CHARACTERIZING DROPLET KINETIC ENERGY APPLIED BY MOVING SPRAY-PLATE CENTER-PIVOT IRRIGATION SPRINKLERS

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ABSTRACT. *The kinetic energy of discrete water drops impacting a bare soil surface is generally observed to lead to a drastic reduction in water infiltration rate due to soil surface seal formation. Under center-pivot sprinkler irrigation, kinetic energy transferred to the soil prior to crop canopy development can have a substantial effect on seasonal runoff and soil erosion. In the design of center-pivot irrigation systems, selection of sprinklers with minimum applied kinetic energy could potentially minimize the seasonal runoff and erosion hazard. The size and velocity of drops from five common center-pivot sprinklers with flow rates of approximately 43 L min*$^{-1}$ *were measured using a laser in the laboratory. The data were used to evaluate various approaches to characterize the kinetic energy transferred to the soil by each of the five sprinklers on a center-pivot irrigation system lateral with 2.5 m spacing between sprinklers. Specific power represents the rate at which kinetic energy per unit area is transferred to the soil as a function of distance from a sprinkler and is analogous to a sprinkler radial water application rate distribution. Specific power was used to estimate actual kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers equally spaced along a center-pivot lateral. Kinetic energy of irrigation sprinklers has traditionally been characterized using area-weighted kinetic energy per unit drop volume. This method heavily favors the largest drops, which travel the farthest from the sprinkler and have the largest kinetic energy. Sprinkler kinetic energy per unit volume of sprinkler discharge was not correlated to actual kinetic energy transferred to the soil by the sprinklers. However, kinetic energy per unit volume of sprinkler discharge was found to be more representative than kinetic energy per unit drop volume. Measured runoff and sediment yield of the sprinklers from a previous study were compared to average specific power. Runoff and erosion appeared to be more dependent on sprinkler type than average specific power. The sprinklers with the lowest runoff and sediment yield had the lowest average specific power. However, there was a substantial increase in runoff and sediment yield with little associated increase in average specific power applied by some sprinklers. The functional difference between sprinklers was the manner in which water drops were distributed over the wetted area with respect to time. Sprinklers that distribute water drops more evenly over the wetted area with respect to time had the highest runoff and sediment yield, and sprinklers that had well defined rotating streams of water drops had the lowest runoff and sediment yield, largely independent of average specific power applied to the soil.*

Keywords. *Center pivot, Infiltration, Kinetic energy, Runoff, Sprinkler irrigation.*

When discrete water drops impact a bare soil surface, a drastic reduction in water infiltration rate is generally observed due to soil surface seal formation. The physical processes of soil surface seal formation are attributed to compaction, aggregate destruction, soil particle detachment, dispersion, and deposition of fine particles in surface pores. These physical processes reduce surface soil porosity and pore size distribution to create a disturbed layer with reduced hydraulic conductivity that expands in size and depth with time (Assouline and Mualem, 1997). The effect that soil surface seal formation has on water infiltration rate has been studied by Agassi et al. (1985, 1994), Thompson and James (1985), Mohammed and Kohl (1987), Ben-Hur et al. (1987), and Assouline and Maulem, (1997). These studies have shown that the kinetic energy of discrete drops impacting a bare soil surface is a primary factor in determining the reduction in water infiltration rate due to soil surface sealing. Much of the research on 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; DeBoer and Chu, 2001; Silva, 2006). Soil surface seal formation leading to a reduction in water infiltration rate in combination with high water application rates under center-pivot sprinkler irrigation exacerbates the potential runoff and erosion hazard.

Soil erosion involves the processes of (1) detachment of soil particle from the soil surface and (2) transport of the soil particles. In interrill erosion, soil particle detachment is caused by drop impact and soil transport is caused by drop splash and runoff sheet flow (Watson and Laflen, 1986). Soil

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particle detachment was found to be related to drop kinetic energy by Ekern (1954), Wischmeier and Smith (1958), Moldenhauer and Long (1964), Bubenzer and Jones (1971), Quansah (1981), Gilley and Finkner (1985), Agassi et al. (1994), and Ben Hur and Lado (2008). Soil detachment is one of the processes contributing to soil surface seal formation. A reduction in infiltration rate due to soil seal formation increases runoff sheet flow and the capacity to transport detached soil particles. The kinetic energy of drops impacting a bare soil surface has a major influence on both runoff and erosion from sprinkler irrigation as well as rainfall.

The influence that kinetic energy applied by center-pivot sprinklers has on infiltration, runoff, and erosion is well known in the center-pivot sprinkler irrigation industry. Over the past two decades, center-pivot sprinkler manufacturers have continued to develop sprinklers that reduce peak water application rates and droplet kinetic energy as a means to sustain water infiltration rates and reduce potential runoff and erosion. Consequently, there are numerous center-pivot sprinkler choices available to the center-pivot sprinkler irrigation system designer and crop producer but limited quantitative information that relates these choices to performance with regard to infiltration, runoff, and erosion. Kincaid (1996) developed a model to estimate kinetic energy per unit drop volume from common sprinkler types as a function of nozzle size and operating pressure for use as a design aid in selecting center-pivot sprinklers. DeBoer (2002) evaluated the kinetic energy per unit drop volume from select moving spray-plate sprinklers for center-pivot irrigation systems and developed a model of kinetic energy as a function of spray-plate type, nozzle size, and operating pressure. Values of kinetic energy per unit drop volume are largely dependent on the drop size characteristics of the sprinklers. Sprinklers with relatively large drop sizes have the highest kinetic energy values, and sprinklers with relatively small drop sizes have the lowest kinetic energy values. The drop size distribution of a sprinkler has a substantial influence on the wetted diameter and application rate distribution profile. In general, sprinklers with relatively small drop sizes have relatively small wetted diameters and result in higher application rates when application rate pattern profiles are overlapped along a center-pivot lateral. Sprinklers with relatively large drop sizes have relatively large wetted diameters and result in lower application rates when application pattern profiles are overlapped along a center-pivot lateral. With regard to runoff and erosion, any benefits associated with lower applied kinetic energy from smaller drops are reduced or eliminated due to the higher application rate, which often exceeds the water infiltration rate of the soil. Consequently, values of kinetic energy per unit drop volume do not identify an optimum sprinkler selection, and thus have not proved useful in center-pivot sprinkler irrigation system design.

