywords. Surfactant, wetting agent, soil penetrant, water saving, drainage, runoff, dry spot, water repellent, hydrophobic, surface tension, infiltration, hydraulic conductivity, moisture content, field capacity, capillary rise, Wet-Sol, WaterMaxx, Ad-Sorb, ADVANTAGE Formula One, anionic, non-ionic, block polymer

Introduction

Agricultural soil in the Pacific Northwestern states of Washington, Idaho, and Oregon is among the richest in the world for producing high-value crops such as potatoes, beans, and onions. Yet, growers face a number of costly irrigation problems. Not only does poor irrigation contribute to lowered yields and produce quality, but wasted water is costly and it can carry away topsoil or increase leaching of pollutants such as nitrates into groundwater.

Yet growers know that experimentation in the field with potential remedies is also costly and risky. Hence, this study investigates a frequently recommended method to improve penetration and distribution of irrigation water by "making water wetter," the application of soil surfactants with irrigation water.

The Need for Wetter Water

Whether center-pivot or surface irrigation systems are used, water fails to penetrate some soils due to surface crusting or hardpan conditions, leading to runoff or evaporation and poor irrigation distribution uniformity from surface ponding. In the opposite scenario, water often drains too quickly in sandy soils to provide adequate moisture content for plant uptake. While percolating, water may not distribute evenly, but instead take preferential pathways through the soil pores so that water and applied nutrients miss plant roots.

Localized dry spots (LDS), which may appear in patchwork patterns across a field, frequently occur when soils become water repellant, also known as hydrophobic. Naturally repellant soils include uncultivated sands of uniform particle size, clay soils with pore spaces too small for water droplets to enter easily, and various grasslands (Sullivan 2001, Doerr et al., 2000). Repellant soils can also be developed by burning fields or from frequent wet and dry cycles (Miller 2002).

Water repellency is believed to be caused by coating of soil particles with hydrophobic organic materials, which occurs when very wet soil dries quickly (Hallett, 2008; Doerr et al., 2000). Healthy soil is coated with wet organic compounds produced by beneficial fungi, other microbes, fluids excreted from plant pores, natural leaf waxes, and any plant residues tilled into the soil. When dry, however, these organic compounds cling to each other (i.e. adhere) and become hydrophobic (i.e. will not bond readily with water). Distribution of fungal species and organic matter will determine where dry spots develop. Water repellent soil layers may develop between layers of healthy, hydrophilic soil in response to burning, climate swings, or mineral profile (Hallett, 2008). LDS may be induced by uneven irrigation coverage that results in uneven wetting of organic compounds across a field (Karnok, 2001). Hence, growers' attempts to compensate for dry periods or new dry spots by temporarily increasing irrigation may unfortunately worsen water-repellent soil conditions over time. This problem only adds to the increased pumping and water costs and leaching of soil nutrients associated with over-irrigating.

An Advertised Solution

A remedy for all these problems is offered by manufacturers of surface-active wetting agents called soil surfactants. These topical treatments are advertised to change soil-water properties: if soil is impermeable, a soil surfactant will reduce crusting and compaction; if the soil is too dry, a soil surfactant will cause water to cling to the soil; if a soil is too wet, a soil surfactant will improve drainage. (These differ from surfactants applied in chemigation as spreaders and stickers.)

All soil surfactants on the market are designed to reduce the surface tension of water, and their main features are summarized in Table 1 from descriptions of various manufacturers. Since water molecules are bound to one another by surface tension (i.e. cohesive forces), then this reduction will make water less likely to bead, more likely to flow into air spaces in the soil, and more likely to spread over the surface of soil particles to adhere to soil. This theoretically should increase infiltration and uniformity of water distribution through the soil. Side benefits may include improvements in air movement (hence, better soil structure), microbial populations, seed germination, and root development.

Table 1. Chemical categories of soil surfactants.

	Common Ingredients	Main Use Characteristics
Anionic	Akyl aral polyethoxylate, ammonium lauryeth sulfate (used in bath products) or alkyl sulfate	• Reduce water surface tension. • Called "flash wetters," these low-molecular weight chemicals leach readily through soil. • May be toxic to some plants or affect some soil structures.
Non-ionic	Akyl -phenyl oxyethylene, phenol or alcohol ethoxylates, and/or organosilicones	• Reduce water surface tension. • Low-molecular weight flash wetters that leach readily. • Some used as spray adjuvants. • Most are chemically non-reactive and biodegradable.
Block Polymer	Alkoxylated polyols	• Achieve the least reduction in water surface tension of the types. • Designed as polar molecules for good residual effect: one end clings to hydrophobic soil, while the other end is hydrophilic and attaches to water molecules to draw them to the soil for long-lasting adsorption. • Biodegradable with low phytotoxicity.

