Proceedings

San Diego

28TH ANNUAL

INTERNATIONAL IRRIGATION SHOW

DECEMBER 9-11, 2007

IRRIGATION ASSOCIATION

Center Pivot Simulator for Evaluating System Design and Management Effects on Infiltration and Erosion

B.A. King and D.L. Bjorneberg[1]

Abstract
A 4-wheeled commercial irrigation boom was modified for use in investigating center pivot design and management effects on infiltration, runoff and erosion of specific soil types. The center pivot simulator used a hydraulic winch attached to the front of a tractor for mobilization and controlled travel speed. A 3 inch diameter 300 ft drag hose is used to supply water to the center pivot simulator. The center pivot simulator was used to conduct two studies to investigate infiltration, runoff and erosion differences of common commercially available center pivot sprinkler types on a Portneuf silt loam soil. Sprinklers used in the first study were: 1) Nelson R3000 with brown plate, 2) Nelson R3000 with red plate, 3) Nelson S3000 with purple plate, and 4) Senninger I-Wob with standard 9-groove plate. Measured runoff was highly variable despite the controlled experimental conditions. Runoff from all sprinkler types increased with number of irrigations indicating that soil surface sealing continued to increase without reaching a maximum after five irrigations. Measured runoff tended to be the highest for the S3000 and I-Wob sprinklers. Sediment loss tended to be highest for these sprinklers as well. The second study investigated differences in runoff and erosion related to kinetic energy of sprinkler droplets from commercial center pivot sprinklers. The sprinklers used in the study were: 1) Senninger I-Wob with standard 9-groove plate, 2) Nelson R3000 with brown plate, 3)Nelson D3000 spray with flat plate and 4) sprinkler 3 with the runoff plot covered with 20-mesh nylon window screen suspended about 1 inch above the soil surface to eliminate sprinkler droplet impact on the bare soil surface. Covering the plot with screen to eliminate sprinkler droplet impact resulted in significantly ($p \leq 0.05$) less runoff and sediment loss for all four irrigation events. The D3000 and I-Wob sprinklers tended to have the greatest runoff and sediment losses. Sprinkler type and configuration had a significant ($p \leq 0.05$) effect on runoff and erosion of a Portneuf silt loam soil.

Introduction

Center pivot irrigation is currently used on approximately 5.2 million acres in the ten western states of the U.S. Center pivot irrigation is a popular choice for many producers due to its large area of coverage, ease of use and degree of automation. The USDA NRCS Environmental Quality Incentives Program (EQIP) commonly cost shares new center pivot irrigations systems used to replace less efficient surface irrigations system as a means to increase irrigation efficiency and reduce ground and surface water degradation. Center pivot irrigated acreage will likely continue to increase in the near future.

Center pivot irrigation is popular with producers but is not necessarily the best irrigation system choice for all conditions. Water application rates often exceed soil infiltration rates for medium- and fine-textured soils, which can result in substantial runoff, erosion and spatial non-uniformity in water application depth on rolling topography. Over the past two decades center pivot sprinkler manufacturers have, and presently, continue to develop sprinklers that reduce peak water application rates and droplet kinetic energy as a means to sustain infiltration rate and reduce runoff hazard. As a result there are numerous center pivot sprinkler choices available for the producer but little quantitative information that relates these choices to performance on a particular soil type.

---

[1]The authors are Bradley A. King, Agricultural Engineer, and David L. Bjorneberg, Agricultural Engineer, USDA ARS NWISRL, 3793 N. 3600 E., Kimberly, Idaho 83341-5076.

Mention of trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the authors or the USDA and does not imply approval of product to the exclusion of others that may be suitable.

The operational characteristics of center pivot sprinklers such as wetted diameter, application rate pattern shape and drop size distribution have been reported in the scientific literature (e.g. Kincaid et al., 1996; Faci et al., 2001; DeBoer, 2001; Sourell et al., 2003; Playan et al., 2004; Kincaid, 2005;). However, studies evaluating the effect operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types are limited. This is especially true for the low organic matter calcareous soils found in the arid western U.S whose aggregate structure readily breaks down under sprinkler droplet impact to form surface seals that reduce water infiltration rates.

Runoff under center pivot irrigation systems tends to be quite variable due to spatial variability in soil texture, roughness and slope (Kincaid, 2002). The effect of small differences in the operating characteristics of commercially available sprinklers on infiltration, runoff and erosion is likely to be small as well. Thus to experimentally evaluate any effect under field conditions, uncontrollable extraneous factors due to spatial variability must be minimized. One approach to accomplish this is to have evaluation measurements collected in close proximity to each other in order to minimize slope and soil physical and chemical property differences. This is virtually impossible with field scale center pivot systems due to their large size and overlapping of sprinkler patterns needed to achieve high water application uniformity. The objective of this study was to overcome this limitation by developing a center pivot simulator that will allow experimental treatments on small replicated field plots for evaluation of center pivot design and management effects on infiltration, runoff, and erosion for specific soil types.

