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Grain Yield and Water Use Efficiency as Affected by Irrigation at Different Growth Stages

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ABSTRACT

Extensive research has been conducted on effects of drought stress on growth and development of soybean but information is rather restricted on the limited-irrigation system by way of precaution against a long-term drought condition in the future. The experiment for limited-irrigation was conducted in transparent vinyl shelter at Asian Vegetable Research and Development Center (AVRDC), Taiwan in 1997. Two soybean varieties, Hwangkeum and AGS292, improved in Korea and AVRDC, respectively were used for this experiment. The relationships between normalized transpiration rate (NTR) and fraction of transpirable soil water (FTSW) in both varieties were similar that the NTR was unchanged until FTSW dropped to about 0.5 or 0.6. At FTSW less than those values, NTR declined rapidly. Days required to harvest in both varieties were significantly prolonged at IR6 treatment compared to any other treatments. Daily mean transpiration rate was significantly higher at IR5 treatment, as averaged over varieties. Similarly, water use efficiency was also high at IR5 treatment. In both varieties, seed yield was the greatest at the IR5 treatment, as compared to any other limited-irrigation treatments, due to the increased seed number and high transpirational water use efficiency. The indices of input water and seed yield for the different limited-irrigation treatments against control indicated that Hwangkeum produced 59.6% or 60.7% of seed yield using 36.1% or 44.9% of input water, as compared to control, by irrigation at only R5 or R6 stages, respectively. The AGS292 produced 56.1% of seed yield with 35.4% of input water of control, when irrigated at R5 stage. The results of this study have elucidated that the limited irrigation at R5 stage in soybean can be minimized yield loss with such small quantity of water under the environment of long-term drought stress and the expected shortage of agricultural water in the future.

Keywords : soybean, limited-irrigation system, fraction of transpirable soil water (FTSW), transpiration rate, water use efficiency, yield.

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Uniform prevalence of an optimal soil water condition throughout an entire growing season is relatively rare event in a soybean [*Glycine max* (L.) Merr.] field. Water stress is the primary yield limiting factor in soybean production (Jin et al., 1997) and it affects every aspect of soybean growing from germination to maturity, including the anatomical, morphological, physiological, and biochemical changes.

Under-ground water depletion in Korea, and increasing energy costs for water pumping, conservation and efficient use of water are key issues and strongly recommended to practice. Soybean may possibly be so adapted for limited irrigation because photosynthesis is continued even at low leaf water potentials (Boyer, 1970).

The sensitivity of soybeans to water stress, when measured in terms of seed yield reduction, tends to increase as the crop advances through its natural sequence of growth and development, with minimal sensitivity during vegetative growth (Ashley and Ethridge, 1978).

The phenologic differential in soybean sensitivity to water stress appeared to be inversely related to the degree of compensation that may occur among the components of seed yield. A stress-induced reduction in a particular yield component may be partially or wholly offset upon the returning to the favorable environmental conditions by an enhancement of a subsequently developed component. Such yield component compensation tends to minimize the adverse effect of the stress on ultimate seed yield. The development of an irrigation management strategy for soybeans requires a knowledge of the effects of irrigation timing on yield and its components, such that yield can be economically optimized with minimal inputs of scheduled irrigation water (Jones and Smajstrla, 1980).

Progress in research on the development of quantitative response functions to soil water deficits has been slow. Part of the problem may be due to the fact that many studies have attempted to characterize water deficits with thermodynamic variables (Sinclair and Ludlow, 1985). These thermodynamic variables are not related directly to plant metabolism that depend on increase in cell volume, such as photosynthesis, cell enlargement, cell division, and N_2 fixation which are particularly sensitive to water deficits (Bennett et al., 1987). As an alternative, Ritchie (1981) proposed that the responses of physiological processes to water deficits could be evaluated as function of available soil water. This concept was refined by Sinclair and Ludlow (1986) to express these processes as functions of the fraction of transpirable soil water (FTSW) remaining in the soil. They defined the total transpirable soil water as the difference between soil water content in the field or pot capacity and the soil water content when transpiration of the drought stressed plants decreased to 10% or less of that of well-watered plants.

The use of FTSW has led to fairly consistent response functions to soil dehydration across a range of various conditions. Transpiration was shown to be unaffected by soil drying until FTSW decreased to the ranges from 0.25 to 0.35 in several grain legumes (Sinclair and Ludlow, 1986). Recently, Lecoeur and Sinclair (1996) reported for field pea that a strong consistency in the relationship of transpiration and leaf area to FTSW was existed across a diversity of experimental conditions and measurement techniques. These relationships represent a relatively easy approach to simulate the effects of drought on field pea behavior and ultimately on crop yield under a range of field conditions. Predictions of soil water balance could provide estimates of FTSW and consequently, estimates of the response of field pea to seasonal changes in soil water deficits.

