Improving Soil Hydrological Behavior for More Efficient Irrigation

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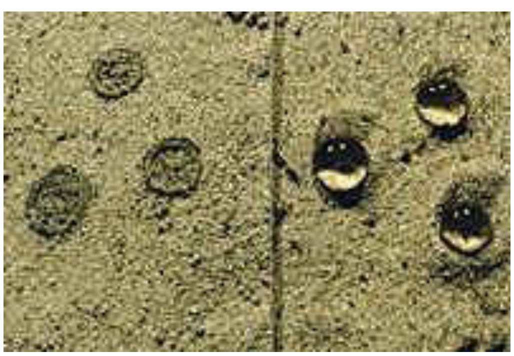
Abstract. *Irrigation efficiency depends largely on irrigation system performance (distribution uniformity), scheduling and the ability of soils to absorb and retain water for optimal use by plants. While many technological advancements have been made with irrigation systems and controllers, less attention has been given to how the soil system is functioning. Factors affecting soil hydrological behavior, especially the development of soil water repellency, can lead to significant reductions in irrigation efficiency. Even low levels of repellency can cause reduced infiltration and retention, increased runoff, variable wetting, preferential flow, and suboptimal growing conditions, all leading to reduced irrigation efficiency and increased water requirements. This has lead researchers to the view that soil water repellency seems to be more the norm than exception. Soil surfactants are capable of improving soil hydrological behavior by correcting or preventing water repellency, resulting in more efficient irrigation and significant water conservation. Examples and results from recent studies around the world are presented.*

Key words. Soil water repellency, soil surfactants, irrigation efficiency, water conservation, runoff, preferential flow.



Water drop penetration in wettable and repellent soil. Preferential flow in repellent soil. Courtesy Alterra,

Introduction

Irrigation efficiency depends largely on irrigation system performance (distribution uniformity), scheduling and the ability of soils to absorb, retain and release water for optimal use by plants. By definition, irrigation efficiency is “the ratio of the average depth of irrigation water beneficially used to the average depth of irrigation water applied” (Rochester, 2006). Simply put this translates to the percentage of the water applied that was beneficially used in the crop management program. Regardless of what the irrigated crop may be, maximizing irrigation efficiency is a desirable goal agronomically, environmentally and economically.

While many technological advancements have been made with irrigation systems and controllers, less attention has been given to how the soil functions with regard to irrigation efficiency. Soil water holding capacities and intake rates, based on generally accepted values, are taken into account in irrigation scheduling and run times. However, changes in soil conditions or behavior, which may compromise expected performance, is often not considered. Increased awareness of changes in soil functionality, the impact of these changes on irrigation efficiency and the practices available to manage them can narrow the gap between theoretical efficiencies and the actual efficiencies achieved by practitioners.

Factors affecting soil hydrological behavior, especially the development of soil water repellency, can lead to significant reductions in irrigation efficiency. Soil water repellency causes at least temporal changes in the hydrological properties of a soil which result in, among other things, increased irrigation requirements. Restoration of soil wettability will improve the hydrological behavior of soils allowing increased irrigation efficiency and significant water conservation in irrigated crop and landscape systems.

Soil surfactants can be used to improve the wettability of soils. Soil surfactants are materials that lower the surface tension of water and, depending upon formulation, can also restore wettability to water repellent mineral or organic soils. Since the invention of the original soil surfactant, AquaGro, in the 1950’s, there have been many advances in surfactant formulation making their use more economically viable for a variety of cropping systems. Where soil wettability is less than optimal, the use of soil surfactants in combination with appropriate irrigation and soil cultivation practices, improves soil hydrological behavior resulting in improved irrigation efficiency and water conservation (Kostka et al., 2007).