Methods and Materials

A 4-wheel commercial irrigation boom 154 ft in length (Briggs Irrigation, Northhamptonshire, UK) was used as the basis for the center pivot simulator. The irrigation boom was modified by increasing the boom height 18 inches and adding additional sprinkler outlets along the boom length. Two additional sprinkler outlets were added between each existing outlet to provide a 48 to 51 inch spacing between adjacent outlets. The commercial irrigation boom uses a hose reel to mobilize the system and supply water to the mobile boom. However, we used a cable winch system to mobilize the irrigation boom and a 3 inch, 300 ft drag hose to supply water to the irrigation boom. The cable winch system consisted of a hydraulic winch (Series 15, Warn Industries, Inc., Clackamas, OR) mounted on the front of a John Deere 1020 tractor. The tractor hydraulic system was used to power the hydraulic winch.

Travel speed of the irrigation boom (towing cable speed) was controlled using a closed-loop electronic control system. Hydraulic fluid flow rate to the winch hydraulic motor was controlled by a electro-hydraulic proportional flow regulator (PFR72-33BM-L160-12T-N-12DL, Hydraforce, Inc., Lincolnshire, IL). The proportional flow regulator controlled hydraulic fluid flow rate proportional to input current to a 12 VDC solenoid supplied by a proportional valve controller (4000046, Hydraforce, Inc., Lincolnshire, IL). The valve controller used a 0-5 VDC input to control output 12 VDC current to the solenoid. A programmable data logger (CR21X, Campbell Scientific Inc., Logan, UT) was used to supply the 0-5 VDC control input. Irrigation boom travel speed was determined by passing the towing cable over a 3 inch diameter rubber roller 16 inches wide mounted on a four-legged metal stand placed about 8 ft in front of the hydraulic winch. An incremental hollow shaft encoder (MEH30-1000P-F1-P-38, CUI, Inc., Beaverton OR), with 1000 pulses per shaft revolution, attached to one end of the rubber roller shaft was used to measure irrigation boom travel speed. A proportional-integral closed-loop control algorithm programmed into the data logger was used to control cable speed to a set value. The control algorithm measured cable speed and updated the 0-5 VDC output to the valve controller once every second to maintain a set travel speed.

The effect of water application and management decisions on runoff and erosion were measured using 3.3 feet (1 m) wide by 6.6 feet (2 m) long plot areas. A metal frame border was used to collect runoff and prevent plot runon from the surrounding area. The metal frame was made of 3/16-inch thick steel 3-inches in width orientated vertically on three sides. The bottom edge of the metal frame was driven into the ground to a depth of about 1.5 inches to channel the runoff and prevent runon. The down slope outlet end of the frame had a horizontal metal lip along its length about 2.5 inches in width for runoff to leave the frame without excessive erosion due to head cutting. Along the down slope length of the metal lip was a metal trough sloped to one edge of the metal frame to collect runoff and channel it to a collection bucket in a hole dug near the corner of the metal frame. The depth of water in the bucket was measured with a ruler to determine runoff volume. The bucket was covered to prevent water from sprinklers contributing to runoff water volume. The combined horizontal width of the lip and trough was about 3.25 inches. Water application to the lip and trough adds to the total runoff volume and was accounted for when calculating plot runoff volume. Average soil moisture in the top 8 inches of the soil profile in each runoff plot was measured using time domain reflectometry (TDR100, Campbell Scientific, Inc., Logan UT) prior to each irrigation event.

The center pivot simulator was used to investigate runoff and erosion of a Portneuf silt loam soil from common commercial sprinkler types found in Idaho. Sixteen runoff plots were installed in a four row by four column arrangement as shown in figure 1. The field area slope ranged from 4 to 6%. The field was roller harrowed prior to establishment of the runoff plots. The metal plot frames were installed at a constant slope of 5%. The soil surface within the metal frames was graded to a 5% slope and smoothed. The rather steep slope and smoothed soil surface of the plots was selected to minimize the unknown and variable surface storage component of the infiltration-runoff-erosion process. Four common commercial sprinklers were used in this first study to investigate infiltration, runoff and erosion differences, if any. They were: 1) Nelson R3000 with brown plate (Nelson Irrigation Corp., Walla Walla, WA) with a 20 psi regulator, 2) Nelson R3000 with red plate with a 20 psi regulator, 3) Nelson S3000 with purple plate with a 15 psi regulator, and 4) Senninger I-Wob with standard 9-groove plate (Senninger Irrigation Inc., Clermont, FL) with 15 psi regulator. Sprinkler nozzle sizes were selected to be representative of those used on the outer end of ¼-mile center pivot systems in Idaho. The sprinkler nozzle sizes were also selected to provide approximately the same flow rate per sprinkler regardless of operating pressure or manufacturer. The selected sprinkler nozzle sizes and corresponding flow rates were; 1) 0.297 inch (#38) rated at 11.28 gpm, 2) 0.297 inch (#38) rated at 11.28 gpm 3) 0.320 inch (#41) rated at 11.48 gpm, and 4) 0.328 inches (#21) rated at 11.36 gpm, respectively. Sprinkler height was approximately 5 feet above ground level. Sprinkler spacing along the boom was 96 to 102 inches. Five consecutive irrigations were applied to the runoff plots with an irrigation interval of 7 to 15 days to allow the soil surface to dry and soil profile to drain between irrigations. All irrigation applications were to bare soil conditions. Only half the length of the irrigation boom was used to apply water to the runoff plots.