Previous Evaluations of Soil Surfactants

Over the past three decades, studies on various soil surfactants have reported both positive and negative results, making it clear more investigation is needed. Studies have mainly focused on field trials over where soil conditions can vary greatly by local features, land use, and irrigation history. Cost analyses are not usually included in reports, and Sullivan's critique of alternative soil amendments cautions that applying soil surfactants adequately may prove costly (2001).

Positive results have been achieved with hydrophobic turfgrass. Severe LDS was reduced in 36 sand-based golf tees treated with a block polymer Aquatrols surfactant (Kostka, 2000). Another study with an Aquatrols surfactant on a putting green showed an increase in soil moisture uniformity, and overall water savings due to a moderation of soil moisture across different irrigation frequencies (Karcher et al., 2005; Aquatrols, 2005). However, timing is key: LDS reduction only persisted three months under a less costly one-time application of surfactants, while regular monthly applications consistently maintained low LDS levels (Miller, 2002).

Some striking successes have been realized with potatoes. In the Pacific Northwest, increases in potato yields and/or tuber yields were observed in 22 to 67% of the hydrophobic soil plots treated with Aquatrols' IrrigAid Gold block polymer surfactant (as cited in O'Neill, 2005). In more than one Wisconsin study, researchers have reported reduction of nitrate leaching and greater yields in surfactant-treated, hydrophic, sandy soils compared to no treatment (Kelling 2003; Lowery 2005). Although 50% increase in water content was seen throughout the growing season after an early surfactant application, further study into optimal timing was recommended (Lowery, 2005). In Colorado, the Platte Chemical Company was sure enough of nonionic surfactants' improvements in both potato yield and reductions in nitrate leaching that they applied for a patent on their own method of applying the surfactant to root zones (World, 2008).

Less promising results are found with other high-value vegetables and grains. A Texas A&M University review of soil surfactant use with corn, potatoes, soybeans, wheat, and grain sorghum cited several studies where no significant increase in yield or nutrient content was observed after applying surface wetting agents (McFarland et al., 2005). After their success on the golf courses, Aquatrols received a 2005 annual report on their IrrigAid Gold and Advantage surfactants that showed no significant differences in either soil moisture contents or pinto bean yields between treated and untreated sandy loam plots in the arid Southwest (O'Neill, 2005).

Surfactant vendors present results in promotional literature as well, which showcase their own trials, customer testimonials, and graphs and percentages taken from academic studies (without showing complete reports and references). These all share the bias that success was achieved in tests selected by the vendors. The soil conditions may have been optimal for that particular surfactant's mechanism of action, and may not exactly match the conditions in the field for which the surfactant is being considered by other growers. This present study differs from such approaches by seeking to level the field by using uniform soil conditions across the tests of different surfactants. The tests themselves attempt to isolate the effects of surfactants on the key physical processes that are behind the many advertised benefits of soil surfactants.

Objectives

This independent study evaluates advertised benefits of soil surfactants from the perspective of classic soil physics. The objectives are to determine if any statistically significant changes are seen in the following soil-water properties when a surfactant is added to irrigation water:

- Rate at which water vertically infiltrates the soil;
- Moisture retention of soil, measured as moisture content two days after irrigation;
- Unsaturated hydraulic conductivity (UHC) as a measure of water distribution in the soil;
- Rate of capillary rise, which is upward movement of a wetting front due to surface tension.

Methods and Materials

The experiments will determine whether surfactants added to irrigation water increase, decrease, or have no effect on the four properties of infiltration rate, field capacity, UHC, and capillary rise. For each experiment, each soil sample will receive one of the following treatments (applied randomly):

- Wet-Sol #233, a nonionic surfactant from Schaeffer Manufacturing Company (St. Louis, MO);
- WaterMaxx II, a block polymer surfactant from Western Farm Service (Fresno, CA);
- Ad-Sorb RST, a block polymer from J.R. Simplot Company – Plant Health Technologies (Boise, Idaho);
- ADVANTAGE Formula One, an anionic soil penetrant from Wilbur-Ellis Company (Fresno, CA);
- Irrigation water without additives (i.e. control treatment).