An growing body of research shows that soil water repellency and associated preferential flow are more common than previously thought - and that application of soil surfactants is an effective remediation strategy (Dekker et al., 2005). However, until recently, the impact of these findings on irrigation efficiency has not yet been widely recognized. This paper and its related presentation summarize the findings as they relate to efficiency of irrigation and water consumption citing some of the recent research results

Soil water repellency and preferential flow

Soil water repellency is a condition that develops in soils causing the soil to resist wetting. It is caused by the accumulation of water repellent/hydrophobic coatings on the soil particle surface (Dekker et al., 2001; Hallett et al., 2001; Karnok and Tucker, 2002), and triggered when a soil drops below a certain critical soil moisture content for that particular soil (Dekker and Ritsema, 1994). A direct consequence of soil water repellency is a reduction in a soil's ability to wet and retain water (Hallett, 2007).

The development of water repellent behavior in soils is more wide-spread than previously thought. Among the first to mention water repellency in North America were Schreiner and Shorey (1910) who wrote in a USDA bulletin: '*…there was found in California a soil which could not be properly wetted, either by man, by rain, irrigation, or movement of water from the subsoil, with the result that the land could not be used properly for agriculture. On investigation it was found that this peculiarity of the soil was due to the organic material, which when extracted had the properties of a varnish – repelling water to an extreme degree."* Since that time, water repellent soils have been identified in a wide variety of soils worldwide and studied in 35 countries on six continents, including in more than 20 states in the United States (Dekker et al., 2005). Dekker et al. (2001) and Karnok and Tucker (2002) also report that soil water repellency develops under a wide range of different plant systems. All of this has lead researchers to the view that soil water repellency seems to be more the norm than exception (Wallis and Horne, 1992; Ritsema and Dekker, 2005).

Preferential flow refers to the movement of water and solutes through specific pathways in only a portion of the soil matrix rather than in a more uniform wetting front as expected from lateral diffusion of water in the soil. Because soil water repellency reduces the wettability of portions of the soil, it leads to the development of preferential flow paths (Dekker et al., 2001). The preferential flow paths often carry applied water and solutes past the active root zone, reducing efficiency of both precipitation and irrigation, and increasing environmental risk.

As noted, soil scientists and hydrologists now consider water repellency and preferential flow to be more the norm than the exception in a wide variety of soils (Dekker et al., 2005). Water repellency in soil and the associated preferential flow are like "barriers" and "leaks" in the soil plumbing system respectively. Their occurrence interferes with the soils ability to effectively capture and distribute rainfall or irrigation water for plant use. It has been observed as well that, even after extended wet periods, soil water repellency and preferential flow paths recur (Oostindie et al., 2005). Even low levels of repellency can cause reduced infiltration and retention, increased runoff, variable wetting and preferential flow. These lead to, among other things, reduced irrigation efficiency, suboptimal growing conditions and increased water requirements.

The development of water repellency in soil can be detected by a variety of methods, the most common of which is the Water Drop Penetration Time (WDPT) test. There are advantages and disadvantages to the various approaches (Hallett, 2007). To quickly and easily determine the presence of soil water repellency for applied purposes like irrigation management, the WDPT test has many advantages. This method is spelled out in detail in the new Soil Science Society of America publication, Soil Science – Step-by-Step Field Analysis (Ritsema et al., 2008).

Soil surfactants are capable of improving soil hydrological behavior by correcting or preventing water repellency, and reducing and preventing preferential flow. The result is more efficient irrigation, reduced environmental risk from preferential flow and water savings of up to 30% or more. This has been extensively studied and documented in turfgrass management (Cisar et al., 2000; Karnok and Tucker 2002; Park et al., 2004; Dekker et al., 2005; Oostindie et al., 2005; Karcher et al., 2006; Aamlid et al., 2007; Hallet, 2007; Leinauer et al., 2007) and is now being explored in agricultural crops as well (Cook et al., 2005; Speth et al., 2005; Rowland et al., 2007).

