Agricultural Research & Technology Open Access Journal
ISSN: 2471-6774
Juniper Publishers
key to the Researchers

Research Article
Volume 27 Issue 1 - September 2022
DOI: 10.19080/ARTOAJ.2022.27.556360

Agri Res & Tech: Open Access J

Wetting Agent Effects on Plant Available Water for Hydrophobic USGA Root Zones

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Submission: September 20, 2022; **Published:** September 27, 2022

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Abstract

Soil hydrophobicity is a common issue for sand-based golf course greens. The most effective tool for control of soil hydrophobicity is use of wetting agents, which are also widely used for water conservation in the industry. Due to the complex chemistry and different purposes for which wetting agents are used, a better understanding of the compounds is needed in order to properly use them. Therefore, this research assessed twenty-one selected wetting agents for their influence on water retention of hydrophobic United States Golf Association (USGA) sands. Using pressure chamber systems, water retention of the wetting agents at field capacity, estimated under pressure of -2.9 kPa, exhibited a wide range between 19.8% and 11.6%, indicating certain wetting agents, such as InfilTRX, could hold up to 70% more water than other wetting agents such as Cascade Plus. Water retention of the wetting agents at permanent wiling point, determined under pressure of -1,500 kPa, ranged from 6.9% to 6.0%, comparable to 6.5% without addition of wetting agents. Plant available water, determined as water retained between these two pressures, was positively correlated (R^2=0.99) with estimated field capacity but not the permanent wilting point. A second experiment discovered that among four selected wetting agents, a lower application rate among five rates between 0.25 to 4 times label rates, consistently retained more water, up to 2.6-fold compared to the highest rate. Overall, this research showed strong evidence that different wetting agents are likely designed for different purposes, and discriminate use is advised.

Keywords: Wetting Agent; Root Zones; Soil Hydrophobicity; Forests; Grasslands; Plants

Abbreviation: USGA: United States Golf Association

Introduction

Soil water repellency or soil hydrophobicity, is a worldwide issue that concerns land managers and scientific communities in over 50 countries [1]. The occurrence of soil hydrophobicity impacts agricultural fields, pastures, forests, grasslands, parks and turf areas across all major soil textures [2], and appears in all climatic regions including dry and arid, as well as warm and humid areas [3]. On intensively managed turf, especially on golf course putting greens that are built based on U.S. Golf Association recommendations USGA [4], occurrence of soil water repellency is literally inevitable. A part of the reason is due to the sand that is used to build and/or topdressing the greens, as sands are more susceptible to the development of hydrophobicity due to their significantly smaller (>105 times) specific surface area (area/mass) compared with peat and clay [5,6]. It is also argued that the significantly smaller specific surface area with higher distribution of macropores in sandy soils provide a preferred habitat for fungal growth rather than bacteria, which further promotes the development of soil hydrophobicity [7]. Subsequently, water bypasses the hydrophobic rootzones and causes preferential flow, leading to the development of localized dry spot.

Managing a quality playing surface while conserving irrigation water is probably one of the most delicate balances that golf course superintendents strive to optimize. On average, over 7.5 billion liters of irrigation water were utilized on a daily basis by the golf industry in the U.S. in 2005, which would have cost $52,400 annually if municipal water was purchased for an average 18-hole golf facility [8]. Since then, water use on golf courses nation-wide has been reduced by 21.8%, attributed collectively to a reduced number of irrigated area, using reclaimed water sources, and a reduction in golf facilities by 600+. However, the national median cost of water has increased by 46% in 2013, despite these changes [9]. To conserve water, superintendents have been taking various agronomic and mechanical approaches, and among them, the most popular method adopted by 94% of golf courses in the U.S. is using wetting agents [9]; with 34% of golf courses directly delivering wetting agents through the irrigation system [8] to save labor.

