Infiltration Characteristics of Bare Soil under Sequential Water Application Events

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Abstract. *The marked reduction in infiltration rate caused by formation of a soil surface seal is a well known phenomenon but often ignored in infiltration models. The effect sequential water application events have on infiltration rate and soil surface seal formation has rarely been investigated. The objective of this study was to investigate the effect sequential water application events have on the infiltration rate of a Portneuf silt loam soil with and without water droplet impact. The Portneuf silt loam soil developed a soil surface seal that reduced infiltration rate both with and without droplet impact on the bare soil surface. When the soil surface was protected during the first rainfall event, drying the soil did not increase infiltration rate for subsequent rainfall events when the soil surface was protected, but drying did increase infiltration when the soil was unprotected in the first rainfall event. Final infiltration rate was inversely related to specific power of the simulated rainfall. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. Given that the Portneuf silt loam soil is extremely vulnerable to surface seal development with little difference in final infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth.*

Keywords. Sprinkler irrigation, Center pivot, Infiltration, Runoff, Soil surface seal, Droplet kinetic energy.

Introduction

The marked reduction in water infiltration rate of bare soils caused by raindrop impact has been recognized for over a century and has been extensively documented and studied over the past 70 years. The decrease in water infiltration rate of soils under droplet impact was first investigated by Duley (1939), Borst and Woodburn (1942), and Ellison (1945). McIntyre (1958) was the first to measure saturated hydraulic conductivity of soil surface seals created by raindrop impact. He found that the saturated hydraulic conductivity of the formed seals was a function of the soil, applied water depth and application rate. Seal saturated hydraulic conductivity was found to be 2 to 3 orders of magnitude less than for the underlying soil. Moldenhauer and Long (1964) found that infiltration rate was a function of soil properties, kinetic energy of the water drops and application intensity. They found that time for runoff to begin was a function of cumulative kinetic energy applied to the soil. Studies of Edwards (1967), Mannering (1967), Sharma (1980), Baumhardt (1985), Mahamad (1985), Thompson and James (1985), Betzalel et al. (1995) have demonstrated the influence droplet kinetic energy and water application rate has on infiltration rate into bare soils.

Nearly all of the research related to soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; Silva, 2006). Soil surface seal formation in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard. Runoff under center pivot sprinkler irrigation is a well recognized problem (Undersander et al., 1985; DeBoer et al., 1992; Hasheminia, 1994; Ben-Hur et al., 1995, Silva, 2006), but is normally unseen because runoff often infiltrates before exiting the field boundary as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field.

Studies' documenting the significant effect water droplet impact has on the infiltration rate of bare soils led to the development of empirical models representing the transient nature of the saturated hydraulic conductivity of soil surface seals during a rainfall event. In general, these models expressed hydraulic resistance or saturated conductivity of the seal layer as an exponential decay function of time or applied droplet kinetic energy (Farrell and Larsen (1972); van Doren and Allmaras (1978); Linden (1979); Moore, et al. (1981); Brakensiek and Rawls (1983); Bosch and Onstad (1988); Baumhardt et al. (1990)). These models all include three or more parameters that need to be estimated from simulated rainfall infiltration experiments. These parameters have not been related to bulk soil properties to expand the models to other soils in general with the exception of Brakesiek and Rawls (1983) who developed a crust factor to account for crusted soil infiltration with the Green and Ampt (1911) infiltration model.

Despite nearly 70 years of research on the reduction of water infiltration rate of bare soils caused by raindrop impact, nearly all studies have been limited to a single water application event. Little is known about how infiltration rate changes under sequential water application events of raindrop impact on bare soil. The objective of this study was to investigate changes in water infiltration rate under sequential water application events with different water droplet kinetic energies and water application rates.

Methods and Materials

Laboratory rainfall simulator tests were conducted on a Portneuf silt loam soil with particle size fractions of 14% sand, 65% silt and 21% clay determined using hydrometer method. Rainfall was simulated on the soil packed in a box measuring 0.3 m wide, 0.45 m deep and 1.0 m long placed on 5% slope. The soil was air dried, sieved and packed to a bulk density of 1.3 to 1.4 Mg m^{-1}. The rainfall simulator produced droplets with kinetic energies per unit volume of 3.9 and 8.5 J m^{-2} mm^{-1} using fall heights of 0.3 and 1.0 m, respectively. Zero kinetic energy water application was simulated by placing an evaporative cooler pad over a screen with 7.6 mm square opening suspended 20 mm above the soil surface. Water application rates ranged from 90 to 120 mm h^{-1}. Rainfall simulation duration ranged from 30 to 60 min. Runoff volume was measured by continuously recording the cumulative weight of runoff water. Total infiltrated volume was determined by weighing the soil box immediately before and after rainfall simulation. Water application rate was calculated by dividing the sum of infiltrated and runoff volumes by time of application. Infiltration rate was calculated as the difference between water application rate and runoff rate, neglecting soil surface storage.

