PARTITIONING OF SPRINKLER IRRIGATION WATER BY A CORN CANOPY

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ABSTRACT. *The total sprinkler irrigation amount is partitioned by the crop canopy into three major components: stemflow, throughfall, and interception storage. A study of the partitioning process by a fully developed corn canopy under low wind conditions was conducted. Nearly 3000 measurements of stemflow were made over the course of 23 irrigation/precipitation events using 240 different plants during the two years of the study. At the same time, nearly 300 measurements of the throughfall were made. The objectives were to determine if the process varies between sprinkler types, to determine what factors affect the partitioning process, and to develop models for the process. The partitioning process was examined at three plant spacings and six irrigation amounts under high-pressure impact sprinklers (HI), low-pressure spray heads on drop tubes at a 2.2 m height (LS), low-pressure spray heads at a 4.1 m height (LS-4.1), and also under natural precipitation. Stemflow decreased linearly with plant spacing and increased linearly with irrigation amount. Throughfall increased linearly with both plant spacing and irrigation amount. After tasseling, stemflow is the predominate flow path for sprinkler irrigation water, accounting for 53% at a typical plant spacing of 20 cm. Throughfall accounted for 43% of a typical irrigation amount (25 mm). Interception storage, estimated by algebraic closure, was 1.8 mm when averaged over all events. Comparisons of the developed models with previous research indicates reasonable stability of the partitioning process even though corn production systems and corn plant structure have changed over time. Statistically significant differences occurred in the partitioning process between the LS, LS-4.1 and the HI systems, with the LS-4.1 and HI systems being more similar to natural precipitation. The similarities in stemflow between the LS-4.1 and the HI systems suggests that the differences in stemflow for the LS system may be caused by the height and angle at which applied water intercepts the crop canopy. The average stemflow percentages for the three plant spacings was 46, 43, and 43% for the LS, LS-4.1, and HI systems, respectively.*
Keywords. *Irrigation, Stemflow, Throughfall, Interception, Partitioning, Crop canopy, Sprinkler pattern.*

Center pivot sprinkler designs can be classified into two major types, impact sprinkler and spray head systems. Impact sprinkler systems typically have significantly higher operating pressures than spray head systems. A large percentage of the center pivot sprinkler irrigation systems currently being placed on southern and central Great Plains farms are classified as low-pressure spray systems. The peak application rate from low-pressure spray heads is significantly higher than that from high-pressure impact systems. Because low-pressure spray heads have a much smaller diameter of applied water, they must apply water at a much higher rate to apply similar amounts of irrigation.

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The total sprinkler irrigation amount is partitioned by the crop canopy into four components: stemflow, throughfall, interception storage, and in-canopy evaporation. Stemflow is the amount of irrigation water that flows down the leaves to the leaf-stalk node and then down the stem to the soil surface. Numerous researchers have pointed out the significance of stemflow for corn (Kiesselbach, 1916; Haynes, 1940; Glover and Gwynne, 1962; Quinn and Laflen, 1983; Steiner et al., 1983; Lamm, 1984; Wesenbeeck and Kachanoski, 1988). Throughfall represents any irrigation water that reaches the soil surface by directly or indirectly falling through the plant leaf structure. Interception storage is the amount of water temporarily remaining on the plant after irrigation. This includes water on leaf and stem surfaces and water trapped in the leaf sheath area. Most interception storage eventually evaporates. In-canopy evaporation is the amount of evaporation occurring within the canopy during the irrigation event. It often is considered negligible (Steiner et al., 1983; Thompson et al., 1996; Schneider and Howell, 1995).

Wesenbeeck and Kachanoski (1988) measured soil water in the tillage layer around corn plants with time domain reflectometry methods. They found an increase in soil water recharge around plants, which they attributed to stemflow. Warner and Young (1989) reported stemflow as high as 40% of the incident rainfall for mature corn and considerable plant-to-plant variation. They also found significant preferential flow immediately beneath the corn row. The interrelationship between stemflow and preferential flow may be of considerable importance for a crop such as corn. Indeed, Glover and Gwynne (1962) reported that stemflow was an important mechanism in survival of corn plants in East Africa. They found wetter soils in a 20 cm band around the plants extending up to 10 cm into the profile as compared to just a few mm in the interrow. Soil sampling also showed a much higher concentration of roots in the areas associated with the deeper wetting fronts.

Quinn and Laflen (1983) reported that, for corn, up to 49% of the incident rainfall was partitioned into stemflow. It was calculated as the difference between incident rainfall and the amount of throughfall collected in troughs beneath the canopy. Stemflow increased as canopy cover increased and tapered off as the crop matured. Increasing the row width from 50 to 75 cm decreased the stemflow percentage from 57 to 43%. Increasing the row width increased the fraction of throughfall percentage from 44 to 57%. Plant spacing was held constant at 30.5 cm.

Steiner et al. (1983) reported direct measurements of stemflow varying from 35 to 64% of incident irrigation amount and a mean of approximately 47% for fully tasseled corn with a leaf area index greater than three. Proportions of stemflow were reported to be similar regardless of whether the water was applied as sprinkler irrigation using low-angle impact sprinklers or received as rainfall. Throughfall ranged from 31 to 55% and averaged 43% of the irrigation amount.

Haynes (1940) measured throughfall for several crops including corn and found that the distribution was influenced by the character of the vegetative growth. The canopy structure for corn tends to pass precipitation toward the plant stem with a "funneling" effect. Haynes found throughfall to be about 70% of the incident precipitation for corn on a seasonal basis. Its distribution was more uniform under drilled crops than under row crops.

Armstrong and Mitchell (1987a) measured the distribution of transformed rainfall under corn and soybean. They pointed out that the redistribution methods are appreciably different. Soybean tends to concentrate the water near the canopy edge, indicating a "shingle" effect. In corn, throughfall is redistributed across the row interspace in an approximately periodic distribution. In a related article, Armstrong and Mitchell (1987b) pointed out that peak throughfall amounts could be as much as 47 times the precipitation amount for discrete locations in the crop canopy. However, the average amount is much less. They attributed this periodicity in throughfall amounts to the periodicity of openings in the canopy or of leaf characteristics.

Steiner et al. (1983) reported interception storage for fully tasseled corn of approximately 2.7 mm. This value compares well with values reported by Seginer (1967) and Smajstrla and Hanson (1980) of 2.5 mm for corn canopies.

In visual observations of center pivot sprinkler-irrigated corn, Lamm (1984) noted significantly more erosion at the base of corn plots irrigated with spray heads on drop tubes than with impact sprinklers. He attributed this to differences in stemflow between the two system types, hypothesizing that stemflow was higher for the spray head system.

Differences in the canopy partitioning process between sprinkler types may have physical and economic importance. Knowledge of differences in stemflow could be important in developing chemigation techniques that call for precise application to the target area that could be either the soil or the foliage. Engineers and sprinkler designers could use partitioning information in design to limit soil erosion and surface sealing by sprinklers. Differences in the partitioning process ultimately could affect infiltration and redistribution of the water in the soil profile. Nonuniform infiltration recently has become an important water quality issue.

One objective of this research was to document if such differences in the partitioning process within a fully developed corn canopy truly exist among center-pivot sprinkler designs and natural precipitation. Other objectives were to determine what factors affect the partitioning process and to develop models for the process.

Procedures

The study was conducted at the Kansas State University Northwest Research-Extension Center at Colby, Kansas, during the summers of 1987 and 1988.

In 1987, the partitioning process was examined for two irrigation amounts (13 and 38 mm) under two sprinkler types: high-pressure impact sprinklers (HI) and low-pressure spray heads on drop tubes at a 2.2 m height (LS). The process was examined at three radii from the center pivot point representing three application intensities. In addition, the process was examined for three corn plant spacings replicated at each radii.

A 126-m, three-span, electric drive, center pivot sprinkler system was used in this study. The center pivot was designed to allow for either high-pressure 310 kPa impact sprinklers or low-pressure 103 kPa spray heads. The HI and LS sprinklers, and pressure regulators were manufactured by Senninger Irrigation Inc., Orlando, Florida. The 360° spray heads (LS) with convex medium serrated impingement pads were mounted on drop tubes leaving the sprinkler approximately 2.2 m above the soil surface which would be down into the upper levels of fully tasseled corn. The resultant impingement angle on fully tasseled corn was approximately 20° from horizontal. The HI sprinklers with a 12° exit trajectory were 4.1 m above the soil surface. The largest concentration of water droplets from these sprinklers struck the crop canopy at approximately 70° from the horizontal. Switching between sprinkler types was accomplished manually. No change was made in the actual center-pivot line pressure, and the LS sprinkler pressure was reduced by regulators.

