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SPRINKLER DROPLET ENERGY EFFECTS ON SOIL PENETRATION RESISTANCE AND AGGREGATE STABILITY AND SIZE DISTRIBUTION

Gary A. Lehrsch and D. C. Kincaid

Sprinkler droplet energy degrades surface soil structure. Modifying sprinkler irrigation systems to reduce droplet energy may reduce surface sealing and crusting, thereby increasing emergence. From 1997 to 2001, we evaluated the effects of sprinkler droplet kinetic energies of 0, 8, and 16 J kg^{-1} on *in situ* surface penetration resistance (PR, a measure of crust strength), aggregate stability (a measure of a soil's resistance to breakdown), and water-stable aggregate size distribution, expressed as a mean weight diameter (MWD). Each year near Kimberly, ID, we planted sugarbeet (*Beta vulgaris* L.) into an initially tilled field of structurally weak Portneuf silt loam (Durinodic Xeric Haplocalcid), then irrigated two to four times using a lateral-move sprinkler system with spray heads having either smooth or spinning, four-groove deflector plates. After the first and last irrigation each year, we measured PR *in situ* and collected soil samples at the surface, 0 to 6 mm. When measured after one irrigation, PR increased, and aggregate stability generally decreased as droplet energy increased, although the magnitude of the response differed from year to year. After multiple irrigations, PR decreased linearly with increasing droplet energy, likely due to erosion of the crusted surface. Five-year average MWD after multiple irrigations decreased by 10%, to 0.42 mm, with droplet energies of 8 J kg^{-1} or more. Trend analysis of soils data from 1998 to 2001 revealed that droplet energies ≥10.6 J kg^{-1} decreased MWD most. Producers should reduce sprinkler droplet kinetic energy to <10.6 J kg^{-1} to minimize surface structural breakdown of recently tilled soil. (Soil Science 2006;171:435–447)

Key words: Crusting, kinetic energy, soil structure, sprinkler irrigation.

SPRINKLER irrigation droplet impact energy on unprotected soil surfaces can increase bulk density, alter surface soil pore size distributions, and weaken or fracture soil aggregates (Glanville and Smith, 1988; Truman et al., 1990). Once surface aggregates are fractured, clay from newly exposed surfaces may be dispersed and transported, with primary particles and aggregate fragments, by infiltrating water into surface pores to obstruct them and form a surface seal and, later, a crust (Farres, 1987; Le Bissonnais et al., 1989; Letey, 1994). The resulting seal reduces infiltration which, in turn, increases runoff and soil erosion (Le Bissonnais and Singer, 1992; Roth and Helming, 1992). Conversely, stable aggregates at and just below the surface will reduce sealing, sustain infiltration, reduce crusting, and lead to more efficient water use (Lehrsch et al., 1996b; Murphy et al., 1993). Aggregate size distribution after energy input is related to

USDA–Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793 N. 3600 E., Kimberly, ID 83341-5076. Dr. Lehrsch is corresponding author. E-mail: Lehrsch@nwisrl.ars.usda.gov. Dr. Kincaid has retired.

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crusts' properties and formation rate and also soil loss (Farres, 1987; Le Bissonnais et al., 1989).

Droplet energy increases soil surface penetration resistance (PR), particularly for recently tilled, low-organic matter soil. Sprinkler droplet energy of 22 J kg^{-1} on a Pullman clay loam (Torrertic Paleustoll) disrupted surface structure sufficiently to form a 1-cm-thick crust that had PR of 0.52 MPa or more (Baumhardt et al., 2004). As soil organic matter decreases, aggregate stability decreases, and droplet energy becomes more effective at increasing surface soil PR (Ramos et al., 2003; Tisdall and Oades, 1982).

Water droplet energy decreases soil surface aggregate stability. Droplet impact disintegrates surface aggregates and compacts soil (Epstein and Grant, 1973). Droplet kinetic energy fractures weak aggregates, producing many small (<0.1 mm) aggregate fragments (Fox and Le Bissonnais, 1998). Indeed, in the first 50 min of simulated rainfall, Farres (1987) found that detachment increased with decreasing aggregate stability. Briggs (1974) found that droplets with relatively high kinetic energy fractured most aggregates larger than 20 mm from a structurally unstable soil. As expected, raindrop impact disrupted aggregates at and near the surface, the uppermost 10 mm, more than at depths of 10 to 20 mm (Briggs, 1974). Surface aggregates that have been weakened, fractured, or disrupted during an irrigation or rainstorm can, upon drying, form massive structure at the soil surface (Bryan, 2000).

In addition to droplet energy, wetting rate greatly affects aggregate breakdown (Nimmo and Perkins, 2002; Six et al., 2004). In a study of 23 eastern Australia soils, Loch and Foley (1994) found aggregate breakdown (to aggregates, fragments, and primary particles <0.5 mm) upon wetting to be affected more by wetting rates than by rainfall kinetic energy. In addition, they found that raindrop impact–induced sealing was caused more by compaction than by aggregate breakdown.

Droplet energy alters aggregate size distributions. Droplet impact from just 6 mm of simulated rain applied at 76 mm h^{-1} significantly decreased the mean weight diameter (MWD) of four, low-organic matter clay soils, relative to tension-wetted controls (Glanville and Smith, 1988). The MWD of three of those four soils was less when the soil surfaces were bare than when covered with a cloth mesh (Glanville and Smith, 1988). Droplet impact accounted for two thirds of the total breakdown of a low-clay, unstable soil, most of which occurred in aggregates of >1 mm, although few aggregates of <0.25 mm resulted (Briggs, 1974). The MWD of three of four clay soils subjected to water droplet impact significantly decreased until 25 mm of rain had been received but changed little thereafter (Glanville and Smith, 1988). Smaller aggregates and aggregate fragments produced by droplet impact (i.e., a smaller MWD) form less permeable surface seals (Le Bissonnais et al., 1989). Soils with smaller MWDs suffer more interrill erosion, leading to greater sediment concentrations in runoff (Fox and Le Bissonnais, 1998), due to the slower settling velocities of the smaller aggregate fragments. The MWD of soil subjected to high droplet energy (29–33 J kg^{-1}) was proportional to those soil's final infiltration rates (Loch and Foley, 1994). After a surface seal had formed, little or no structural deterioration occurred; in other words, the MWD was relatively constant thereafter (Ragab, 1983). Greater MWDs lead to seals made up of coarser aggregate fragments (Fox and Le Bissonnais, 1998). As MWD increases, the saturated hydraulic conductivity of a surface seal also increases (Ramos et al., 2003).