Considerable information is available on the effects of moisture deficits and irrigation at different growth stage of soybean, but data are limited on the minimum amount of water to produce economic yield under drought stress condition. The objectives of this study were (1) to characterize relationship between drought stress and transpiration for two soybean varieties improved at different environments, (2) to assess the adaptability of the soybean plant to limited irrigation under drought stress condition, and (3) to determine the minimum water amount required as well as the most critical irrigation time which can minimize yield loss under long-term drought stress condition.

MATERIALS AND METHODS

Relationship between relative transpiration and soil water supply

Plant materials and growth conditions

This experiment was conducted at Asian Vegetable Research and Development Center (AVRDC) in Taiwan to determine the relationship between transpiration and soil water supply prior to subsequent experiment on the possibility of limited irrigation in soybean cultivation. Seeds of Hwangkeum and AGS292 improved at National Crop Experiment Station, Suwon, Korea and AVRDC, respectively, were sown at 15 cm diameter plastic pots in transparent vinyl shelter. Plants were thinned to one per pot at V2 growth stage (Fehr and Caviness, 1977). There were 3 well-watered plants and 3 drought stressed plants for each variety.

Measurement of transpiration

Evaporation from soil surface was minimized by covering the soil surface with aluminum foil at V4 growth stage, and then water deficits were imposed. One day before water withheld, all pots were saturated with tap water, allowed to drain overnight, and then weighed to determine the initial pot capacity weight. Plants were weighed in the early every morning, about 9:00. Transpiration rate was calculated as the difference in pot weight between successive days. Water of equivalent weight to the daily loss was added to the well watered pots. The duration from water withheld to transpiration rates approached zero was about 14 days.

Fraction of transpiration soil water

The data were analysed by comparing the relative transpiration (RT) with the fraction of transpirable soil water (FTSW) for each pot. The value of RT was calculated as the ratio of the daily water loss from the drought stressed plant to the mean daily loss from the well-watered plant. Total transpirable soil water (TTSW) was calculated by the difference between initial pot capacity weight and its weight on the day when RT reached 0.1 or less. The FTSW was calculated as the fraction of the total transpirable soil water remaining in the soil at any time. The FTSW was calculated as follows:

FTSW = (pot weight - pot weight when RT is less than 0.1) / TTSW

Response to limited-irrigation at different growth stages

The experiment was conducted in transparent vinyl shelter with two soybean varieties, Hwangkeum and AGS292. Seeds were sown in 15-cm-diameter pots and one plant per each pot was retained. The day/night temperatures in transparent vinyl shelter were approximately 48℃/24℃. Until the 3rd or 4th leaves were fully expanded, all pots were well-watered. When the 3rd or 4th leaves were fully expanded, water treatments were applied. The treatments were; (1) well-watered during the vegetative growth stage and minimum-watered after then (Wveg), (2) well-watered at R_2 stage and minimum-waered at the other growth stages (IR2), (3) well-watered at R4 stage and minimum-watered at the other growth stages (IR4), (4) well-watered at R5 stage and minimum-watered at the other growth stages (IR5), and (5) well-watered at R6 stage and minimum-watered at the other growth stages (IR6), (6) minimum-watered throughout the entire growing season (Min), (7) well-watered throughout the entire growing season as the control (WW). Pot weights for well-watered and minimum watered treatments were maintained at 90% and 82% of the pot capacity weight, respectively. For this potting soil, those weights corresponded to 0.6 and 0.2 fraction of the transpirable soil water, respectively.

In the afternoon prior to initiation of treatments, all pots were fully watered and allowed to drain overnight. The pots were weighed to determine the initial pot capacity weight. Pots were covered with aluminium foil to prevent soil evaporation.

All pots were weighed daily, and transpiration rate was calculated gravimetrically per plant on a daily basis and expressed relative to the well-watered treatment. The dates of each reproductive growth stage were recorded. Biomass of each parts, yield components, and seed quality were measured by single plant base.

This experiment was designed randomized completed block with a factorial of varieties and water treatments, and each treatment had 4 replications. Data were analysed by SAS package and graphed with SigmaPlot program.