King and Bjorneberg (2009) evaluated runoff and erosion from five common center-pivot sprinklers on multiple soils and found significant differences between center-pivot sprinkler types of equal flow rates. Estimated values of kinetic energy per unit drop volume for these sprinklers using the models of Kincaid (1996) and DeBoer (2002) did not correlate with measured runoff or erosion rates. This lack of correlation was unexpected and suggested that kinetic energy per unit drop volume may not represent actual kinetic energy applied by the sprinklers. Determination of kinetic energy applied by overlapping sprinkler application patterns along a center-pivot lateral has not been studied. The objectives of this study were to evaluate the kinetic energy applied to the soil in the center-pivot sprinkler experiments of King and Bjorneberg (2009) and compare the results with single sprinkler kinetic energy per unit drop volume and kinetic energy per unit sprinkler discharge. Runoff and erosion measured by King and Bjorneberg (2009) as related to the rate at which kinetic energy was applied to the soil was investigated.

Methods and Materials

The sprinklers used in this study and corresponding operating pressures and nozzle sizes are listed in table 1. The I-Wob sprinkler (Senninger Irrigation, Inc., Clermont, Fla.) utilizes an oscillating plate with nine grooves of equal geometry to break up the nozzle jet and create discrete water drops. The R3000 sprinklers (Nelson Irrigation Corp., Walla Walla, Wash.) use rotating plates with grooves to break up the nozzle jet and create discrete streams of water leaving the plate edge. The R3000 sprinkler with the brown plate has ten grooves with multiple trajectories angles and widths. The R3000 sprinkler with the red plate has six grooves of equal trajectory angle (12°) and width. Both R3000 sprinklers have plate rotational speeds of 2 to 4 revolutions per minute. The S3000 sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) also uses a rotating plate with grooves to break up the nozzle jet. The rotating plate has six grooves of equal trajectory angle (20°) and width and a rotational speed of 400 to 500 revolutions per minute. The D3000 sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) has a fixed flat plate to break up the nozzle jet into discrete water drops. Sprinkler operating pressures were selected to be representative of field installations on center-pivot sprinkler irrigation systems in southern Idaho. Sprinkler nozzle sizes were selected to provide nearly equal flow rates at the given operating pressures based on manufacturer data. Sprinkler flow rate is representative of that found near the end of the lateral on 390 m long center-pivot sprinkler irrigation systems in southern Idaho.

Drop sizes and drop velocities from the sprinklers were measured using a Thies Clima Laser Precipitation Monitor (TCLPM, Adolf Thies GmbH & Co. KG, Göttingen, Germany) (King et al., 2010). The tests were conducted in the laboratory with no wind. Drop size and velocity measurements were collected at 1 m increments from the sprinkler. A minimum of 10,000 drops were measured at each measurement location except at the most distal radial location, where a minimum of 4,000 drops were measured to save time. Sprinklers were positioned on the end of a drop tube with nozzle discharge directed vertically downward 0.8 m above the laser beam of the TCLPM. Pressure regulators with nominal pres–

Table 1. Sprinklers and corresponding operating pressure, nozzle diameter and flow rate used in study.

Sprinkler	Pressure (kPa)	Nozzle Dia. (mm)	Flow Rate[a] (L min^{-1})
Senninger I-Wob standard 9-groove plate	103	8.33	43.2
Nelson R3000 brown plate	138	7.54	42.7
Nelson R3000 red plate	138	7.54	42.7
Nelson S3000 purple plate	103	8.14	43.5
Nelson D3000 flat plate	103	8.14	43.5

[a] Manufacturer's published data.

sure ratings for the test condition were used to control pressure at the base of the sprinkler. A pressure gauge located between the pressure regulator and sprinkler base was used to monitor pressure during a test. Pressure values were within ±7 kPa of the nominal pressure rating. Specific details of the experimental methods are provided by King et al. (2010).

Radial application rate distributions for the sprinklers were also determined in the laboratory. Catch cans, 150 mm in diameter and 180 mm tall spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. Sprinkler height was 0.8 m above can opening. The duration of each test was 30 to 60 min. Water collected in each can was measured using a graduated cylinder. Application rate was calculated based on the diameter of the catch cans and the duration of each test.

Area-weighted kinetic energy per unit drop volume, KE_d (J L^{-1}), of each sprinkler was computed as:

$$KE_d = \frac{\sum_{i=1}^{R}\left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^3}{6}}\right)A_i}{\sum_{i=1}^{R}A_i} \quad (1)$$

where R is the number of radial measurement locations, ND_i is the number of drops measured at the ith radial location, ρ_ω is the mass density of water (kg m^{-3}), d_j is the measured diameter (m) of the jth drop, v_j is the measured velocity (m s^{-1}) of the jth drop, and A_i is the wetted area (m^2) associated with ith radial location. The resulting value represents the average kinetic energy per liter of drop volume applied over the wetted area.

