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# Growth stage scheduling criteria for sprinkler-irrigated soybeans *

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**Summary.** Soybean [*Glycine max* (L.) Merr.] producers in the Great Plains region usually employ either a seasonal soil water balance approach, or a growth stage sensitivity approach, relative to scheduling sprinkler irrigation events. We conducted an empirical evaluation of the response of six soybean cultivars to three irrigation strategies. One was an irrigation scheduling (IS) system based solely on maintaining a soil water content in the root zone between 50% and 80% of the total plant available soil water capacity. The other two strategies involved the same depletion criterion for triggering irrigation events, except that the first irrigation was intentionally delayed until the flowering (FL) stage, or the mid-pod elongation (PD) stage. The total water amount applied during each season was approximately similar for the IS, FL, and PD strategies. Thus, the primary difference among the three strategies was the time frame during which irrigation events were scheduled. In the 1983 test, the yields attained in the IS, FL, and PD treatments were not significantly different from each other (i.e. 4.08, 4.08, and 4.04 Mg/ha, respectively), and were nearly double the yield obtained in the nonirrigated (NI) check treatment (2.29 Mg/ha). In the 1984 test, the yields of the IS, FL, and PD treatments were again not significantly different (2.02, 2.05, and 2.22 Mg/ha, respectively). However, the 1984 yield response to irrigation was also not significant relative to the NI check (1.90 Mg/ha), primarily because of low plant populations and a shorter growing season. Thus, this two-year experiment indicated that delaying irrigation until the FL or the PD stages of soybean reproductive development could be just as effective (i.e. 1983 data), or at least no more ineffective (i.e. 1984 data), in enhancing soybean yield compared to the IS strategy (Fig. 1). The soil water balance and soybean growth stage sensitivity approaches, when combined, could thus constitute an effective strategy of soybean sprinkler irrigation management in the Great Plains region.

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A substantial amount of the soybean [*Glycine max* (L.) Merrill] production area in the semi-arid Northern Great Plains states is irrigated, either by furrow or by sprinkler methods of water application (Elmore et al. 1988). Because of the importance of irrigated soybean production in this region, much research has been directed towards the identification of an optimal irrigation management strategy that will consistently (from year to year) maximize the yield response of soybeans to appropriately timed irrigation events.

Two different approaches have been used in designing an optimal irrigation scheduling system. One approach is based on research results which have indicated that, on moderate to heavy textured soils, soybean yield response varies significantly relative to furrow irrigation events timed during ontogenetic development. For example, Brady et al. (1974) reported that irrigation commenced during the vegetative growth stages was no more effective in enhancing soybean seed yield than when irrigation was first commenced at the onset of reproductive development. Korte et al. (1983 a, 1983 b) observed a consistently negligible yield response to a single irrigation applied during flowering, in contrast to a consistently large response to a single irrigation applied during pod elongation. Kadhem et al. (1985 a, 1985 b) confirmed that the mid-flowering stage was the least responsive to a coincidently timed irrigation, whereas the mid- to late pod elongation stages were the most responsive. These results were observed for both indeterminate and determinate cultivars.

Specht and Williams (1983) have suggested a "critical growth stage approach" for soybean irrigation management in the Great Plains region. They recommended that soybean producers should (*1*) avoid (if possible) any irrigation prior to and during the flowering stage, (*2*) always apply sufficient water during the pod elongation stage to quickly recharge the total plant available soil water in the crop root zone, and (*3*) apply subsequent irrigation(s) during the seed enlargement stage, if soil water conditions so dictate. Because the crop must rely entirely on stored soil water (plus rainfall) prior to pod elongation, the authors cautioned that this irrigation management strategy required a deep soil of moderate to high water-holding capacity, and a fully recharged soil moisture volume at the time of planting.

The other approach to soybean irrigation management is based on the observation that timely replenishment of the soil water depleted by cumulative evapotranspiration (ET) will usually optimize total dry matter production (Hanks et al. 1969). Irrigation scheduling models based on this "soil water balance approach" were described in a review by Jones and Smajstrla (1980). Whenever the soil water depletion in the crop root zone approaches some specified "critical" limit (usually 50% of the total plant available soil water), an irrigation event is scheduled to recharge the soil water volume back to 80% or more.

In their recent review, Van Doren and Reicosky (1987) observed that in an ideal irrigation scheduling system, the crop should signal when to irrigate, whereas the soil should indicate how much water to apply. Thus, the critical growth stage and soil water balance approaches could be integrated into a single irrigation scheduling model, if the critical soil water depletion value could be automatically adjusted during the growing season to reflect ontogenetic differences in irrigation responsivity. However, a computer-based irrigation scheduling model would require a mathematical yield response function that would predict the relative yield reduction resulting when various growth stages were subjected to differing degrees of water stress. Various authors have reported on their attempts to develop such a function (Hiler et al. 1974; Smajstrla and Clark 1982; Martin et al. 1984).

The critical growth stage approach outlined by Specht and Williams (1983) was developed on the basis of results obtained with furrow irrigation systems. Delaying the first irrigation until the pod elongation stage may, in some years, require the application of substantial water amounts when irrigation is finally commenced in order to replenish the large volume of soil water that has been depleted. This may be difficult to achieve with some sprinkler irrigation systems that simply do not have the capacity to deliver, in a relatively short time, the amount of water that would be necessary to recharge the soil water content at the pod elongation stage (Elmore et al. 1988).