RESULTS

Relationship between relative transpiration and fraction of transpirable soil water

There was significant difference between two varieties in the amount of total transpirable soil water. AGS292 had the higher total transpirable soil water (1,381 g pot^{-1}) than Hwangkeum (1,251 g pot^{-1}). This indicated that the amount of water extracted from soil by AGS292 was greater than Hwangkeum.

The pattern of normalized transpiration rate plotted against pot weight rate (PWR), calculated as the ratio of pot weight to pot capacity weight, was similar between two varieties. The relationship between normalized transpiration rate and PWR for each variety is shown in Fig. 1. From these linear equations (R^2=0.639** for Hwangkeum, R^2=0.775** for AGS292), the PWRs were obtained where normalized transpiration rate was zero for Hwangkeum (0.77) and AGS292 (0.76). These values indicated that the potting soil had relatively high potential to retain water to the surface of soil particles.

Normalized transpiration rates (NTR) were 1.1 and 0.9 for Hwangkeum and AGS292, when FTSW was greater than 0.5 and 0.6, respectively (Fig. 2). The transpiration rate was unchanged until FTSW dropped to about 0.5 for Hwangkeum and about 0.6 for AGS292. NTR declined rapidly when FTSW has less than those values. A Weibull curve was used to describe the relationship between NTR and FTSW. Due to differences in plant size and microenvironmental variation both within and between varieties, a number of plants had RT values that were below or above 1.0. To reduce this variation, data were normalized by dividing the RT value of individual plant for limited-irrigation treatment by the mean of RT values for well-watered plants.

Consequently, there was no difference between Hwangkeum and AGS292 for responses of transp-iration to water supply from soil, even if their abilities for water extraction from soil were different. Responses to limited-irrigation at different growth stages

Changes of days required to each growth stage

The duration from planting to harvest in both

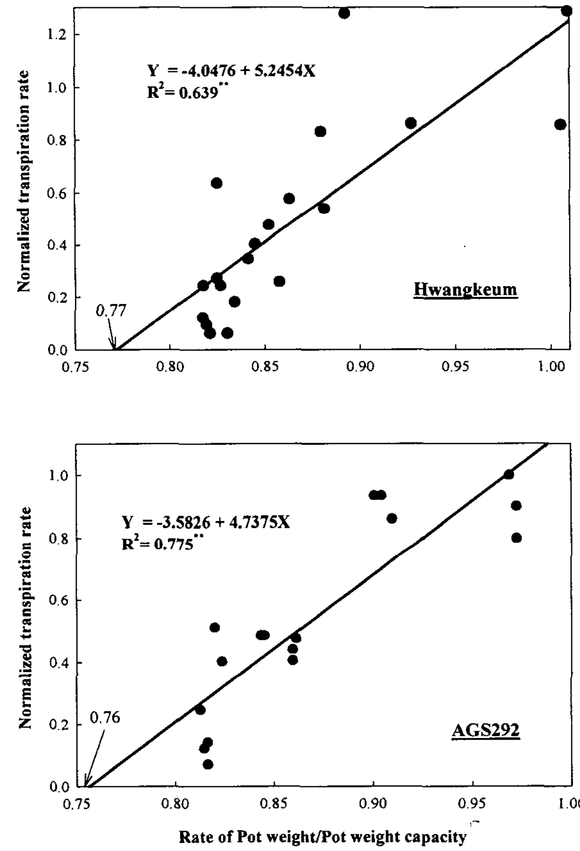

Fig. 1. Relationship between the normalized transpiration rate and the rate of pot weight to pot weight capacity for Hwangkeum and AGS292.