The center pivot sprinkler irrigation system covered 5 ha directly under the lateral and had a total cropped area of approximately 5.3 ha on a land slope of approximately 0.5%. This study was superimposed onto a larger study area examining tillage and sprinkler type effects. Design of the existing sprinkler-tillage study allowed for this irrigation amount partitioning study to be superimposed in the northeast corner of the southern half of the center pivot sprinkler-irrigated area. This site allowed for separate irrigation of the partitioning study under the LS sprinklers and concurrent irrigation with the sprinkler-tillage study under the HI sprinklers. The study area was located between the second and third towers of the center pivot (75 and 113 m) and was buffered by at least 10 m of corn planted on all sides. Because of the prevailing southwest wind direction, the sprinkler lateral usually was nearly perpendicular to the wind as it crossed the study area.

The four combinations of sprinkler type and irrigation amount in 1987 were replicated randomly at least four times, with minor exceptions, within each four-event block at the start of each time block. The irrigation schedule for the larger sprinkler tillage study was made to make projections of anticipated irrigation dates for the HI sprinklers. The HI sprinkler treatments had to be scheduled concurrently with irrigation for the sprinkler-tillage study. In most cases, this did not present a problem; however, if the first randomization seriously delayed a needed irrigation event, the events were re-randomized to provide a more reasonable schedule. The partitioning process was studied in fully tasseled corn for 19 events during the period 23 July through 19 August 1987. The first five events were excluded from analysis because of severe leakage from the stemflow collection units. Stemflow and throughfall were measured for the one precipitation event during the period.

The partitioning process was examined for five irrigation amounts (3, 6, 19, 38, and 51 mm) in 1988 at two radii from the center pivot point. Each combination of sprinkler type and irrigation amount was conducted once during the season. The partitioning process was studied in fully tasseled corn for 14 events during the period 29 July through 18 August 1988, which included three significant precipitation events. An additional LS event, with the spray heads located above the canopy at a height of 4.1 m, was conducted to examine the effect of LS sprinklers height on the partitioning process. The 1988 combinations of sprinkler type and irrigation amount were assigned randomly during the study period, but no attempt was made to block the five combinations. As in 1987, the HI sprinkler treatments had to be scheduled concurrently with irrigation for the sprinkler-tillage study.

Application intensity increases with distance from the center of the center-pivot system. The partitioning process was studied at the three intensities in 1987 obtained at distances 81.7, 93.9, and 106.1 m from the pivot point (fig. 1). These distances coincided with location of LS devices. The LS sprinklers were 3.05 m apart, and the HI sprinklers were 12.2 m apart. There was a 1.5 m offset between the two sprinkler types, resulting in HI locations at 83.2, 95.4, and 107.6 m. In 1988, only the first two intensity sites were studied. The actual intensities were computed from data obtained during the irrigation events. The intensity factor is tied to the distance from the pivot point, so any other differences in plot areas will be included in the intensity factor results.

Corn hybrid Pioneer 3377 was planted in 76 cm rows on 24 April 1987, and 27 April 1988. Six corn rows were precisely centered and circularly planted at the desired radius, such that a LS sprinkler would pass between two corn rows (sprinkler lateral nearly perpendicular to corn rows). Three plant spacings of 20, 30, and 41 cm were obtained by hand thinning and were randomized within each intensity site.

At each intensity-plant spacing subsite, primary data collection was made on two adjacent corn rows located 38 and 114 cm from the corresponding LS sprinkler. Because the LS sprinkler effectively irrigates 4 rows, by symmetry, the two-row arrangement gave satisfactory representation. It was assumed that the location of the data collection site was not critical for the HI sprinklers, because of their wide rotating pattern and the contribution from adjacent HI sprinklers.

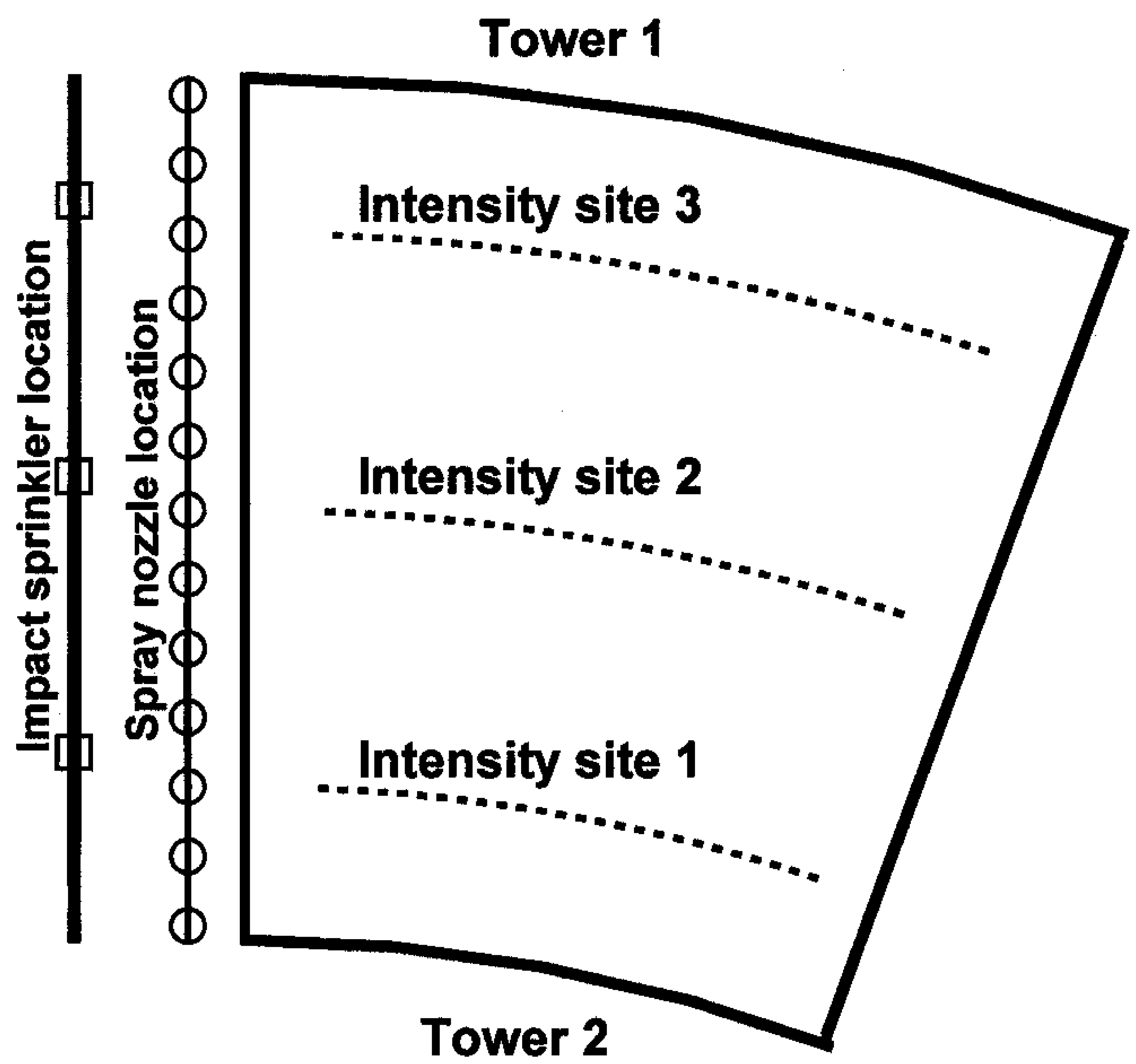

Figure 1–General layout of the three intensity sites in relation to the location of the sprinklers. Only the first two intensity sites were used in 1988.

Plant characteristics were measured after the corn was fully tasseled (growth stage R1, 75% of the plants with silks visible) during a four-day period, 20-23 July 1987 and during a two-day period, 27-28 July 1988.

The actual plant spacing was defined as the average of the distances to the nearest adjacent plants and was measured to the nearest centimeter. The circumference of each plant stalk at the first node was measured to the nearest millimeter. Corn stem diameter is often linearly related to leaf area (Splinter, 1974). Plant spacing and circumferences of the plants used in the partitioning measurements was recorded in both years.

In 1987, plant and leaf heights were measured to the nearest 5 cm to the tip of the tassel for each plant selected for measurement of the partitioning process. In 1988, 10 plants adjacent to each intensity-plant population subsite were selected for measurement. This was done to minimize the stress from human traffic to the leaf structure in the measurement area.

Leaf length and width were measured to the nearest centimeter and millimeter, respectively, for each plant in 1987. In addition, a set of five plants from the general field area was cut and brought into the lab for leaf area measurement. The leaf areas, leaf lengths and leaf widths from these five plants were used to develop an equation to compute leaf area in cm^2:

$$LA = 0.76\ SUM_{All}\ (LL \times LW) \tag{1}$$

where the sum total of the product of all leaf lengths (LL) in cm and leaf widths (LW) in cm is multiplied by 0.76.

This equation compares favorably with one reported by Steiner et al. (1982) for which the slope was 0.79. In 1988, 10 plants adjacent to each intensity-plant population subsite were selected for measurement. Equation 1 was used to calculate the leaf area for these 10 plants, and the mean was used as the average value for the subsite. Leaf area index (LAI) is defined as the ratio of leaf area to land area. For an individual plant, this equation would be:

$$LAI = LA/(PS_a \times RW) \quad (2)$$

where leaf area (LA) is expressed in cm^2, and actual plant spacing (PS_a) and row width (RW) are expressed in cm.