Wetting agents are amphiphilic molecules which contain a hydrophobic/lipophilic region that are oil-loving and can adhere onto hydrophobic sand surfaces, and a hydrophilic region that can "hold" onto water molecules. The balance between the two regions, termed hydrophilic-lipophilic balance, determines the degree of lipid- or water-solubility of the wetting agents [10]. In other words, the chemical property of the wetting agent molecules determines if it is better to be used for accelerating water infiltration or increasing water retention. Based on their chemistry, Zontek and Kostka [11] divided the wetting agents in the turf market into five groups; they are polyoxyethylene and alkylphenol ethoxylates, block copolymers, alkyl polyglucosides, modified methyl capped block copolymers, and organic solvent and surfactant complexes. The complexity of the wetting agent chemistry and the various purposes for which people use wetting agents, such as increasing soil water movement, improving water retention, promoting homogenous soil moisture, and preventing the development of localized dry spots, contribute to our inability to answer the number one question superintendents have, "which wetting agent is the best?" [12]. Therefore, the objectives of this research were to evaluate the effects of selected twenty-one wetting agents on water retention capacities at estimated field capacity and permanent wilting point, and subsequently determine their influence on plant available water for a hydrophobic USGA sand.

Materials and Methods

This experiment was carried out in a pressure chamber system located at the University of Missouri, Columbia, Missouri. The hydrophobic sands were collected from a USGA green at the University of Missouri South Farm Research Center, where localized dry spots have been documented. The collected sands were then separated from plant debris before thoroughly mixed, bench dried, and stored for future use. The hydrophobicity of the sand was determined using the molarity of ethanol droplet test, and was determined to be 3.4 M, which falls in the very severe hydrophobic category [13]. The organic matter of the sand was determined to be 1.73%. The particle analysis revealed that the sands consisted of 6.76% very coarse sand, 12.74% coarse sand, 58.73% medium sand, 20.75% fine sand, and 1.02% very fine sand [4]. At a bulk density of 1.49 g cm^{-3}, the total porosity of the sands was determined to be 43.8%, with 24.5% capillary porosity and 19.4% air-filled porosity.

The hydrophobic sands were packed in rubber rings (5.2 cm diameter and 1.0 cm depth) to a consistent bulk density (1.49 g cm^{-3}) with a 31.6 g mass. The rings were then placed onto the center of petri dishes (8.8 cm diameter and 1.7 cm depth) before adding various wetting agent solutions to the outside space of the rings, allowing the solutions to seep in underneath and saturating the sands. Following saturation, the rubber rings containing the samples were carefully transferred from petri dishes to selected ceramic pressure plates with the desired bubbling pressure. Due to the hydrophobic nature of the sands, water by itself did not saturate the sands using the same method described above. Instead, sand-filled rings were placed on the ceramic pressure plates where 1 cm depth of distilled and deionized water was maintained outside of the rings for a 24-hour period to ensure fully saturating the sands. The porous plates with samples were then placed into the pressure chambers, and subjected to pressure treatment at two pressures, -2.9 kPa and -1,500 kPa, for estimated field capacity and permanent wilting point, respectively [14]. After five days equilibration, the samples were transferred to moisture cans, and their masses were recorded before and after oven drying at 105 °C for 48 h [15]. The gravimetric water content corresponding to each pressure value was calculated and adjusted to volumetric water content using the bulk density of the samples. Plant available water was then estimated by subtracting the lower limit (1500 kPa, permanent wilting point) from the upper limit (-2.9 kPa , field capacity) [16,17].

Two experiments were performed in the laboratory using the pressure chamber system. The first study evaluated 21 wetting agent solutions made with distilled and deionized water at the highest label suggested rate (Table 1) for their water retention capacity. Based on results from Study 1, Study 2 selected four wetting agents, representing various water retention capacities, and tested their effects on water retention at five rates, i.e., 0.25, 0.5, 1, 2, and 4 times label rates as described in Table 1. Both studies were arranged in a completely randomized design with eight replications. All data collected were subjected to analysis of variance using the PROC GLM procedure of SAS 9.4 (SAS Institute, Cary, NC), and significant means were separated based on Fisher's Protected LSD at $P \leq 0.05$. Pearson correlation was also performed among response variables collected from Study 1, to determine the relationship between field capacity, permanent wilting point, and plant available water influenced by the 21 wetting agents. In Study 2, significant interactions between wetting agent and application rate were detected for all response variables; hence multiple comparison was performed accordingly.