The primary objective of the experiment described in this report was to evaluate soybean yield response to three strategies of sprinkler irrigation management. One treatment was an irrigation scheduling (IS) system based entirely on the seasonal soil water balance approach. The other two treatments involved delaying the first seasonal irrigation until the flowering (FL) or the mid-pod elongation (PD) stages, and then scheduling all subsequent irrigation events on the basis of the soil water balance approach. The FL strategy, although not recommended by Specht and Williams (1983) for furrow irrigation systems, was included in this sprinkler irrigation experiment in order to determine its suitability as an alternative to the PD strategy with respect to those low capacity sprinkler systems in which the first irrigation cannot be reasonably delayed until the time of pod elongation (Elmore et al. 1988).

## Materials and methods

The experiment was conducted in 1982, 1983, and 1984 at the University of Nebraska Agricultural Research & Development Center (ARDC) located near Mead, NE. However, the 1982 experiment was abandoned because above-normal July and August rainfall in that year did not allow the establishment of the desired irrigation treatments. The soil at the test site is a Sharpsburg silty clay loam (fine, montmorillitic, mesic Typic Argiudoll). This moderately fertile soil is deep, well-drained, and has an available water-holding capacity of approximately 0.17 cm/cm.

Field preparation for the experiment consisted of fall-plowing after harvest of the previous crop of maize (*Zea mays* L.). In the following spring, the test site was field-cultivated twice, and then once again after the application of a pre-plant herbicide mixture consisting of the recommended rates of trifluralin [a,a,a-trifluoro-2,6-dinitro-N,N-dipropyl-*p*-toluidine] and metribuzin [4-amino-6-tert-butyl-3-(methylthio)-as-triazin-5(4 H)-one]. Weed control was excellent in both years. The experiments were planted on 26 May 1983 and 6 June 1984 using a row spacing of 0.76 m, a seeding depth of about 30 mm, and a viable seeding rate of 37.5 seed/$m^2$ for the five indeterminate cultivars 'Platte' (Maturity Group II), 'Century' (II), 'Mead' (III), 'A3127' (III), and 'Williams 82' (III) and 56.0 seed/$m^2$ the determinate cultivar 'Hobbit' (III). Final harvest populations were 30.5 and 45.0 plants/$m^2$ in 1983, and 20.5 and 23.5 plants/$m^2$ in 1984, for the respective cultivar types. The low 1984 plant populations were attributable to cool temperatures and heavy rainfall (causing soil surface crusting) shortly after planting, which reduced germination and emergence.

The agronomic response of the six soybean cultivars to three different strategies of sprinkler irrigation management was evaluated in this experiment. A nonirrigation check (NI) was included as a control treatment. In the irrigation scheduling (IS) treatment, the times (and water amounts) of the seasonal irrigation events were predicted solely on the basis of maintaining a soil water depletion status between 50% and 80% of the total plant available soil water capacity in the developing crop root zone during the entire growing season. In the second treatment, the first irrigation was intentionally delayed until the onset of the flowering (FL) stage, but thereafter all subsequent irrigation events were scheduled on the basis of the same 50% to 80% depletion criteria. In the third treatment, the first irrigation was intentionally delayed until the mid-pol elongation stage (PD), at which time four successive water applications were given during a 2-week period to recharge the soil water content to 80% or more of the total plant available soil water capacity, with all subsequent irrigation events again scheduled on the basis of the 50% to 80% depletion criteria. This experimental protocol resulted in the IS, FL, and PD treatments receiving approximately the same total amount of seasonal irrigation water (from 23 to 25 cm). The phenological staging system of Fehr and Caviness (1980) was used to determine when the FL (R1.0) and PD (R3.5) stages were attained for each cultivar. Because there was about a 6-day difference in R-stage development between the early and late maturing cultivars, an average R-value was computed for use in irrigation timing.

The experimental design consisted of a split-plot arrangement of the IS, FL, PD and NI treatments as main plots (four replications of each), with the six cultivars randomly arranged as subplots within the main plots. In order to isolate each main plot from the effects of sprinkler irrigation administered to adjacent main plots, a large peripheral border of soybeans was planted around each main plot, resulting in man plots 48.8 m wide and 48.8 m long. Because the experiment required a large field area, the main plots were arranged in a 4 × 4 latin square. Such a design permitted variability arising from lateral and longitudinal gradients in soil heterogeneity between main plots to be partitioned out of the main plot error variance term. Each cultivar subplot was 3.05 m wide (i.e. four plant rows) and 18.3 m long. A sprinkler pipeline bisected the IS, FL, and PD main plots perpendicularly to the plant row direction, with three cultivar subplots positioned on each side of the pipeline. The 3 × 2 arrangement of the six subplots occupied a 9.15 m × 36.6 m area in each main plot.