Standard rain gages were used to measure the above-canopy irrigation amounts (SG). They were located at ground level at the edge of each intensity site in a bare area, so they did not measure a true above-canopy amount. However, it was the only practical way to estimate the quantity under the two different types of sprinklers. Rain gages at a height close to the LS sprinklers will not provide an accurate catch. The method used in this study should provide a good estimate of the SG amount because actual within-canopy droplet evaporation is considered negligible. The SG amount was measured at only one location for each intensity site but repeated samples (3) were taken to reduce measurement errors. The commercial rain gages with a 10 cm opening and 280 mm capacity provided accurate readings to the nearest 0.25 mm.

An electronic tipping bucket rain gage also was used to measure the SG amount at each intensity site and provided the basis for computation of irrigation intensity. The electronic rain gages had 22-mm diameter openings and each tip of the bucket represented 0.25 mm.

Stemflow was collected on 16 individual plants at each intensity-plant spacing subsite (eight plants from each of the two rows) with special collection units fabricated at the research center (fig. 2). The collection tube was constructed from approximately an 18 cm section of 5 cm ID SDR 26 PVC pipe with a full length slot cut with a jigsaw. The slot allowed the collection tube to be pried open enough to fit around a growing corn plant stem. A small metal tube was glued in a hole near the base of the collection tube opposite the slot. A transfer hose connected to the metal tube was used to drain the water from the stemflow collection tube to the reservoir jug that held accumulated stemflow until it could be measured. The corn plants were stripped of the lower two leaves, which were fully mature at this date, to provide a smooth surface for mounting the stemflow collection unit. The stem area was dried with a cloth to facilitate the taping and sealing of the stemflow collection unit just above the second node. Small quantities of carpenter's glue and dry masonry cement were added to the collection tube to help prevent water leakage through the tape. A small spacer prevented the top of the collection tube from touching the corn plant. A sample schematic drawing of a typical intensity-plant spacing subsite is shown in figure 3. Not all subsites would have a SG measurement site immediately adjacent. The volumetric stemflow amount was modified for the actual land area represented by a plant (actual plant spacing × row spacing) to give a stemflow amount in depth which would be a more practical comparison to the SG amount. The stemflow amounts were measured within 2 h of the irrigation event, except for night time precipitation events. In this case, stemflow was measured commencing at 8:00 A.M. the following day.

Throughfall was collected at each intensity-plant spacing subsite with specially constructed pans, 230 mm in height and 66 cm in length, just fitting between the 76-cm corn rows. Pan width was a multiple of plant spacing (either 1 or 2) and thus ensured that a pan covered a ground area representative of the plant spacing. General measurements of throughfall were made rather than specific measurements related to stemflow of certain plants. This was because of the physical limitations of putting the stemflow collection units and throughfall collection gages in the same location. Throughfall was measured at two locations at each intensity-plant spacing subsite. One pan was centered beneath the LS sprinkler between the rows, and the other was centered in the adjacent two rows (fig. 3). The throughfall volume was divided by the land area to express the actual throughfall amount as a depth.

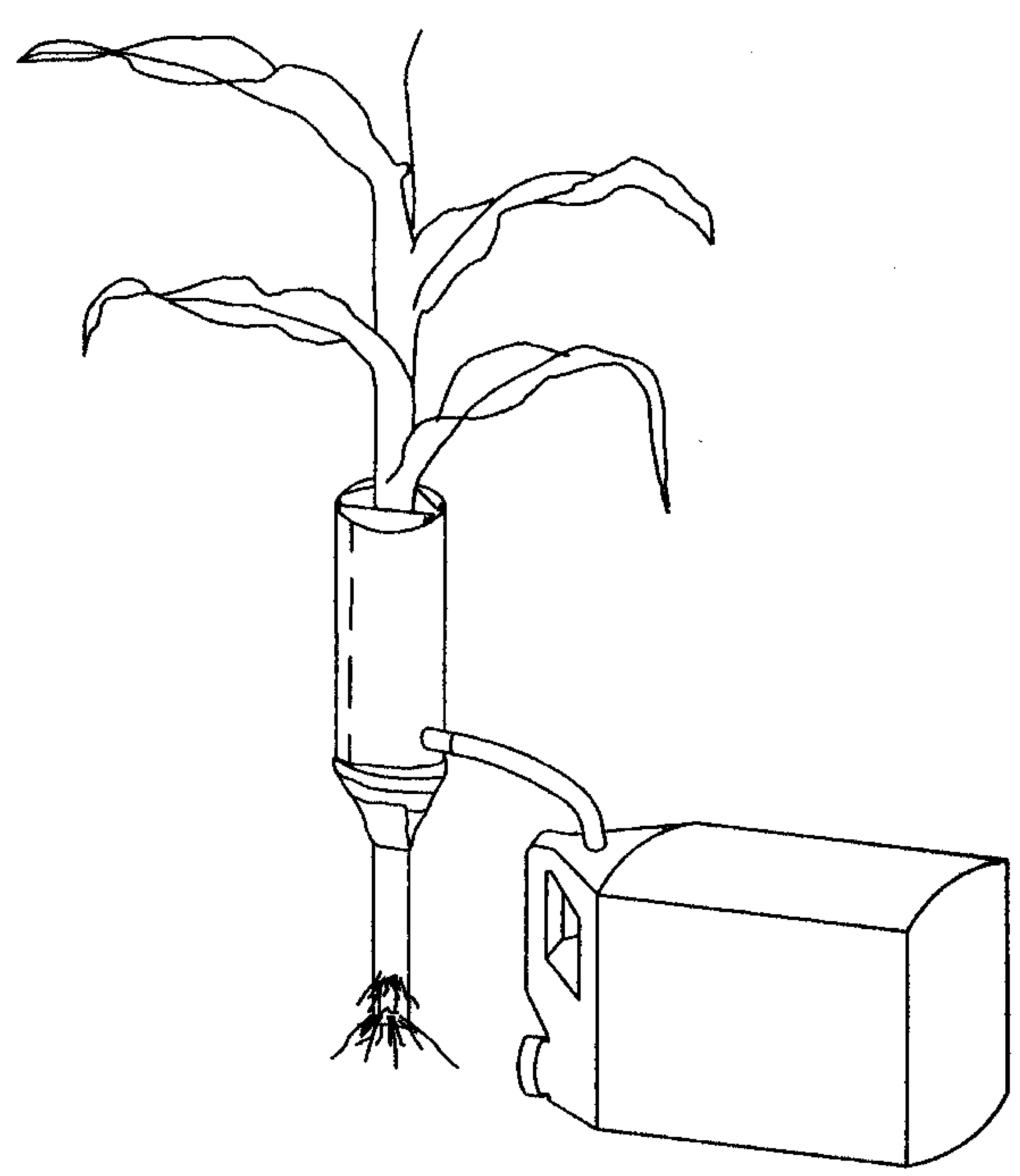
Figure 2–Stemflow collection unit attached to a corn plant.