Results and Discussion

Selected Wetting Agents on Field Capacity Estimates

After forcing the hydrophobic sand to saturate without addition of wetting agent, the amount of water retained at field capacity, estimated under the pressure point of -2.9 kPa, averaged 24.0%. The saturation happened also because water repellency can be reduced upon contact with water over time [18]. This figure supports the soil porosity that determined the amount of micropores to be 24.5%. Following wetting agent applications, water retention estimated at field capacity fell into a wide range

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between 19.8% and 11.6% (Figure 1), lower than the theorical figure if the soil could be adequately saturated. This result is intriguing as it indicates that certain wetting agents could allow much of the water, up to 53% of water that could have possibly been retained, to move deeper in the soil profile. It is important to emphasize that under field conditions, however, saturation of the hydrophobic USGA rootzone with water repellency at 3.4 M, which was categorized as very severe [13], does not happen unless under an unlikely circumstance where significant ponding pressure can be maintained. Nevertheless, end-users need to be aware of the possibility that certain wetting agents, depending on their chemistry and designed function, could reduce water retention to a suboptimum level, especially for a rootzone mix that is relatively coarse and contains less organic matter.

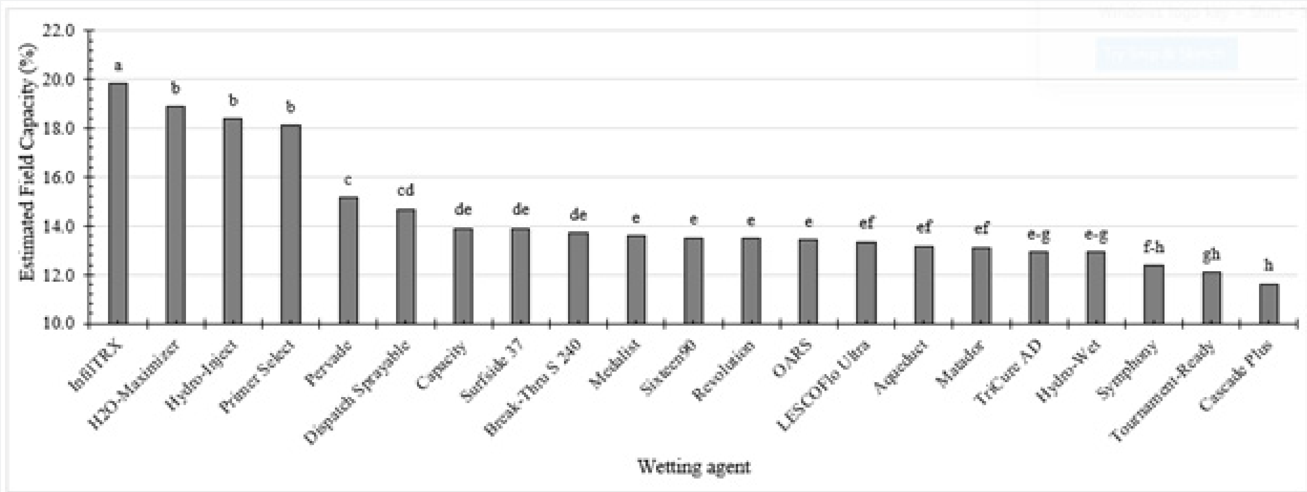

Figure 1: Estimated field capacity (%) of twenty-one wetting agents evaluated in Study 1. Bars labeled with different letters are significantly different based on Fisher's Protected LSD at P≤0.05.

Table 1: Description of the twenty-one wetting agents included in Study 1.