The soil was dried between water application events by placing the runoff box in a walk-in forced air drying room with a temperature of 60 ºC for 5 to 10 days. Soil moisture in the top 20 cm of soil was measured with TDR (TDR 100, Campbell Scientific, Inc. Logan, UT)

Specific power (W m^{-2}) also termed kinetic energy flux density (Thompson and James, 1985) can be calculated for a rainfall simulator with constant application rate and drop kinetic energy as:

$$SP = \frac{KE_d \cdot R}{3600} \tag{1}$$

where KE_d is droplet kinetic energy per unit volume (J m^{-2} mm^{-1}) and R is application rate (mm hr^{-1}).

Results and Discussion

Infiltration rate for the Portneuf silt loam soil under zero specific power (protected soil surface) with two sequential (fig. 1A) and three sequential (fig. 1B) rainfall events indicates that infiltration rate decreases after the first rainfall event even in the absence of raindrop impact. Final infiltration rate was approximately 38 mm hr^{-1} for the first application event and approximately 20 mm hr^{-1} for subsequent application events. Reduced infiltration rate with subsequent water application events suggests the formation of a soil surface seal without raindrop impact. Physical (nonbiological) soil surface seals can be caused by a number of physical processes. Soil surface seals result from deposition of dispersed soil particles within soil surface pores which subsequently clog pores creating a low permeability layer at the soil surface (Assouline, 2004). Most commonly, the presence of dispersed soil particles is due to the breakdown of soil aggregates by raindrop impacts and/or slaking processes but can be due to deposition of dispersed soil particles carried by overland flow. Soil surface seals are generally classified as either structural or sedimentary features (Neave and Rayburg;, 2007; Assouline, 2004). Structural seals form in association with raindrop impact on bare soils while sedimentary seals result from lateral redistribution of sediment by runoff or wind and does not require direct soil impact by rainfall (Neave and Rayburg; 2007). The apparent soil surface seal leading to a reduction in infiltration rate for the second and third rainfall events with zero specific power on the Portneuf silt loam soil are sedimentary in nature. Since the soil surface is completely protected, the source of soil particles forming the surface seal are from slaking of soil surface aggregates under saturated conditions, which are subsequently redistributed by runoff. Soil aggregate structure is greatly reduced when soil water approaches saturation (Francis and Cruse 1983). Under unsaturated soil surface conditions (no runoff) surface aggregate strength would be greater and soil surface seal development would likely be reduced or absent. Further research is necessary to investigate this aspect.

To investigate the influence of droplet impact on soil surface seal development and infiltration rate of the Portneuf silt loam soil, two separate tests with simulated rainfall with specific power levels of 0.12 W m^{-2} and 0.27 W m^{-2} were applied followed by zero specific power water application after the soil had dried, figures 2A and 2B, respectively. For the first rainfall event with 0.12 W m^{-2} specific power applied final infiltration rate was approximately 33 mm hr^{-1} and for a first rainfall event with specific power of 0.27 W m^{-2} the final infiltration rate was approximately 8 mm hr^{-1}. The higher specific power greatly reduced final infiltration rate. In both tests, infiltration rate at the end of the second zero specific power water application event was higher than at the end of the first rainfall event when drops impacted the soil surface. This indicates that the effect of the soil surface seal on infiltration was reduced by drying. The soil surface cracked when dried which apparently fractured the soil surface seal, increasing infiltration rate. This is in contrast to the situation where zero specific power was applied with multiple water application events and infiltration rate was lower for the second water application event (figs. 1A and 1B). With zero specific power water application, drying the soil surface did not increase infiltration rate. Apparently, the soil surface seal formed under zero specific power is more permanent than that developed under water droplet impact.