Runoff

Runoff of irrigation or rainfall results in a loss of water which is wasteful, raises the risk of pollution and erosion, and increases irrigation requirements. Runoff is increased when water is applied at excessive precipitation rates or when infiltration is reduced. While compaction has long been recognized as a cause of reduced infiltration, soil water repellency is another cause of reduced infiltration and increased runoff. This has been verified in numerous studies (Dekker et al., 2005). And while this consequence has been recognized for some time in the case of severe water repellency, it has more recently been discovered to occur with very low levels of repellency as well (Hallet et al., 2001).

Soil surfactants have been shown to increase infiltration into soils and accordingly reduce runoff significantly. Morgan, Letey and others observed this in early research with surfactants in the 1960's (Morgan et al., 1966). More recent research has documented reductions in runoff on a variety of surfactant treated soils under a variety of slope angles. A 19.4% reduction in runoff on a surfactant treated clayey Crosby soil with a 4% slope was documented by Sepulveda (2004). Oostindie et al. (2005) recorded reduced runoff and increased soil moisture on a water repellent sand in a sloped fairway that had been treated with a soil surfactant. On a loamy sand with an 8% slope, Mitra et al. (2006) found that soil surfactant applications doubled the time to runoff, from 20 minutes to more than 40 minutes, and total runoff was reduced more than 30%. By reducing runoff, soil surfactants increase efficient irrigation, reduce irrigation requirements and lessen the potential for contaminants to enter surface waters or storm water systems.

Infiltration and root zone wetting

Infiltration and root zone wetting are fundamental to effective irrigation and irrigation efficiency. When soils are functioning well, as is still so often expected, infiltration and root zone distribution of applied water will both be fairly uniform. This will result in relatively high distribution uniformity (DU) in the soil as well as on the surface as is generally expected. However, soil water repellency can interfere with infiltration and water distribution in the soil resulting in significant variation in moisture content throughout the root zone (Dekker and Ritsema, 1994; Park et al., 2005). This has been found to be true in many soils such as sand, loam, clay and peat (Dekker et al., 2001; Dekker et al., 2005). Hallett et al. (2004) have also found this to be true even at low, "subcritical" levels of soil water repellency. When infiltration is compromised by soil water repellency, root zone DU will be lower than irrigation DU on the surface, leading to reduced irrigation efficiency.

In addition to reduced efficiency in water distribution in the root zone, the aforementioned preferential flow paths will form. This occurs as the repellent parts of the soil, which are not wetted, become drier and the wettable areas become the channels through which water and solutes are transported (Dekker et al. 2001). As a result, a significant portion of the water and solutes intended for the root zone will bypass it instead (Dekker and Ritsema,1994; Ritsema et al., 2001). This increases waste, irrigation need and the risk of environmental contamination by solutes reaching groundwater faster than expected.

Since soil surfactants reduce soil water repellency and facilitate wetting, their use in soils with even subcritical water repellency can lead to significant improvements in infiltration and root zone DU. Park et al. (2004), among others, report significantly reduced repellency and improved wettability when surfactants are applied with some regularity. In a very water repellent sand, Oostindie et al (2005) report significantly more consistent moisture levels and, correspondingly much lower coefficients of variation, in surfactant treated soils (average variation 10.4%) compared to adjacent untreated soil during the same period (average variation >50%). Reducing water repellency and increasing soil wettability and root zone moisture distribution uniformity reduces irrigation requirement, preferential flow and associated environmental risk (Oostindie et al., 2005; Park et al., 2005; Karcher et al., 2006; Aamlid et al., 2007) significantly increasing the efficiency of irrigation.

Plant available water

The Irrigation Association definition of irrigation refers to intentional application of water to provide water to plants for crop production or sustained growth (Rochester, 2006a). Plant available water (PAW), the available water located in the root zone, is therefore an important aspect of irrigation management and efficiency. As PAW values for use in irrigation scheduling are calculated from expected soil water holding capacity and plant root zone depth (The Irrigation Association, 2003), the actual behavior of the soil will affect the effectiveness and efficiency of the irrigation events. When PAW is compromised plants do not have access to expected amounts of water with the result that crop quality will suffer and/or excess water will be required.