Application volume weighted kinetic energy per unit drop volume, KE_v (J L^{-1}), of each sprinkler was computed as:

$$KE_v = \frac{\sum_{i=1}^{R}\left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^3}{6}}\right)A_i \cdot AR_i}{\sum_{i=1}^{R}A_i \cdot AR_i} \quad (2)$$

where AR_i is sprinkler application rate (mm h^{-1}) associated with the ith radial location. The resulting value represents the average kinetic energy per liter of sprinkler discharge applied over the wetted area and accounts for relative differences in drop volume applied with distance from the sprinkler.

The specific power, SP (W m^{-2}), as a function of radial measurement location for each sprinkler was computed as:

$$SP_i = \left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^3}{6}}\right)\cdot\frac{AR_i}{3600} \quad (3)$$

SP represents the time derivative of kinetic energy per unit area, i.e., the rate at which kinetic energy is transferred to the soil surface as a function of radial distance from the sprinkler. SP is sometimes referred to as droplet energy flux (Thompson and James, 1985). A sprinkler radial SP distribution is analogous to a sprinkler radial water application rate distribution. The depth of water applied by a center-pivot sprinkler irrigation system can be determined by integrating the composite overlapped sprinkler application rate distribution perpendicular to the sprinkler lateral with respect to time. Similarly, the kinetic energy applied by a center-pivot irrigation system can be determined by integrating the composite overlapped sprinkler SP distribution perpendicular to the sprinkler lateral with respect to time.

A sprinkler overlap model written in Visual Basic was used to compute the composite water application rate distribution using a 0.3 m distance increment perpendicular to the sprinkler lateral. The sprinkler application rate distributions determined in the laboratory were used in the sprinkler overlap model. The sprinkler application rate distributions were interpolated to 0.3 m distance increments using cubic spline interpolation between catch can measurements. The modeled sprinkler spacing along the lateral was 2.5 m.

Water application depth was determined by numerically integrating the composite sprinkler application rate distribution perpendicular to the sprinkler lateral with time. The time required by the sprinkler lateral to pass over a location and apply 25 mm of water was numerically determined by adjusting the integration time period (sprinkler lateral travel speed).

The sprinkler overlap model was also used to compute the composite SP distribution perpendicular to the sprinkler lateral with time. The SP distribution was determined at 0.3 m increments based on cubic spline interpolation of the SP_i at each ith radial measurement location (eq. 3). The kinetic energy applied by 25 mm of water application was determined by numerically integrating the composite SP distribution perpendicular to the sprinkler lateral using the same time period required to apply 25 mm of water. Applied kinetic energy per unit volume of water application, KE_a (J m^{-2} mm^{-1}), was determined by dividing the total applied kinetic energy by the depth of water application (25 mm).

Results and Discussion

Measured drop size distributions for the five high flow rate sprinklers used in the study are shown in figure 1. The drop size distribution of the D3000 sprinkler had the smallest range in drop size and the smallest maximum drop size (approx. 3.0 mm) of five sprinklers used in the study. Approximately 90% of the applied water volume (d_{90}) was from drops less than 2.0 mm in diameter. The I-Wob sprinkler had the largest range in drop size with a maximum drop diameter of approximately 5.5 mm. The drop size distributions of the R3000 red plate and S3000 sprinklers were very similar to each other, as was expected since both use 6-groove moving spray-plates. The d_{30} through d_{80} drop sizes of the R3000 red plate sprinkler were slightly smaller than those of the S3000 sprinkler. This was largely due to the higher pressure used with the R3000 red plate sprinkler. This outcome was unexpected because the S3000 sprinkler is generally considered to provide smaller drops that are less destructive to the soil

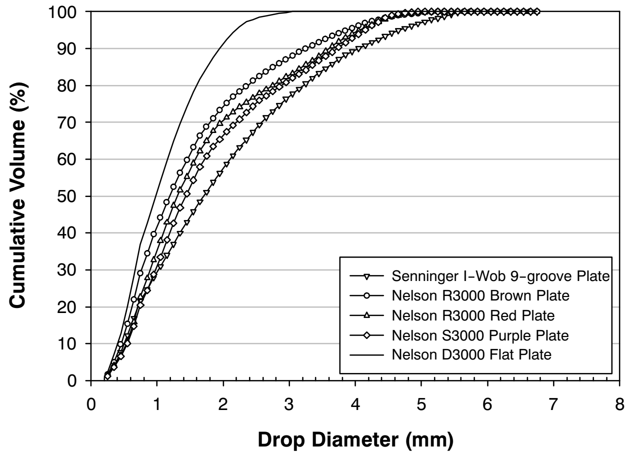

Figure 1. Measured drop size distributions for each of the five sprinklers used in study.

surface structure with lower operating pressure. The R3000 brown plate sprinkler had a range in drop size similar to the R3000 red plate and S3000 sprinklers. Surprisingly, though, the d_{10} through d_{98} drop sizes of the R3000 brown plate sprinkler were smaller than for the R3000 red plate, S3000, and I-Wob sprinklers. This outcome was likely due to the multi-trajectory design of the multi-grooved moving spray-plate, which allows the drop size distribution to be manipulated by design of the individual grooves on the plate. Based solely on measured drop size distributions and the fact that larger drops possess greater kinetic energy, relative ranking of the sprinklers would rank the I-Wob as having the greatest potential destructive effect and the D3000 having the least potential destructive effect, with the remaining sprinklers ranked according to d_{90} drop sizes.