Infiltration rate of the Portneuf silt loam soil under multiple rainfall events with a specific power of 0.25 W m^{-2} (fig. 3) decreases rapidly to and returns to a relatively low final rate of approximately 12 mm hr^{-1} during each subsequent application event. Even though the soil was dried between rainfall events, drying had little effect on infiltration rate after 10 minutes with nearly the same infiltration rate at the end of each rainfall event. Apparently, cracking of the soil surface with drying had little lasting effect

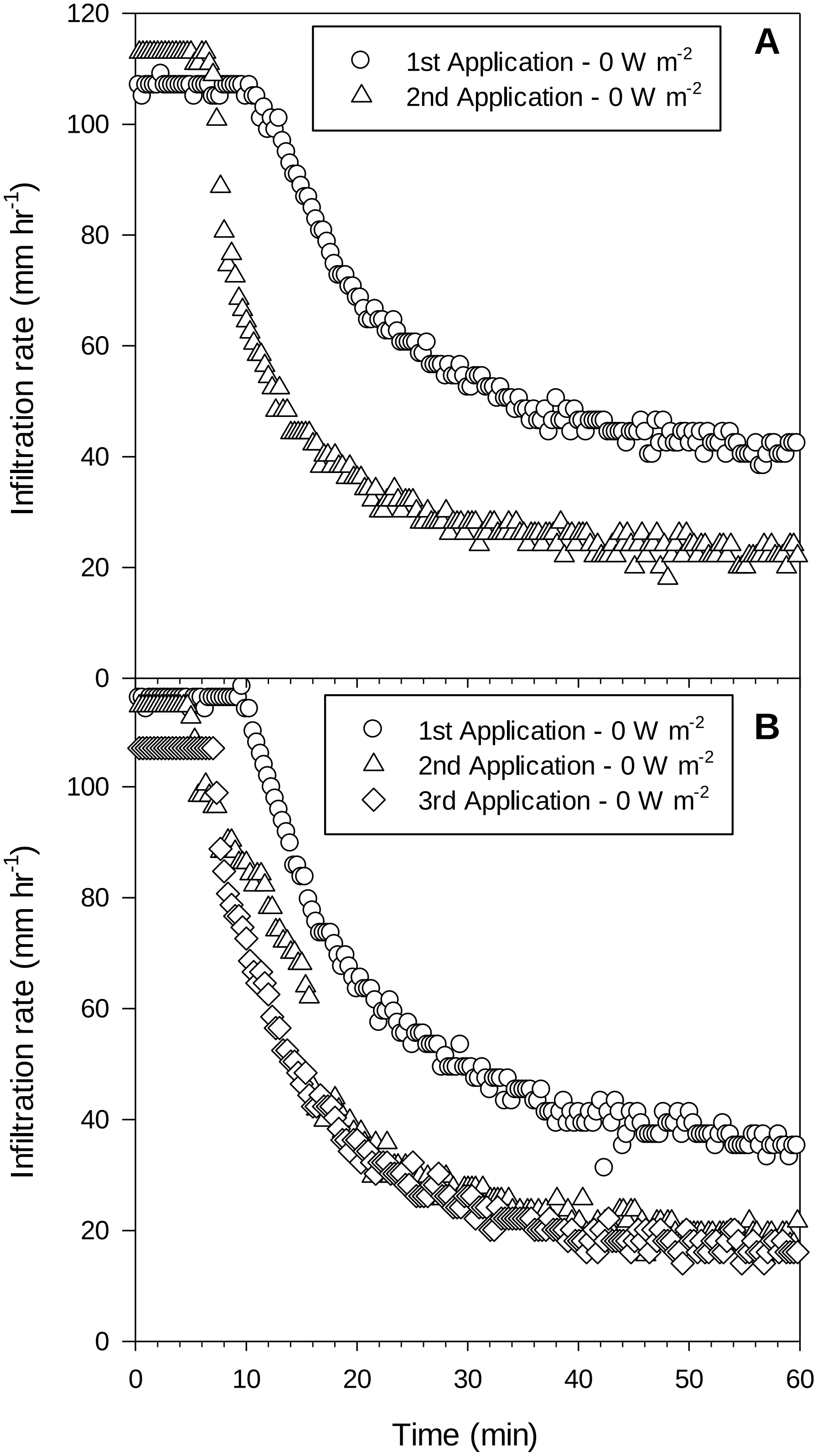

Figure 1. Infiltration rate of Portneuf silt loam soil under two (A) and three (B) sequential simulated rainfall events with zero specific power (soil surface protected).