Sprinkler droplet energy affects soil hydraulic properties, especially infiltration rates (Lehrsch and Kincaid, 2000). Surface soil structural breakdown from a droplet energy of only 4.5 J kg^{-1} hastened sealing and decreased the final infiltration rates of two coarse-textured soils (Agassi et al., 1994). As droplet kinetic energy increased, ponding occurred sooner (Bloem and Laker, 1994). Infiltration rates were less with, rather than without, droplet energy because of pore size distribution changes at and below the soil surface (Baumhardt et al., 2004).

Structural breakdown leads, ultimately, to the formation of soil crusts that inhibit the emergence of seedlings of many crops (Goyal, 1982; Singer and Warrington, 1992). To obtain adequate stands, producers in sprinkler-irrigated areas may be forced to apply postplant preemergent irrigations to reduce crust strength as seedlings are emerging (Awadhwal and Thierstein, 1985). Although small drops with less kinetic energy at times enhance seedling emergence (Epstein and Grant, 1973), large drops with relatively more kinetic energy hinder seedlings from emerging.

Spray heads on center pivot irrigation systems can be inexpensively and easily modified to reduce both the water volume applied per pass (≤5 mm) and its droplet energy (Kincaid, 1996) until seedlings have emerged and an adequate stand is present. Thereafter, the pivot's spray heads can be reconfigured to apply greater water volumes (at their necessarily greater energy) for the remainder of the crop's growing season. Knowing soil response to water droplet impact energy will enable engineers to better design and producers to better manage irrigation systems to minimize surface sealing, thus maximizing infiltration and reducing both runoff and irrigation-induced erosion (Lehrsch et al., 2005a). Reducing sprinkler droplet energy should minimize surface aggregate breakdown and subsequent crust formation. With less droplet energy striking the soil surface, more aggregates should remain intact, and surface soil PR should be less.

To date, few investigators have reported soil responses to a range of water drop or sprinkler droplet kinetic energies. Moreover, greater study of the subject has been recommended (Braunack and Dexter, 1989; Bryan, 2000; Trout et al., 1990). In our research, we hypothesized that sprinkler droplet energy reductions would improve surface soil physical properties and thereby increase seedling emergence and infiltration under sprinkler irrigation. Our primary objective was to evaluate the effects of sprinkler droplet kinetic energy rates on soil PR, aggregate stability, and water-stable aggregate size distribution at the soil surface (0- to 6-mm depth) after one and after multiple irrigations of an initially tilled, structurally weak Portneuf silt loam. Our secondary objective was to quantify droplet energy effects on seedling emergence.

MATERIALS AND METHODS

The experiment was conducted from 1997 to 2001 on a Portneuf silt loam, a coarse silty, mixed, superactive, and mesic Durinodic Xeric Haplocalcid (McDole and Maxwell, 1987) at 42°31, N latitude and 114°22, W longitude. The site was about 1.8 km southwest of Kimberly, ID, at an elevation of 1186 m on a field fallowed in 1996. The Portneuf's Ap horizon contained about 560-g silt/kg, 220-g clay/kg, and about 9.3-g organic C/kg. Its cation exchange capacity was 190 $mmol_c\ kg^{-1}$. The Portneuf had a saturated paste pH of 7.7, calcium carbonate equivalent of about 75 $g\ kg^{-1}$, paste extract electrical conductivity (EC_e) of 1.1 $dS\ m^{-1}$, and sodium adsorption ratio (SAR) of 0.87. The soil, with its predominant coarse clay being illite, exhibited little shrinking or swelling (Lentz et al., 1996). The Portneuf soil was quite susceptible to structural breakdown, having little organic matter and surface aggregates that fractured readily with only moderate energy input (Lehrsch and Kincaid, 2000; Lehrsch et al., 1991).

In the fall before each study year, the site was moldboard-plowed to a depth of 0.18 m. Generally in early spring, we prepared a seedbed by tilling the site with an offset disk (to 0.10 m), then roller-harrowing twice (to 65 mm). Sugarbeet (*Beta vulgaris* L., Hilleshög Mono-Hy[1] cv. WS PM-9) was planted 21 mm deep every 0.16 m into 0.56-m rows using a four-row, Milton[1] planter, traveling at 3.72 $km\ h^{-1}$. At planting, we formed 75-mm-deep, triangular-shaped furrows every 0.56 m across the four-row-wide (2.2 m) by 13.1-m-long plots, thus leaving low, flat-topped beds on all plots. Each plot's long axis was parallel to the lateral of the irrigation system (described below). A diversion ditch was formed at the upslope plot edge to intercept sediment-laden runoff from upslope. We also used a reservoir tillage implement to form 0.22-m-deep basins every 0.76 m in each furrow that minimized runoff (Lehrsch et al., 2005a). Standard cultural practices were used to control insects and weeds. Sugarbeet seedlings that emerged from the center 9.14 m of each of two interior rows were last counted 25 to 45 days after planting. Final emergence was calculated as the ratio of emerged seedlings to seeds sown, expressed as a percent.

We irrigated all plots using a 152-m, four-span, lateral-move sprinkler system equipped with 103-kPa nozzle pressure spray heads positioned 1.8 m above the soil surface and either 1.5 or 2.4 m apart. Sprinkler droplet kinetic energy was applied at three rates: 0, 8, and 16 $J\ kg^{-1}$ (0, 8, and 16 $J\ m^{-2}\ mm^{-1}$). The 0-$J\ kg^{-1}$ plots were covered with two layers of 20-mesh, nylon window screen having openings of about 1.2 × 1.2 mm, suspended about 50 mm above the soil on a coarse grid of 6-mm metal bar. The nylon screen absorbed the sprinkler droplets' kinetic energy (Ahuja et al., 1982; Loch and Foley, 1994) yet held little water when the irrigation ended. Moreover, water drops falling only 50 mm from the screen to the soil cause little damage to soil surface structure (Moss and Green, 1987). The sprinkler

[1]Manufacturer or trade names are included for the reader's benefit. The USDA–Agricultural Research Service neither endorses nor recommends such products.