Radial application rate distributions for each of the five sprinklers used in the study are shown in figure 2. The I-Wob and R3000 brown plate sprinklers had the largest wetted radiuses of the five sprinklers, and the D3000 had the smallest wetted radius. The wetted radius of each sprinkler was correlated with the largest drop size of each sprinkler. The I-Wob and R3000 brown plate sprinklers had the largest drop sizes and hence the largest wetted radiuses of the five sprinklers. These sprinklers had about a 1 m greater wetted radius than the S3000 and R3000 red plate sprinklers.

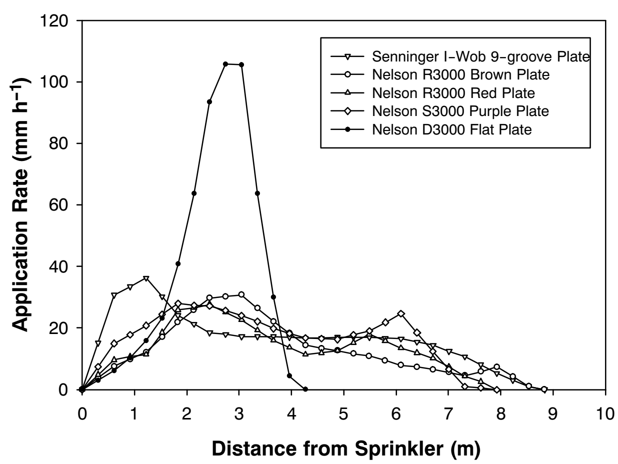

Figure 2. Radial application rate distributions for each of the five sprinklers used in study.

Computed KE_d values for each of the five sprinklers are shown in table 2. Based on KE_d, the I-Wob had the highest kinetic energy, and the D3000 had the lowest. This was expected based on the drop size distributions for the two sprinklers (fig. 1) and the fact that calculation of kinetic energy based on equation 1 is area weighted, which heavily favors the largest drops, which travel the farthest from the sprinkler and have the greatest kinetic energy. The relative ranking of the R3000 brown plate and S3000 sprinklers based on KE_d was essentially reversed from the ranking based on d_{90} drop sizes. The R3000 brown plate sprinkler, which had the smallest d_{10} through d_{95} drop sizes of the three sprinklers, had the largest KE_d value of the three sprinklers. This was due to the area weighting associated with equation 1. Of the three sprinklers, the R3000 brown plate sprinkler had the largest d_{98} to d_{100} drop sizes, which travel farther from the sprinkler (fig. 2) and are heavily weighted even though the largest drops constitute less than 2% of total sprinkler volume. This outcome suggests that area-weighted kinetic energy per unit drop volume is not necessarily a good indicator of kinetic energy transferred to the soil by irrigation sprinklers, but it has traditionally been used to compare relative potential soil surface destructive effect of sprinklers (Kincaid, 1996; DeBoer, 2002).

Computed KE_v values for each of the five sprinklers are also shown in table 2. The relative ranking of the sprinklers from highest to lowest kinetic energy changed between KE_d and KE_v. Based on KE_v, the R3000 red plate sprinkler had the highest kinetic energy, and the R3000 brown plate sprinkler had the lowest kinetic energy. The R3000 red plate sprinkler had the highest KE_v value because of the peak in application rate present at approximately 6 m from the sprinkler (fig. 2). The combination of this peak in application rate multiplied by area (eq. 2) heavily weights the kinetic energy of the relatively large drop size at 6 m and resulted in the greatest value of KE_v. In general, sprinklers that have a peak in application rate near the outer radial extent will have higher values of KE_v than sprinklers that have decreasing application with radial distance. The D3000 sprinkler, which had a peak in application rate at its outer radial extent (fig. 2), does not have the lowest value of KE_v despite having the smallest drop size distribution. This outcome contradicts conventional wisdom that a sprinkler with smaller drop sizes results in less kinetic energy transferred to the soil. The relative ranking of sprinklers according to KE_v rather than KE_d are reflective of the drop sizes associated with sprinkler discharge and should provide a method of characterizing sprinklers that is directly related to the kinetic energy transferred to the soil.

Computed SP values for each of the five sprinklers as a function of radial distance from the sprinkler are shown in figure 3. The D3000 sprinkler had the greatest peak SP value of all the sprinklers, approximately five times that of the other

Table 2. Computed kinetic energy per unit drop volume (KE_d), kinetic energy per unit sprinkler discharge (KE_v), and applied kinetic energy per unit irrigation depth (KE_a) for each sprinkler used in study.

Sprinkler	KE_d (J L^{-1})	KE_v (J L^{-1})	KE_a (J m^{-2} mm^{-1})
Senninger I-Wob standard 9-groove plate	13.7	12.7	11.0
Nelson R3000 brown plate	13.5	11.9	9.7
Nelson R3000 red plate	13.3	13.2	12.2
Nelson S3000 purple plate	12.2	12.0	10.9
Nelson D3000 flat plate	8.6	12.1	11.8

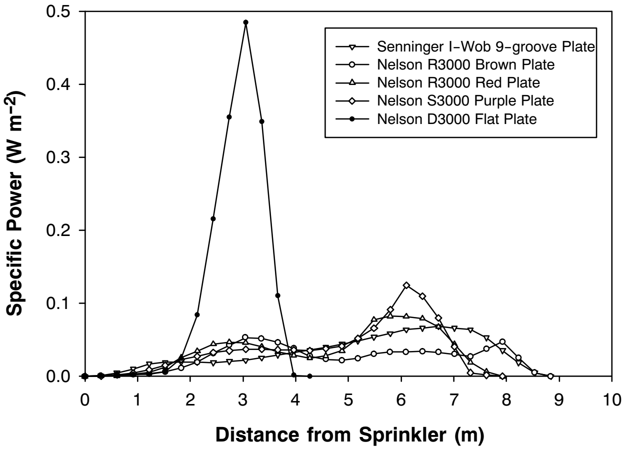

Figure 3. Specific power as a function of radial distance from sprinkler for each of the five sprinklers used in study.