The four sprinkler configurations (treatments) were randomly assigned to the sixteen plots with one treatment per row and column in order to obtain a Latin Square statistical design. Twelve of the sixteen plots were covered with waterproof polyethylene tarps when the center pivot simulator passed over the plot area with a particular sprinkler treatment. Then the center pivot simulator sprinklers were changed, the tarps repositioned and the simulator repositioned and towed upslope over the plot area again to apply a different sprinkler treatment. Two irrigation treatments were completed in a given day with the remaining two the following day. All the tarps were installed and removed at the same time to minimize differences in soil drying between irrigation events. There were four washouts at the lower end of the metal frames underneath the overflow lip that prevented accurate measurement of runoff during two irrigation events. A tractor problem prevented accurate runoff data collection for the R3000 sprinkler with the red plate on the fourth irrigation event. For irrigations events where loss of runoff data occurred, the results were analyzed using a Randomized Block experimental design with uneven sample sizes.

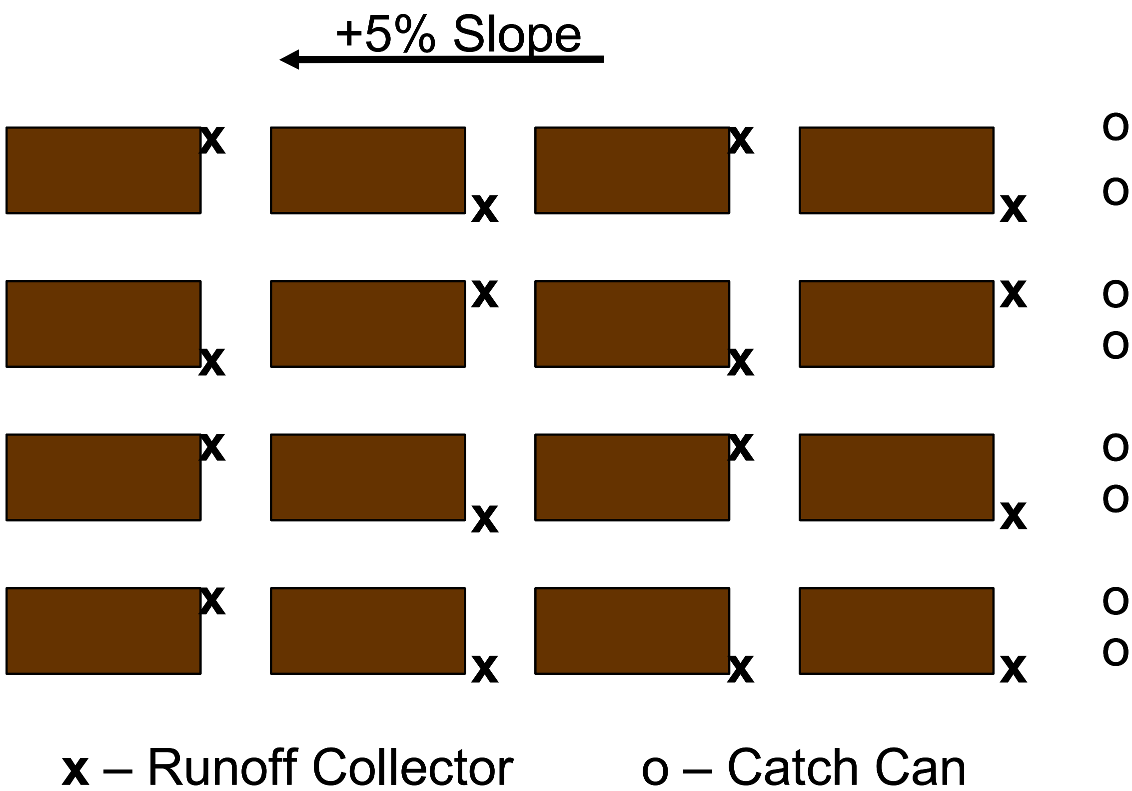

Figure 1. Runoff plot layout used in both field studies.

Statistical analysis was conducted using the SAS GLM procedure and Duncan's Multiple Range test for comparison of treatment means (SAS, 2007). Sediment mass in runoff was measured using vacuum filtration and filter paper.

The center pivot simulator was also used to investigate the effect droplet kinetic energy from common commercial center pivot sprinkler types has on infiltration, runoff and erosion of a Porrneuf silt loam soil. The same sixteen runoff plots used in the first study were used in the second study. The soil within the metal frames was tilled with a garden-type rear-tined rototiller and the soil surface graded to a 5% slope and smoothed. The sprinklers selected to provide a range in sprinkler droplet kinetic energy were; 1) Senninger I-Wob with standard 9-groove plate (Senninger Irrigation Inc., Clermont, FL) with a 15 psi regulator, 2) Nelson R3000 with brown plate (Nelson Irrigation Corp., Walla Walla, WA) and a 20 psi regulator, Nelson D3000 spray with flat plate with a 15 psi regulator, and 4) sprinkler 3 with the runoff plot covered using 2 layers of 20-mesh nylon window screen to eliminate sprinkler droplet impact on the bare soil surface. The 20-mesh screen had openings about 0.05-inch square and was suspended about one inch above the soil surface on a coarse grid of ¼-inch diameter wire paneling. Droplet kinetic energy was dissipated on the nylon screen above the plot surface. Sprinkler nozzle sizes were selected to provide approximately equal flow rate per sprinkler regardless of sprinkler type or manufacturer. The selected sprinkler nozzle sizes were; 1) 0.328 inch (#21) rated at 11.36 gpm, 2) 0.297 inch (#38) rated at 11.38 gpm, 3) 0.320 inch (#41) rated at 11.48 gpm and 4) 0.320 inch (#41) rated at 11.48 gpm, respectively. Sprinkler height was approximately 5 feet above ground level. Sprinkler spacing along the irrigation boom was 96 to 102 inches. Four consecutive irrigations were applied to the runoff plots with an irrigation interval of 7 to 10 days to allow the soil surface to dry and soil profile to drain between irrigations. All irrigations were to bare soil conditions. Only half of the boom length was used to apply water to the runoff plots. Irrigation events were completed in a single day.