A solid-set sprinkler system, previously described by Specht et al. (1986), was used for the application of water in each treatment. The sprinkler system was operated only at dawn or dusk (wind speeds less than 1 m/sec) in order to minimize disturbance of the water application gradient generated by the sprinkler. Under these conditions, the system delivered a constant amount of water along any line parallel to the sprinkler pipeline (i.e. across the plant rows of the various cultivar subplots), but a linearly decreasing amount of water along any line perpendicular to the sprinkler pipeline (i.e., down the plant rows of the subplots). The latter effect constituted a third factor evaluated in this experiment, namely a gradient in water application. The proximal (relative to the sprinkler pipeline) 6.1 m section of the 18.3 m long cultivar subplots represented the experimental unit on which soil water content was periodically monitored for use in scheduling irrigation in each of the three treatments. However, in order to monitor the water distribution gradient generated at each irrigation, water collection gauges (graduated in 0.25 mm units) were placed in the center of the proximal, central, and distal 6.1 m sub-subplot sections of the 18.3 m cultivar subplots as described by Specht et al. (1986). The water amounts applied across the gradient for each irrigation event occurring in each of the three irrigation scheduling strategies are presented in Table 1. The individual and seasonal water amounts applied to the central and distal sub-subplots were about 50% and 10%, respectively, of those applied in the proximal sub-subplots.

The soil water content in the crop root zone of the proximal sub-subplots in each of the three irrigation treatments (and nonirrigated check treatment) was estimated on a daily basis with the assistance of an irrigation scheduling program resident on the AGNET (Agricultural Management Network) computer system. This computer system was easily accessed using a personal computer equipped with a modem to emulate a remote terminal. A complete description of the computer program ('IRRIGATE') with a detailed explanation of its calibration and use can be found in the report by Tscheschke et al. (1978). In brief, the computer program used a modified Penman equation (Jensen et al. 1971) to calculate daily estimates of ET values from automatically inputted meteorological data collected at an ARDC official weather station about 1 km from the experimental site. The ET data, coupled with on-site rainfall and irrigation data, were then used to update (on a daily basis) a soil water budget that tracked the status of the actual soil water depletion occurring in a proximal sub-subplot. Separate "field" files were established for the IS, FL, PD, and NI treatments. When querid, the program provided a printed listing of estimated daily soil water depletion values from the data of planting to the "current" access date. The program also projected values for up to 14 days beyond the access date (using historical meteorological data for computing daily ET on the projected future dates), thereby providing sufficient lead-time for the scheduling of irrigation events. The program used a total plant available soil water depletion value of 50% in the crop root zone as the criteria for triggering all irrigation events (except as noted for the first irrigation in the FL and PD treatments). The depth of the developing crop root zone was periodically estimated during the growing season by the program. The program also permitted the input of data obtained from a user-selected choice of various soil moisture sensing devices (Eisenhauer et al. 1979; Dorn et al. 1984; Yonts and Klocke 1985). To take advantage of this option, electrical gypsum blocks were installed at four soil depths (i.e. 0.15, 0.45, 0.75, and 1.05 m) in the center of the proximal sub-subplots of all main plot treatments. The data collected from these blocks (recorded about twice per week) provided frequent measures of the actual soil water status which were used by the program the periodically correct (if necessary) its ET-based estimates of the soil water status.

Agronomic data were collected from an end-trimmed (at maturity) 3.05 m section of the center two rows of the 6.1 m long 4-row proximal, central, and distal sub-subplots. Seed yield (adjusted to a standard 13% seed moisture content), days to maturity, plant height, lodging score (1 = erect; 5 = prostrate), 100-seed weight, seeds/ha, and a visual seed quality score (1 = very good; 5 = very poor) were determined as described previously (Korte et al. 1983 a). The data obtained for each measured trait were subjected to an analysis of variance (ANOVA) appropriate for a split-plot experimental design involving a latin square arrangeent of main plots (Cochran and Cox 1957). Data obtained from the proximal, central, and distal sub-subplots were analyzed as three independent data sets, because of their sequential (rather than randomized) arrangement across cultivar subplots. Years, irrigation strategies, and cultivars were considered to be fixed effects in these analyses. Appropriate $F$-tests were conducted to determine the statistical significance of the ANOVA main effects and interactions. Differences among the IS, FL, PD and NI treatment means, and among the six cultivar means, were examined for statistical significance using Duncan's Multiple Range Test. Any significant interaction between the cultivars and irrigation treatments was examined by graphing the pertinent data and using an appropriate LSD (calculated on the basis of $P = 0.05$) to interpret the statistical nature of that interaction.

## Results and discussion

The amount of rainfall received at the test site during the period 1 May through 31 October was slightly above normal in both years, totaling 500 mm in 1983 and 550 mm in 1984, vs. the long term average of 460 mm (Table 1). However, rainfall during July, August, and early September was limited in each year.

Soil water depletion values, as estimated by the computer program, first approached 50% on 12 July 1983 and 18 July 1984, thereby triggering the first irrigation event in the IS treatment on these dates (Table 1). The R1.0 flowering stage was attained about 18 July of each year, at which time the first irrigation in the FL treatment was applied. The R3.5 mid-pod elongation stage was attained on 27 July 1983 and 1 August 1984, and the first irrigation in the PD treatment was applied on those dates. During a 10- to 14-day timeframe immediately thereafter, four separate irrigations were applied to the PD treatment in order to bring the soil water depletion to less than 50% as soon as possible (achieved by 9 August in both years). Aside from the intentional delay in applying the first irrigation in the FL and PD treatments, irrigation events prior to 10 August in all three treatments were applied in strict accordance with the irrigation dates and amounts projected by the IRRIGATE computer program. However, irrigation events after 10 August of each year were coincidently applied in all three treatments, primarily because the irrigation dates projected by the computer program for all three irrigation treatments were generally similar.