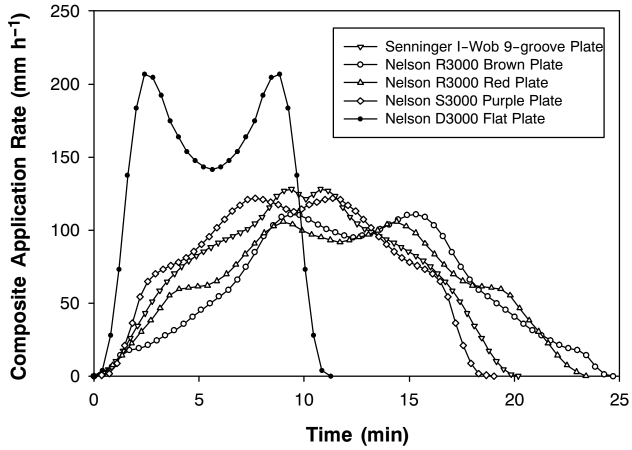

Figure 4. Composite application rate profile perpendicular to sprinkler lateral for each of the five sprinklers used in the study. Sprinkler spacing along the lateral is 2.5 m. Time duration of each application rate pattern represents the time required for the irrigation system to apply an irrigation depth of 25 mm.

sprinklers. This outcome was not expected given that the D3000 sprinkler had the smallest drop sizes of all the five sprinklers. This outcome demonstrates that despite the relatively small drop sizes of the D3000 sprinkler, kinetic energy is transferred to the soil surface at a relatively high rate due to the relatively small wetted radius of the sprinkler. If peak specific power is a primary factor in soil surface seal formation and sheet erosion, then the D3000 sprinkler would not be the sprinkler of choice. Thompson and James (1985) and Mohammed and Kohl (1987) found that as specific power increased (constant rate), water infiltrated prior to ponding decreased, indicating that peak specific power maybe a primary factor in soil surface seal formation.

Composite water application rate distributions computed by the sprinkler overlap model are shown in figure 4 for each of the five sprinklers used in the study. The composite water application rate distribution shown in figure 4 is an average rate between adjacent sprinklers spaced 2.5 m along the lateral. The horizontal axis in figure 4 is time rather than distance and represents time for the center-pivot sprinkler lateral to pass over a fixed location. The area under each composite application rate distribution represents 25 mm of water application. Time average composite water application rates for the five sprinklers are given in table 3. The R3000 brown plate sprinkler had the lowest average composite water application rate, and the D3000 sprinkler had the highest. The average composite water application rate of each sprinkler is inversely related to sprinkler wetted radius since the flow rates of the sprinklers (based on manufacturer's published data) were nearly equal and sprinkler spacing along the lateral was equal.

Composite specific power distributions computed by the sprinkler overlap model using a 2.5 m sprinkler spacing are shown in figure 5 for each of the five sprinklers used in the study. The composite specific power shown in figure 5 is average specific power between adjacent sprinklers along the lateral. The horizontal axis in figure 5 is time and identical to that of figure 4 for each sprinkler. The area under each composite specific power distribution represents the total kinetic energy applied per unit area (J m^{-2}) for an irrigation application depth of 25 mm. The total kinetic energy applied by each sprinkler with 25 mm of water application is included in the legend of figure 5 for reference. Total kinetic energy per unit depth of water application, KE_a (J m^{-2} mm^{-1}), is shown in table 2 for each sprinkler. Total kinetic energy per unit depth of water application in units of J m^{-2} mm^{-1} is used because it is a more intuitive unit of measure than J L^{-1} but is numerically equivalent to kinetic energy per unit volume applied (J L^{-1}) (1 mm of water over 1 m^{2} equals 1 L).

Based on kinetic energy per unit depth of water application (KE_a in table 2), the relative ranking of the sprinklers from highest to lowest kinetic energy was R3000 red plate,

Table 3. Average composite water application rate and average composite specific power computed by sprinkler overlap program for each sprinkler used in study.

Sprinkler	Application Rate (mm h^{-1})	Specific Power (W m^{-2})
Senninger I-Wob standard 9-groove plate	73.3	0.224
Nelson R3000 brown plate	59.5	0.161
Nelson R3000 red plate	63.6	0.215
Nelson S3000 purple plate	77.2	0.234
Nelson D3000 flat plate	129.7	0.425

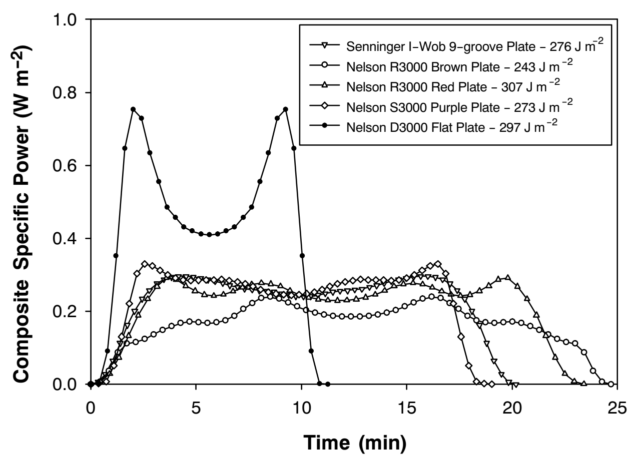

Figure 5. Composite specific power application profile perpendicular to sprinkler lateral for each of the five sprinklers used in the study. Sprinkler spacing along the lateral is 2.5 m. Time duration of each application curve represents the time required for the irrigation system to apply an irrigation depth of 25 mm. The total kinetic energy transferred to bare soil with an application depth of 25 mm for each sprinkler is given in the legend.