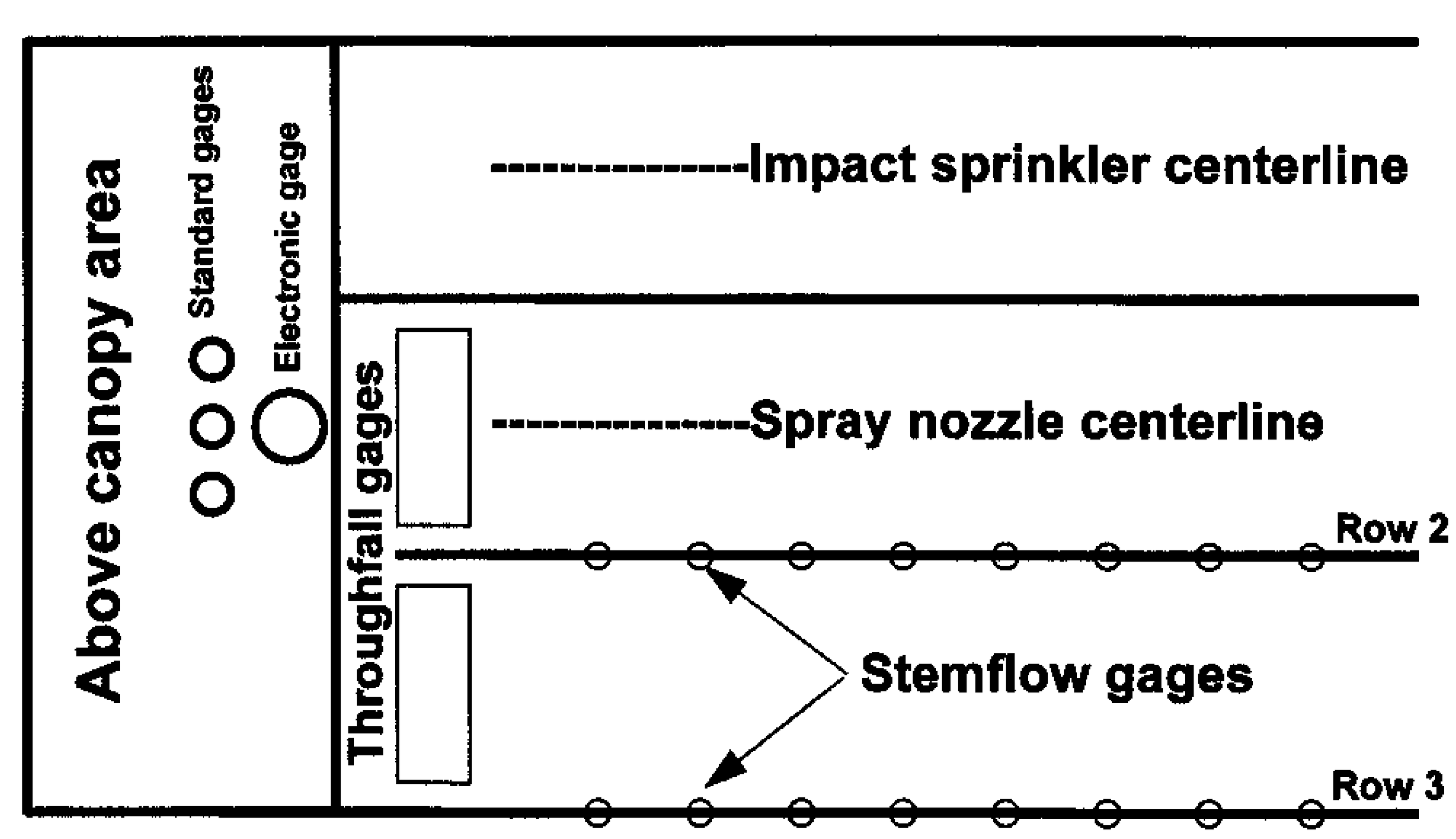

Figure 3–Schematic of a typical intensity-plant spacing subsite showing how the various measurement units were situated.

Hourly weather data were recorded at an automated weather station located approximately 1000 m from the study site. Data collected included air temperature, relative humidity, wind direction, wind speed (0.5 m/s threshold), and solar radiation. Generally, the irrigation events were conducted before dawn to avoid adverse wind conditions.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Weather conditions varied from year to year, event to event, and sometimes during the event. In 1987, the first few events were conducted after sunrise. However, weather conditions change rapidly on the High Plains after sunrise, so later events were conducted before dawn whenever possible to minimize experimental error. The events were of different duration because of the differences in sprinkler types and irrigation amounts. Sometimes the wind would be high before dawn and the event had to be canceled or postponed to later in the day. However, when the wind speed increased during an event, the event would continue.

In 1987, the events used in the analysis were characterized by low average wind speeds, which were often below the 0.5 m/s sensor threshold (data not shown). The relative humidity was fairly low during the events, which would tend to increase evaporative losses. However, since the wind speed was low and most events were conducted early in the morning, evaporative losses due to advection would be low.

In 1988, nearly all of the events were conducted before dawn or late in the evening. The relative humidity was fairly high during nearly all of the events. The high relative humidities would have resulted in lower evaporative demands. The average wind speeds were higher than in 1987, but the wind speed exceeded 4.5 m/s in only one event when the speed reached 5.5 m/s (data not shown).

The weather factors during the events in both years should have had relatively minor effects on the partitioning process because of the timing of most of the events, and because events were canceled on windy days.

MODELING OF STEMFLOW AMOUNT

Analysis of Covariance. The study included five class variables: sprinkler type, irrigation amount, intensity site, nominal plant spacing, and row. Two of these have continuous variable counterparts. There were two nominal class amounts, 13 mm and 38 mm, in 1987. The effects of these classes or the actual amounts can be examined in regression. Similarly, the three nominal plant spacings had continuous actual plant spacing counterparts.

Analysis of covariance (AOC) was performed on the 1987 data to broadly establish the importance or lack of importance of the class variables in the prediction of stemflow amount. A previous graphical analysis had shown that the stemflow amount was related linearly to the covariates, SG, and PS_a. So these terms, when appropriate, would be logical covariates in the AOCs.

The AOC revealed significant differences between the event types. The stemflow amount was significantly higher for the LS sprinkler than the other two event types (data not shown). There was not enough information at the $P = 0.05$ significance level to conclude that the stemflow amounts were different for the HI and the precipitation (R) events. From this analysis, it was concluded that a model for each sprinkler type is warranted, and that HI affects the stemflow part of the partitioning process somewhat similarly to natural rainfall.

The AOC did not show enough evidence to suggest that the corn row affected the stemflow amount for either the HI event or the single (R) event in 1987. However, the row did have a significant effect on stemflow amount for LS sprinklers. The LS sprinkler pattern was distorted by nearby row (Row 2) and, therefore, less irrigation water reached the row (Row 3) 1.1 m distance from the LS sprinkler. Averaged over the two rows, the LS sprinklers resulted in the highest stemflow amount for a given irrigation event. This means that the distortion of the pattern by Row 2 increased the overall average stemflow amounts for the LS events, even though less stemflow was occurring on Row 3 (fig. 3). The conclusion to be drawn from this analysis is that the data can be pooled across row location for the HI and R events. However, for the LS events, a better fit can be obtained if row location is considered.

For a single event at the end of the study in 1988, the LS sprinklers were raised to a height of 4.1 m, the same height as the HI sprinklers. This configuration (LS-4.1) was used to determine if the row effect that was so prominent for the LS events was more related to the sprinkler type or the sprinkler pattern distortion caused by Row 2. An AOC did not show enough evidence at the 0.05 significance level to conclude that row affects stemflow amount for the LS-4.1 configuration. From this analysis, one could conclude that the row effect for the LS sprinklers was related more to pattern distortion by the row than to the properties of the LS sprinkler. The LS-4.1 configuration was similar to HI and R events in the way it affected stemflow amount. This suggests that the differences in stemflow for the LS system may be caused by the LS sprinkler height and/or the angle that water strikes the crop canopy.

Statistically significant differences in stemflow amounts occurred between the intensity sites. The trend was toward lower stemflow amounts for the higher intensity sites. This trend held even for the R event, which could reasonably be expected to have the same intensity for the three locations. Other differences in the sites, such as plant factors, were probably more important than the sprinkler application rate. It was concluded that the experimental design did not allow a clean separation of intensity effects. The data were pooled across intensity site, and no further speculation on the effect of intensity on the partitioning process was made.

Regression Analysis. An overall regression model to predict stemflow amount, S_a for the sprinklers in 1987 was constructed. Averaging across intensity sites, rows, and individual plants resulted in 36 data points in the model. Each data point represented 48 measurements, provided there were no missing data. For the 12 sprinkler events in 1987, there were 1728 possible measurements, with only 16 missing. For the purposes of regression, a full model was constructed including the five plant variables, actual plant spacing (PS_a), plant height (THT), stem diameter (DIA), leaf area (LA), and leaf area index (LAI). The above-canopy irrigation amount (SG) was also included as was its square term ($SG \times SG$). One cross effect was included ($PS_a \times SG$), which seemed appropriate based on a preliminary graphical analysis. The full model was:

$$S_a = f(PS_a, THT, DIA, LA, LAI, SG, SG \times SG, PS_a \times SG) \quad (3)$$

Some of the plant variables are related to each other and, therefore, are not independent. Leaf area index is related inversely to plant spacing by definition. Some of the variables that affect stemflow are not required in the model because of these interrelationships. For this reason, a backwards selection procedure was used in the regression analyses, and nonsignificant independent variables were removed. The only plant characteristic that remained in the model was PS_a, which was incorporated in the cross product, $PS_a \times SG$. Other factors, such as LAI are still highly correlated with stemflow but can be accounted for with the inclusion of PS_a in the model. The intercept was removed from the model to satisfy the boundary condition of no stemflow with no irrigation.

Rearranging the variables and parameter estimates resulted in the 1987 equation:

$$S_a = (0.638 - 0.00693\ PS_a) \times SG \quad (4)$$

for PS_a in cm and S_a and SG in mm. The model fit the overall data very well with a standard error of the estimate, $SE_{y.x}$ (also called root mean square of the error), of 1.41. This is an estimate of the variance about the regression line. The RSQUARE of the model is no longer valid because the intercept of the model has been removed.

Similarly, regression was performed on the 10 sprinkler events in 1988. Averaging across intensity sites, rows, and individual plants resulted in 30 data points in the model. Each data point represented 32 measurements, provided there were no missing data. In 1988 there were 960 possible measurements, with only 22 missing. Regression using the backwards selection procedure yielded a model with independent variables identical to those in the final 1987 model. The parameter estimates varied only slightly from those in 1987 (table 1). Though the equations look slightly different, there is little difference in the predicted values over the range of variables studied. The overall data for both years were combined for an overall prediction equation (table 1), which fit the measured stemflow amount well (fig. 4).