Differences in the total seasonal amount of irrigation water applied in the proximal sub-subplots of each of the three irrigation treatments were small, averaging less

**Table 1.** Precipitation received, and irrigation water amounts applied, in the proximal, central, and distal sub-subplots of the IS, FL, and PD sprinkler irrigation management strategies, which were evaluated in a soybean experiment conducted near Mead, NE during 1983 and 1984

| Month | Day | Rainfall (mm) | Sprinkler irrigation management strategy[a] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IS (mm) | | | FL (mm) | | | PD (mm) | | |
| | | | Proximal | Central | Distal | Proximal | Central | Distal | Proximal | Central | Distal |
| 1983 | | | | | | | | | | | |
| May | sum: | 124 | | | | | | | | | |
| Jun | sum: | 179 | | | | | | | | | |
| Jul | 12 | | 32 | 18 | 0 | | | | | | |
| | 18 | | 31 | 16 | 3 | 31 | 16 | 3 | | | |
| | 24 | 2 | 30 | 15 | 3 | 30 | 15 | 3 | | | |
| | 27 | 3 | | | | | | | 41 | 19 | 4 |
| | 29 | 3 | | | | | | | | | |
| | 30 | 5 | | | | | | | | | |
| | 31 | 7 | | | | | | | | | |
| Jul | sum: | 20 | 93 | 48 | 5 | 61 | 30 | 5 | 41 | 19 | 4 |
| Aug | 01 | | 35 | 19 | 1 | 35 | 19 | 1 | 35 | 19 | 1 |
| | 05 | | | | | | | | 29 | 19 | 2 |
| | 06 | 7 | | | | | | | | | |
| | 09 | | | | | 28 | 17 | 1 | 28 | 17 | 1 |
| | 15 | | 33 | 19 | 2 | 33 | 19 | 2 | 33 | 19 | 2 |
| | 20 | 10 | | | | | | | | | |
| | 21 | 22 | | | | | | | | | |
| | 22 | 12 | | | | | | | | | |
| | 23 | 10 | | | | | | | | | |
| | 28 | 1 | 32 | 20 | 2 | 32 | 20 | 2 | 32 | 20 | 2 |
| Aug | sum: | 62 | 99 | 57 | 4 | 127 | 75 | 5 | 157 | 93 | 7 |
| Sep | 06 | 2 | 49 | 17 | 9 | 49 | 17 | 9 | 49 | 17 | 9 |
| | 15 | 11 | | | | | | | | | |
| | 20 | 23 | | | | | | | | | |
| | 28 | 1 | | | | | | | | | |
| | 29 | 35 | | | | | | | | | |
| Sep | sum: | 72 | 49 | 17 | 9 | 49 | 17 | 9 | 49 | 17 | 9 |
| Oct | sum: | 41 | | | | | | | | | |
| 1983 | sum: | 497 | 240 | 122 | 18 | 236 | 122 | 19 | 246 | 129 | 19 |
| 1984 | | | | | | | | | | | |
| May | sum: | 125 | | | | | | | | | |
| Jun | sum: | 166 | | | | | | | | | |
| Jul | 03 | 1 | | | | | | | | | |
| | 04 | 13 | | | | | | | | | |
| | 06 | 15 | | | | | | | | | |
| | 17 | 5 | | | | | | | | | |
| | 18 | | 36 | 18 | 1 | 36 | 18 | 1 | | | |
| | 24 | | | | | 28 | 17 | 3 | | | |
| | 26 | 9 | | | | | | | | | |
| Jul | sum: | 42 | 36 | 18 | 1 | 64 | 35 | 3 | 0 | 0 | 0 |

**Table 1.** (continued)

| Month | Day | Rainfall (mm) | Sprinkler irrigation management strategy[a] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IS (mm) | | | FL (mm) | | | PD (mm) | | |
| | | | Proximal | Central | Distal | Proximal | Central | Distal | Proximal | Central | Distal |
| Aug | 01 | | 27 | 20 | 1 | 27 | 20 | 1 | 27 | 20 | 1 |
| | 04 | 1 | | | | | | | | | |
| | 05 | | | | | | | | 27 | 17 | 4 |
| | 08 | | | | | | | | 32 | 22 | 0 |
| | 09 | | 32 | 14 | 3 | 32 | 14 | 3 | 32 | 14 | 3 |
| | 16 | | | | | | | | | | |
| | 21 | 24 | | | | | | | | | |
| | 23 | | 33 | 20 | 1 | 33 | 20 | 1 | 33 | 20 | 1 |
| | 25 | | 28 | 22 | 1 | 28 | 22 | 1 | 28 | 22 | 1 |
| Aug | sum: | 25 | 148 | 97 | 7 | 148 | 97 | 7 | 207 | 135 | 11 |
| Sep | 02 | 28 | | | | | | | | | |
| | 04 | 1 | | | | | | | | | |
| | 08 | 3 | | | | | | | | | |
| | 10 | 1 | | | | | | | | | |
| | 11 | | 45 | 16 | 4 | 45 | 16 | 4 | 45 | 16 | 4 |
| | 24 | 6 | | | | | | | | | |
| | 25 | 5 | | | | | | | | | |
| Sep | sum: | 43 | 45 | 16 | 4 | 45 | 16 | 4 | 45 | 16 | 4 |
| Oct | sum: | 145 | | | | | | | | | |
| 1984 | sum: | 545 | 228 | 130 | 11 | 257 | 147 | 14 | 25.12 | 15.06 | 1.47 |