D3000, I-Wob, S3000, and R3000 brown plate, respectively. This ranking was similar to the ranking based on KE_v, as the R3000 red plate sprinkler had the greatest kinetic energy applied and the R3000 brown plate sprinkler had the lowest kinetic energy applied. It was unexpected these two sprinklers, which are hydraulically very similar (only different plate design), would apply the highest and lowest kinetic energy of the five sprinklers used in the study. The R3000 red plate sprinkler did not have the largest d_{20} through d_{98} drop sizes but yet had the highest kinetic energy applied of the five sprinklers. Another unexpected outcome was that the D3000 sprinkler with the smallest drop sizes would apply the second highest kinetic energy of the five sprinklers. This outcome is contrary to conventional thought that center-pivot sprinklers with small drop sizes transfer the least kinetic energy to the bare soil surface. This conventional thought follows from characterization of sprinkler kinetic energy based on equation 1 and the relatively small drop sizes of the D3000 sprinkler.

The relationship between average composite water application rate and average composite specific power for the five sprinklers is shown in figure 6. There is a good linear relationship between the two average composite values, with $R^2 = 0.98$. This relationship was expected given that specific power is linearly related to sprinkler application rate (eq. 3). The significance of the relationship shown in figure 6 is that efforts by center-pivot sprinkler manufacturers to develop sprinklers with greater wetted radius to reduce composite water application rates has also reduced specific power applied. The relationship also shows that some relatively large drops from center-pivot sprinklers that are needed to increase wetted radius and reduce composite application rate do not necessarily result in greater transfer of kinetic energy to the soil. Average composite specific power is based on the sum of drop size classes and not just a single drop size. Thus, if there are few large droplets, then the overall kinetic energy applied will not be affected.

The relative ranking of the sprinklers based on mean volume drop size (d_{50}) and the various sprinkler kinetic energy parameters is summarized in table 4. Each parameter listed in table 4 results in a different relative ranking between sprinklers. Mean volume drop, KE_d, and KE_v are not correlated with applied kinetic energy (KE_a) and are therefore not suitable parameters for characterizing kinetic energy transferred to the soil by the sprinklers. Correlations between average composite specific power and KE_a and runoff and soil erosion from sprinkler irrigation need to be investigated to determine which parameter best represents the effect that sprinkler drops have on soil surface sealing and soil particle detachment and transport.

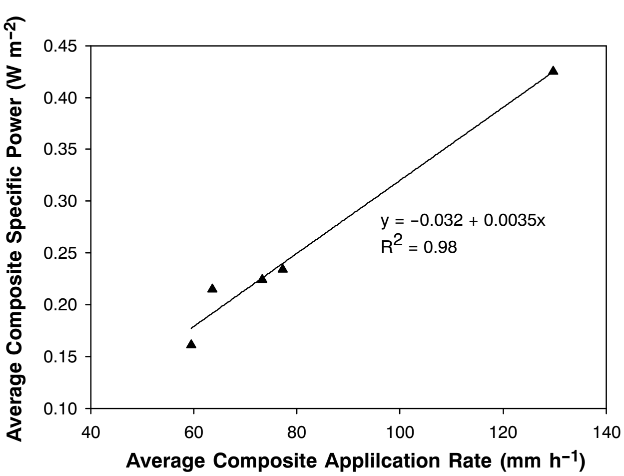

Figure 6. Relationship between average composite application rate and average composite specific power for the five sprinklers used in the study.

Table 4. Relative ranking of sprinklers based on d_{50} drop size and kinetic energy parameters. Ranking is from highest to lowest parameter value, with 1 being the highest.

Sprinkler	d_{50}	KE_d	KE_v	KE_a	SP
Senninger I-Wob standard 9-groove plate	1	1	2	3	3
Nelson R3000 brown plate	4	2	5	5	5
Nelson R3000 red plate	3	3	1	1	4
Nelson S3000 purple plate	2	4	4	4	2
Nelson D3000 flat plate	5	5	3	2	1

Percent runoff averaged across three soils measured by King and Bjorneberg (2009) for four of the sprinklers used in this study is shown in figure 7 as a function of average composite specific power applied (table 3). Runoff was from 1 m wide × 2 m long plots on a 5% slope with 25 mm of water application on freshly tilled bare soil. Percent runoff for a freshly cultivated bare loam soil after 20 min of rainfall simulation with varying levels of applied specific power adapted from Mohammed and Kohl (1987) is also shown in figure 7. Runoff plot size was 1 m square with a 2% slope. The rainfall simulator used multiple VeeJet nozzles (Spraying System Co., Wheaton, Ill.) to obtain a wide range in specific power. There is a good linear relationship ($R^2 = 0.93$) between percent runoff and applied specific power for the data of Mohammed and Kohl (1987), suggesting that a similar relationship may exist for center-pivot sprinklers. Percent runoff measured by King and Bjorneberg (2009) for three of the four sprinklers used in this study plot reasonably close to the regression line for the Mohammed and Kohl (1987) runoff data. Direct comparison of the two data sets is not possible due to different soils, slopes, and time distributions of specific power application. In addition, specific power was constant with time for the Mohammed and Kohl (1987) data but varied with time (fig. 5) for the study by King and Bjorneberg (2009). Runoff could be influenced by drop size distribution, which likely differs between data sets even though specific power calculated using equation 3 does not differentiate between drop size distributions. Additional research is needed to determine if differing drop size distributions with equivalent specific power affects runoff.