Wetting agent	Company	Active ingredient	Rate (ml/L)
Aqueduct	Aquatrols; Paulsboro, New Jersey	50% nonionic polyols, 5% 1,2-propanediol, 45% inert ingredients	62.51
Break-Thru S 240	Evonik Corporation; Richmond, Virginia	75% polyether modified trisiloxane	1.07
Capacity	Becker Underwood, Inc.; Ames, Iowa	100% proprietary blend of nonionic surfactants	31.25
Cascade Plus	Precision Laboratories, LLC; Waukegan, Illinois	10% alcohol ethoxylates, 90% polyethylene and polypropylene glycols	31.25
Dispatch Sprayable	Aquatrols; Paulsboro, New Jersey	30% alkoxylated polyols, 21% glucoethers, 49% water	7.81
H2O Maximizer	KALO, Inc.; Overland Park, Kansas	28% carbohydrate surfactant, poloxanlene, poly (2-propenamide), 72% inert ingredients	39.07
Hydro-Inject	Harrell's LLC; Lakeland, Florida	17% alkoxylated polyols, 83% inert ingredients	7.81
Hydro-Wet	KALO, Inc.; Overland Park, Kansas	87.5% blend of poloxanlene, 2-butoxyethanol, 12.5% inert ingredients	31.25
InfilTRx	Aquatrols; Paulsboro, New Jersey	20% non-ionic polyols, 80% water	7.81
LESCOFlo Ultra	LESCO, Inc.; Cleveland, Ohio	90% polyether polyol, 10% glycol ether	62.51
Matador	ENP Investments, LLC; Mendota, Illinois	100% alkyl block polymer	23.44
Medalist	KALO, Inc.; Overland Park, Kansas	30% proprietary blend of nonionic carbohydrate surfactants, polyoxyethylene-polyxypropylene glycol, polydimethylsiloxane, 70% inert ingredients and formulation aids	31.25

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OARS	Aqua-Aid, Inc.;	80% polyoxyalklene polymers, 10% potassium salt of alkyl, 10% inert ingredients	23.44
Pervade	Floratine Products Group, Inc.; Collierville, Tennessee	72% proprietary blend of di-sulfosuccinate surfactants, 28% buffers, couplers, and stabilizers ineffective as adjuvants	7.81
Primer Select	Aquatrols; Paulsboro, New Jersey	100% alkoxylated polyols	15.62
Revolution	Aquatrols; Paulsboro, New Jersey	100% modified alkylated polyol	23.44
Sixteen90	Aquatrols; Paulsboro, New Jersey	99.5% propoxylated polyethylene glycols, 0.5% water	24.99
Surfside 37	Montco Products Corporation; Bear Creek, Pennsylvania	37% nonylphenoxypoly (ethyleneoxy) ethanol, 18% polyoxyethylene esters of cyclic acid, and 14% polyethylene glycol	23.44
Symphony	Harrell's LLC; Lakeland, Florida	100% polyoxyalkylene polymers with HydrOtech (blend of Multi-Hydroxy polyoxyalkylene polyethers and organic acid correction complex)	19.53
Tournament-Ready	KALO, Inc.; Overland Park, Kansas	62% alkylpolyglycoside and siloxane solution, 38% Polyalkoxylate blend	31.25
TriCure AD	Mitchell Products; Millville, New Jersey	100% dihydrooxirane, epihydrin	15.63

Among the wetting agents evaluated, InfilTRX yielded the highest water retention at estimated field capacity, which was 71% greater than one of the wetting agents that retained the least amount of water, Cascade Plus (Figure 1). Although both InfilTRX and Cascade Plus are straight block copolymers [11], InfilTRX yielded the highest surface tension at 44.8 mN m^{-1}, compared to Cascade Plus with its surface tension determined to be 29.9 mN m^{-1} at the label rate [19]. Early research has reported that surface tension is negatively correlated to hydraulic conductivity [20]; hence, InfilTRX-treated rootzone likely retains more water for a relatively longer period of time, compared to compounds that exhibit lower surface tension such as Cascade Plus.