Each experiment will be performed in two types of soil from the Columbia River Basin: Warden silt loam and Quincy sand. Experiments will be replicated four times in each soil type, leading to 20 samples (5 treatments × 4 replicates) for silt loam and 20 for sand. Constants related to the soil water properties of infiltration rate, field capacity, UHC, and capillary rise will be derived from the measured data. Statistical differences among surfactant treatments and the control will be determined for each soil type by an Analysis of Variance (ANOVA) test on the means (average values) of the derived constants using Statistical Analysis System (SAS) software.

Surfactant Selection and Concentrations

The selected surfactants span the chemical categories and are all commonly used by Pacific Northwest growers and supplied by local distributers. Concentrations were determined for the tests of infiltration rate and moisture content based on the volume of surfactant V_s that the soil sample would see if it were irrigated as part of a larger field. Hence, the volume of surfactant applied to each sample was obtained by determining what fraction of the amount recommended for an acre would equate to the fraction of an acre taken up by a soil sample:

$$V_s \,/\, Recommended\ Volume\ for\ Acre = Sample\ Cross\text{-}sectional\ Area \,/\, Acre \qquad (1)$$

The median value from the manufacturer's range of recommended amounts was used so as not to bias the study toward lesser or greater chances of obtaining the advertised effects. Finally, the volume V_s of each surfactant was mixed with sufficient irrigation water (about 161 ml for these samples) to penetrate the soil sample to a 1-cm depth. UHC and capillary rise experiments were sample-volume independent, and hence used the same concentrations as for the infiltration rate and moisture content experiments. The surfactant volumes used were 0.271 ml, 0.181 ml, 0.090 ml, and 16.9 µl, respectively for Wet-Sol, WaterMaxx II, Ad-Sorb RST, and Formula One, and all were applied toptically in 161 ml of water.

Infiltration Rate Experiment

Infiltration rate was tested by siphoning irrigation water from a Mariotte-type reservoir into clear plexiglass columns filled with approximately 20.5 in. (52 cm) of air-dried, sifted soil to which the surfactant had been added in 1 cm of water (see Figure 2). A shake-cup-and-drop method of filling ensured uniformity across the columns and random particle distribution, while pounding the columns settled the particles. The bottom of each column was covered with wire mesh netting (0.2 cm holes) to allow drainage, while a slip of filter paper (150mm diameter pores) was placed on the mesh to hold the soil.

The water reservoir enabled air inflow through a tube (anchored by a rubber stopper on reservoir top) so that pressures could equalize after the siphon was released into a soil column open to the atmosphere as shown in Figure 1. The column was placed at a height that ensured (by the pressure head) that water would flow into the column until a pond formed on the soil surface that was level with the tube end. Thereafter, to keep the pond height constant, the reservoir continued to supply water to the soil column at just the rate necessary to replace the water that infiltrated the soil.

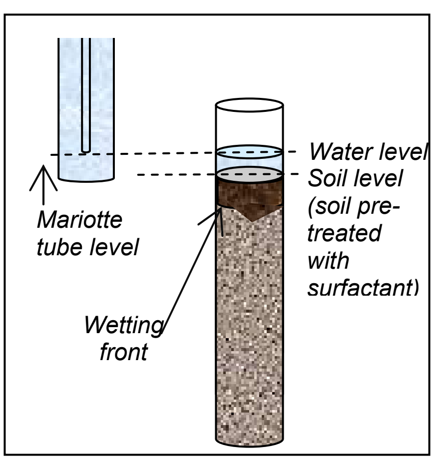

Figure 1. Mariotte principle is utilized in irrigating soil columns for infiltration rate experiments.

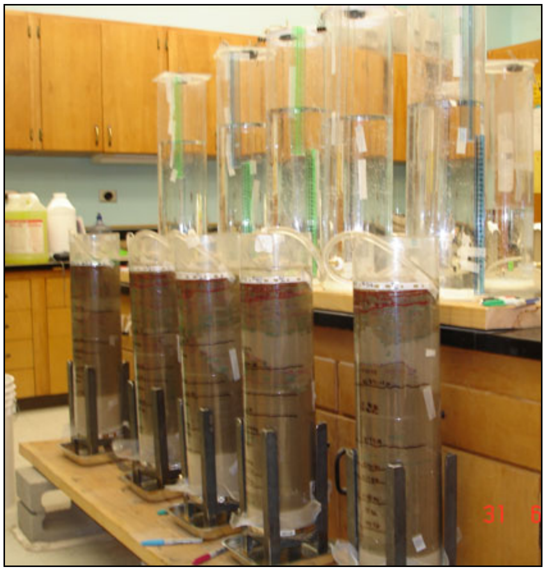

Figure 2. Irrigation of one treatment set during infiltration rate experiment.