[a] IS – Irrigation scheduled by soil water balance during the entire growing season; FL – Irrigation not commenced until flowering, but scheduled by soil water balance thereafter; PD – Irrigation not commenced until pod elongation, but scheduled by soil water balance thereafter; NI – Nonirrigated check treatment

than 10 mm in 1983, and about 29 mm in 1984 (Table 1). This approximate similarity in total seasonal water amount permitted an unconfounded comparison of the IS treatment, in which the total amount of irrigation water was distributed over the entire growing season, versus the FL and PD treatment, in which an approximately similar total water amount was distributed over a shorter timeframe commencing with a specified reproductive stage.

*Seed yield*

The 1983 growing season provided an excellent test year for evaluating soybean yield response to irrigation. The mean yield obtained with irrigation (averaged over the proximal sub-subplot data for the three treatment strategies) was 4.07 Mg/ha, which was nearly double the 2.29 Mg/ha yield attained in the nonirrigated plots (Table 2). Seed yields obtained with the IS, FL, and PD irrigation management strategies were very similar, averaging just over 4 Mg/ha in each case (Table 2). Although the irrigation treatment × cultivar interaction was found to be statistically significant in the 1983 data, this interaction was primarily due to genotypic differences in the magni-

**Table 2.** Seed yield means for the 1983 and 1984 sprinkler irrigation management treatments (averaged over six cultivars) in the three water level sub-subplots that were proximal, central, and distal to the sprinkler pipeline. Irrigation dates and water amounts applied to the three sub-subplots within each treatment are documented inTable 1

| Year | Treatment* | Water level sub-subplot (mg/ha) | | |
|---|---|---|---|---|
| | | Proximal | Central | Distal |
| 1983 | IS | 4.08 a** | 3.88 a | 3.02 a |
| | FL | 4.08 a | 3.89 a | 3.06 a |
| | PD | 4.04 a | 3.67 a | 2.66 ab |
| | NI | 2.29 b | 2.23 b | 2.16 b |
| Irrigation mean: | | 4.07 | 3.82 | 2.91 |
| 1984 | IS | 2.02 a** | 2.16 ab | 2.00 a |
| | FL | 2.05 a | 2.21 ab | 1.96 a |
| | PD | 2.22 a | 2.29 a | 2.10 a |
| | NI | 1.90 a | 1.80 b | 1.87 a |
| Irrigation mean: | | 2.10 | 2.22 | 2.02 |

* IS, Irrigation scheduled by soil water balance during the entire growing season; FL, Irrigation not commenced until flowering, but scheduled by soil water belance thereafter; PD, Irrigation not commenced until pod elongation, but scheduled by soil water balance thereafter; NI, Nonirrigated check treatment.

** Within each data column for each year, means followed by the same letter were not statistically significant from each other ($P > 0.05$)

tude of the yield differential between irrigated and nonirrigated means. This yield differential ranged from 1.2 Mg/ha for Williams 82 to 2.2 Mg/ha for Platte, with those of the other cultivars falling between these extremes (Fig. 1). These data confirmed previous work showing that Williams 82 (Fig. 1). These data confirmed previous work showing that Williams 82 was less responsive to irrigation than the other cultivars (Korte et al. 1983a; Kadhem et al. 1985a; Specht et al. 1986). Averaged over the three irrigation treatments, the determinate cultivar Hobbit exhibited the highest yield with irrigation (i.e. 4.39 Mg/ha); however, its yield was not significantly different from the slightly lower yields obtained with Century and A3127 (i.e. 4.31 and 4.18 Mg/ha, respectively), two short indeterminate cultivars (Fig. 1).

The 1984 growing season was suboptimal with respect to providing a good evaluation of soybean yield responses to the three irrigation strategies. Although the 1984 NI yields were not much lower than those attained in 1983, the 1984 yields obtained with the IS, FL, and PD treatments were only slightly and nonsignificantly enhanced relative to those obtained in the NI treatments (Table 2). This lack of yield response to irrigation may have been due to either the low plant populations, or the shorter growing season which possibly prevented an irrigation-induced lengthening of maturation (Table 3). The latter effect has been observed to be associated with yield response to irrigation in other research (Korte et al. 1983a; Specht et al. 1986). There was no significant interaction of cultivars with irrigation treatments in 1984 (Fig. 1).