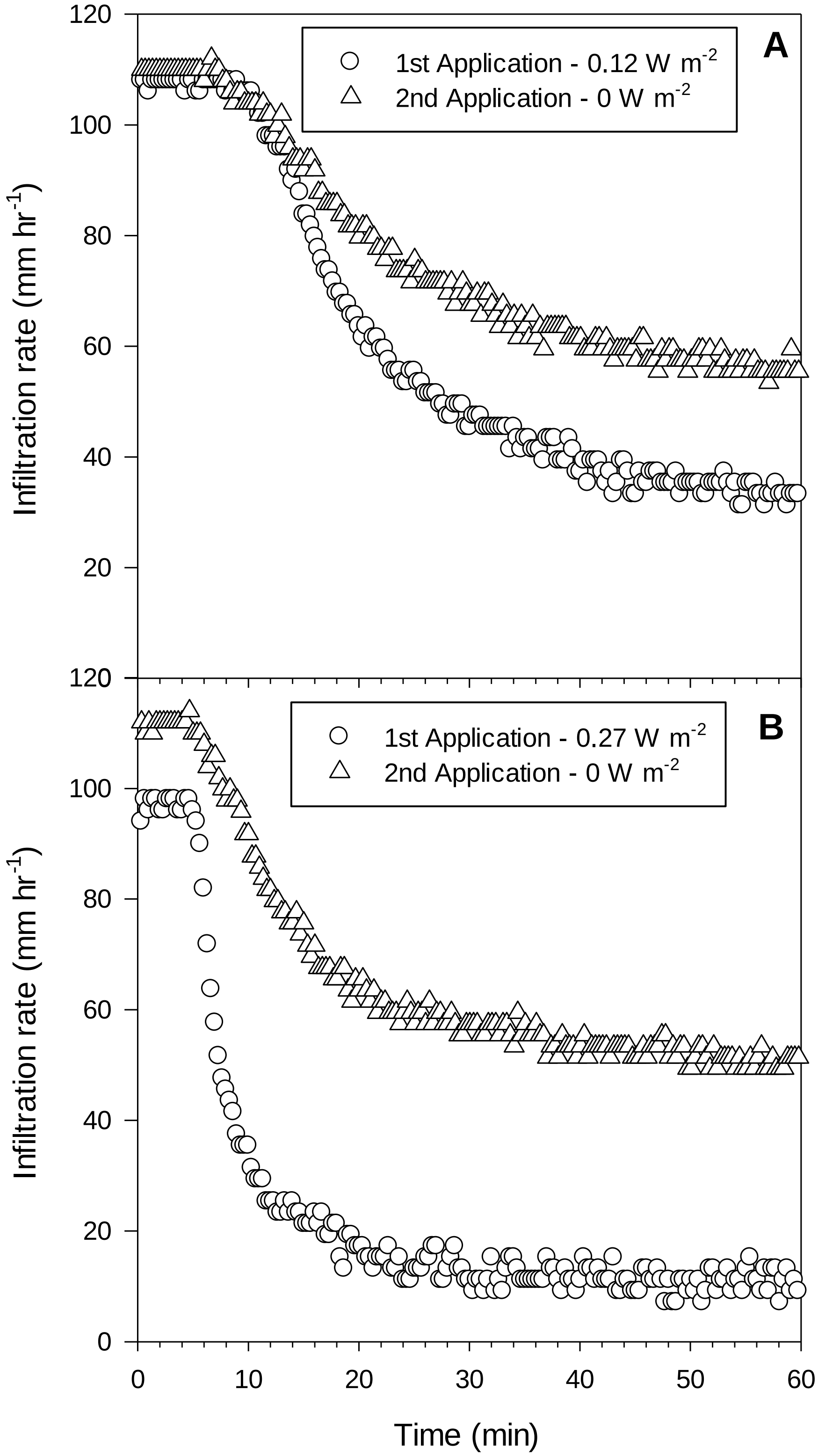

Figure 2. Infiltration rate of Portneuf silt loam for sequential simulated rainfall events of 0.12 W m^{-2} specific power on bare soil followed by protected soil surface (A) and 0.27 W m^{-2} specific power on bare soil followed by protected soil surface (B).