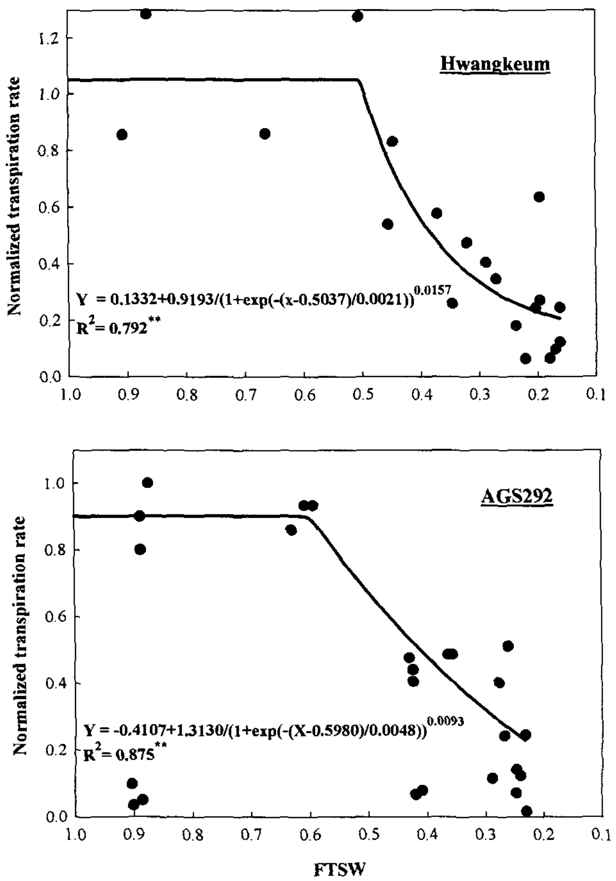

Fig. 2. Relationship between the normalized transpiration rate and the fraction of transpirable soil water (FTSW) for Hwangkeum and AGS292.

varieties was significantly prolonged by IR6 treatment due to the lengthy R6 stage (Table 1). It would indicate that irrigation at R6 stage activates the accumulation and allocation of photo and nitrogen assimilates to seed, thus this stage need more time to maintain source-sink balance. The Wveg and IR2 treatments as well as Min treatment shortened the duration for seed formation and seed filling (R5 and R6 stages) but prolonged the duration from flowering (R2) to full pod stage (R4). The prolonged durations from R2 to R4 in Wveg or IR2 treatments may be associated with production of many flowers due to the well-watered condition of R2 stage, thereafter shortage of water at R3 and R4 stage.

Daily transpiration and total amount of water applied during growing season

Daily mean transpiration according to different limited-irrigation treatments, averaged over Hwangkeum and AGS292, was significantly high at IR5 treatment (Table 2), which indicated R5 stage was the most critical period consuming large amount of water. Especially, the daily transpiration rate of R5 stage by IR5 treatment was recovered up to similar level with that of control in both varieties, as 174.8 g plant-1 day-1 for Hwangkeum and 139.2 g plant-1 day-1 for AGS292, compared with those of other stages by the corresponding limited-irrigation treatments (Table 2). However, total and daily amount of water input applied throughout growing season for limited-irrigation treatment except for control was the greatest at IR6 treatment due to its longest growing season (Table 1 and 3).

Water use efficiencies based on transpiration and input water

Water use efficiencies based on the amount of total transpiration (TWUE) and input water (IWUE) were shown in Table 4. The tendencies of water use efficiency for limited irrigation treatments were slightly different. TWUE for Hwangkeum was high at IR4, IR5, and IR6 treatments, and in AGS292, IR5 treatment had higher TWUE than any other treatments (Table 4). For IWUE, Hwangkeum had the highest value at IR4 treatment, but there was no significant difference except for IR6 treatment which had the lowest IWUE (Table 4). However, both of two varieties tended to have high values for TWUE and IWUE in the case of IR5 treatment.

The relationships between the total amounts of water loss and input water during growing season were shown in Fig. 3. In both of two varieties, total amount of water loss was always greater than that of water input. By regression analysis, the increasing rates of water loss to input water were estimated as 0.91 and 0.92 for Hwangkeum and AGS292, respectively. This result indicated that plant used 91% or 92% of input water for transpiration. In order to estimate input water use efficiency (IWUE) and transpirational water use efficiency (TWUE), seed yields for each treatment was regressed against the corresponding total amounts of input water (Fig. 4) and water loss (Fig. 5). Seed yield was increased in the form of sigmoidal curve (S-shape) as the total amounts of input water or water loss increased in both varieties. The regression equations in Fig. 4 and 5 demonstrate the nature of variable IWUE (seed yield / total amount of input water) and TWUE (seed yield / total amount of water loss). The slopes of IWUE and TWUE indicated that the water amount of more or less than optimum level would be decreased water use efficiency. Therefore, for the successful limited-irrigation cultivation, one of the most important factor would be determination of amount and timing of irrigation to come up with high water use efficiency as well as high potential of seed production.

Table 1. Number of days required to respective growth stages at different irrigation treatments for Hwangkeum (H) and AGS292 (A).