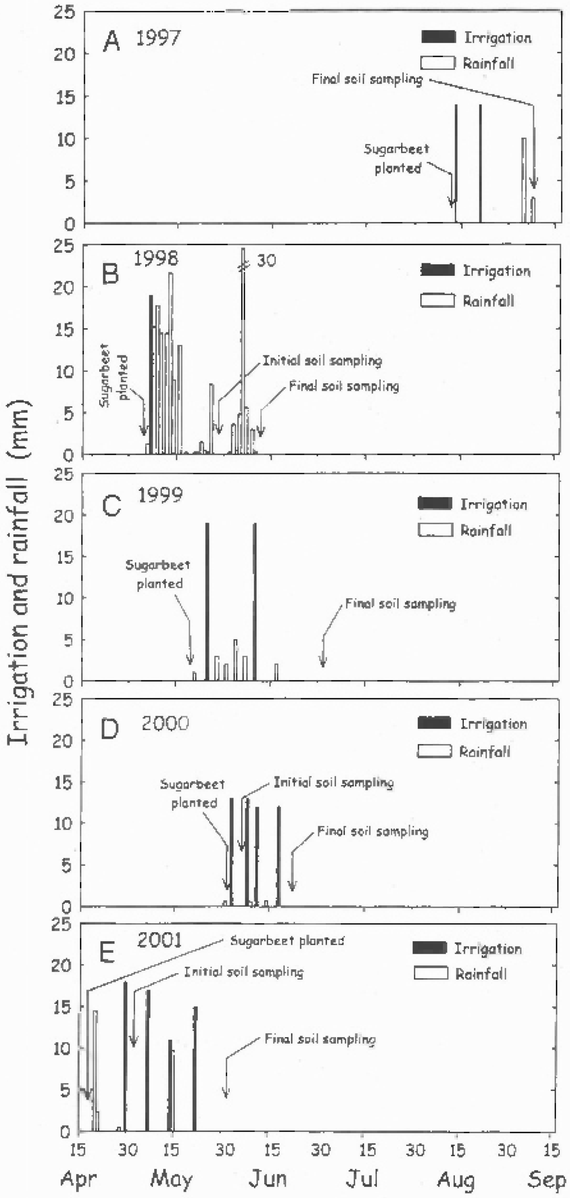

Fig. 1. Timing of planting, irrigations, soil sampling, and rainfall received during each field season from 1997 to 2001. In general, whenever we measured surface soil PR, we collected about 80 g of soil for subsequent aggregate analyses. When we measured PR on August 13, 1997 and May 28, 1999; however, we collected only about 15 g, sufficient only for measuring gravimetric water content.

system's spray heads were modified to produce droplets that struck the soil surface with nominal kinetic energies of either 8 or 16 J kg^{-1}. Spray heads with flat, smooth deflector plates applied water that had a droplet size distribution with a median volumetric drop diameter (d_{50}) of 0.7 to 0.8 mm and droplet kinetic energy that averaged 8 J kg^{-1} and ranged from 7 to 9 J kg^{-1}, as estimated by Kincaid (1996) and Kincaid et al. (1996). In contrast, spray heads with spinning, four-groove plates applied water that had a d_{50} of 3.3 mm and kinetic energy that averaged 16 J kg^{-1} and ranged from 15 to 19 J kg^{-1}. In the absence of wind, droplet energies of 10 J kg^{-1} or more are common for center pivots with single-nozzle, impact-type sprinklers in southern Idaho (Kincaid, 1996). Spray head nozzle diameters ranged from 4.0 to 5.4 mm, spaced as necessary to equalize application rates among spans. The lateral discharge rate was about 7.2 L min^{-1} m^{-1}, typical for middle spans of a center pivot's lateral in southern Idaho.

We used this sprinkler system to apply water with an application intensity of about 37 mm h^{-1} to field plots two to four times in the 4 to 5 weeks after planting sugarbeet each year (Fig. 1). Sprinkler application intensity was held constant throughout the study to ensure similar aggregate wetting rates (Loch and Foley, 1994). In each irrigation each year, the water depth applied did not vary across droplet energy rates. The depth applied varied slightly, however, from irrigation to irrigation (Fig. 1). Depth of water applied in each irrigation was calculated using the lateral's discharge rate and ground speed. We applied 17 mm (S.D., ±3 mm) of water, on average, at Irrigation 1. At each subsequent irrigation, we applied 14 mm (S.D., ±3 mm) (excluding natural rainfall). Most of the region's irrigation water is withdrawn from the Snake River and distributed via canals and laterals. The water commonly has a pH of 8.2, an EC of 0.5 dS m^{-1}, and a SAR of 0.65 (Lentz and Sojka, 1994).

Rainfall was generally sparse during each year's field season, as is common (McDole and Maxwell, 1987) (Fig. 1). In fact, <19 mm of rain fell during three of the five field seasons. The exception, however, was 1998. In just 11 days, from Day of Year (DOY) 126 to DOY 136, the site received 107 mm of rain, more than one third of the mean annual precipitation. Such rainfall occurring within 24 h of the season's first irrigation was considered part of the first irrigation. This unusually large amount of rain in 1998 affected some monitored parameters (described in more detail in the next section). Also in 1998, the 30 mm of rain that fell on DOY 156 was considered the season's second irrigation.

We measured surface soil PR (Lowery and Morrison, 2002) about 4 days after the first postplant irrigation (i.e., about midway between Irrigations 1 and 2) and 14 days after the last irrigation with a calibrated Geotester[1] penetrometer

(Model HM-502 Geotester,[1] Gilson Co., Inc., Lewis Center, OH). The device was a 130-mm-long, hand-operated, direct-reading penetrometer with a 6.0-mm-diameter rod, a flat 6.4-mm-diameter tip, and a dial gauge that indicated maximum unconfined compressive strength as kilograms of force. We measured *in situ* PR of undisturbed soil in the plant row on a bed center in four areas of each plot by probing vertically downward at about 10 mm s^{-1} 10 times per plot from the soil surface to 6 mm, manually recording the maximum force after each probing. PR, expressed in megapascal, was calculated by dividing the force by the cross-sectional area of the rod tip. For additional details on our PR measurement procedure, see Lehrsch et al. (2005b). We used the arithmetic average of the PRs of all probings in a plot as that plot's PR in subsequent statistical analyses.