Hence, the drops in the reservoir's water levels over time represented the infiltration rate. Water levels were recorded every 2 to 5 minutes for sand, and 3 to 10 minutes for silt until the soil column reached saturation and began to drip water. The infiltration rate decreased exponentially over time, as shown.

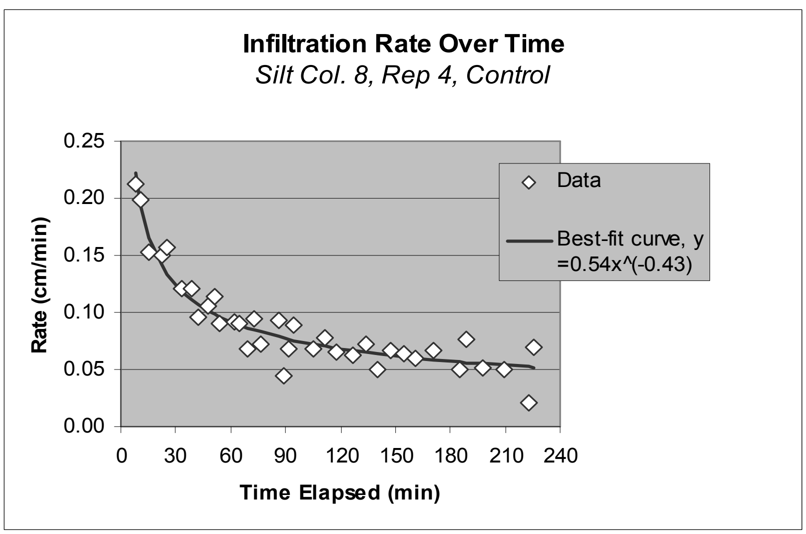

Figure 3. Typical infiltration rate curve obtained from experimental data.

Regression analysis showed that a power function of the form $y(t) = at^b$ best fit the infiltration rate curve. Hence, the data followed the form of the modified Lewis-Kostiakov equation for infiltration rate: $\bar{I}(t) = ak\, t^{(a-1)} + F_o$, with F_o always greater than or equal to zero. SAS ANOVA was finally applied to determine statistical differences in the Lewis-Kostiakov coefficients among the treatments.

Moisture Content at Field Capacity

The soil-moisture retention of the columns from the infiltration rate experiment was determined indirectly by collecting weight data and calculating gravimetric moisture content (θ_m), volumetric moisture content (θ_v), and bulk density (P_b). Columns were weighed just prior to irrigation and again after the soil had drained for two days (with columns covered with tin foil to prevent evaporation). This represented a field capacity condition, in which all the soil moisture that could be pulled by gravity had drained.

The equations for calculating $\theta_m, \theta_v,$ and P_b are:

$$\theta_m = M_w / Ms \tag{2}$$

$$\theta_v = \theta_m \times P_b/P_w \tag{3}$$

$$P_b = M_s / V_t \tag{4}$$

where M_s is the mass of soil in the column, M_w is the mass of water in the soil at field capacity, V_t is the total volume of soil and water, and P_w is the density of water, known to be 1000 kgm^{-3}.

The masses can be represented by weights measured in the lab, as they relate directly through the gravitational constant. Hence, dry soil weight corresponds to M_s, while M_v is represented by subtracting the soil's weight from the total (soil plus water) weight at field capacity. Gravimetric water content is then approximated as follows:

$$\theta_m \approx (\textit{wet weight} - \textit{dry weight}) / \textit{dry weight} \tag{5}$$

After determining θ_m for each column, the bulk densities were obtained using the soil height and column radius to calculate V_t, and θ_v was found from θ_m and P_b. Finally, the three values of gravimetric water content, volumetric water content, and bulk density for each column were statistically compared for variance across treatments using the same SAS ANOVA applied for infiltration rate constants.

Unsaturated Hydraulic Conductivity Experiments

Hydraulic conductivity is one of the most important soil-water properties, encompassing both lateral and vertical water movement in the unsaturated zone (i.e. still able to receive more water). In layman's terms, hydraulic conductivity accounts for the movement of water from wet to dry areas of the soil.