Variety	Treat[§]	V stage[†]	R1-2	R3	R4	R5	R6	R7	Total
H	Wveg	33.0	9.3	7.5	4.0	14.8	15.3	10.3	94.0
	IR2	33.8	5.8	8.0	7.0	10.8	17.5	10.5	93.3
	IR4	35.0	8.0	5.0	2.7	17.3	10.3	9.7	88.0
	IR5	33.5	7.0	5.0	5.5	13.5	12.0	7.0	83.5
	IR6	35.0	9.5	4.8	3.8	13.5	31.3	5.8	103.5
	Min	35.0	10.0	8.5	7.0	10.0	18.0	5.5	94.0
	WW	33.0	5.5	2.5	3.3	17.5	19.3	13.5	94.5
	Mean	34.0	7.7	5.8	4.6	14.1	18.4	9.3	93.9
A	Wveg	32.3	6.0	10.3	6.0	10.0	19.3	9.3	93.0
	IR2	32.0	3.8	3.8	4.5	14.3	15.3	14.5	88.0
	IR4	32.3	9.3	9.0	3.0	15.0	10.7	4.7	84.0
	IR5	32.8	7.8	7.8	3.8	13.3	12.5	6.0	83.8
	IR6	32.8	8.0	10.3	3.8	13.8	32.5	5.8	106.8
	Min	32.3	7.7	8.3	4.0	10.0	16.7	9.7	88.7
	WW	32.0	3.3	3.5	3.0	14.3	22.3	8.0	86.3
	Mean	32.3	6.4	7.5	4.0	13.0	18.8	8.3	90.3
$LSD_{0.05}$[‡]		1.0	2.1	2.5	2.5	3.7	5.9	5.9	6.5

[†] Vegetative stage

[‡] LSD to compare treatment within variety.

[§] Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimum-watered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

Table 2. Amount of daily transpiration at respective growth stages in different irrigation treatments for Hwangkeum (H) and AGS292 (A).

Variety	Treat[§]	Transpiration rate ($g\ plant^{-1}day^{-1}$)							Mean
		V[†] stage	Reproductive stage						
			R2	R3	R4	R5	R6	R7	
H	Wveg	135.0	52.8	50.0	41.4	46.5	41.0	24.8	56.7
	IR2	88.7	181.5	192.3	49.3	56.2	42.5	25.6	73.6
	IR4	78.7	56.3	43.5	130.6	60.7	46.4	27.0	58.7
	IR5	82.5	68.5	64.5	50.2	174.8	52.5	34.1	87.3
	IR6	78.5	55.9	45.9	55.9	55.3	94.7	76.7	74.7
	Min	83.5	62.0	58.2	44.2	46.5	37.0	21.0	49.1
	WW	143.5	188.7	266.3	216.2	192.2	178.0	88.9	164.9
A	Wveg	144.6	52.6	36.1	28.4	49.7	35.7	14.0	51.2
	IR2	86.5	113.6	107.0	62.1	32.8	35.0	25.8	50.9
	IR4	85.8	35.7	53.2	111.4	57.2	32.1	15.9	51.5
	IR5	90.0	34.3	32.6	43.8	139.2	44.6	23.9	67.3
	IR6	87.0	35.1	30.9	33.7	51.7	83.0	24.5	61.5
	Min	86.5	39.1	35.1	37.0	40.0	28.3	19.0	40.6
	WW	147.3	119.0	119.0	205.7	161.5	144.8	61.5	139.9
$LSD_{0.05}$[‡]		11.8	27.5	93.4	28.7	25.6	21.4	17.1	17.6

[†] Vegetative stage.

[‡] LSD to compare treatment within variety.

[§] Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimum-watered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

Table 3. Total and daily amount of water applied from V3 to R8 growth stage at different irrigation treatments for Hwangkeum (H) and AGS292 (A).

Water amount	Variety	Irrigation treatment§						
		Wveg	IR2	IR4	IR5	IR6	Min	WW
		------------ g plant^{-1} 83days^{-1}------------						
Total‡	H	2,371d†	3,063cd	2,559d	3,984bc	4,947b	706e	11,026a
	A	1,920d	1,845d	1,359de	2,769c	3,996b	965e	7,823a
		------------ g plant^{-1} day^{-1}------------						
Daily	H	28.6	36.9	30.8	48.0	59.6	8.5	132.8
	A	23.1	22.2	16.4	33.4	48.1	11.6	94.3

†Same letter are not significantly different at the 0.05 probability level with a Duncan's multiple range tést.
‡Sum of the amount of water input during 83 days, from V3 to R8.
§ Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimum-watered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

Table 4. Transpirational water use efficiency (TWUE) and input water use efficiency (IWUE) under different irrigation treatments for Hwangkeum and AGS-292.