PR depends on soil water content (Sojka et al., 2001). Accordingly, when we measured PR, we collected soil samples from the same areas in each plot to determine gravimetric water content, aggregate stability, and water-stable aggregate size distribution. One composite soil sample of about 80 g was collected using either a small spatula (Loch and Smith, 1986) or the sampler of Reginato (1975) to a depth of 6 mm from undisturbed soil above the seed line in each plot after the first and last irrigations. We determined gravimetric water content on a subsample, then stored the remaining moist soil in an air-tight container at +6 °C for further analysis. Aggregate stability of these samples was measured using the procedure of Nimmo and Perkins (2002), modified by Lehrsch et al. (1991) to use field-moist, 1- to 4-mm aggregates, rather than air-dry, 1- to 2-mm aggregates. Those aggregates were slowly wetted to a water content of 0.30 kg kg^{-1} with a cool aerosol produced by a nonheating vaporizer (Humidifier Model No 240, Hankscraft,[1] Reedsburg, WI) before wet sieving. Aggregate stability was reported as the weight percent of aggregates that remained stable atop a 0.25-mm sieve after being sieved in deionized water for 180 s. We also measured the water-stable aggregate size distribution of the soil samples using the procedure of Nimmo and Perkins (2002), modified so that duplicate, 25-g samples of field-moist aggregates that passed an 8-mm sieve were slowly aerosol-wetted to 0.30 kg kg^{-1}. Immediately thereafter, each duplicate was sieved for 600 s in tap water through a nest of sieves with openings of 4.75, 2.0, 1.0, and 0.25 mm. The tap water had a pH of 7.6, EC of 0.7 dS m^{-1} and SAR of 1.7 (Lehrsch et al., 2005b). Each resulting size distribution was expressed as an MWD (van Bavel, 1949) calculated as per Angers and Mehuys (1993). Using this procedure, a soil sample's MWD could be no less than 0.125 mm nor more than 6.375 mm. We measured MWD on four randomly selected replicates (logistical constraints prevented the measurement on all replicates). We used the arithmetic average of the MWDs from the duplicates as the plot's MWD in subsequent statistical analyses.

The experimental design was a randomized complete block with eight replicates of the three droplet energy rates. We used SAS (SAS Institute Inc. 1999)[1] to perform a multiyear analysis of variance (ANOVA) using either general linear model or mixed-model procedures with block within year as the random factor and a significance probability of 5%. Mixed-model grouping options accounted for heterogeneous variances in the PR, aggregate stability, and emergence data. In the MWD analysis, a reciprocal square-root transformation was first applied to the data to stabilize its error variance, then an ANOVA was run with year modeled as a fixed effect. Because we expected droplet energy to only decrease MWD, we separated least-squares MWD means using a one-tailed Dunnett's test versus our control, the 0-J kg^{-1} treatment. Least-squares MWD means were subsequently back-transformed into original units for presentation. In the ANOVA, we also used contrasts to test for linear and quadratic (curvilinear) trends in each variable's response to increasing droplet energy each year. For the most complex trend found significant, a regression equation was fitted to the data. When the resulting equation was curvilinear, the quadratic equation's first derivative was set equal to zero and solved for the droplet energy corresponding to response variable maxima or minima. Three droplet energies were sufficient to statistically characterize a curvilinear relationship but insufficient to establish, for example, a spline-fit regression model because the droplet energy of the join point will always be the intermediate droplet energy, regardless of its magnitude (B. E. Mackey, 2005, USDA-ARS, Albany, CA, personal communication). Where present, we reported the continuous response of any monitored soil physical property to sprinkler droplet energy. We also determined pairwise degrees of association among the physical properties and emergence using Kendall's coefficient of rank correlation, a nonparametric statistic.

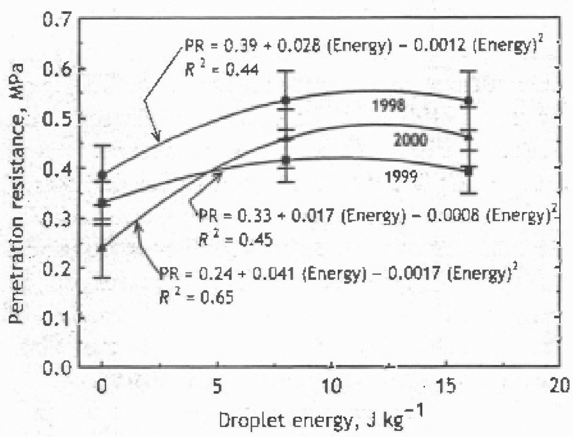

Fig. 2. Sprinkler droplet energy effects on PR measured after one irrigation in each year. Each mean (n = 8) is shown with its 95% confidence interval.

RESULTS AND DISCUSSION

Penetration Resistance

Droplet energy applied to recently tilled seedbeds increased surface soil PR in 3 of 5 years, although the magnitude of the response differed from year to year (Fig. 2). In 1997 and 2001, droplet energy did not affect PR measured after one irrigation of recently tilled soil. In each of the 3 remaining years, however, a quadratic trend in the response of PR to increasing droplet energy was significant at $P <$ 0.043 (Fig. 2). Throughout the droplet energy range, PR in 1998 exceeded that in 1999 and 2000. This greater resistance was likely a consequence of the energy input from the large amount of rain that began to fall 1 day after planting and continued nearly every day for the next 10 days in 1998 (Fig. 1). PR responses to droplet energy in 1999 and 2000 were similar (Fig. 2), due in part to the absence of appreciable rainfall between the first irrigation and the PR measurement those years (Fig. 1). A visual inspection of the three plotted equations suggests that PR would be greatest (e.g., seedling emergence most hindered) at droplet energies from 10 to 12 J kg^{-1}. Stated differently, 10 to 12 J kg^{-1} droplet energy maximized PR and formed a crust, based on these data. Droplet energy applied to recently tilled seedbeds consolidates surface soil, increasing its bulk density (Epstein and Grant, 1973) and, consequently, its PR (Sojka et al., 2001).