The four sprinkler configurations (treatments) were randomly assigned to the sixteen plots with one treatment per row and column in order to obtain a Latin Square statistical design. Statistical analysis was conducted using SAS GLM procedure and Duncan's Multiple range test for means comparison (SAS, 2007). During the first irrigation event ponding on the layers of the nylon screen was observed which caused some uneven water application over the plot area. One layer of the nylon screen was removed for subsequent irrigation events, which alleviated ponding on the screen cover.

Results

Percent runoff (runoff volume / application volume x 100) for each sprinkler type and irrigation event in the first study are shown in figure 2. Application depths for the five irrigation events were 0.96, 0.8, 0.6, 0.6, and 0.6 inches, respectively. Soil moisture in the top 8 inches of the soil profile measured prior to each irrigation event averaged 0.15, 0.15 0.14, 0.15, and 0.13 inches/inch for the five irrigation events, respectively. Runoff measurements were highly variable despite the controlled experimental conditions and small distances between plots, limiting detection of significant differences in runoff among sprinkler types. In general, percent runoff increased with the number of irrigations. This result is attributed to reduced infiltration rates caused by soil surface sealing due to sprinkler droplet impact on the bare soil

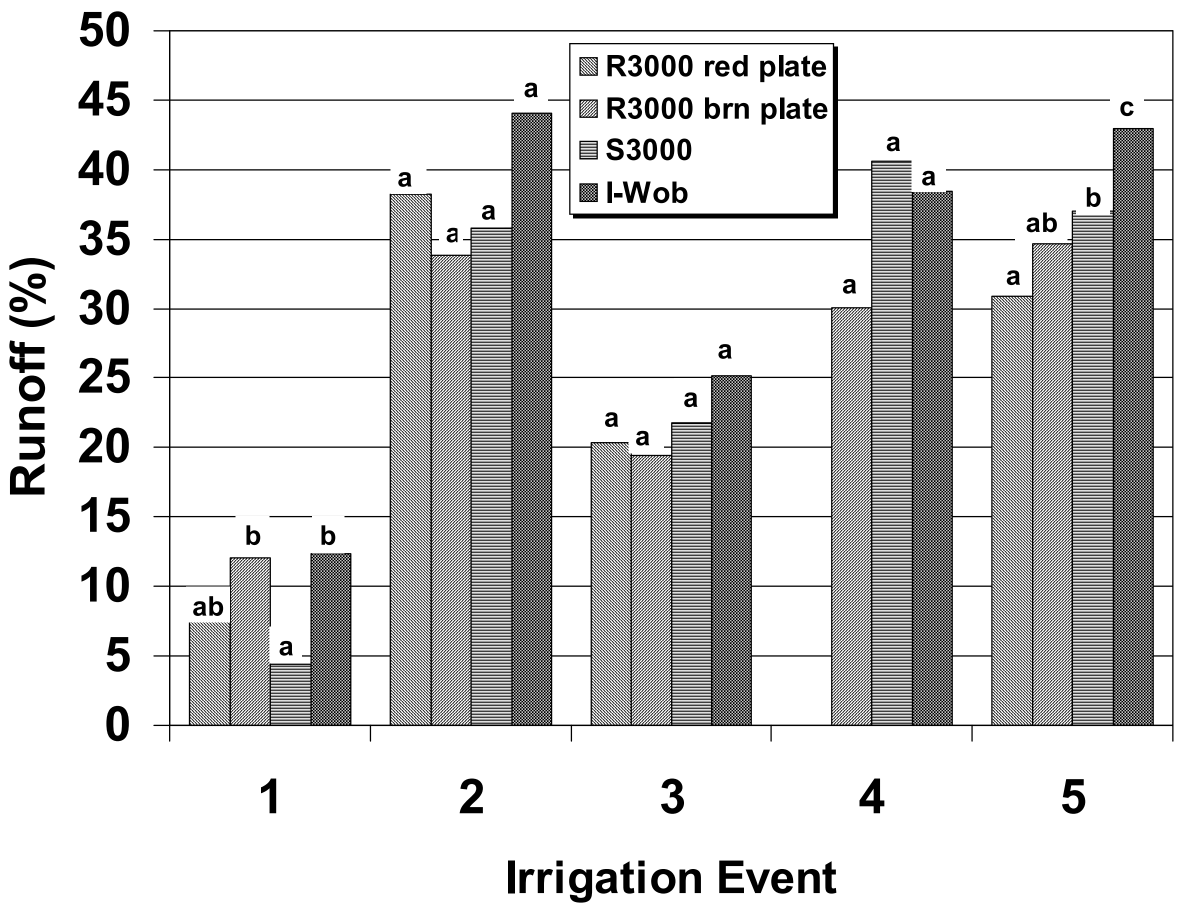

Figure 2. Percent runoff measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

surface and consistent with the findings of Thompson and James (1985), DeBoer et al., (1988), Agassi et al., (1994) and Lersch and Kincaid (2000). Percent runoff continued to increase for irrigations three through five indicating that soil surface sealing increased with continued irrigation without reaching a maximum. By the fifth irrigation event a trend in runoff percentage differences between sprinkler types began to appear but additional testing is required to verify this result.