As shown in Figure 4, 100-ml mini-disk infiltrometers (Decagon Devices, Inc) were filled with a surfactant-water solution, of the same concentrations used previously, and then set on air-dried, sifted soil in shallow containers (5-in height, 9-in. diameter). Once the porous end of the infiltrometer contacted the soil, the solution spread freely out and down into the soil, while measurements similar to infiltration rate were taken. Water levels were recorded over time, every 10 seconds for silt and 5 seconds for sand. This time, cumulative infiltration was calculated as the drop in water level normalized by the cross-sectional area of the infiltrometer.


Figure 4. One researcher reads the water level on the mini-disk infiltrometer in the hydraulic conductivity experiment, while another records the readings at regular time intervals.

Cumulative infiltration data was fit to a simplified form of the Richard's Equation. Derived from the universal Darcy's Law, the Richard's Equation includes a theoretical UHC as a function of soil moisture content, denoted as *K(θ)*:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial K(\theta)}{\partial z} + \frac{\partial}{\partial z}[K(\theta)\frac{\partial \psi(\theta)}{\partial z}] \qquad (6)$$

where *z* is the position variable (facing doward) and *ψ* is the matric potential, also a function of moisture content.
However, the Richard's Equation is difficult to solve in this form, so numerical solutions have been discovered as simplifications for irrigation over short time periods. The form used for this study is the same as described by Hallett (2008), and represents cumulative irrigation as a function of time, I(t), as being composed of a nonlinear term with coefficient C_1, related to sorptivity, and a linear term with coefficient C_2, which is proportional to hydraulic conductivity.

$$I(t) = C_1\, t^{1/2} + C_2\, t \qquad (7)$$

Using this simplified model, hydraulic conductivity was indirectly analyzed through the constant value C_2. Regression was applied to determine values of C_1 and C_2 that gave the best I(t) curve-fit to the data. The results were analyzed with the SAS ANOVA program used previously to find any significant statistical differences in the C_2- coefficient across treatments.

Capillary Rise Experiments

Effects of the different surfactants on surface tension will be examined through a capillary rise test for the initailly-unsaturated soil condition. These tests were not yet conducted at the time of writing, but results will be announced in the presentation of this study at the November 2008 Irrigation Show in Anaheim, CA.

Clear plastic columns of 3-4 cm diameter and approximately 1 foot height will be filled with the same air-dried, sifted silt loam and sandy soils, then placed in 1-inch ponds of the treatment solution — a mixture of the same concentrations of surfactant and water used previously. A reservoir containing more of the treatment solution will be attached so as to resupply the pond at the same rate the water was taken up by the soil, according to the Mariotte principle. (Note: setup resembled an automatically-refilling watering dish for pets.)

Transparent rulers and transparent sheets will be attached to the clear columns for recording the heights of the wetting front and tracing its pattern at regular intervals of time. The rates at which the wetting fronts rise vertically will be statistically compared across the treatments with the same SAS ANOVA program used previously.

Results and Discussion

To compare the effects of different treatments, one or more key parameters were found for each of the soil-water properties of infiltration rate, moisture retention (at the field capacity condition), and hydraulic conductivity (in unsaturated soil condition). These parameters were statistically analyzed for the variance among their means with a SAS ANOVA (GLM) procedure. If the variance among the means was less than 5% (i.e. if a Pr-value of 0.05 was given by the SAS program), this variance was then considered significant. This meant that the surfactant showed a less than 5% chance of its key parameter's mean being significantly different from the key parameters' means of the other treatments.

Table 2 shows the key parameters that were analyzed, and the ANOVA Pr-values obtained. For the sand experiments, only 3 of the 4 planned replicates have been processed to date and soil columns are still drying from the unsaturated hydraulic conductivity experiments. Capillary rise experiments are also still underway. The remaining experiments will be completed and the results reported during the 2008 Irrigation Show held November 2-4, and the authors will be pleased to respond to requests for updated documents.

Table 2. Statitistical results from analysis of variance across the experimental treatments.