After multiple irrigations, PR responded linearly to droplet energy each year. For 3 of the 5 study years, PR tended to decrease with increasing droplet energy; in 2 of those 3 years, the decrease was significant at $P < 0.003$ (Fig. 3). One year, 2001, was somewhat unusual in that PR tended to increase slightly with droplet energy, although the linear trend was not significant ($P > 0.061$). Nevertheless, these common PR decreases with increasing droplet energy suggest that, later in the growing season, surface crusts that had formed earlier were weakened by erosion, with soil at the crust surface being detached by sprinkler droplet kinetic energy, then transported from the bed center by overland flow. When irrigating, particularly later in the season, we frequently observed sediment-laden runoff flowing from the beds into furrows and basins. Droplet impact can detach silt and clay from soil crusts formed earlier (Epstein and Grant, 1973) and can decrease the surface bulk density of an already sealed silt loam (Fohrer et al., 1999).

To quantify PR response to water content, we collected soil samples when we measured PR. Water contents of surface soil samples collected after one irrigation were similar among energy rates, with each rate's 5-year average being 0.09 kg kg^{-1} (data not shown). When we measured PR after multiple irrigations, the corresponding soil water content in 1998 was 0.07 kg kg^{-1} for the 0-J kg^{-1} energy rate, greater statistically ($P < 0.002$) but not practically than the 0.05 kg kg^{-1} for the 8- and 16-J kg^{-1} energy rates. Greater soil water contents often reduce PR (Sojka et al., 2001), yet they did not in 1998 (Fig. 3). In our study, water contents were too low to appreciably affect PR.

Aggregate Stability

As found for PR, the interaction of droplet energy with year was significant whenever

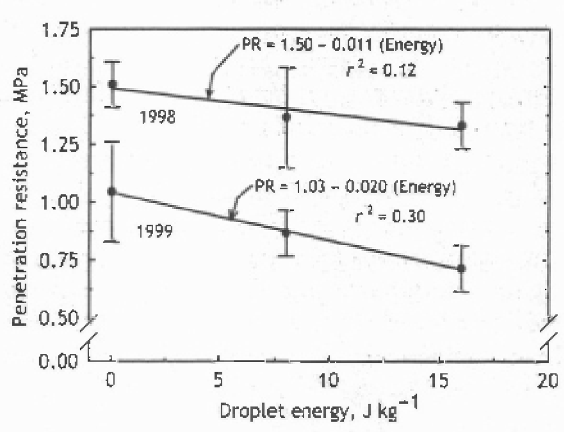

Fig. 3. Sprinkler droplet energy effects on PR measured after multiple irrigations in 1998 and 1999. Each mean (n = 8) is shown with its 95% confidence interval.

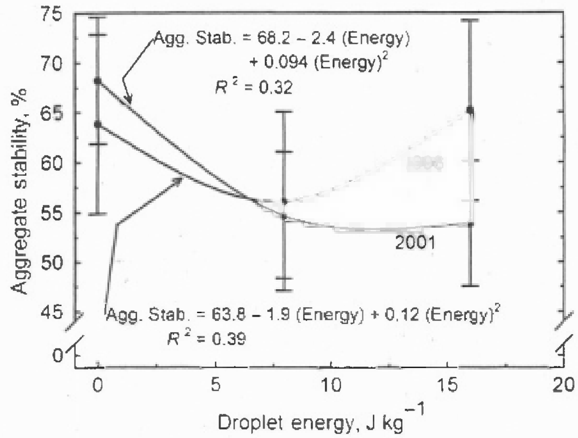

Fig. 4. Sprinkler droplet energy effects on aggregate stability measured after one irrigation in 1998 and 2001. Each mean (n = 8) is shown with its 95% confidence interval.

aggregate stability responded to energy as a main effect. Aggregate stability measured after one irrigation tended to decrease initially as droplet energy increased in 1998, 2000, and 2001 (in 1997 and 1999, insufficient data were collected for analysis). In 1998 and 2001, curvilinear trends were significant ($P < 0.011$) in aggregate stability response to increasing droplet energy (Fig. 4). Two-year average aggregate stability decreased from 66% to 55%, that is, by about one sixth, as droplet energy increased from 0 to 8 J kg^{-1} (Fig. 4). The stability increase from 8 to 16 J kg^{-1} in 1998 may have been due to the fracturing, then eroding of unstable surface aggregates by high energy droplets and runoff, respectively, to leave stable aggregates behind (discussed in more detail in the following section). These findings and earlier ones (Lehrsch et al., 1996b) reveal that moderate rates of sprinkler droplet kinetic energy weakened surface aggregates, causing them to fracture when subsequently wet sieved. When measured after multiple irrigations, aggregate stability was not affected (P = 0.117) by droplet energy.

Aggregate Size Distribution

Five-year Data Set

We analyzed MWD measured after multiple irrigations in all 5 years. When MWD was averaged across droplet energy, no consistent temporal trend was evident (Fig. 5). In fact, in the 5-year study, the greatest MWD, 0.59 mm, occurred in 1999 only to be followed in the very next year with the lowest, 0.35 mm. Neither tillage nor soil water contents at the time of secondary tillage caused year-to-year variation in MWD. All tillage, whether primary in the fall or secondary in the spring, was similar from one year to the next. Care was taken to time secondary tillage and planting at water contents well below the Portneuf silt loam's plastic limit, 0.23 g g^{-1}, the water content at which most compaction and structural degradation occur. Soil water contents measured in the uppermost 0.10 m of the profile at about tillage time, although only for the last 3 years of the study, were 0.17 g g^{-1} in 1999, 0.13 g g^{-1} in 2000, and 0.12 g g^{-1} in 2001. On the whole, those water contents were no more than 75% of the soil's plastic limit and did not vary appreciably in the region's semiarid environment. Although the energy input from the 1998 rainfall (Fig. 1) may partly explain that year's relatively low MWD, no other explanation is apparent for the year-to-year variation in MWD (Fig. 5). Although not quite significant at P = 0.05, increasing sprinkler droplet kinetic energy tended to reduce MWD. Our study's 5-year average MWD without droplet energy was greatest, 0.47 mm, but decreased by 10% to 0.42 mm with droplet energies of 8 J kg^{-1} or more (data not shown). Droplet kinetic energy fractures surface aggregates, particularly the larger weaker ones, reducing MWD (Briggs, 1974; Glanville and Smith, 1988).