Sediment losses for each sprinkler type and irrigation event in the first study are shown in figure 3. In general, sediment loss was positively correlated with runoff volume. Since measured runoff was highly variable, so was measured sediment loss. However, for irrigation events three through five a trend starts to emerge where the I-Wob produced the highest sediment loss of the four sprinkler types even though runoff was not necessarily the highest. The S3000 sprinkler produced the next highest sediment loss. These two sprinkler types appear visually to spread the sprinkler droplets out more evenly over the wetted diameter with respect to time than the R3000 sprinkler. This functional difference may cause sediment to remain in suspension in overland flow for a longer duration allowing it to be more readily transported down slope. Average sediment concentration in the measured runoff for each sprinkler type is shown in figure 4. For irrigation events two through five, sediment concentration tended to be lowest for the R3000 sprinklers and was significantly ($p \leq 0.05$) less for irrigation events three and four. The very high

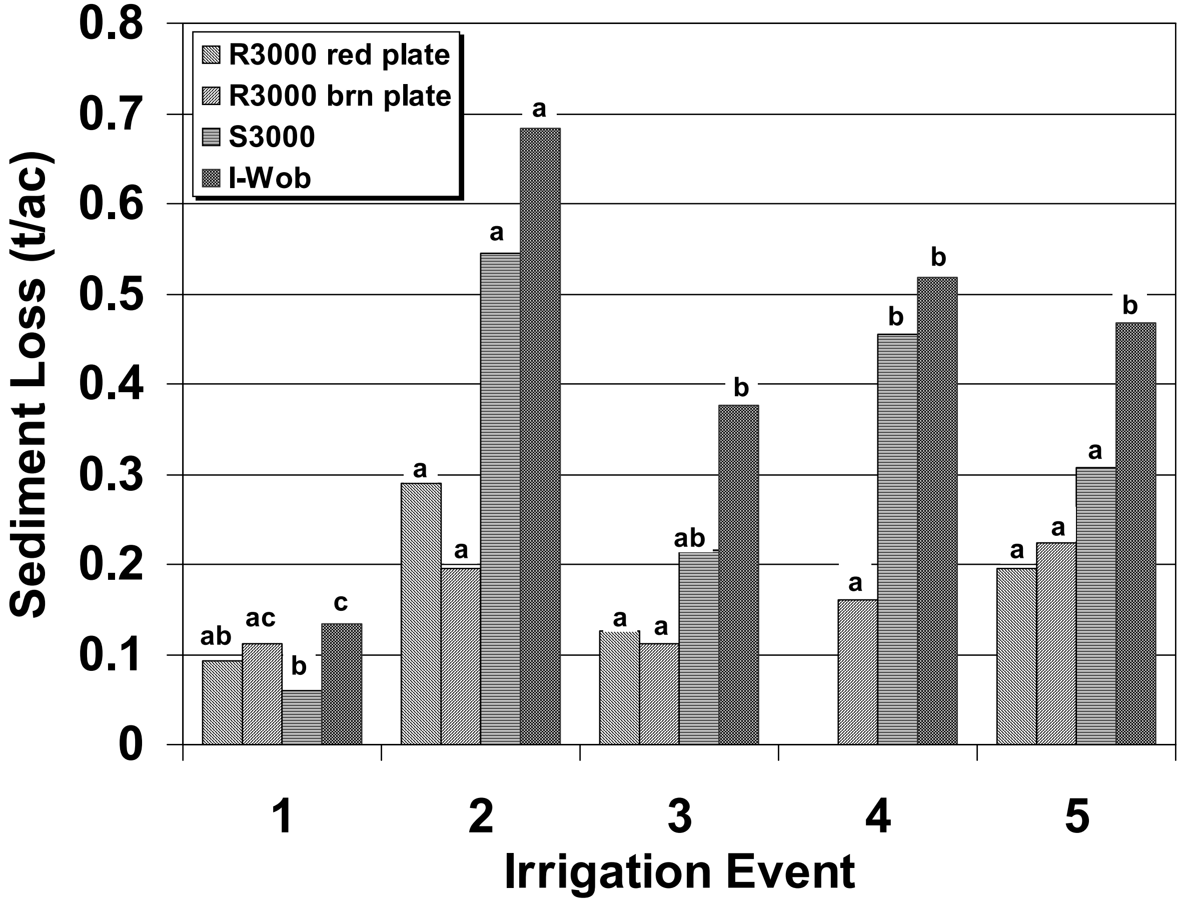

Figure 3. Sediment loss measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