Irrigation¶ treatment	Hwangkeum		AGS292	
	TWUE†	IWUE‡	TWUE	IWUE
	------------ mg g^{-1} ------------			
Wveg	0.78ab§	1.31abc	0.59b	1.11ab
IR2	0.39bc	0.62cd	0.58b	1.14ab
IR4	1.12a	1.79a	0.69b	1.54a
IR5	0.98a	1.36ab	1.08a	1.64a
IR6	0.88a	1.09bc	0.52b	0.67c
Min	0.08c	0.19d	0.61b	1.59a
WW	0.73ab	0.80bcd	0.90ab	1.02ab

†TWUE = grain yield / total transpiration.
‡IWUE = grain yield / total input water.
§ Within columns, means followed same letter are not significantly different at the 0.05 probability level with a Duncan's multiple range test.
¶Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimum-watered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

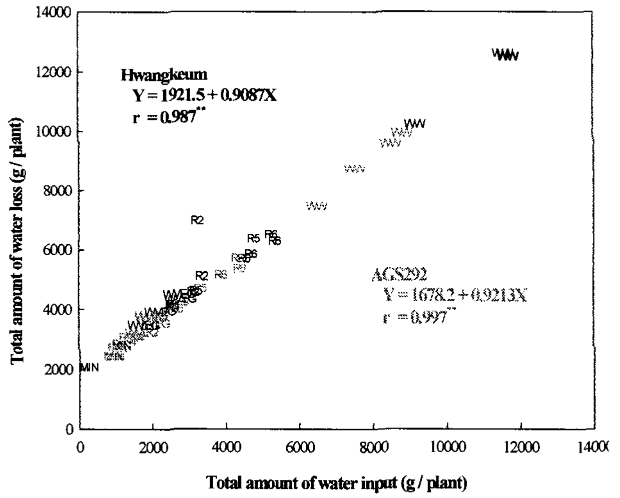

Fig. 3. Relationship between the total amounts of water loss and water input during growing season according to irrigation treatments.

Responses of seed yield and yield component to limited- irrigation

The number of pod in Hwangkeum and AGS292 was significantly increased at all limited-irrigation treatments compared with Min treatment. The R5- and R6-irrigated plants had great number of pod in limited-irrigation treatments (Table 5). However, number of seed of R6-irrigated plant in both varieties was not increased as many as increase of its pod number due to increase of abnormal seed (Table 5). On the other hand, single seed weight was greater at IR6 treatment than any other treatments due to its decreased seed number in irrigation at R6 stage. Podshell weight of both varieties was decreased by limited-irrigation compared with control, and the greatest reduction of podshell weight was occurred at

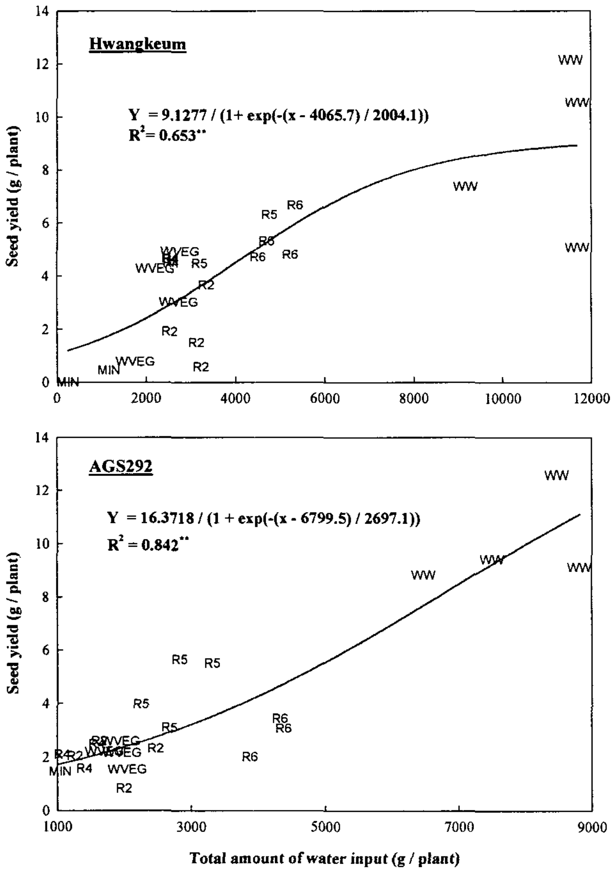

Fig. 4. Relationship between seed yield and total amount of water input during growing season according to irrigation treatment for Hwangkeum and AGS292.