2000 and 2001 Data Set

In the final 2 years of the study, we expanded data collection to enable us to statistically analyze MWD responses to year, droplet energy, and sampling period. MWD was significantly affected by the main effect of year

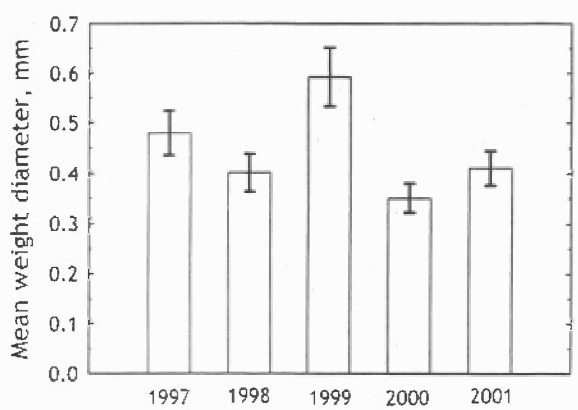

Fig. 5. Surface soil aggregate size distribution as MWD after multiple irrigations from 1997 to 2001. Data have been averaged across droplet energy (not significant at P = 0.080). Each mean ($10 \le n \le 12$) is shown with its 95% confidence interval.

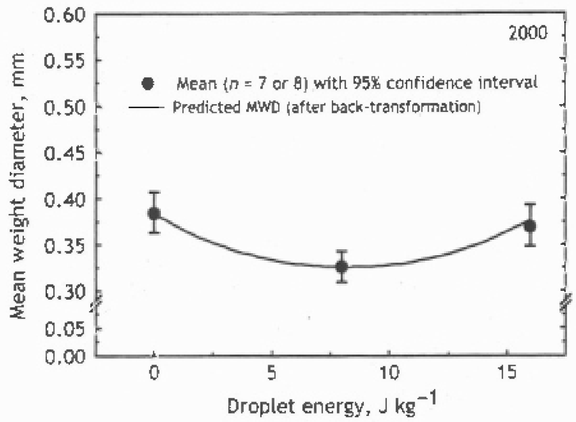

Fig. 6. Sprinkler droplet energy (DE) effects on aggregate size distribution as MWD in 2000. Data have been averaged across sampling period (not significant at $P = 0.063$). Each mean (n = 7 or 8) is shown with its 95% confidence interval. The fitted line shows values that were first predicted on the transformed scale using $MWD_{transf} = 1.613 + 0.034$ (DE, J kg^{-1}) $- 2.06 \times 10^{-3}$ $(DE)^2$ ($R^2 = 0.36$*) then back-transformed into original units (*Significant at $P = 0.05$).

($P < 0.006$) and by the main effect of droplet energy ($P < 0.004$) but not by the main effect of sampling period ($P = 0.398$). MWD was not significantly affected by any of the interactions involving year, droplet energy, and sampling period.

When we examined the response of the 2-year MWD data set to droplet energy, we found a significant quadratic trend ($P < 0.012$) of energy on MWD. Because we suspected that a trend in the response of MWD to droplet energy might differ from year to year, we analyzed each year separately. Indeed, when averaged across the nonsignificant sampling period factor, MWD responded to droplet energy in a curvilinear manner (significant at $P < 0.001$) in 2000 (Fig. 6) but in a linear manner (significant at $P < 0.002$) in 2001 (Fig. 7). Our 2000 data suggest that sprinkler droplet energy rates of about 8 J kg^{-1} maximize surface soil structural breakdown (Fig. 6). Zobeck and Popham (1990) also found, for 3- of 4-tillage implements, that a single-parameter measure of aggregate size distribution decreased, then increased slightly with cumulative precipitation, a surrogate measure of water droplet energy.

MWD responded to droplet energy curvilinearly in 2000 but linearly in 2001 because surface aggregates responded to high droplet energy rates differently in 2000 than in 2001. In both years, MWD decreased as droplet energy increased from 0 to 8 J kg^{-1}. Only in 2000, however, did MWD increase as droplet energy increased from 8 to 16 J kg^{-1} (Fig. 6). With only moderate droplet energy input of 8 J kg^{-1} in 2000, surface aggregates may have been weakened, although not fractured by droplet energy during the irrigation. When those weakened surface aggregates were sampled then wet sieved, they may have fractured or disintegrated into microaggregates of <0.25 mm (Six et al., 2004), yielding relatively low MWDs. With excessive energy input of 16 J kg^{-1}, however, weakened aggregates may have been fractured during the irrigation, with their fragments and other loose unstable material on the soil surface being detached by droplet energy and transported from the beds by overland flow (Epstein and Grant, 1973), leaving relatively stable, larger aggregates behind. Drying and consolidation (Bryan, 2000) could then have strengthened the aggregates remaining on or near the soil surface atop the beds, accounting for the larger MWD measured at greater droplet energy rates in 2000 (Fig. 6). Alternatively, sprinkler droplets with excessive kinetic energy may have eroded a soil crust to uncover subsurface areas with stable unbroken aggregates (Ambassa-Kiki and Lal, 1992). In 2001, in contrast, droplet kinetic energy from irrigation to irrigation continuously weakened surface aggregates, leading to a monotonic decrease in MWD with increasing droplet energy (Fig. 7). Zobeck and Popham (1990) also presented data showing that a single-parameter descriptor of

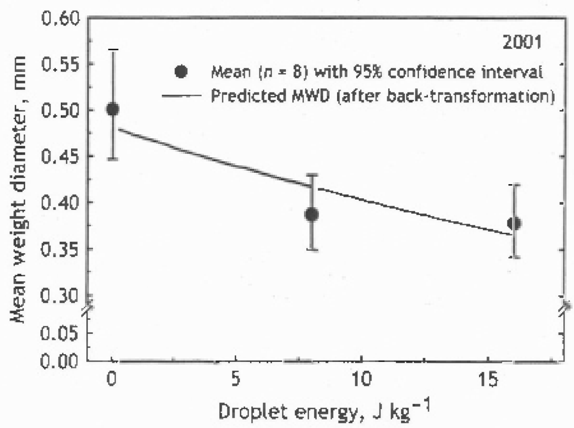

Fig. 7. Sprinkler droplet energy (DE) effects on aggregate size distribution as MWD in 2001. Data have been averaged across sampling period (not significant at $P = 0.555$). Each mean (n = 8) is shown with its 95% confidence interval. The fitted line shows values that were first predicted on the transformed scale using $MWD_{transf} = 1.442 + 0.013$ (DE, J kg^{-1}) ($r^2 = 0.19$*) then back-transformed into original units (*Significant at $P = 0.05$).