Selected Wetting Agents on Permanent Wilting Point Estimates

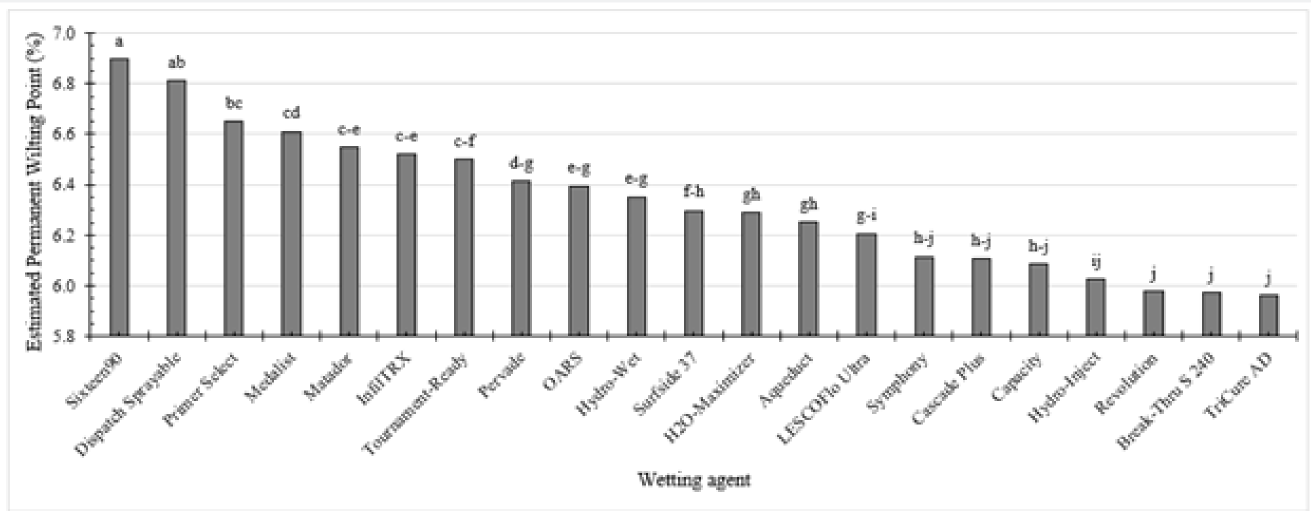

Figure 2: Estimated permanent wilting point (%) of twenty-one wetting agents evaluated in Study 1. Bars labeled with different letters are significantly different based on Fisher's Protected LSD at P≤0.05.

At permanent wilting point, estimated at pressure point of -1,500 kPa, water retention was determined to be 6.4% without addition of wetting agent. Wetting agent applications resulted in significant differences in water retention, ranging from 6.9% to 6.0% (Figure 2). Treatment with InfilTRX yielded 6.5% of water at permanent wilting point, which was comparable to 6.4% with water only after forced saturation. Among the 21 wetting agents evaluated, two of them, Sixteen90 and Dispatch Sprayable, resulted

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in 6.8% or greater water retention, which was significantly higher than the amount of water retained following InfilTRX application. This result indicates that an additional amount of water can be potentially retained beyond the point for plants to uptake following applications of these two wetting agents.

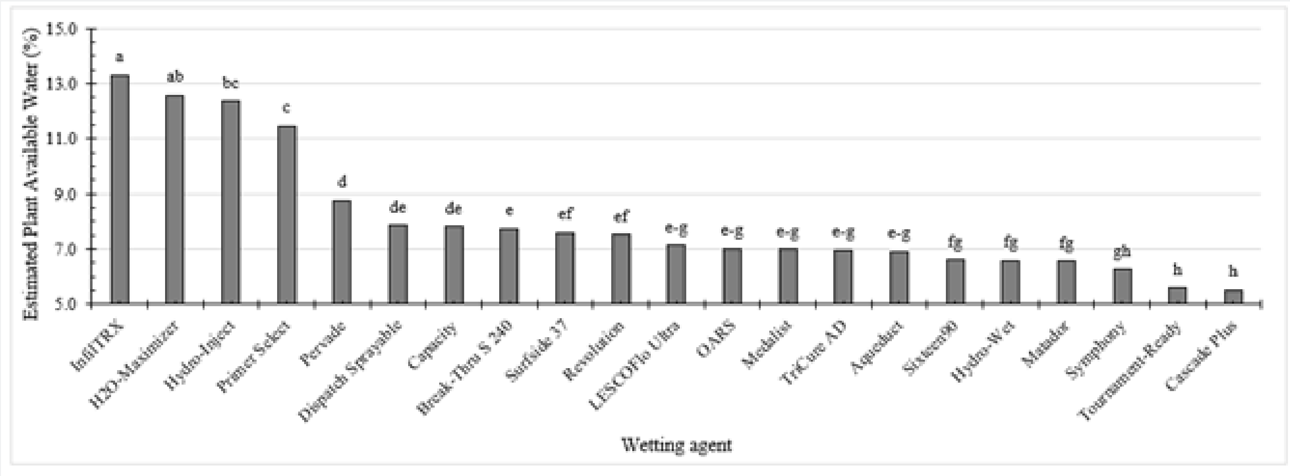

Figure 3: Estimated plant available water (%) of twenty-one wetting agents evaluated in Study 1. Bars labeled with different letters are significantly different based on Fisher's Protected LSD at P≤0.05.