The AOC showed differences in the amounts of stemflow between event types. The stemflow amount was greater for LS than for HI, R, and LS-4.1 events. The AOC also showed a difference in stemflows between rows for the LS system. Therefore, regression equations

Table 1. Summary of regression equations to predict stemflow amount using the model form $S_a = f(SG, PS_a \times SG)$

Event Type	Year	Regression Equation for Stemflow Amount (S_a) in mm*	$SE_{y.x}$ in mm
All sprinklers	87	$S_a = (0.638 - 0.00693\ PS_a) \times SG$	1.41
All sprinklers	88	$S_a = (0.726 - 0.00769\ PS_a) \times SG$	1.26
All sprinklers	87-88	$S_a = (0.685 - 0.00754\ PS_a) \times SG$	1.69
HI, R, and LS-4.1 event	87-88	$S_a = (0.710 - 0.00885\ PS_a) \times SG$	1.39
LS Row 2	87-88	$S_a = (0.839 - 0.01082\ PS_a) \times SG$	1.77
LS Row 3	87-88	$S_a = (0.520 - 0.00295\ PS_a) \times SG$	1.79
LS sprinklers	87-88	$S_a = (0.671 - 0.00669\ PS_a) \times SG$	1.63

* Plant spacing (PS_a) is in cm and irrigation amount SG) is in mm.

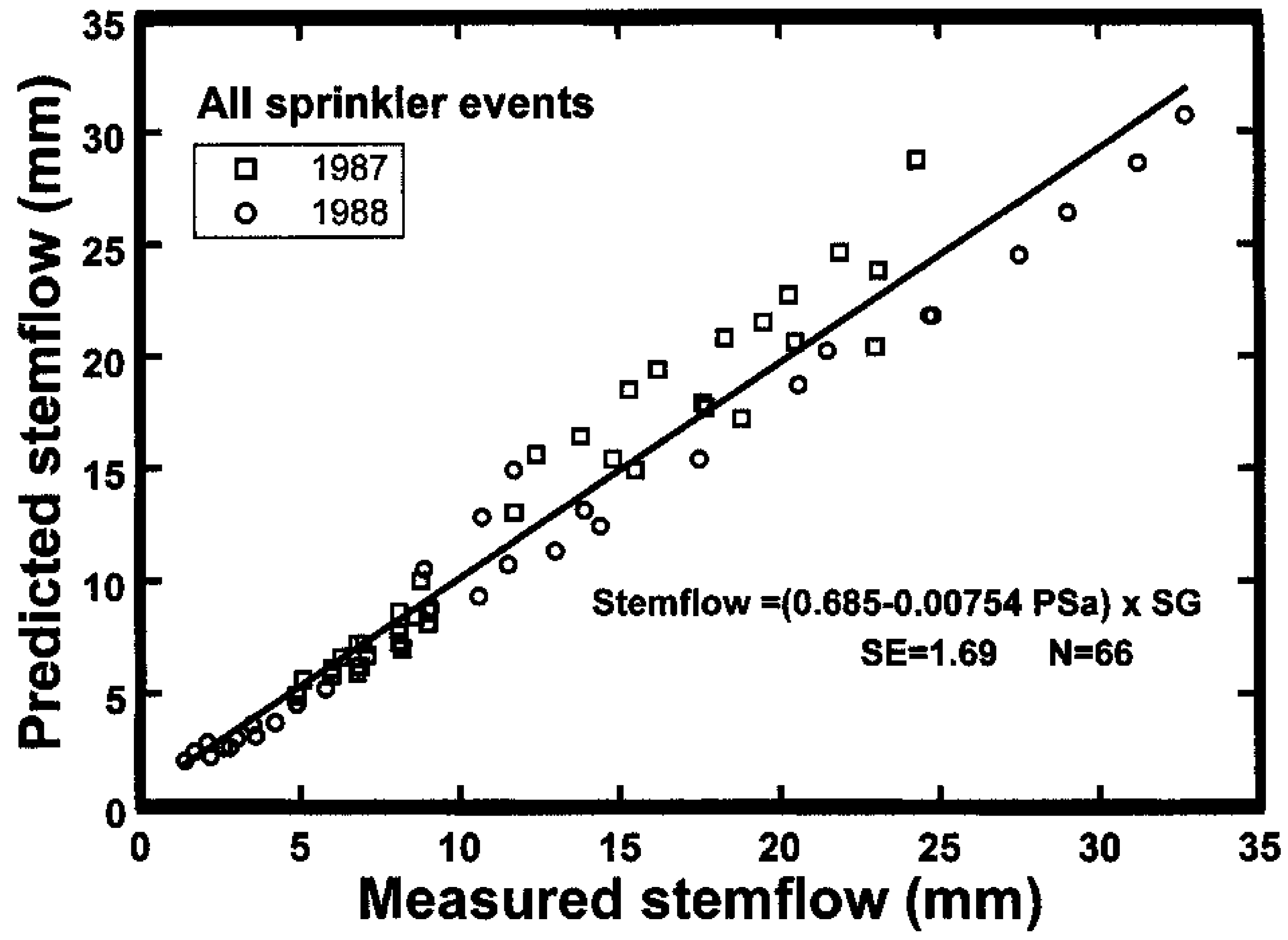

Figure 4–Relationship of measured and predicted stemflow amounts for all sprinkler events in 1987-1988. Each data point represents the average of 48 measurements in 1987 and 32 in 1988.

for the individual event type and rows for the LS system are warranted.

A regression was performed on the combined HI, R, and LS-4.1 data from 1987 and 1988 to predict stemflow amount using a model of the form:

$$S_a = f(SG, PS_a \times SG) \quad (5)$$

similar to the form of the overall 1987-1988 equation. The resulting regression equation (table 1) gives essentially equal predictions to the overall combined 1987-1988 equation.

The distortion of the spray pattern for the LS events by the nearby row (Row 2) resulted in higher stemflow amounts for this row than for the row 1.14 m farther away (Row 3). Row 2 also showed a greater effect of plant spacing. Individual regression equations for stemflow amount were generated for each corn row for the LS events (table 1). Over the entire range of plant spacings, Row 2 had approximately 19% higher stemflow amounts compared to Row 3. However, at the 20-cm plant spacing, Row 2 had approximately 35% greater stemflow amounts than Row 3. At the 41-cm plant spacing, the predicted stemflow amounts for the two rows were almost equal. This is a logical result. As the plant spacing increased, there was less distortion of the spray pattern by Row 2, and the row effect disappeared.

An overall regression equation for the LS events was generated by averaging across both rows (table 1). This equation is useful for predictions of the aggregate field average stemflow. It underestimated the stemflow amount for Row 2 by approximately 40% and overestimated the amount for Row 3 by approximately 17% at the 20-cm plant spacing. Over the entire range of plant spacings, this overall LS equation predicted stemflow amounts about 7% higher than those predicted by the combined HI, R, and LS-4.1 equation. However, at the 41-cm spacing, the difference was approximately 10%.

The several regression equations to predict stemflow amount that have been presented are summarized in table 1. The overall two-year sprinkler equation generally shows a good fit with either data set (1987 or 1988). This is encouraging, because it indicates stability in the parameter estimates at least for this center-pivot sprinkler system and corn variety. Most of the popular corn varieties presently being marketed have similar canopy structure. The high-pressure impact center pivot sprinkler system (HI) is still used widely on areas with high runoff potential. The low-pressure spray system on drops (LS) is also very common in the southern and central Great Plains.

The equations were developed under relatively stable weather conditions usually before dawn. Therefore, these equations might need to be modified before being used under other conditions. Windy conditions that cause the plant leaves to move probably would reduce stemflow amounts and increase throughfall amounts. Gusty wind conditions would likely cause more plant-to-plant variability in stemflow amounts. Hot, sunny conditions might increase interception losses, but probably would not appreciably affect stemflow amounts under the high application rates of the outer spans of center pivot sprinklers.

Stemflow and Its Consequences. The practice of placing the LS sprinklers down into the top 30 cm of the corn canopy is promoted widely in the southern and central Great Plains as a means of reducing evaporation. However, these potential water savings must be balanced against lower distribution uniformity caused by the spray pattern distortion. Some of the uniformity problems, in terms of less water for crop use, are buffered by the deep silt loam soils in the area. Higher or lower irrigation amounts at some points on the soil surface may be buffered partially by the infiltration and soil water redistribution processes. In addition, the distortion occurs only after tasseling, so the irrigation uniformity problem probably does not cause large yield differences on these deep soils, as long as the LS sprinkler spacing is fairly close. On most of the systems in northwest Kansas, the LS sprinkler spacing is typically 240 to 300 cm. The combined sprinkler equation gives a relatively good estimate of the stemflow amount for the LS events when only an aggregate field estimate is needed. However, much row-to-row variation occurs, and a better prediction can be obtained for a particular row by using the appropriate row equation.