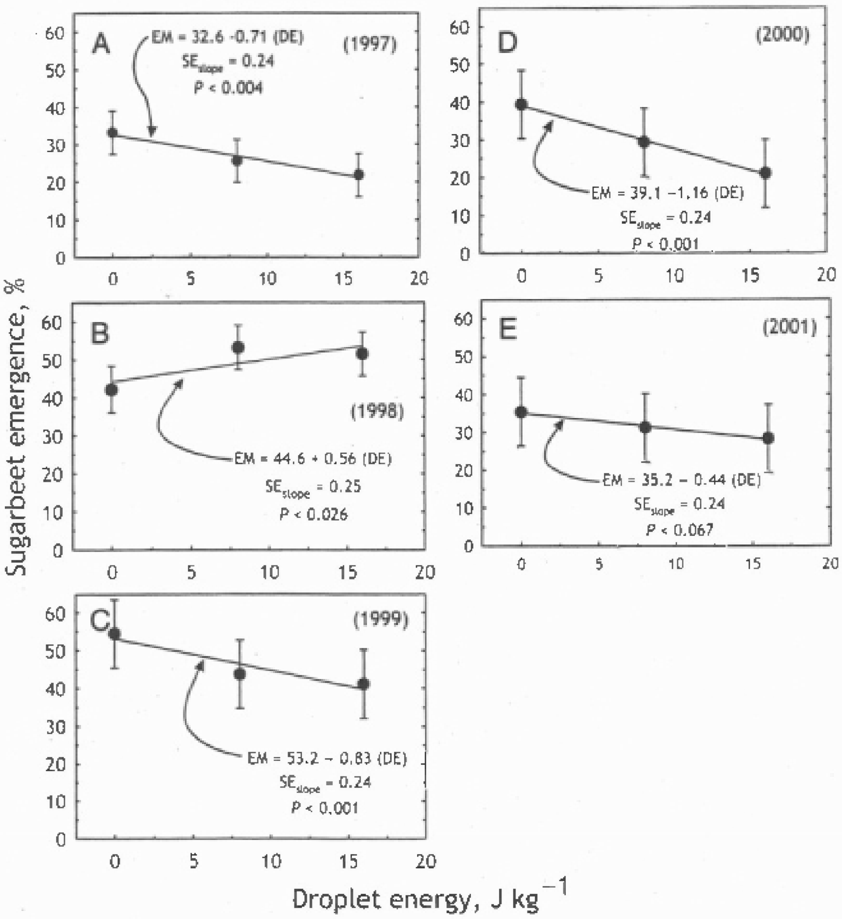

Fig. 8. Sprinkler droplet energy (DE) effects on sugarbeet seedling emergence (EM) from 1997 to 2001. Each mean (n = 8) is shown with its 95% confidence interval. SE indicates standard error.

aggregate size distribution after moldboard plowing decreased monotonically during the last 7 months of a 10-month study of precipitation effects on surface soil structure.

The significant response of MWD to droplet energy in the last 2 years of the study, but not in the entire 5 years, is worthy of note. During the study, our site had been fallowed with no annual input of crop residue yet was irrigated frequently, particularly early in each growing season. Such management year after year likely reduced surface soil organic C (not measured), which in turn would have reduced aggregate stability leading to poorer soil structure (Kay and Angers, 2002) and, in general, smaller MWDs at the end rather than at the beginning of the 5-year study (Fig. 5).

Emergence

Sugarbeet seedling emergence increased linearly as droplet energy decreased from 16 to 0 J kg^{-1} in 4 of 5 study years (Fig. 8). Based on data from all years except 1998, emergence increased by 1.08-fold (significant at $P < 0.001$) with every 10-J kg^{-1} decrease in droplet energy. An emergence increase of 1.08-fold is sufficient to potentially increase southern Idaho sugarbeet growers' net income by more than US$7 annually (V. Jaro, 2006, The Amalgamated Sugar Co, Boise, ID, personal communication). This emergence increase is similar to that found in earlier research (Lehrsch et al., 1996a) where a 10-J kg^{-1} decrease in sprinkler droplet kinetic energy increased sugarbeet seedling emergence 1.13-fold.

The anomalous increase in seedling emergence with increasing droplet energy in 1998 (Fig. 8b) was attributed to both rainfall and soil strength. Just 1 day after planting in 1998, rain began and continued for nearly 2 weeks (Fig. 1). Energy from this rain likely masked our droplet energy treatment effects. Soil strength also played a role. Surface soil PR measured in 1998 after the first irrigation was among the highest measured in any of the 5 years of study (Fig. 2). Moreover, as the 1998 growing season progressed, increasing droplet energy significantly decreased surface PR

TABLE 1

Correlations between soil penetration resistance, physical properties, and sugarbeet seedling emergence, calculated using data from 1997 to 2001

Property	Correlation coefficient[†]					
	Sugarbeet seedling emergence	PR after multiple irrigations	PR after one irrigation	MWD after multiple irrigations	MWD after one irrigation	Aggregate stability after multiple irrigations
Aggregate stability after one irrigation	+0.20*	−0.06	−0.23**	+0.12	+0.25*	+0.33***
Aggregate stability after multiple irrigations	+0.36***	−0.01	−0.10	+0.32***	+0.43***	
MWD after one irrigation	+0.38***	−0.03	−0.36**	+0.42***		
MWD after multiple irrigations	+0.24**	+0.11	−0.22*			
PR after one irrigation	+0.01	+0.31***				
PR after multiple irrigations	+0.21***					

[†]Kendall's coefficient of rank correlation; $34 \leq n \leq 120$.