Wetting agent Sixteen90 contains 95% of propoxylated polyethylene glycol, another straight block copolymer [21]. Polyethylene glycol is a widely used compound for reducing osmotic potential and hence water potential [22], thus resulting in elevated water retention. One of common uses of polyethylene glycol in medicine is for osmotic laxation [23]. Combination of Sixteen90 with Dispatch sprayable, a blended product that contains alkyl polyglucoside and a straight block copolymer [24], has resulted in a consistently softer creeping bentgrass (*Agrostis stolonifera L.*) putting green surface compared to the control [21], indicating a potentially wetter rootzone condition.

Selected Wetting Agents on Available Water Capacity

Plant available water, calculated as the difference between water retained at field capacity and permanent wilting point, was determined to be 17.7% without addition of wetting agent. The 21 wetting agents evaluated resulted in a broad range of plant available water between 13.3% and 5.5% (Figure 3). Although it appeared that none of the wetting agent applications improved the amount of water that could theoretically be available, this was again unlikely under field conditions as the hydrophobic rootzone would not saturate without significant ponding of water. On the other hand, the substantial difference among wetting agents for their influences on water retention has been reported early by Leinauer et al. [25], who found that only one wetting agent tested, Primer 604, consistently improved water retention of the sand-based turfgrass rootzone, while another wetting agent, Midorich, showed no difference compared to the untreated control.

Based on the amount of water that are available for plants, the 21 wetting agents tested can be generally divided into five groups (Figure 3). The first group contains only InfilTRX, which resulted in the highest plant available water above 13%. The second group contains H2O-Maximizer, Hydro-Wet Injectable, and Primer Select, with their plant available water ranging between 13% and 11%. The third and the fourth groups contain wetting agents that produced moderate amounts of plant available water, ranging between 9% and 7.5%, or 7.5 % and 6.3%, respectively. The last group included Tournament-Ready and Cascade Plus, both generated a relatively low plant available water at 5.6% or below.

Correlation tests indicated that plant available water was not correlated with the amount of water retained at permanent wilting point; instead it was positively correlated ($P<0.001$) to water retained at field capacity with a correlation coefficient of 0.99. This result explains the relatively high amount of available water following InfilTRX application, as it retained the greatest amount of water at field capacity (Figure 1). Similarly, the three wetting agents that were categorized in the second group based on plant available water described above, i.e., H2O-Maximizer, Hydro-Wet Injectable, and Primer Select, also retained relatively high amounts of water at field capacity.

The same trend described above also supports the results of water retention following applications of Tournament Ready and Cascade Plus, with both fall into the last group with low amounts of plant available water at 5.6% or below (Figure 3). This result indicates that applications of these two compounds might lead to relatively drier rootzone conditions and hence, they may not be the best choice if water conservation is desired. However, it is important to point out that wetting agents are designed and

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used for various purposes. Early research reported that products like Tournament-Ready and Cascade Plus demonstrated a fast infiltration into hydrophobic sand with a hydraulic conductivity of 28 or 30 mm min^{-1}, respectively [26]. In comparison, wetting agents Surfside 37 and Revolution, which generated modest amounts of plant available water at 7.6% or 7.5% respectively (Figure 3), exhibited slower infiltration with hydraulic conductivity determined to be 14 or 20 mm min-1, respectively [26]. Therefore, products like Tournament-Ready or Cascade Plus would be best used for fast drainage, especially following a major rainfall event. On the other hand, it is also imperative to understand that when irrigation water was not limited, products like Cascade Plus retained as much water as other wetting agents such as OARS, under field conditions [27]. This is partially because when extra moisture is available in the rootzone, the plants will transpire this water, resulting in comparable soil moisture contents under field conditions.