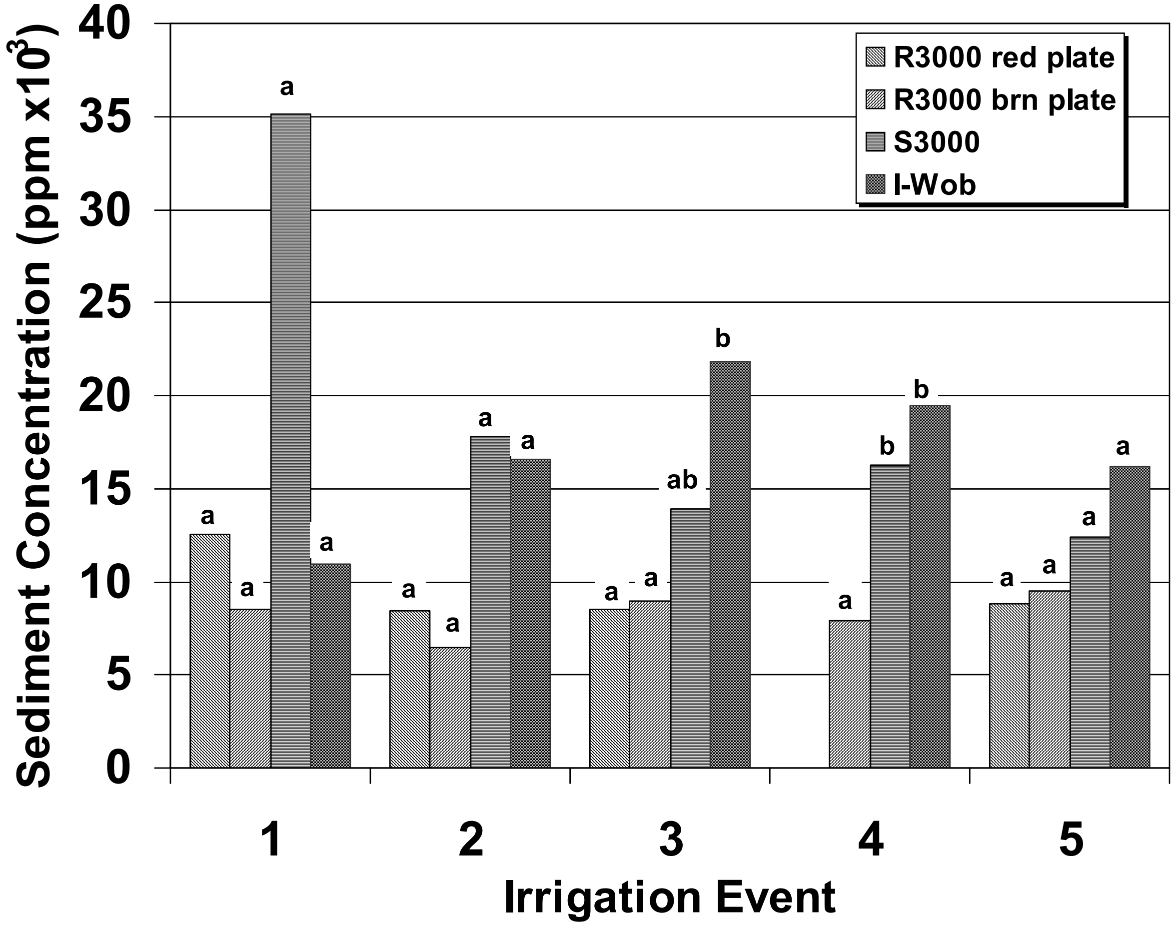

Figure 4. Sediment concentration measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

sediment concentration for the S3000 sprinkler for irrigation event one is the result of a single runoff measurement with an extremely high sediment concentration (0.19 pounds) associated with a very small runoff volume (0.1 gallon). Another possible explanation for the differences in sediment concentrations in the measured runoff is a difference in breakdown rate of soil surface aggregate structure releasing fine grain material at different rates between sprinkler functional types.

Percent runoff for each sprinkler type and irrigation event in the second study is shown in figure 5. Application depths for the four irrigation events were 0.96, 0.6, 0.6, and 0.6 inches, respectively. Soil moisture in the top 8 inches of the soil profile measured prior to each irrigation event averaged 0.12, 0.13, 0.14, and 0.15 inches/inch for the four irrigation events, respectively. The measured runoff was again quite variable. However, for irrigation events one, three and four the I-Wob and D3000 spray sprinklers produced the highest runoff volumes. The peak application rate of the D3000 spray was about 50% higher than the I-Wob or R3000 sprinklers due to its smaller wetted diameter. The higher peak application rate of the D3000 spray is largely responsible for the high measured runoff despite the lower kinetic energy of the droplets due to there smaller size. For irrigation events one, two, and three, measured runoff for the R3000 sprinkler was not significantly different than that of the covered plot with