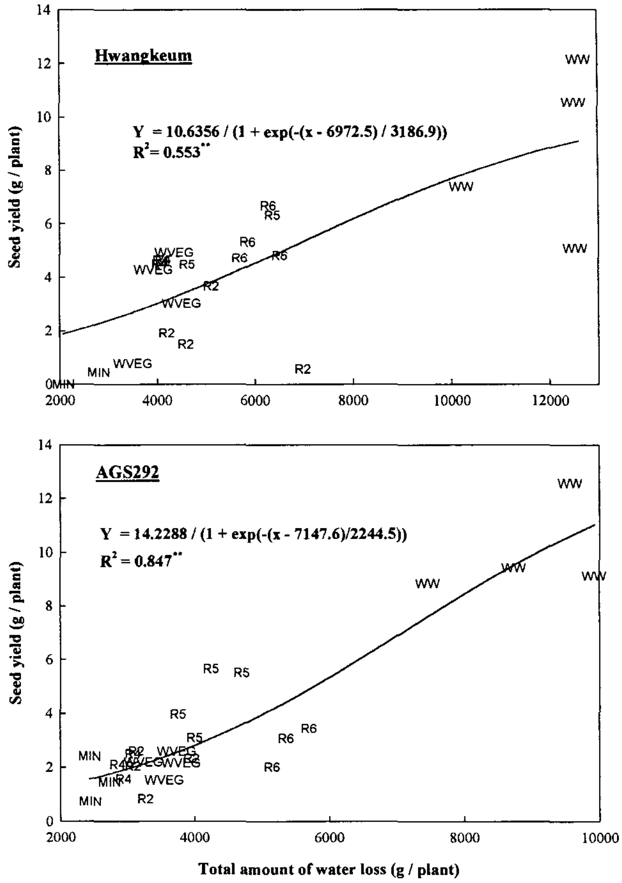

Fig. 5. Relationship between seed yield and total amount of water loss during growing season according to irrigation treatments for Hwangkeum and AGS292.

Min treatment becase of its poor photosynthetic reaction by shortage of water during growing season (Table 5). Seed yield per plant base was increased at IR4, IR5, and IR6 treatments for Hwangkeum which might due to increased seed number for IR4 and IR5 treatments and increased single seed weight for IR6 treatment. In AGS292, seed yield per plant was also increased at IR5 treatment with increased seed number. These yield response to limited-irrigation seemed to be highly related to the TWUE rather than IWUE (Table 4).

Indices of total water input and seed yield

The indices of total water input and seed yield for irrigation treatments against control were shown in Table 6. In comparison with control, Hwangkeum produced 59.6% or 60.7% of seed yield using 36.1% or 44.9% of input water by IR5 or IR6 treatment, respectively. AGS292 produced 56.1% of seed yield with 35.4% of input water by IR5 treatment.

DISCUSSION

Relationship between Relative Transpiration and Fraction of Transpirable Soil Water

The relationship between normalized transpiration rate (NTR) and the fraction of transpirable soil water (FTSW) were similar for the two varieties (Fig. 2), despite of the differences of their breeding site and their reactions to water deficit (Fig. 1). This suggests that stomatal control of water loss is determined by soil water status rather than by bulk plant water status (Bates and Hall, 1981). Both varieties had normalized transpiration rates (NTR) comparable to those of well-watered plants until FTSW fell to 0.5 or 0.6, below which sharp decline of NTR was found. This result was consistent with finding from three separate field studies with soybeans (Burch et al., 1978; Mason et al., 1980; Meyer and Green, 1981);

Table 5. Influence of irrigation treatment on grain yield parameters for Hwangkeum (H) and AGS292 (A).

Variety	Treat†	No. of pod	Podshell wt.	No. of seed	Seed wt.	Total seed wt.	Abnormal seed wt.
		$plant^{-1}$	$g\ pod^{-1}$	$plant^{-1}$	$g\ seed^{-1}$	----- $g\ plant^{-1}$	-----
H	Wveg	16.0	0.146	16.5	0.195	3.2	1.1
	IR2	19.8	0.092	10.5	0.180	1.9	2.3
	IR4	18.3	0.147	23.0	0.200	4.6	0.5
	IR5	24.5	0.165	30.5	0.175	5.3	0.8
	IR6	20.3	0.165	18.5	0.291	5.4	1.1
	Min	8.0	0.031	1.5	0.073	1.1	0.1
	WW	31.3	0.255	38.0	0.234	8.9	4.8
A	Wveg	13.0	0.133	9.8	0.223	2.2	1.0
	IR2	13.3	0.137	9.0	0.215	1.9	1.5
	IR4	13.3	0.170	10.0	0.204	2.0	1.0
	IR5	18.0	0.243	22.3	0.204	4.6	1.0
	IR6	17.0	0.178	9.0	0.318	2.9	4.2
	Min	12.0	0.111	7.0	0.230	1.6	1.3
	WW	26.8	0.279	38.5	0.212	8.2	1.7
$LSD_{0.05}$†		4.6	0.058	9.0	0.061	2.6	1.6

†LSD to compare treatment within variety.
†Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimum-watered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

Table 6. Indices of total water input (TWI) and seed yield for minimum and limited irrigation treatments, as compared to the control (WW).