Significant at *, **, and *** $P = 0.05$, 0.01, and 0.001, respectively.

(Fig. 3), suggesting erosion of high-strength, high–bulk density surface layers (Fohrer et al., 1999) which would explain the observed emergence increase with increasing droplet energy (Fig. 8b).

Soil Property Relationships

Both aggregate stability and MWD were significantly correlated with sugarbeet seedling emergence (Table 1). All correlation coefficients were positive, indicating that the more stable the soil structure, the greater the emergence. PR measured after one irrigation was not correlated with emergence; when measured after multiple irrigations, PR was correlated with emergence, although surprisingly in a positive manner. Droplet energy–induced compaction and erosion of plot surfaces may have interacted in some way to obscure the inverse relationship that we expected. PR measured after multiple irrigations was not correlated with any physical property, save one, PR measured after one irrigation (Table 1).

Aggregate stability and MWD, whether measured after one or multiple irrigations, were negatively correlated with PR measured after one irrigation, significantly so in three of four instances (Table 1). Ramos et al., (2003) also found MWD to be inversely proportional to PR. Stable structure lessens surface sealing and crust formation, thereby reducing PR. Although all four measures of structural stability were positively correlated with one another, aggregate stability measured after one irrigation was significantly correlated only with MWD measured after one irrigation. This finding showed that the early-season stability of 1- to 4-mm aggregates (measured for aggregate stability) was varying in proportion to the early-season stability of larger and smaller aggregates (measured for MWD). In other words, droplet energy affected aggregates with diameters from 4 to 8 mm and <1 mm similarly to 1- to 4-mm aggregates. In general, however, larger aggregates are less stable than smaller aggregates (Six et al., 2004; Tisdall and Oades, 1982).

MWD was the soil property measured after one irrigation that was best correlated with sugarbeet seedling emergence (Table 1). The positive correlation coefficient revealed that any management practice that would increase MWD would also increase emergence. One cost-effective practice to increase MWD or at least minimize its decrease under sprinkler irrigation would be to modify center pivot irrigation systems to reduce droplet energy to 8 to 10 J kg^{-1} or less (Figs. 6 and 7, discussed in more detail below). A producer should also irrigate as few times as possible applying no more water than necessary with sprinkler heads as low as possible between planting and emergence (Trout et al., 1990). Another practice effective under both irrigation and rainfall would be to maintain crop residues on the soil surface to absorb water drop or sprinkler droplet kinetic energy (Lehrsch et al., 2005a; Trout

TABLE 2

Sprinkler droplet kinetic energy thresholds at which structural breakdown would be greatest

Year	Response variable†	Droplet energy threshold J kg^{-1}
1998	PR	11.8
1998	Aggregate stability	8.2
1999	PR	10.2
2000	PR	12.1
2000	MWD	8.2
2001	Aggregate stability	13.0
	Mean (±S.D.)	10.6 (±2.1)

†All variables except MWD in 2000 were measured after one irrigation of recently tilled soil. MWD data in 2000 were pooled across sampling periods.

et al., 1990), thereby minimizing structural breakdown (Glanville and Smith, 1988).

Because MWD was positively correlated with aggregate stability (Table 1), any management practice that increases the one will also increase the other. Managers should incorporate organic amendments, such as manure or whey, into their soil. Those amendments increase both soil organic matter and aggregate stability (Lehrsch et al., 1994; Tisdall and Oades, 1982). Similarly, producers should avoid management practices that decrease aggregate stability or organic matter, positively correlated with one another (Lehrsch et al., 1991; Tisdall and Oades, 1982). Managers should not burn crop residues; such avoidance has an added environmental benefit of not emitting CO_2, the greenhouse gas of greatest concern. Moreover, farmers should till no more than necessary while minimizing the weights of equipment used (in so doing, reduce fuel costs) and, when necessary, till only at appropriate soil water contents (Trout et al., 1990).

Droplet Energy Threshold

Soil surface structure is poor when PR is greatest and aggregate stability and size are least. Our fitted responses of PR, aggregate stability, and MWD to energy enabled us to calculate the droplet energy most damaging to soil surface structure (Table 2). Based on this study's significant findings, sprinkler droplet energy of 10.6 J kg^{-1} causes the greatest structural deterioration of a Portneuf silt loam, an agriculturally important soil in the Intermountain Region of the Pacific Northwest.

Stated another way, droplet energy rates of <10.6 J kg^{-1} minimize surface soil structural breakdown. Fortunately, sprinkler systems can be modified to keep droplet energies less than this rate. Spray heads operated at nozzle pressures of ≥103 kPa equipped with nozzles of ≤5.4 mm and with smooth deflector plates would, in the absence of wind, keep droplet kinetic energies at <8 J kg^{-1}, approximately 1 S.D. below the mean shown in Table 2. Alternatively, spray heads operated at pressures of ≥130 kPa equipped with spinning plates having six or more grooves would also keep energies at <8 J kg^{-1}. Yet another option to keep droplet energy low would be to equip spray heads with nozzles of <5 mm, if possible, until seedlings have emerged.

SUMMARY AND CONCLUSION

In our study of sprinkler droplet kinetic energy effects on surface soil PR, aggregate stability, and water-stable aggregate size distribution of Portneuf silt loam, we found that PR measured after one irrigation increased at a decreasing rate as sprinkler droplet kinetic energy increased from 0 to about 12 J kg^{-1}. After 2 or more irrigations, PR decreased linearly with increasing droplet energy.

After one irrigation, aggregate stability at the soil surface (0–6 mm) decreased by about one sixth as droplet energy increased from 0 to 8 J kg^{-1}. After two or more irrigations, 5-year average aggregate MWD decreased by 10%, compared with controls, with droplet energies of ≥8 J kg^{-1}.

Sugarbeet seedling emergence increased linearly as sprinkler droplet kinetic energy decreased in 4 of 5 study years. Sugarbeet emergence increased by 1.08-fold with every 10-J kg^{-1} decrease in droplet energy. We conclude that sprinkler droplet kinetic energy should be reduced to <10.6 J kg^{-1} (S.D., ±2.1 J kg^{-1}) to protect the surface structure of recently tilled soil by minimizing aggregate breakdown, thereby reducing crusting and increasing seedling emergence.

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