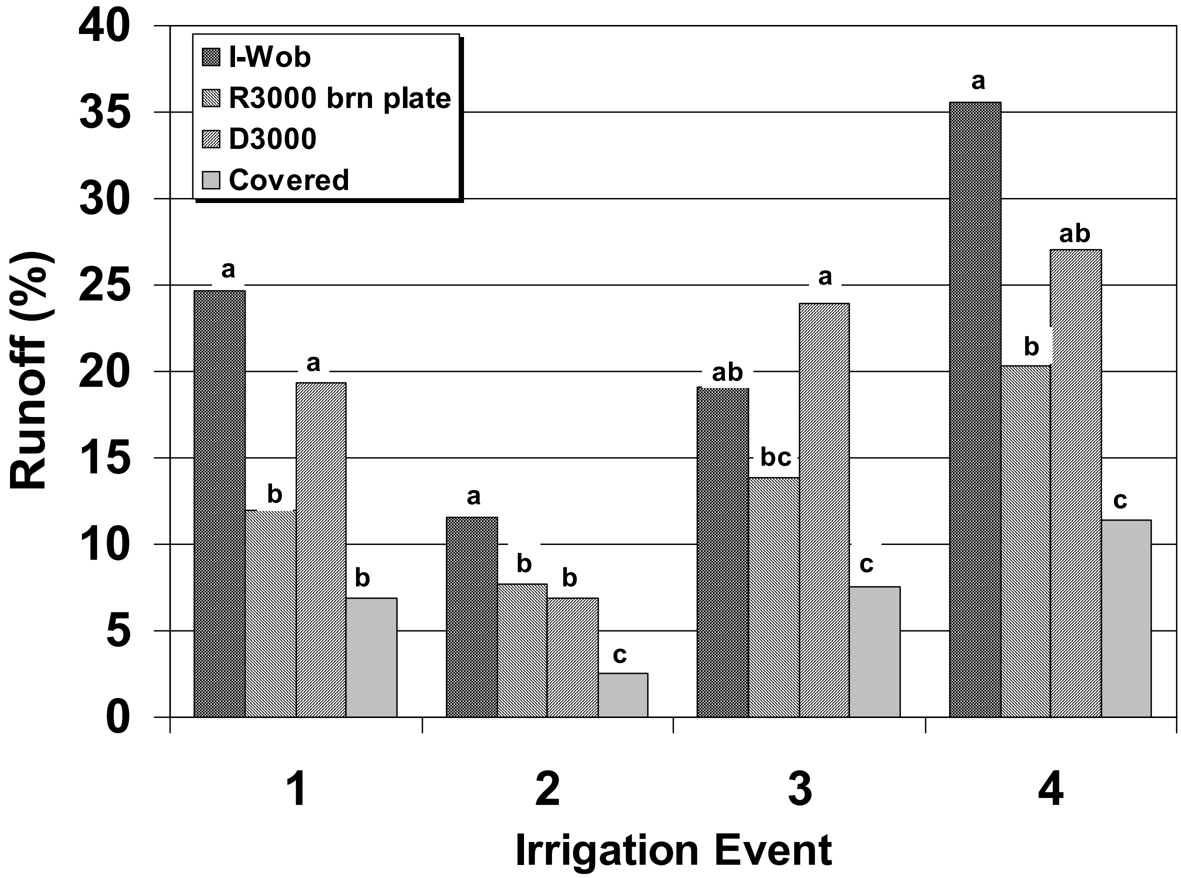

Figure 5. Percent runoff measured for the four irrigation events in the second field study. Columns with the same letter are not significantly different at the 0.05 level.

the D3000 spray sprinkler. Percent runoff continued to increase for irrigations two through four indicating that soil surface sealing increased with continued irrigation regardless of kinetic energy level.

Sediment losses for each sprinkler type and irrigation event in the second study are shown in figure 6. In general, sediment loss is positively correlated with runoff volume. The I-Wob and D3000 sprinklers produced the highest sediment losses. This is consistent with the results of the first study were sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time produce the highest sediment losses. For the first two irrigation events the R3000 and covered plot treatment had significantly ($p \leq 0.05$) less sediment loss than the I-Wob sprinkler. For irrigation events two through four, all the sprinklers resulted in significantly higher sediment loss compared to the covered soil surface.

Summary and Conclusions

A 4-wheeled commercial irrigation boom was modified and used to simulate center pivot irrigation to small replicated runoff plots. The center pivot simulator uses a hydraulic winch attached to the front of a tractor for mobilization and as a means to provide controlled travel speed. A 3 inch diameter 300 ft drag