The seed yield data obtained in this experiment led to the conclusion that delaying sprinkler irrigation until the flowering (FL) or the pod elongation (PD) stages was no less effective in the 1983 test, and no more ineffective in the 1984 test, in enhancing soybean yield compared with a seasonal irrigation scheduling (IS) method. This

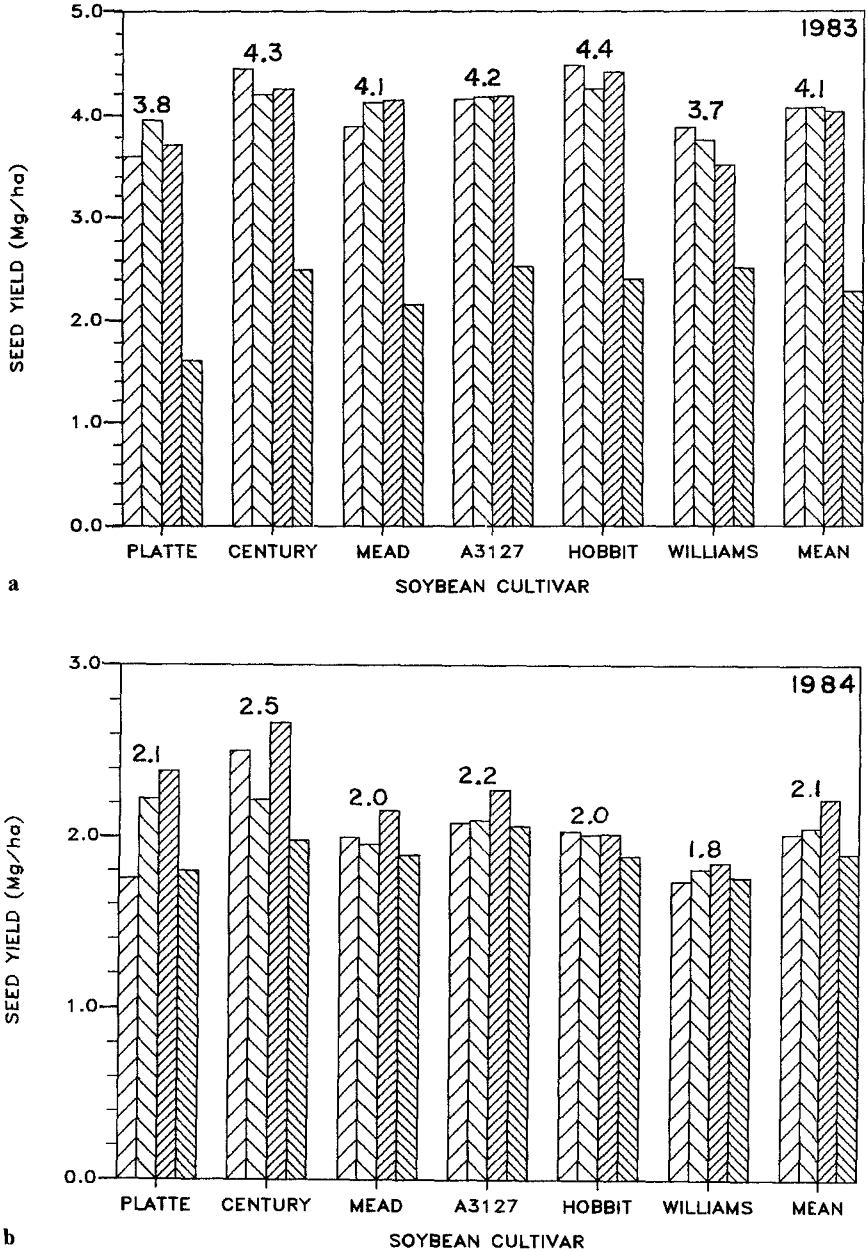


**Fig. 1 a, b.** Seed yield responses of each of six soybean cultivars to the three strategies (proximal plots) of sprinkler irrigation management and a nonirrigated check treatment in 1983 (**a**) and 1984 (**b**). The four vertical bars above each cultivar represent the following treatments (from left to right): IS – irrigation scheduled by soil water balance during the entire growing season; FL – irrigation not commenced until flowering, but scheduled by soil water balance thereafter; PD – irrigation not commenced until pod elongation, but scheduled by soil water balance thereafter; NI – nonirrigated check. Numerical data presented at the top of the figure represent the seed yield response of each cultivar averaged over the three irrigation strategies. Cultivars are ordered from left to right on the basis of early to late maturity conclusion, however, must be qualified based on a comparison of the 1983 IS, FL, and PD mean yields attained in the proximal, central, and distal sub-subplots (Table 2), in which the amount of water applied was 100%, 50%, and 10%, respectively, of that applied in the proximal sub-subplots (Table 1). As the amount of water applied at each irrigation (and over the season) decreased from the proximal to the distal sub-subplots, the 1983 yield response to all three irrigation treatments also declined (Table 2); however, the yield decline was larger in the PD treatment than in the IS or FL treatment, resulting in a nonsignificant difference between the PD and NI treatments in the distal sub-subplots. The 1983 sub-subplot data suggested that the use of the PD strategy as a tactic to justify a intentional reduction in the total seasonal water amounts (below an amount that ordinarily would be applied throughout a growing season using an IS strategy) would likely lessen the yield response to irrigation. Elmore et al. (1988) have provided additional evidence supporting this observation.

