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ARTICLE

The effect of water stress in regulated deficit irrigation on soybean yield (*Glycine max* [L.] Merr.)

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Abstract The objective of this research was to investigate the effect of water stress in regulated deficit irrigation (RDI) on the yield of soybean growing on *Ultisol* soil. This research was conducted under plastic house on the experimental farm of Lampung Polytechnique from August to November 2004. The water stress treatments in regulated deficit irrigation were ET_1 ($1.0 \times ET_c$), ET_2 ($0.8 \times ET_c$), ET_3 ($0.6 \times ET_c$), ET_4 ($0.4 \times ET_c$) and ET_5 ($0.2 \times ET_c$), arranged in a randomized block design with four replications. ET_c means crop evapotranspiration under standard condition, which was well watered. For example, the ET_2 ($0.8 \times ET_c$) treatment means that the amount of supplied water per a day is the same as the crop adjustment evapotranspiration (ET_{cadj}) with the value 0.8 of water stress coefficient (K_s). The RDI treatments were carried out just at vegetative phase and its treatments were stopped at the beginning of flowering phase, and afterwards the treatments were watered at $1.0 \times ET_c$. The results showed that since week II, the soybean experienced stress throughout the growth period except ET_2 treatment. ET_2 treatment started to be stressed at week V and continued to be stressed until the harvest time. At the ET_3 treatment, the critical water content (θ_c) of soybean was reached at week II, and the θ_c was 0.24 m^3/m^3 on the average. The RDI at vegetative period significantly affected the yield. The highest yield was ET_1 (35.2 g/plant), followed by ET_2 (31.0 g/plant), ET_3 (18.1 g/plant), ET_4 (7.6 g/plant), and ET_5 (3.3 g/plant). The optimal water management of soybean with the highest yield efficiency was regulated deficit irrigation with water stress coefficient (K_s) of 0.80 for vegetative phase.

Keywords Ultisol · Water stress coefficient · Yield efficiency · Optimal water management

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Introduction

In the year 2004, national consumption of soybean in Indonesia was 2.02 million ton, but national production just achieved 0.71 million ton and the remaining 1.31 million ton of soybean was imported to meet 65% of national consumption (Marwoto et al. 2005). In particular, soybean production in Lampung province in 2003 was 3.97×10^3 ton from cropping area of 3.91×10^3 ha, or 1.02 ton/ha (Statistical Bureau 2003). The low national production of soybean was due to the low productivity and small cropping area. One of the reasons why the cropping area decreased was the limitation of water resources (Fagi and Tangkuman 1985).

However, efficient use of water resources depends on reducing water losses, which can be minimized through use of new irrigation techniques such as irrigation programs with deficient evapotranspiration. Demand for evapotranspiration (ET) can be reduced either through agronomic measures or use of deficit irrigation programs. The main approach in deficit irrigation practice is to increase water use efficiency by partially supplying the irrigation requirement and allowing water stress to planned plant during one or more periods of the growing season with the least impact on crop yield (Kirda et al. 1999).

The yield of soybean in the dry season with adequate irrigation was 1.97 ton/ha, but in the wet season was 0.61 ton/ha (Baharsyah et al. 1985). Usually, soybean is planted in paddy fields after the second harvesting of the paddy rice at the end of rainy season, through the dry season. Therefore, water availability becomes a limiting factor of production, so that the possibility of implementing deficit irrigation method is inevitable.

According to Allen et al. (1998), the evapotranspiration under water stress condition when soil water content falls below the critical water content is called as the adjustment evapotranspiration (ET_{cadj}), which can be calculated by the following equation.

$$ET_{cadj} = K_s \, ET_c \tag{1}$$

$$ET_c = K_c \, ET_o \tag{2}$$

where ET_c is the crop evapotranspiration under standard condition, which was well watered (mm/day), ET_o is evapotranspiration of reference crop (mm/day), K_c is crop coefficient (no dimension), K_s *is* water stress coefficient (no dimension).

Value of K_s is important for estimating ET_{cadj}, so that the deficit irrigation scheduling can be made. K_s describes the effect of water stress on crop transpiration (Allen et al. 1998).

According to Doorenbos and Kassam (1979), the K_c of soybean during the initial, the development, the mid season, late season and harvest stage was 0.35, 0.75, 1.075, 0.75, and 0.45, respectively. The average K_c values of the whole growing period were between 0.7 and 0.8, or 0.75.