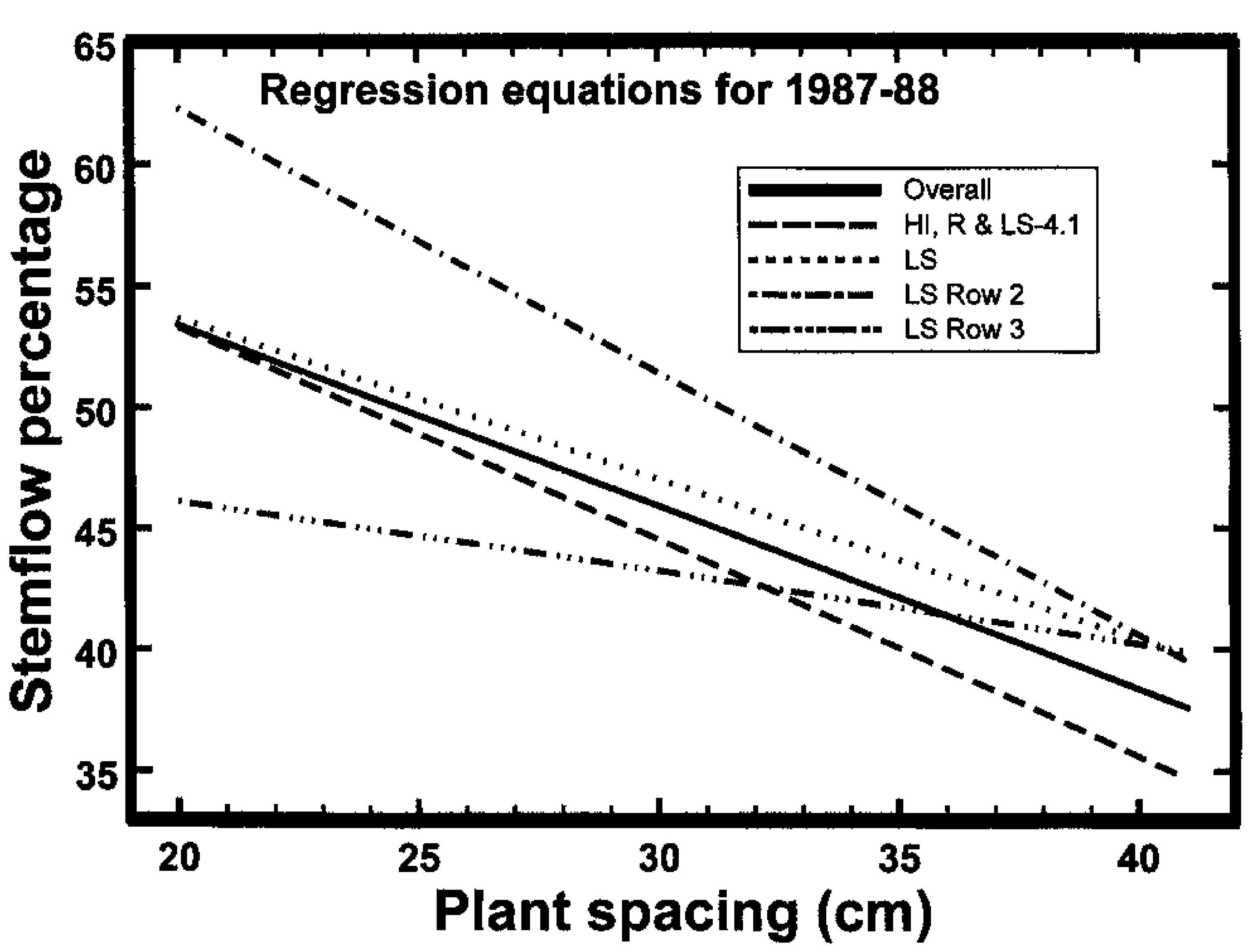

Figure 5–Stemflow as a percentage of a typical irrigation amount (25 mm) as related to the corn plant spacing for the various regression equations for 1987-1988.

The stemflow as a percentage of the irrigation amount is presented in figure 5 for the two-year overall equations. At a typical irrigated corn plant spacing of 20 cm, the average stemflow was approximately 53% of a typical 25-mm irrigation amount. This value is slightly higher than the values of 49% and 44% reported by Quinn and Laflen (1983) and Steiner et al. (1983), respectively. The stemflow percentage decreased linearly with increased plant spacing over the range of spacings examined. Leaf area index decreases with increased plant spacing (eq. 2) and thus the "funneling" surface decreases resulting in less stemflow. The prediction equations seemed to give reasonable results compared to the limited data in the literature.

The stemflow percentages for the two rows under the LS system varied by approximately 16% at the typical 20-cm plant spacing; the value is 62% more for Row 2 and 46% for Row 3. This may have considerable significance to the process of chemigation. If the target area of the chemical is the foliage, these variations in stemflow may be unacceptable. In many situations, the crop producer will plant the rows parallel to the field boundary rather than circularly. In this case, although the row effect might disappear, one would expect more plant-to-plant variation. The stemflow amount would vary depending on the proximity of a plant to a LS sprinkler and would be higher for closer plants. The aggregate field average stemflow amount probably would be similar to the case of the circular rows in this study. Wind direction also could skew the uniformity of stemflow amounts, depending upon the row orientation in relation to the sprinkler location. If the wind direction is perpendicular to the sprinkler lateral and parallel to the corn rows, the uniformity should be similar to the results of this study. If the wind direction is parallel to the sprinkler lateral and perpendicular to the row, the row-to-row differences might be reduced, because the wind would alter the travel distance of the spray.

Buschman et al. (1985) measured European corn borer control under chemigation for the two sprinkler types (LS and HI) at both Colby and Garden City, Kansas. The HI system gave much better control at both locations. They did not indicate whether the entire LS spray pattern was sampled for efficacy of the chemicals. Some rows could have shown higher efficacy because of the differences in stemflow.

If drop tubes are not used, the LS sprinklers are the same height as the HI sprinklers. This would be similar to the case where the LS sprinklers were raised to truss height (LS-4.1). This configuration performed similarly to the HI system in terms of the amount of stemflow recorded. In addition, no row effect occurred. This suggests that the LS sprinklers at truss height may be better than when on drop tubes, if distribution uniformity is a critical factor, such as for a chemigation event.

Kiesselbach (1916) reported that approximately 3 L of water run down the outside of a fully developed corn plant for each 25 mm of irrigation water. The plant spacing was not indicated, and the data likely were collected from an isolated potometer. However, the overall 1987-88 prediction equation for all sprinkler events predicted 2.94 L for a 25-mm irrigation event for the 41-cm plant spacing after proper conversion of the equation to predict a volumetric amount. Little interaction occurred among plants at this higher plant spacing, so the situation might be similar to the case of plants grown in isolated potometers. The overall equation also gives an upper limit of the stemflow amount at approximately 3 L for each 25 mm of irrigation as plant spacing is increased further.

Modeling of Throughfall

The throughfall amount (T_a), stemflow amount (S_a), and interception storage amount (I_a) add up to the above canopy irrigation amount (SG). Because T_a and S_a are the two major addends that result in SG, it would follow that factors affecting stemflow also would affect throughfall. It was assumed that there was no need to perform separate AOC for T_a and that it could be predicted by a regression model of the form:

$$T_a = g(SG, PS_a \times SG) \qquad (6)$$

Averaging across intensity sites and row location for the 12 sprinkler events in 1987 resulted in 36 data points, each representing six measurements. In 1988, there were five HI events and five LS events. Averaging across the two intensity sites and two row locations resulted in 30 data points, each representing the average of four measurements. Separate regression equations were developed for throughfall using the 1987 and 1988 data (table 2). The effect of plant spacing on T_a was insignificant in 1988 over the range of plant spacings examined. The factor was left in the equation for the purposes of consistency with the 1987 and combined results. The combined data (1987-1988) were used to develop an overall throughfall equation (table 2 and fig. 6). Note that the slope of the plant spacing effect for the T_a is positive; whereas, the slope was negative for the S_a. As PS_a increases, S_a approaches zero. As S_a approaches zero, T_a approaches 100% of SG. The predicted throughfall expressed as a percentage of a typical 25-mm irrigation amount (SG) increased from 43.4% at the 20-cm plant spacing to 50.0% at the 41-cm plant spacing.

Table 2. Summary of regression equations to predict throughfall amount using the model form $T_a = g(SG, PS_a \times SG)$

Event Type	Year	Regression Equation for Throughfall Amount (T_a) in mm*	$SE_{y.x}$ in mm
All sprinklers	87	$T_a = (0.373 + 0.00457\ PS_a) \times SG$	1.90
All sprinklers	88	$T_a = (0.387 + 0.00068\ PS_a) \times SG$	0.88
All sprinklers	87-88	$T_a = (0.372 + 0.00313\ PS_a) \times SG$	2.33
HI, R, and LS-4.1 event	87-88	$T_a = (0.332 + 0.00457\ PS_a) \times SG$	2.25
LS Row 2	87-88	$T_a = (0.477 + 0.00137\ PS_a) \times SG$	3.49
LS Row 3	87-88	$T_a = (0.333 + 0.00242\ PS_a) \times SG$	1.53
LS sprinklers	87-88	$T_a = (0.408 + 0.00181\ PS_a) \times SG$	2.17

* Plant spacing (PS_a) is in cm and irrigation amount (SG) is in mm.