It should be mentioned here that it is possible for a PD strategy to generate high yields and unintentionally result in less total seasonal water being applied (relative to an IS strategy) in some years. This could occur if a large amount of rainfall were to occur immediately after the application of an early irrigation event in an IS strategy. Such an irrigation would not have been applied in a PD strategy. This consideration would suggest that a PD strategy may be more efficient in some years than an IS strategy. However, as Elmore et al. 1988) pointed out, a PD irrigation strategy requires a sprinkler system with a capacity sufficient to deliver the water volumes necessary to quickly recharge the soil water content at the pod elongation stage.

*Maturity*

In 1983, the three irrigation treatments generated about a 6- to 7-day delay in maturity relative to the nonirrigated check (Table 3). Such irrigation-induced maturity delays are not uncommon, as noted by Specht et al. (1986). Maturity delays in the 1984 irrigation treatments (about 2–3 days) were less than those in 1983, probably because of the shorter growing season caused by the late planting date and cooler than normal fall temperatures. No significant interaction of irrigation strategy with cultivar was detected for maturity in either year.

*Plant height and lodging*

The three irrigation treatments resulted in a significant increase in plant height and lodging when compared to the nonirrigated check in both years (Table 3). Although the PD treatment resulted in shorter plants than the IS and FL treatments in both years, the differences were not statistically significant except for the IS vs. PD comparison in 1983. However, the PD treatment did result in significantly less lodging compared to the IS and FL treatments in both years. Previous workers have shown that plant height progressively increases in the indeterminate cultivars until meristematic activity at the main stem apex ceases at about the mid-pod elongation stage (Kadhem et al. 1985a: Korte et al. 1983a). Irrigation applied before that stage stimulates vegetative growth, thereby resulting in increased plant height and concomitant increased risk of lodging. Therefore, delaying irrigation until pod elongation mitigates the occurrence of irrigation-induced increases in plant height and lodging. Irrigation treatments had little effect on plant height or lodging in Hobbit, a determinate

**Table 3.** Agronomic data obtained for the 1983 and 1984 sprinkler irrigation management treatments (averaged over six cultivars) in the water level sub-subplots that were proximal to the sprinkler pipeline

| Year | Treat-ment* | Agronomic character | | | | | |
|---|---|---|---|---|---|---|---|
| | | Days to maturity (days) | Plant height (cm) | Lodging score (units) | 100-seed weight (g) | Number of seed per unit area ($10^6$/ha) | Seed quality score (units) |
| 1983 | IS | 122.6 a** | 92.5 a | 2.04 a | 15.78 a | 25.96 a | 1.29 b |
| | FL | 122.6 a | 89.3 ab | 1.81 a | 15.35 a | 26.71 a | 1.35 b |
| | PD | 122.2 a | 84.8 b | 1.38 b | 15.26 a | 26.61 a | 1.31 b |
| | NI | 116.2 b | 66.9 c | 1.02 c | 14.53 a | 15.52 b | 2.29 a |
| Irrigation mean: | | 122.5 | 88.9 | 1.74 | 15.47 | 26.43 | 1.32 |
| 1984 | IS | 119.2 a** | 81.2 a | 1.88 a | 15.00 a | 14.02 a | 2.33 a |
| | FL | 118.8 a | 81.5 a | 2.08 a | 14.95 a | 14.18 a | 2.29 ab |
| | PD | 118.7 a | 80.3 a | 1.60 b | 14.65 a | 15.63 a | 2.15 ab |
| | NI | 116.3 b | 66.1 b | 1.17 c | 14.76 a | 13.88 a | 2.02 b |
| Irrigation mean: | | 118.9 | 81.3 | 1.85 | 14.87 | 14.61 | 2.26 |

* IS, Irrigation scheduled by soil water balance during the entire growing season; FL, Irrigation not commenced until flowering, but scheduled by soil water balance thereafter; PD, Irrigation not commenced until pod elongation, but scheduled by soil water balance thereafter; NI, Nonirrigated check treatment.

** Within each data column for each year, means followed by the samé letter were not statistically significant from each other ($P > 0.05$)

cultivar in which meristematic activity at the main stem apex ceases at the onset of the R1.0 flowering stage. This difference between Hobbit and the other cultivars was the primary reason a significant irrigation treatment × cultivar interaction was detected for plant height and lodging in both years.

*Seed number and size*

The yield components of seed number and seed size can be substantially influenced by the timing of single irrigation events before or after stage R4.0, as was demonstrated by Kadham et al. (1985b). However, in the present experiment, all three treatments involved commencing irrigation before that stage. No statistically significant differences in 100-seed weight were detected for the IS, FL, PD, and NI treatments averaged over cultivars in either year (Table 3). A significant irrigation treatment × cultivar interaction in the 100-seed weight data was, however, detected in 1983. Irrigation tended to increase seed size (relative to the NI check) in the earliest maturing cultivar (i.e. Platte), but tended to depress seed size in the latest maturing cultivar (i.e. Williams 82), with other cultivars falling between these extremes depending upon their relative maturity. This genotypic differential occurred because each irrigation event exerted its influence at a later phase of the reproductive ontogeny of Platte compared to that of Williams 82. In any case, most of the 1983 yield response to irrigation was attributable to an increase in seed number in the IS, FL, and PD treatments relative to the NI check (Table 3). There was no effect of irrigation treatment on seed number in 1984.