Sediment loss per unit depth of water applied (sediment yield) measured by King and Bjorneberg (2009) is shown in figure 8 as a function of average composite specific power applied (table 3). Sediment yield for a tilled bare silt loam soil for 30 min rainfall simulation following initiation of runoff for varying levels of applied specific power, adapted from Thompson et al. (2001), is also shown in figure 8. Thompson et al. (2001) used an indoor rainfall tower that had drop formers to simulate rainfall. Plot size was 1 m long × 0.3 m wide with a 2% slope. There is an excellent linear relationship ($R^2 = 0.99$) between sediment yield and applied specific power for the data of Thompson et al. (2001), suggesting that a similar relationship may exist for center-pivot sprinklers. Sediment yield measured by King and Bjorneberg (2009) for one of the sprinklers used in this study plots near the regression line for the data of Thompson et al. (2001), and sediment

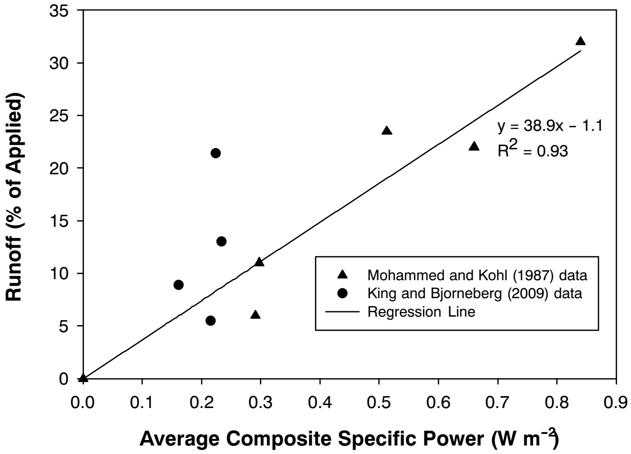

Figure 7. Runoff percentage (adapted from King and Bjorneberg, 2009) averaged over three soil types for four of the sprinklers used in this study (dots) as a function of average composite specific power, and runoff percentage after 20 min of rainfall simulation to a freshly cultivated bare loam soil as a function of specific power (regression line; adapted from Mohammed and Kohl, 1987).

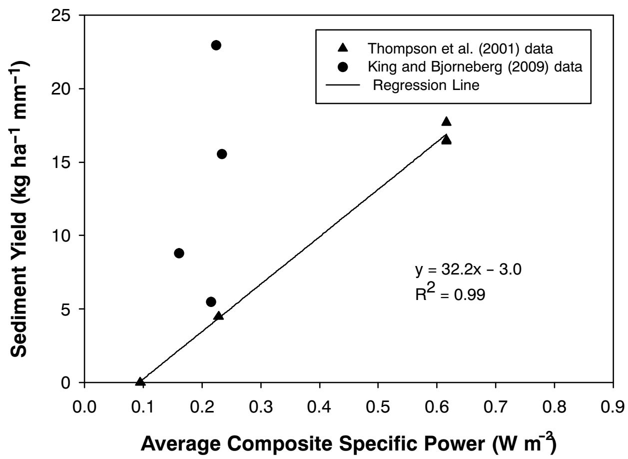

Figure 8. Sediment yield (adapted from King and Bjorneberg, 2009) averaged over three soil types for four of the sprinklers used in this study (dots) as a function of average composite specific power, and sediment loss for 30 min rainfall simulation following the initiation of runoff from a silt loam soil as a function of specific power (regression line; adapted from Thompson et al., 2001).

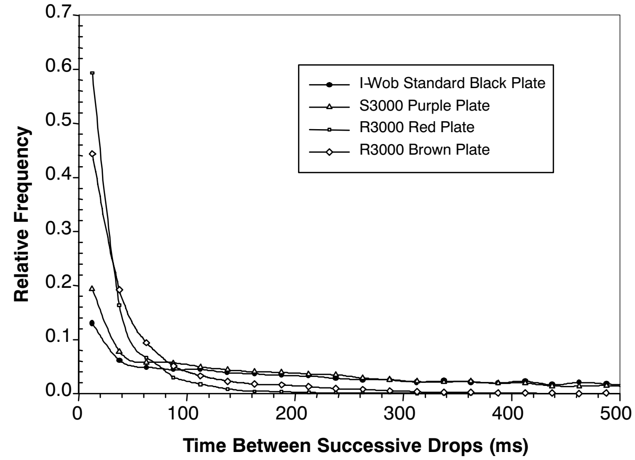

Figure 9. Relative frequency distribution of time between successive drops measured by laser instrument located 6 m from the sprinkler in 50 ms time intervals ranging from 0 to 500 ms.