Soil water repellency reduces actual PAW because it “locks out” part of the soil’s water holding potential. In severe cases it can render soils non-usable for crop production as the soil is unable to accept or hold water necessary for plant growth (Hallett et al., 2001). In less severe cases, because water is not available in parts of the root zone, it can cause reduced plant performance (Cisar et al., 2000; Cook et al., 2005; Leinauer et al., 2007). Unaddressed, this reduced PAW also reduces irrigation efficiency.

The use of soil surfactants to restore soil wettability and increase infiltration, soil water contents and root zone uniformity results in improved soil behavior with regard to PAW. This has been documented by an increasing number of researchers working with a variety of different crops. Significant increases in soil water contents after treatment with surfactant have been documented by many researchers (Karnok and Tucker, 2001; Cook et al., 2005; Mitra, 2005; Oostindie et al., 2005). Improved crop performance with the same or reduced irrigation, indicating improved PAW, has also been reported in turfgrass maintenance by Cisar et al. (2000), Karnok and Tucker (2001), Mitra (2005), Oostindie et al. (2005), and Park et al. (2004, 2005) among others; and by Cook et al. (2005) with potatoes and Rowland et al. (2007) with peanuts. Managing soil behavior to ensure expected levels of PAW is fundamental to achieving efficiency in irrigation.

Water conservation through efficient irrigation

Clearly, efficient irrigation is impossible without well designed, installed, operated and maintained irrigation systems. Nonetheless, it is also true that how water moves in the soil is key to overall irrigation efficiency, crop performance and water conservation. When water movement into and through soils becomes erratic, even the most well designed and managed irrigation system will fall short of expected and desired goals. Consequently, more irrigation is often applied because plants exhibit stress, which increases consumption and reduces the efficiency of the irrigation program. In addition to well designed and operated irrigation systems, water can be conserved by increasing the efficiency of water delivery to the soil through management practices that ensure desirable soil hydrological behavior.

Soil surfactants ensure that soils are wettable so that irrigation applied at appropriate precipitation rates, as well as rain fall, will move quickly and uniformly into soils. An increasing amount of research by scientists of varying disciplines is showing that more effective delivery of water to the root zone, especially where soil water repellency is a factor, can result in very significant reductions in water use or requirements. In turfgrass management, reductions of at least 20% (Kostka et al., 2005; Oostindie et al., 2005) and in some cases more than 50% (Park et al., 2005; Karcher et al., 2006) have been reported. A summary of research in this regard was published by Kostka et al. (2007). The use of soil surfactants allows conservation of water and greater irrigation efficiency.

Conclusion

When soil hydrological behavior is affected by water repellency, efficiency of irrigation declines leading to either increased water consumption to meet plant needs, or reduced “crop” performance. Soil water repellency is more common than previously recognized and, even at very low levels, significantly impacts soil hydrological behavior. Correction or avoidance of soil water repellency keeps soils wettable, improving hydrological behavior and, therefore, irrigation efficiency, crop performance and efficiency of water use.

The development of water repellency can be detected using the Water Drop Penetration Time test. Once detected, water repellency can be managed with the use of soil surfactants to improve efficiency of irrigation. Although scientists do not yet know exactly why, soils that have a critical water content threshold for water repellency seem to remain susceptible to water repellency below that moisture level, even after long wet periods or remediation efforts. Therefore, especially during drier periods, water repellency can be expected to recur in areas where it has been previously detected.

Soil surfactants are a reliable management technology for restoration for reducing, and possibly avoiding development of, water repellency and associated preferential flow. The result is maintenance or restoration of soil wettability and improved infiltration and root zone distribution uniformity. Research worldwide is increasingly indicating that certain soil surfactant formulations significantly improve soil hydrological behavior allowing more efficient irrigation, improvement in crop response and significant reductions in water consumption. Further research regarding the relationship between managing soil hydrological behavior with surfactants and irrigation system design and operation holds promise for allowing irrigators to achieve new levels of irrigation and water use efficiency in irrigated crop and landscape systems.

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