*Seed quality*

In 1983, seed quality was substantially improved by irrigation, with the IS, FL, and PD treatments differing significantly from the NI check, but not significantly from each other (Table 3). The 1983 irrigation-induced improvement in seed quality was large in Platte, a cultivar genetically predisposed to poor seed quality, but was intermediate or small in the other cultivars, thus resulting in a significant irrigation strategy × cultivar interaction. Irrigation tended to worsen seed quality in 1984, but the effect was significant only for IS vs. NI.

## Conclusions

The data presented in this paper indicated that soybean irrigation management strategies which involved a delay in the first irrigation until either the flowering (FL) or the pod elongation (PD) stages were no less effective in generating a yield increase than was an irrigation scheduling (IS) strategy in which the first irrigation was commenced earlier. In the 1983 experiment, yields obtained in all treatments were similar and exceeded 4 Mg/ha. Although the yield response to irrigation in 1984 was minimal due to other limiting factors, the yields attained with the three treatments were still not significantly different. We thus conclude that, for soybeans grown on deep soils of moderate to high water-holding capacity (fully recharged at planting), sprinkler irrigation can be delayed until the mid-pod elongation stage without serious impact on the expected yield response to irrigation. This conclusion is in agreement with those reached by Brady et al. (1974), Korte et al. (1983 a) and Kadhem et al. (1985 a), whose research involved furrow rather than sprinkler irrigation. It should be noted, however, that the use of a PD strategy necessitates an immediate recharge of the soil water content when sprinkler irrigation is finally commenced. Since this may be difficult to achieve with a low capacity sprinkler system, soybean producers possessing such systems will probably have to resort to commencing irrigation earlier, using either the IS or FL strategies of irrigation scheduling (Elmore et al. 1988).

## References

Brady RA, Stone LR, Nickell CD, Powers WL (1974) Water conservation through proper timing of soybean irrigation. J Soil Water Conserv 29:266

Cochran WG, Cox GM (1957) Experimental design, 2nd edn. Wiley, New York

Dorn TW, Eisenhauer DE, Fischbach PE (1984) Irrigation scheduling using tensiometers and evapotranspiration on deep sandy soils. University of Nebraska Coop Ext Service, EC 84–724

Eisenhauer DE, Fischbach PE, Trimmer WL, Krohn RA (1979) Irrigation scheduling using soil moisture blocks in deep soil. University of Nebraska Coop Ext Service. EC 79–723

Elmore RW, Eisenhauer DE, Specht JE, Williams JH (1988) Soybean response to limited-capacity sprinkler irrigation systems. J Prod Agric 1:196

Fehr WR, Caviness CE (1980) Stages of soybean development. Iowa Agric Exp Stn SR-80

Hanks RJ, Gardner HR, Florian FL (1969) Plant growth – evapotranspiration relations for several crops in the central great plains. Agron J 61:30

Hiler EA, Howell TA, Lewis RB, Boos RP (1974) Irrigation timing by the stress day index method. Trans Am Soc Agric Eng 17:393

Jensen ME, Wright JL, Pratt BJ (1971) Estimating soil water depletion from climate, crop and soil data. Trans Am Soc Agric Eng 14:954

Jones JW, Smajstrla AG (1980) Application of modeling to irrigation management of soybeans. In: Corbin FT (ed) Proceedings of the Second World Soybean Research Conference, 26–29 March 1979, Raleigh, NC. Westview Press, Boulder, p 571

Kadhem FA, Specht JE, Williams JH (1985a) Soybean irrigation serially time during stages R1 to R6. I. Agronomic responses. Agron J 77:291

Kadhem FA, Specht JE, Wiliams JH (1985b) Soybean irrigation serially timed during stages R1 to R6. II. Yield component responses. Agron J 77:299

Korte LL, Specht JE, Williams JH, Sorenson RC (1983b) Irrigation of soybean genotypes during reproductive ontogeny. II. Yield component responses. Crop Sci 23:528

Korte LL, Williams JH, Specht JE, Sorenson RC (1983a) Irrigation of soybean genotypes during reproductive ontogeny. I. Agronomic responses. Crop Sci 23:521

Martin DL, Watts DG, Gilley JR (1984) Model and production function for irrigation management. J Irrig Drain Eng 110:149

Smaljstrla AG, Clark GA (1982) Water stress effects on water use and yield of soybeans. Soil and Crop Science Society of Florida, Proceedings 41:178

Specht JE, Williams JH (1983) Soybean cultivar response to irrigation timing. In: Wilkinson D (ed) Proceedings of the Thirteenth Soybean Seed Research Conference, 6–7 December 1983, Chicago, IL. American Seed Trade Association, Washington, D.C., p 40

Specht JE, Williams JH, Weidenbenner CJ (1986) Differential responses of soybean genotypes to a seasonal soil water gradient. Crop Sci 26:922

Tscheschke P, Gilley JR, Thompson TL, Fischbach PE (1978) IRRIGATE – A scheduling model. Agric Eng 59:45

Van Doren Jr DM, Reicosky DC (1987) Tillage and irrigation. In: Wilcox JR (ed), Soybeans: improvement, production, and uses, 2nd edn. American Society of Agronomy, Madison, p 391

Yonts CD, Klocke NL (1985) Irrigation scheduling using crop water use data. University of Nebraska Coop Ext Service G85–753