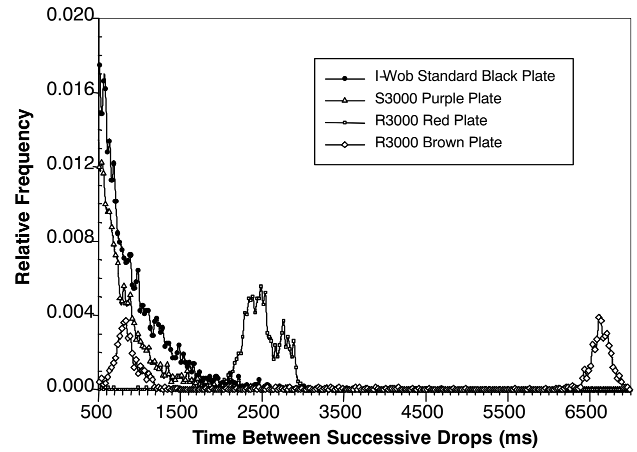

Figure 10. Relative frequency distribution of time between successive drops measured by laser instrument located 6 m from the sprinkler in 50 ms time intervals ranging from 500 to 7200 ms. (Note: vertical scale is different from fig. 9).

yield for two of the sprinklers deviate substantially from the regression line. Direct comparison of the two data sets is not possible due to different soils, slopes, and time distributions of specific power application. Peak specific power may be a more important parameter than average specific power in regard to runoff. Additional research is needed to evaluate this issue. Soil erosion could be influenced by drop size distribution, which likely differs between data sets even though specific power calculated using equation 3 does not differentiate between drop size distributions. Additional research is needed to determine if differing drop size distributions with equivalent specific power affects soil erosion.

For both the runoff and sediment yield data (figs. 7 and 8) from King and Bjorneberg (2009), there appeared to be a dependency on sprinkler type. The R3000 sprinklers had the lowest runoff and sediment yield and also had the lowest average composite specific power applied. There was a substantial increase in runoff and sediment yield with little associated increase in average composite specific power applied for the I-Wob and S3000 sprinklers. One functional difference between the R3000 sprinklers and the other two sprinklers was the manner in which the water drops were distributed over the wetted area with respect to time. The I-Wob and S3000 sprinklers distribute water drops more evenly over the wetted area with respect to time than the R3000 sprinklers, which have well defined streams of water drops rotating around the sprinkler. This difference is depicted in figures 9 and 10, which show the relative frequency distribution of the time between successive drops measured by the laser instrument located 6 m from the R3000, S3000, and I-Wob sprinklers used in this study. For all four sprinklers, the highest relative frequency of time between successive drops occurred over the time interval of 0 to 50 ms (fig. 9). This indicates that all these sprinkler plates rotate concentrated streams of drops formed from grooves on the plates. The R3000 sprinklers have well defined streams relative to the other two sprinklers, as indicated by the relatively high frequency in the 0 to 50 ms time interval between successive drops. The peak in relative frequency at 2500 ms for the R3000 red plate sprinkler (fig. 10) corresponds to the time interval between each of the defined streams of drops from the rotating grooved plate to impact the laser instrument. Roughly 1 of every 100 drops detected by the laser instrument had a time interval of 2500 ms between successive drops. The peak in relative frequency at 850 and 6600 ms for the R3000 brown plate sprinkler (fig. 10) corresponds to the time interval between defined streams of drops from the rotating grooved plate to impact the laser instrument. Roughly 2 of every 120 drops detected by the laser instrument had a time interval between successive drops of either 850 or 6600 ms. The I-Wob and S3000 sprinklers functioned nearly equivalent in regard to distributing the drops over the wetted area with respect to time. With regard to sediment yield, more uniform distribution of water drops over the wetted area with respect to time may cause detached soil particles to remain in suspension in sheet flow for a relatively longer time, allowing detached soil particles to be transported farther by sheet flow. This effect may also influence dispersion and deposition of fine particles in surface pores of soil, leading to differences in runoff among sprinklers. Additional measurements are needed of runoff and sediment loss for the same sprinklers with different values of specific power applied in order to more fully explore the effect that average composite power has on sprinkler runoff and erosion.

Conclusions

Kinetic energy of center-pivot sprinklers can be characterized multiple ways. Area-weighted kinetic energy per unit drop volume has traditionally been use in the literature. Kinetic energy per unit volume of sprinkler discharge is another possible characterization. Kinetic energy per unit drop volume is heavily weighted by the largest drops and does not characterize sprinkler kinetic energy transferred to the soil. Kinetic energy per unit volume of sprinkler discharge is more reflective of sprinkler kinetic energy transferred to the soil, but it still does not represent relative differences in actual kinetic energy transferred to the soil between various sprinklers. Kinetic energy transferred to the soil by five common center-pivot sprinklers for a specific flow rate and lateral spacing was calculated based on measured drop size and velocity. The results demonstrated that sprinklers with the smallest drop sizes do not necessarily transfer the least kinetic energy per unit depth of water applied. Conversely, sprinklers with the largest drop sizes do not necessarily transfer the greatest kinetic energy to the soil. The results demonstrated that the conventional thought that sprinkler drop size alone determines kinetic energy transferred to the soil is incorrect.

Sprinkler specific power, which is defined as the rate at which kinetic energy is transferred to the bare soil surface, was used to calculate kinetic energy transferred to the soil by center-pivot irrigation. Runoff and sediment loss were not well correlated with composite specific power applied across sprinklers. There appeared to be a dependency on sprinkler type. The functional difference between the R3000 sprinklers and the I-Wob and S3000 sprinklers was the manner in which the water drops were distributed over the wetted area with respect to time. The I-Wob and S3000 sprinklers distributed water drops more evenly over the wetted area with respect to time than the R3000 sprinklers, which have well defined rotating streams of water drops. This functional difference between sprinklers could have an effect on the runoff and erosion rate of sprinklers. Additional measurements are needed of runoff and sediment loss for sprinklers with different values of specific power applied in order to more fully explore the effect that composite power has on sprinkler runoff and erosion.

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