Similar to the regression analysis of stemflow, T_a was expected to vary with event type. Regression equations (table 2) for the various event types were generated using the model expressed in equation 6. Regression analysis of the HI, R, and LS-4.1 event data for both 1987 and 1988 resulted in an $SE_{y.x}$ of 2.25. However, the coefficient of variation of the model was 21%, indicating considerable variation. Throughfall amounts were appreciably different between Rows 2 and 3 for the LS events, with more modeling variation for Row 2 (table 2). Over the range of plant spacings examined, T_a for Row 2 was approximately 28% higher than for Row 3. The row effect for S_a disappeared at the high 41-cm plant spacing. This was not true for the T_a, because the difference was approximately 23% at the 41-cm plant spacing. This is probably because the spray pattern was distorted by both rows for the throughfall collection unit for Row 3 (fig. 3). An overall LS equation can be used for prediction of an aggregate field average T_a for the LS system (table 2).

Throughfall and Its Consequences. The throughfall as a percentage of irrigation amount is presented in figure 7 for the two-year overall equations. At a typical 20-cm plant spacing, the throughfall is 43% of the irrigation amount. This value compares well with the two-year average value of 47.6% reported by Steiner et al. (1983). Quinn and Laflen (1983) reported the throughfall to be 57% for corn at the 12th week stage with a 30-cm plant spacing and a 75-cm row spacing. The overall equation predicted 47% for this spacing. However, the data of Quinn and Laflen were collected under a rainfall simulator, and characteristics of throughfall could differ from a center pivot.

The throughfall percentages for the two rows under the LS system were 50.4 and 38.1% for Row 2 and Row 3, respectively. Stemflow was also higher for Row 2. This

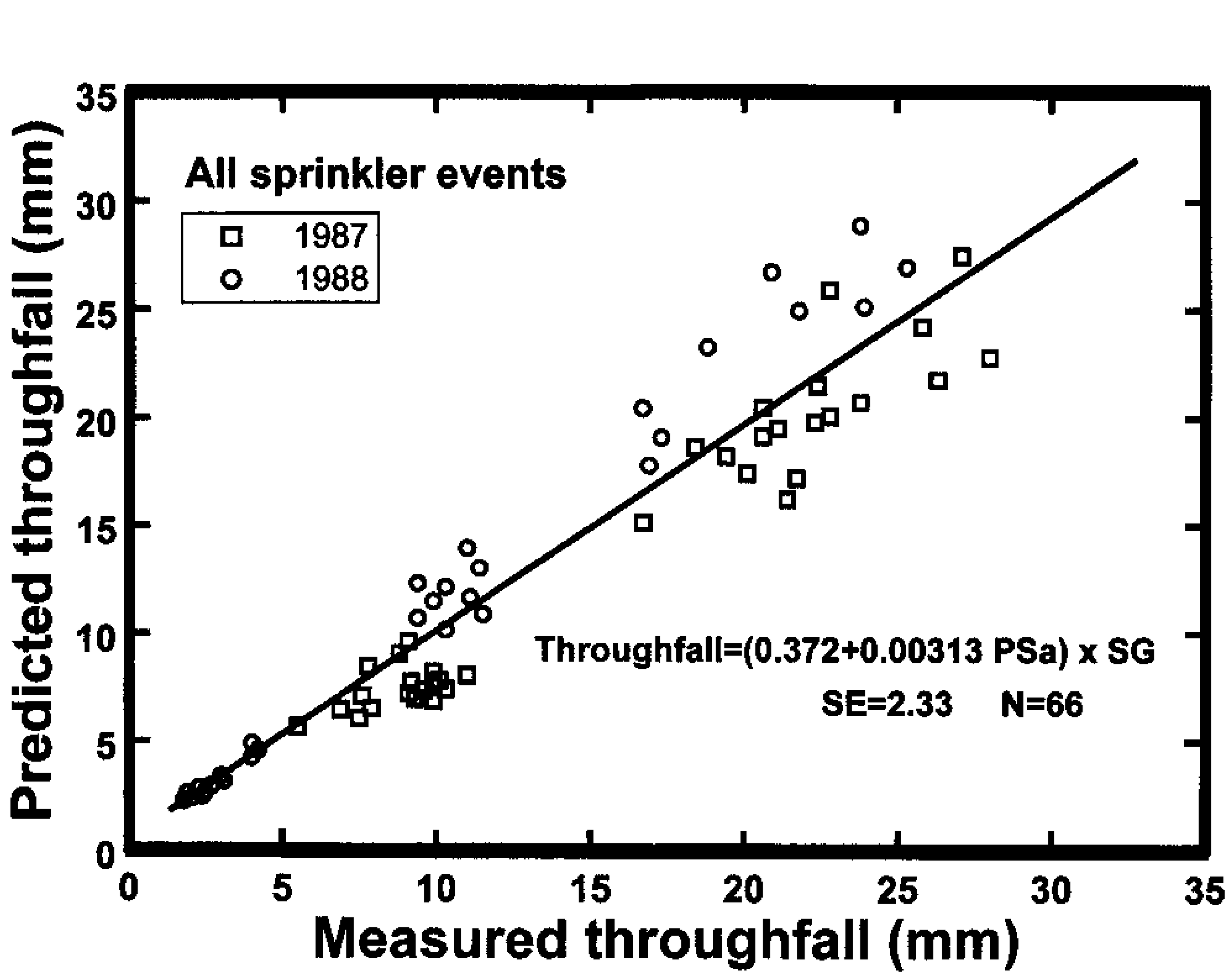

Figure 6–Relationship of measured and predicted throughfall amounts for all sprinkler events in 1987-1988.

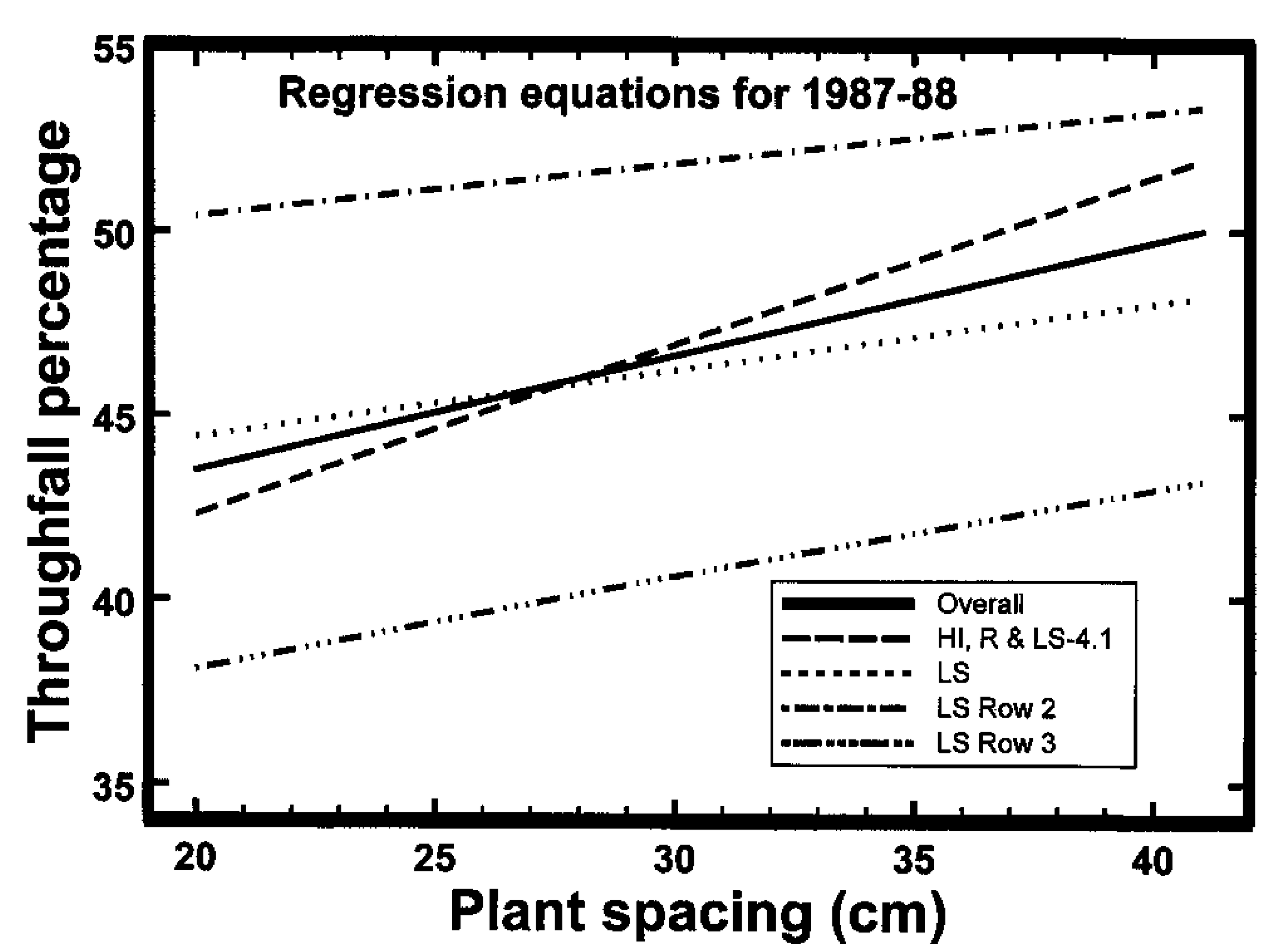

Figure 7–Throughfall as a percentage of a typical irrigation amount (25 mm) as related to the corn plant spacing for the various regression equations for 1987-1988.

means that the spatial distribution uniformity of irrigation was poor under the LS system.