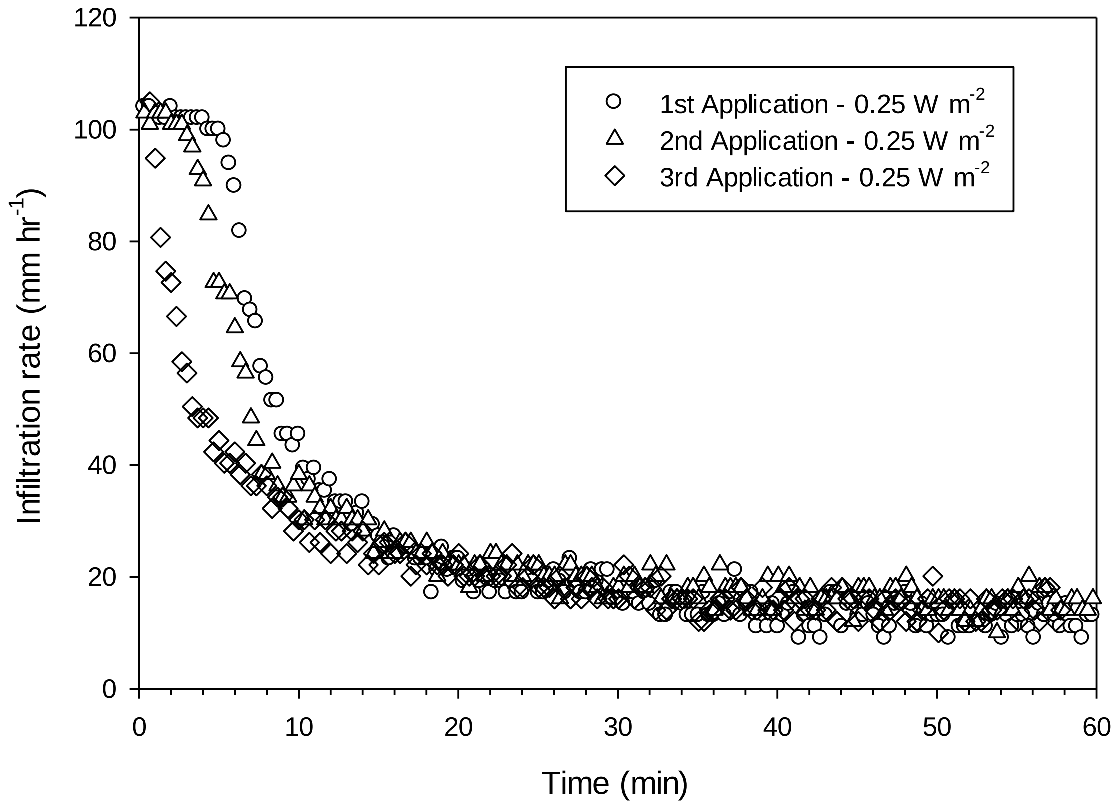

Figure 3. Infiltration rate of Portneuf silt loam soil for three sequential simulated rainfall events on bare soil with 0.25 W m^{-2} of specific power.

when water droplets impacted the bare soil surface. The time to runoff decreased with each simulated rainfall event (fig. 3) indicating an additive effect to how rapidly the soil surface seal developed with each subsequent rainfall event. The final filtration rate did not continue to decrease with each subsequent rainfall event, which is a common assumption. The final infiltration rate appears to be inversely related to specific power with greater specific power resulting in lower final infiltration rate.

For the Portneuf silt loam soil used in this study, the results indicate a soil surface seal that reduces infiltration rate will develop with sequential water application regardless of whether or not droplets impact the bare soil surface. Drying the soil increased infiltration rate for subsequent water application without droplet impact (zero specific power), but had no effect on infiltration rate for subsequent water application with droplet impact. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. This result is similar to that of Neave and Rayburg (2007) who found no significant difference in runoff between protected and bare soil conditions under sequential simulated rainfall on a sandy loam soil. The implication for center pivot sprinkler irrigation on a Portneuf silt loam soil is that infiltration rate will decrease to less than 20 mm hr^{-1} regardless of the degree of soil surface cover. The final infiltration rate will depend upon the specific power of the sprinkler used. Given that a soil surface seal is going to develop with little difference in infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth. Sprinklers with large wetted diameters also have large drops resulting in relatively high kinetic energy per unit drop volume but not necessarily the greatest specific power (King and Bjorneberg, 2012). This combined with the relatively limited range in specific power of center pivot makes sprinkler with large wetted diameters the best choice for the Portneuf silt loam soil.

Conclusions

The Portneuf silt loam soil developed a soil surface seal that reduced infiltration rate both with and without droplet impact on the bare soil surface. When the soil surface was protected during the first rainfall event, drying the soil did not increase infiltration rate for subsequent rainfall events when the soil surface was protected, but drying did increase infiltration when the soil was unprotected in the first rainfall event. For the Portneuf silt loam soil, sedimentary soil surface seals appear to be more stable than structural soil surface seals. Final infiltration rate was essentially constant between sequential simulated rainfall events when droplets impacted the bare soil surface. Final infiltration rate was inversely related to specific power of the simulated rainfall. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. Given that the Portneuf silt loam soil is extremely vulnerable to surface seal development with little difference in final infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth.

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