Variety	Index	Treatment†					
		Wveg	IR2	IR4	IR5	IR6	Min
				----------- %	-----------		
Hwangkeum	TWI	21.5	27.8	23.2	36.1	44.9	6.4
	Yield	36.0	21.3	51.7	59.6	60.7	12.3
AGS292	TWI	24.5	23.6	17.4	35.4	51.1	12.3
	Yield	26.8	23.2	24.4	56.1	35.4	19.5

†Wveg; well-watered during the vegetative growth stage and minimum watered after then, IR2; well-watered at R2 stage and minimum-watered at the other growth stages, IR4; well-watered at R4 stage and minimum-watered at the other growth stages, IR5; well-watered at R5 stage and minimumwatered at the other growth stages, IR6; well-watered at R6 stage and minimum-watered at the other growth stages, Min; minimum-watered throughout the entire growing season, WW; well-watered throughout the entire growing season as the control.

NTR = 1 until FTSW fell to 0.2.

Soybean may differ in the rate of water loss and the amount of water they are able to extract from the soil. Crop water loss is a function of environmental conditions and the rate of leaf area development. The amount of transpirable soil water in this study was greater in AGS292 than in Hwangkeum. Although *Ratcliff et al.* (1983) suggested that there was little variation in the amount of available soil water among soils except for sands, there might be differences in the amount of water extracted by different varieties, either because of peculiar soil characteristics or specific rooting behaviour.

Responses to limited-irrigation at different growth stages

The duration from planting to harvest in both varieties was significantly prolonged by IR6 treatment due to the lengthy R6 stage (Table 1), as reported by Westgate et al. (1989). The results of measurement for daily transpiration indicated that R5 stage was the most critical period for water requirement (Table 2). On the other hand, total amount of water input applied throughout growing season for limited-irrigation treatment was the greatest at IR6 treatment due to its longest growing season (Table 3). The tendencies of water use efficiencies, TWUE and IWUE, for limited-irrigation treatments were slightly different (Table 4), but the high values for TWUE and IWUE were obtained at IR5 treatment in both varieties. This result is quite well agreed with the conclusion of Stewart et al. (1983) that water use efficiency could be increased with limited irrigation. When seed yield for each treatment was regressed against the corresponding total amount of water loss (Fig. 5) and water input (Fig. 4) for growing season, yield response to limited-irrigation highly related to TWUE rather than IWUE. It indicated that plant with high TWUE, such as R4-, R5-, and R6-irrigated plant for Hwangkeum and R5-irrigated plant for AGS292 in this study could produce high seed yield (Table 4 and 5). This fact is similar to the report that soybean might possibly be adapted for limited irrigation because photosynthesis continued at low leaf water potentials (Boyer, 1970). In addition to, the slopes of regression equations for TWUE and IWUE indicate that the water amount of more or less than optimum level would decrease water use efficiency (Fig. 4 and 5). Therefore, for the successful limited-irrigation cultivation, one of the most important factor would be determination of amount and timing of irrigation to come up with high water use efficiency as well as high potential of seed production. Jones and Smajstrla (1980) reported that the development of an irrigation management strategy for soybeans required a knowledge of the effects of irrigation timing on yield and its component, such that yield could be economically optimized with minimal inputs of scheduled irrigation water. From this point of view, for limited-irrigation, the favourable irrigation time to produce an economic yield which means to minimize the yield loss under severe drought stress was R5 stage. This result corresponds with the conclusion of Constable and Hearn (1980) that irrigating frequently before pod filling was unnecessary since moderate irrigation frequency in the vegetative stage was sufficient to grow a plant to satisfactory size to set enough seeds for maximum yield. Moreover, the result from the relationship between the indices of input water and seed yield for irrigation treatment against control (Table 6) would suggested that limited irrigation for R5 stages in soybean could be minimized yield loss with application of a small quantity of water under the environment of long-term drought stress and the shortage of agricultural water.

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