Throughfall was less under the HI system than under the LS system at the 20-cm plant spacing. However, at the larger spacings, throughfall for the HI system was higher than that for the LS system. This may be related to how the systems deliver the irrigation water. The HI system delivers water in fairly large periodic pulses; whereas, the LS system delivers the water in a continuous stream of water droplets. The periodic loading of the plants by the HI system can cause the leaves to bounce up and down during the pulse. This movement of the leaves might be restricted at the 20-cm spacing. However, at the larger spacings, this movement might cause much of the water to leave the leaf surface as throughfall rather than as stemflow.

Estimation of Interception Storage Amount

This study did not directly measure the interception storage amount (I_a), but it can be estimated from algebraic closure:

$$I_a = SG - (S_a + T_a) \qquad (7)$$

SG, S_a, and T_a are all measured variables containing experimental error and of considerably larger magnitude than I_a. As a result, the variation in I_a estimates can be easily larger than I_a itself. The residual I_a from equation 7 was calculated for all the events and plant spacings during the two-year study. The average interception storage from these 81 estimates was 1.8 mm; however, the standard deviation was 2.0 mm. The maximum residual was 11.0 mm; whereas, the minimum was -3.2 mm. Because the estimates of I_a were highly variable, no regression models will be presented.

The I_a was 1.85 mm for the LS events versus 2.06 mm for the HI events, which may indicate a slight reduction in evaporation losses. The R events had the lowest interception, 1.13 mm. This may be related to the weather conditions during the storms or to the fact that most of the precipitation amounts were relatively small. For the single LS-4.1 event, the average interception storage, 2.03 mm, is comparable to that of the HI event. The differences among all three event types are small giving further credibility to the assumption that within-canopy evaporation losses are small or negligible.

The interception storage estimates were obtained from data often collected before dawn under relatively low wind conditions. They do not include appreciable canopy evaporative losses that might occur during the irrigation/precipitation event. The problem of estimating I_a is not new. Whether the estimates are made by watering plants and then weighing, calculation of the residual as done in this study, or using a microclimate model, they are open to discussion. Probably for this reason, a range of 1.5 to 2.5 mm covers most of the estimates in the literature.

Conclusions

Methods were developed for predicting the stemflow and throughfall components of the irrigation partitioning process. The data used to develop the models were obtained under low or no wind conditions usually before dawn. Therefore, the equations may need to be modified for windy conditions. These models do a relatively good job of predicting the components on an aggregate basis. The regression analyses revealed that stemflow and throughfall amounts were related most highly to plant spacing and irrigation amount. The stemflow amount decreased linearly with plant spacing (PS_a) and increased linearly with irrigation amount (SG). The throughfall increased linearly with both increased PS_a and SG. Other plant factors such as height, leaf area, stem diameter, and leaf area index did not significantly ($P = 0.05$) add precision to the model. At the three nominal plant spacings of 20, 30, and 41 cm, the predicted stemflows expressed as a percentage of the irrigation amount for all sprinkler types were 53.4, 45.9, and 37.6%, respectively. The predicted throughfall expressed as a percentage of the irrigation amount was 43.5, 46.6, and 50.0%, for the three plant spacings, respectively. At typical irrigated corn plant spacings, stemflow is the predominate flow path for irrigation water after tasseling, and throughfall is slightly lower.

The partitioning process differed considerably between the low-pressure spray heads on drop tubes (LS) events and the high-pressure impact sprinkler (HI) events. The LS events not only had higher stemflow amounts but also had large differences between row location. The distortion of the spray pattern that occurs when the LS sprinklers are placed on drop tubes down into the canopy heavily influenced the partitioning process. This factor should be considered in designing multipurpose center pivot sprinkler systems. The stemflow amounts in the HI events were more similar to those in the precipitation events than to those in the LS events. Raising the LS sprinklers above the crop canopy resulted in stemflow amounts similar to those with the HI events and eliminated the row effect. These facts should be considered when chemigation procedures are being developed, when point data for irrigation amounts under crop canopies are being examined, and in cases where uniform soil water redistribution is crucial.

Interception was estimated by subtracting the stemflow and throughfall amounts from the irrigation amount. Assuming that in-canopy evaporation is negligible during the events, the residual was an estimate of interception storage. Because stemflow, throughfall, and irrigation amount are all measured variables containing experimental error, the error associated with this method of estimating interception storage is high. The mean interception value based on 81 separate estimates was 1.8 mm with a standard deviation of 2.0 mm.

References

Armstrong, C. L., and J. K. Mitchell. 1987a. Transformations of rainfall by plant canopy. *Transactions of the ASAE* 30(3): 688-696.

_____. 1987b. A comparison of rainfall distribution under different plant canopies. ASAE Paper No. 87-2509. St. Joseph, Mich.: ASAE

Buschman, L. L., F. R. Lamm, P. E. Sloderbeck, and G. L. Dick. 1985. Chemigation in corn: Effects of nonemulsifiable oils and sprinkler package on the efficacy of corn borer (*Lepidoptera: Pyralidae*) insecticides. *J. Econ. Entomol.* 78(6): 1331-1336.

Glover, J., and M. D. Gwynne. 1962. Light rainfall and plant survival in east Africa. I. Maize. *J. Ecol.* 50: 111-118.

Haynes, J. L. 1940. Ground rainfall under vegetative canopy of crops. *Agron. J.* 32: 176-184.

Kiesselbach, T. A. 1916. Transpiration as a Factor in Crop Production. Res Bull No 6. Lincoln, Nebr.: Nebraska Agric. Expt Station.

Lamm, F. R. 1984. Comparison of spray and impact sprinkler performance. ASAE Paper No. MCR-84-153. St. Joseph, Mich.: ASAE.

Quinn, N. W., and J. M. Laflen. 1983. Characteristics of raindrop throughfall under corn canopy. *Transactions of the ASAE* 26(5): 1445-1450.

Schneider, A. D., and T. A. Howell. 1995. Reducing sprinkler water losses. In *Proc. Central Plains Irrigation Shortcourse*, Garden City, Kans., 7-8 Feb 1995, 60-63. Manhattan, Kans.: Biological and Agricultural Engineering, Kansas State University.

Seginer, I. 1967. Net losses in sprinkler irrigation. *Agric. Meteorol.* 4: 281-291.

Smajstrla, A. G., and R. S. Hanson. 1980. Evaporation effects on sprinkler irrigation efficiencies. *Proc. Soil & Crop Sci. Soc. Florida* 39: 28-33.

Splinter, W. E. 1974. Modeling of plant growth for yield prediction. *Agric. Meteorol.* 14: 243-253.

Steiner, J. L., E. T. Kanemasu, and R. N. Clark. 1983. Spray losses and partitioning of water under a center pivot sprinkler system. *Transactions of the ASAE* 26(4): 1128-1134.

Steiner, J. L., E. T. Kanemasu, W. L. Powers, and D. L. Pope. 1982. Monitoring soil moisture in irrigated corn and sorghum with a programmable calculator. *Kansas Water News* 24-25: 3-8. Kansas Water Office, Topeka, Kansas.

Thompson, A. L., D. L. Martin, J. M. Norman, and T. A. Howell. 1996. Scheduling effects on evapotranspiration with overhead and below canopy application. In proceedings of the international conference *Evapotranspiration and Irrigation Scheduling,* 3-6 Nov. 1996, 182-188. St. Joseph, Mich.: ASAE.

van Wesenbeeck, I. J., and R. G. Kachanoski. 1988. Spatial and temporal distribution of soil water in the tilled layer under a corn crop. *Soil Sci. Soc. Am. J.* 52(2): 363-368.

Warner, G. S., and R. A. Young. 1989. Preferential flow beneath corn rows. ASAE Paper No. 89-2568. St Joseph, Mich.: ASAE.

Variables and Abbreviations

AOC = analysis of covariance
DIA = stem diameter
HI = high pressure impact sprinkler
I_a = interception storage amount
LA = leaf area
LAI = leaf area index
LL = leaf length
LS = low pressure spray head
LS-4.1 = low pressure spray head at 4.1 m height on top of sprinkler lateral
LW = leaf width
PS_a = actual measured plant spacing between adjacent plants
R = rainfall event
RW = corn row width
S_a = stemflow amount
SG = above-canopy irrigation amount caught in standard rain gages.
T_a = throughfall amount
THT = plant height