Similarly, wetting agents such as OARS, representing organic acid redistribution system, or Matador retained moderate amounts of plant available water at 7.0% or 6.6%, respectively (Figure 3). They are however, not designed to improve water retention. Instead, wetting agents in this category are designed to remove organic coatings that cause soil hydrophobicity, rather than simply forming a bridge between the hydrophobic soil surface and water molecules, thus improving water retention. An early laboratory-based research reported that after saturating the hydrophobic sand columns with Matador and followed by three rinses, a significant amount of particulate organic carbon was removed, nearly 7 times to the water-only treatment Song et al. [28], indicating a substantial amount of organic coatings that caused the soil hydrophobicity were displaced. This removal of organic coatings reduced the hydrophobicity of the sand from moderate (2.2 M) to zero, and totally restored the wettability of the sand. Collectively, these results emphasize the importance of understanding different wetting agents, and selecting them prejudicially based on the desired objectives.

Effects of Application Rates for Selected Wetting Agents

Based on the results from Study 1, four wetting agents, i.e., InfilTRX, Dispatch Sprayable, Sixteen90, and Cascade Plus, were selected from the different groups, and assessed at five application rates. At estimated field capacity, water retention following wetting agent applications generally showed a declining trend from the range of 22.3% to 16.3% at 0.25× label rate, to 15.6% to 11.9% at 4× label rate, with a maximum 35% decrease (Table 2). There were two exceptions, however, where water retention with Sixteen90 reached a plateau at 2× and 4× label rates, and Cascade Plus actually showed a rebound at rates higher than 1× label rate. This phenomenon is most likely caused by the formation of self-associated micelles of the wetting agent molecules in the liquid phase, after they reach saturation point or critical micelle concentration [29]. Beyond this concentration, wetting agent molecules congregate in such an orientation that their non-polar tails form a hydrocarbon-like core while their hydrophilic polar heads face outside interacting with bypassing water [30]. As the micelles precipitate on the soil particles, they retain water thus increasing water retention of the soil. Before reaching this critical concentration, which varies by chemistry and environmental factors, it appeared that using a lower concentration of the wetting agents would be beneficial for the purpose of water conservation.

Table 2: Estimated field capacity (%) influenced by interaction of the selected four wetting agents and their rates at 0.25, 0.5, 1, 2, and 4 times of label rates.

Wetting agent	Estimated field capacity (%)				
	0.25×	0.5×	1×	2×	4×
Cascade Plus	16.3 a3†	15.5 b3	11.6 e4	12.4 d3	13.5 c2
Dispatch Sprayable	18.2 a2	15.8 b23	14.7 c2	13.0 d2	11.9 e3
InfilTRX	22.3 a1	20.3 b1	19.8 b1	16.5 c1	15.6 d1
Sixteen90	18.2 a2	16.3 b2	13.5 c3	12.9 c23	12.9 c2

†Means in the same row followed by different letters are significantly different based on Fisher's Protected LSD at P≤0.05; Means in the same column followed by different numbers are significantly different based on Fisher's Protected LSD at P≤0.05.

Among the four wetting agents, InfilTRX showed the greatest water retention at the estimated field capacity, regardless of rate (Table 2). In contrast, Cascade Plus yielded a low water retention at 1× label rate or below. These results agree with the trend demonstrated in Figure 1. At estimated permanent wilting point, however, InfilTRX retained a higher amount of water at 0.25× or 0.5× label rates, but resulted in a low water retention at 2× and 4× label rates (Table 3). At 4× label rate, all wetting agents except InfilTRX held more water, up to 22% more, at the estimated permanent wilting point than 6.4%, the amount of water that would be held without addition of wetting agent following adequate saturation by force. A close examination revealed that InfilTRX was the only wetting agent among the four tested products that showed a decreasing trend as the concentration increases, while others demonstrated a general increasing trend as concentration increases. This likely resulted from wetting agent molecules that attached to the sand surfaces which, in turn, withhold additional water at the estimated permanent wilting point. Early research

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has shown that some of the wetting agent molecules applied to the hydrophobic soil would stay in the system, even after three water rinses [28]. Depending on the chemistry, certain compounds such as OARS, could retain up to 49% of their organic carbon, an indirect measurement of the wetting agent molecules from the product, in the hydrophobic sands in a laboratory-based experiment, resulting in 27% increase of the solid phase organic carbon on the sands, compared to untreated control [28]. Collectively, these results indicate that higher-than-label rates, or frequent application of certain wetting agents, might lead to accumulation of wetting agent molecules in the soil system and depending on the chemistry, might lead to elevated water retention beyond the point that plants can uptake water.