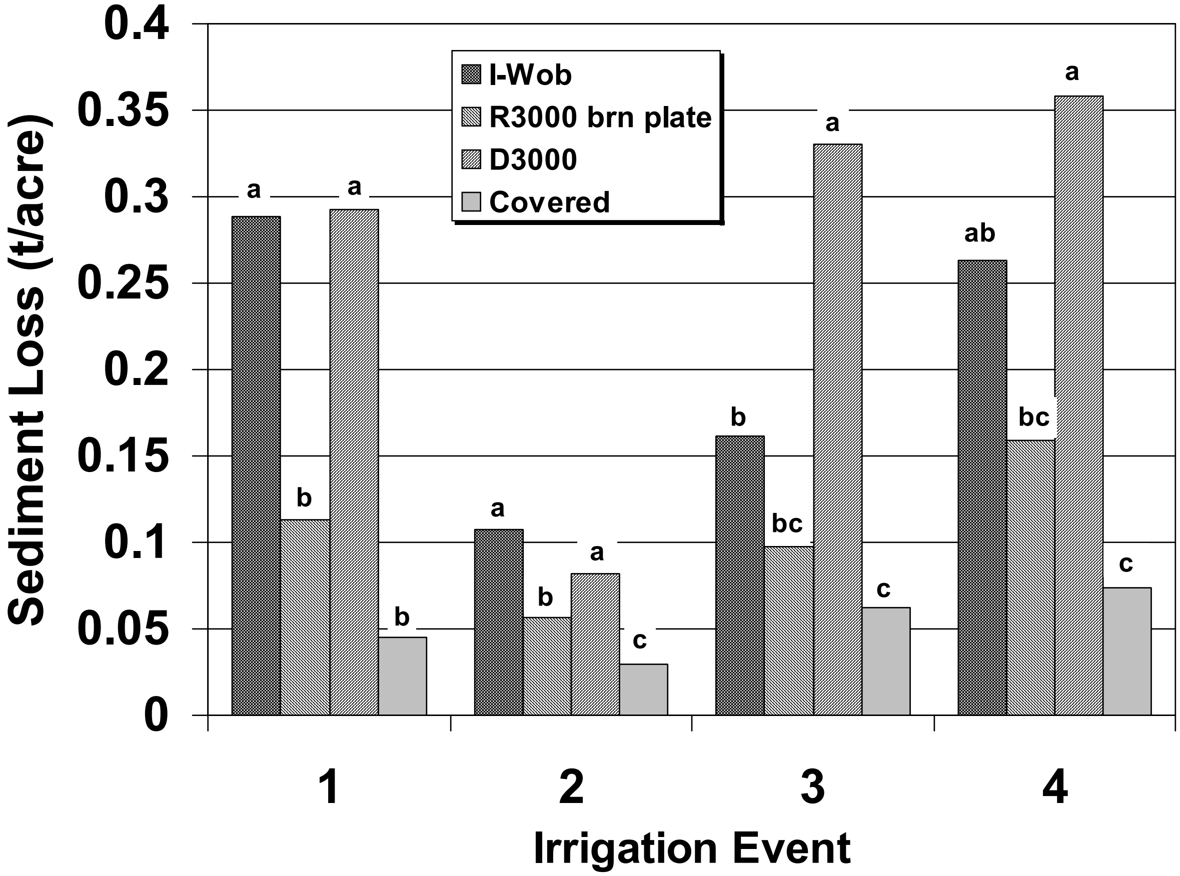

Figure 6. Sediment loss measured for the four irrigation events in the second field study. Columns with the same letter are not significantly different at the 0.05 level.

hose is used to supply water to the center pivot simulator. The center pivot simulator was used to conduct two studies to investigate infiltration, runoff and erosion differences of common commercially available center pivot sprinkler types on a Portneuf silt loam soil.

The results of the two runoff studies on a Portneuf silt loam soil indicate that center pivot sprinkler types that visually appear to more uniformly distribute droplets over the wetted area with respect to time tend to produce more runoff and sediment loss. This may be due to detached soil particles remaining suspended in overland flow for longer periods of time resulting in greater transport down slope and/or faster breakdown of soil aggregate structure releasing fine grained soil particles sooner. The results also show that sprinkler type and configuration has a significant effect on runoff and sediment losses for a Portneuf silt loam soil. Runoff experiments need to be conducted on additional soils and varying water application depths to validate these results.

Acknowledgement
The Briggs Irrigation boom used in this study was provided by Nelson Irrigation Corp. Walla Walla, WA through a material transfer agreement with the USDA ARS Northwest Irrigation and Soils Research Laboratory.

References

Agassi, M., D. Bloem, and M. Ben-Hur. 1994. Effect of drop energy and soil and water chemistry on infiltration and erosion. *Water Resources Research* 30(4):1187-1193.

DeBoer, D.W. 2001. Sprinkler application pattern shape and surface runoff. *Trans. ASAE* 44(5):1217-1220.

DeBoer, D.W., Asghar Moshref-Javadi, and S.T. Chu. 1988. Application of the Green-Amp infiltration equation to sprinkler irrigation management. *Applied Agricultural Research* 3(3):128-132.

DFaci, J.M., R. Salvador, E. Playan, and H. Sourell. 2001. A comparison of fixed and rotating spray plate sprinklers. *J. Irrig. Drain. Eng. ASCE* 127(4):224-233.

Kincaid, D.C. 2005. Application rates from center pivot irrigation with current sprinkler types. *Applied Engineering in Agriculture* 21(4):605-610.

Kincaid, D.C. 2002. The WEPP model for runoff and erosion prediction under sprinkler irrigation. *Trans. ASAE* 45(1):67-72.

Kincaid, D.C., K.H. Solomon and J.C. Oliphant. 1996. Drop size characteristics for irrigation sprinklers. *Trans. ASAE* 39(3):839-845.

Lersch, G.A. and D.C. Kincaid. 2000. Sprinkler droplet energy effects on infiltration and near-surface, unsaturated hydraulic conductivity. p. 283-286. In: D. Bosch et al., (eds.) *Preferential flow: water movement and chemical transport in the environment.* Proc. 2nd Int. Symp. , Honolulu, HI.

Playan, E., S. Garrido, J.M. Faci and A. Galan. 2004. Characterizing pivot sprinkler using an experimental irrigation machine. *Agricultural Water Management* 70:177-193.

SAS. 2007. Statistical Analysis Software version 9.1.3. Statistical Analysis Institute, Inc., Cary, NC, USA.

Sourell, H., J.M. Faci, and E. Playan. 2003. Performance of rotating spray plate sprinklers in indoor experiments. *J. Irrig. Drain. Eng. ASCE* 129(5):376-380.

Thompson, A.L. and L.G. James. 1985. Water droplet impact and its effect on infiltration. *Trans. ASAE* 28(5):1506-1510.