Soil Type	**Soil-water Property**	**Parameters Analyzed**	**Pr-values**
Silt	Infiltration rate	Rate constant *a*, for best-fit curve $\bar{I}(t) = ak\, t^{(a-1)} + F_o$	0.503
	Moisture retention at field capacity	θ_m, gravimetric moisture content θ_v, volumetric moisture content P_b, bulk density	0.763 (θ_m) 0.507 (θ_v) 0.194 (P_b)
	Unsaturated hydraulic conductivity	C_2 in best-fit curve, $I(t) = C_1\, t^{1/2} + C_2\, t$	0.443
Sand	Infiltration rate	Rate constant *a*, for best-fit curve $\bar{I}(t) = ak\, t^{(a-1)} + F_o$	0.411
	Unsaturated hydraulic conductivity	C_2 in best-fit curve, $I(t) = C_1\, t^{1/2} + C_2\, t$	0.620

As seen above, all the parameters showed greater than 20% likehood of having their means overlapping, so to speak, with the means of any other surfactants or the control treatment. Hence, this study showed no significant difference in soil-water properties across the treatments of 4 different types of surfactant and irrigating with no surfactant.

Nevertheless, one cannot interpret these results as proving that surfactants do not produce significant changes in soils. One must remember that the soils in these experiments used were sifted and uniformly settled into columns, without clods or uneven compaction. Also, though the soils were typical of Pacific Northwest fields where high-value crops are grown in furrows, they appeared free of some of the unique problems of water repellency that have been known to develop. Hence, these experimental soils are not actually the target customers for soil surfactants, which are advertised to ameliorate problem conditions in soils.

Researchers evaluating the success of numerous soil additive experiments have found similar results as achieved so far in this study: applying surfactants to normal (wettable) soils did not produce any noticeable changes (McFarland, 2005). Likewise, Sullivan's review of many soil amendments includes soils that already have good structure in his list of soils in which beneficial effects from surfactants should not be expected. Hence, the results from this study may be supporting a theory that soil surfactants have no effect on non-problem soils.

A balanced interpretation of these results would be to consider this type of study as a gateway to a full investigation of surfactants' physical effects. A full understanding of their activities during irrigation must begin with studies such as this that isolate the effects of the wetting agents on physicochemical properties of soil-water without soil problems in the picture.

Then for a study to be considered complete, it must proceed with a closer look at the effects of soil variations on the surfactants' action. The soil conditions should be varied in the lab, while still maintaining a controlled environment that assures uniform conditions across treatments, to investigate in more detail such scenarios as initial penetration in crusted or compacted soils, and moisture retention or distribution patterns in water repellent soils. Again, using classic soils physics methods will be applied, and perhaps digital imaging software can be used for observing wetting fronts (in case of preferential flows). Further helpful to understanding soil surfactant effects and still in the realm of soil physics, would be an examination of the surfactants more closely by measuring their surface tension; this would help explain the effects they may have on water and soil particles. The surfactant solution's critical mass should also be obtained or tested to verify that concentrations used in experiments (which, in this study, have been based soley on field applications) are appropriate for the surfactants' compositions.

Additionally, persistence experiments should also be conducted to see if accumulation of surfactant molecules in the soil may produce any effects on soil-water properties. If any of the above-mentioned experiments with problem soils should show improvements in soil-water properties after surfactants are applied, then the longer-term effects of surfactant treatments should be investigated to answer the question of how long the positive results will continue before the soil surfactants are drained away or biodegrade.

Conclusion

Again, no signficant statistical differences were noted among all surfactant treatments and the control, but the value of this study was to determine whether surfactants acted directly on the soil-water properties of two soil types typical in the Pacific Northwest for growing high-value crops. The results answered that adding soil surfactants to irrigation water did not produce any significant changes for the soil-water properties of infiltration rate, soil moisture content and bulk density, unsaturated hydraulic conductivity, and capillary rise, at least not for healthy and uniformly distributed soils immediately after the initial treatment.

Further studies with surfactants are needed. We recommend more tests on those properties of the surfactants that would influence their effects on soil-water, and experiments with varying soil conditions in the lab, especially water repellency.

In response to all the soil-improvement products being offered today, the North Central Regional Committee (NCR-103) was formed to investigate claims and advise consumers on a number of soil additives and conditioners, including surfactants (Iowa, 2004). NCR-103, which can boast Dr. Kelling of the Wisconsin potato studies as a member, cautions that reliable standardized procedures have not yet been developed to evaluate effects of various types of products on soil physical properties (North, 2004). Perhaps as further academic studies such as this one are conducted, new collaborations will be formed among universities and with industry partners that will lead to such standards, or at least, to an understanding of best practices so that growers can base their purchasing decisions on science-based evaluations of the effects of using these products in irrigation.

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