Table 3: Estimated permanent wilting point (%) influenced by interaction of the selected four wetting agents and their rates at 0.25, 0.5, 1, 2, and 4 times of the label suggested rates.

Wetting agent	Estimated permanent wilting point (%)				
	0.25×	0.5×	1×	2×	4×
Cascade Plus	6.6 c12†	6.2 d2	6.1 d3	7.4 b1	7.8 a1
Dispatch Sprayable	6.3 c2	6.4 c12	6.8 b1	7.0 b2	7.4 a2
InfilTRX	6.7 a1	6.6 a1	6.5 a2	6.1 b3	6.0 b3
Sixteen90	6.4 c2	6.6 c1	6.9 b1	7.5 a1	7.7 a1

†Means in the same row followed by different letters are significantly different based on Fisher's Protected LSD at P≤0.05; Means in the same column followed by different numbers are significantly different based on Fisher's Protected LSD at P≤0.05.

Subsequently, estimated plant available water showed a general declining trend as the wetting agent concentration increases, with a maximum 2.6-times the amount water held at 0.25× compared to 4× label rate (Table 4). This result again indicates that a lower rate might be a better choice when water conservation is the goal. Regardless of the rate, however, InfilTRX application resulted in the greatest plant available water, supporting the results shown in Figure 1. Cascade Plus, on the other hand, demonstrated a relatively lower plant available water in all rates except the 4× label rate. As discussed above, formation of micelles may have contributed to the elevated plant available water following Cascade Plus application at a higher rate.

Table 4: Estimated plant available water (%) influenced by interaction of the selected four wetting agents and their rates at 0.25, 0.5, 1, 2, and 4 times of the label suggested rates.

Wetting agent	Estimated plant available water (%)				
	0.25×	0.5×	1×	2×	4×
Cascade Plus	9.7 a3†	9.1 a2	5.5 b4	5.1 b3	5.6 b2
Dispatch Sprayable	11.9 a2	9.4 b2	7.9 c2	6.0 d2	4.5 e3
InfilTRX	15.6 a1	13.8 b1	13.3 b1	10.4 c1	9.5 d1
Sixteen90	11.8 a2	9.7 b2	6.6 c3	5.5 d23	5.2 d23

†Means in the same row followed by different letters are significantly different based on Fisher's Protected LSD at P≤0.05; Means in the same column followed by different numbers are significantly different based on Fisher's Protected LSD at P≤0.05.

Conclusion

This research showed that following applications of 21 wetting agents, there is a significant segregation regarding water retention for hydrophobic USGA sands. Some of the wetting agents, such as InfilTRX, could hold up to 1.4-times additional plant available water than others, such as Cascade Plus. On the other hand, wetting agents such as Cascade Plus may not have been designed for water retention; instead, early research has shown that it yielded a much faster hydraulic conductivity compared to other wetting agents, indicating its supreme role in water infiltration and hence, drainage. This research, therefore, provided a strong evidence that not all wetting agents are created equal, and users should select the proper wetting agents based on their objectives. This research also demonstrated that for the same wetting agent, a lower rate might be of interest for water conservation purposes, as lower rates of the wetting agents evaluated in this research all led to greater water retention, up to 2.6-times the highest rate. Future research in this direction would be benefited from adding more root zone water pressures, as this current research only focused on two pressure points for estimating field capacity and permanent wilting point. Measurement at more root zone pressures between these two points will likely answer the question of how much readily available water a wetting agent-treated soil can hold, as under field conditions, it is rare that a rootzone soil is allowed to reach permanent wilting point.

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Acknowledgement

This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 1006256.

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How to cite this article: Mingyan J, Matthew C F, SH Anderson, Xi Xiong. Wetting Agent Effects on Plant Available Water for Hydrophobic USGA Root Zones. Agri Res & Tech: Open Access J. 2022; 27 (1): 556360. DOI: 10.19080/ARTOAJ.2022.27.556360

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