According to Doorenboss and Kassam (1979), in order to quantify the effect of water stress, it is necessary to derive the relationship between relative yield decrease and relative evapotranspiration deficit given by the following equation.

$$1 - Y_a/Y_m = K_y \, (1 - ET_a/ET_m) \tag{3}$$

where $1 - Y_a/Y_m$: relative yield decrease, Y_a: actual yield, Y_m: maximum yield (under no water stress condition), $1 - ET_a/ET_m$: relative evapotranspiration decrease, K_y: yield response factor, ET_a: actual evapotranspiration, and ET_m: maximum evapotranspiration (under no water stress condition).

The effect of water stress, especially at vegetative phase of groundnut has been reported by Nautiyal et al. (2000). They stated that water deficit stress during the vegetative phase, can increase water use efficiency (WUE) significantly. Bustomi Rosadi et al. (2005), according to pot experiment in their greenhouse, stated that the soybean plant started to experience water stress at the fourth week from planting, if soil water was maintained at 40–60% available water deficit for the whole growing period. It meant that available water deficit strongly affected the soybean growth from the end of vegetative phase (fourth week) to the generative phase and the available water deficit gave no significant effect to the soybean growth at the vegetative phase except at the fourth week. So there is a possibility to apply the deficit irrigation at the vegetative phase to achieve an optimal yield. But, there remains question how to apply this result on the field, actually. So there is a need to modify the treatments in order to clear the relation between ET and available soil water depletion. The modification treatments in deficit irrigation research are known as the regulated deficit evapotranspiration (RDE) or regulated deficit irrigation (RDI). ''Regulated'' means that the deficit irrigation was applied just at certain growth period, e.g., vegetative phase in this research.

Based on the explanation above, it is necessary to find an efficient and effective use and management of water so that the soybean cropping area can be increased; therefore it is important to know the K_s value in RDI condition. So, if these values were known and full irrigation was restricted by the availability of water, the deficit irrigation can be applied, which allows maintaining soil water content below full irrigation at certain growth period, to achieve an optimal yield. The objective of this research was to investigate the effect of water stress in RDI at vegetative phase on the water use efficiency of soybean (var. *Willis*) in the frame of optimum water management.

Materials and methods

This research was conducted under plastic house in an experimental farm of Lampung Polytechnique from August to November 2004. Soybean cultivar used was *Willis*. The soil was sandy loam in texture and classified as *Ultisol*. Soil water content at field capacity (34.7 kPa) was 0.352 m^3/m^3 and wilting point (1,585 kPa) was 0.223 m^3/m^3. Therefore, total available water (TAW), that is the total soil water content between field capacity and permanent wilting point, was 0.128 m^3/m^3. The elevation of site was 43 m above sea level. The average air temperature was 26.3°C and the relative humidity was 60.8%.

The water stress treatments in RDI imposed were: ET_1 ($1.0 \times ET_c$), ET_2 ($0.8 \times ET_c$), ET_3 ($0.6 \times ET_c$), ET_4 ($0.4 \times ET_c$) and ET_5 ($0.2 \times ET_c$) arranged in a randomized complete block design with four replications. The area of each treatment plot was 1×1.5 m^2, and the distance between plots was 1 m. The RDI treatments were given just at vegetative phase (1 month after planting) and its treatments were stopped at the beginning of flowering phase,

Fig. 1 Irrigated water of each week at regulated deficit irrigation treatment

Week		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Day		1-7	8-14	15-21	22-28	29-35	36-42	43-49	50-56	57-63	64-70	71-77	78-84
Crop stages		Initial		Develop-ment		Mid season				Late season		Harvest	
Treatments		Water stress period				Full irrigation						No irrigation	
Irrigated water (mm/d)	ET_1	$1.0\times ET_c$				$1.0\times ET_c$						0	
	ET_2	$0.8\times ET_c$				$1.0\times ET_c$						0	
	ET_3	$0.6\times ET_c$				$1.0\times ET_c$						0	
	ET_4	$0.4\times ET_c$				$1.0\times ET_c$						0	
	ET_5	$0.2\times ET_c$				$1.0\times ET_c$						0	

ET_c: crop evapotranspiration under standard condition (mm/d)

and afterwards the treatments were watered at $1.0 \times ET_c$ (see Fig. 1). On the day before planting, the soil was saturated with water, and irrigation was given at two days interval by handycan. For example, the ET_2 ($0.8 \times ET_c$) treatment means that the amount of supplied water per day is the same as the crop adjustment evapotranspiration (ET_{cadj}) with the value 0.8 of water stress coefficient (K_s). The amount of each irrigation was the same as the 2 days accumulated ET_{cadj} according to the treatments. ET_{cadj} was calculated by formula (1), and ET_o was measured by class A pan with pan coefficient (K_{pan}) being 0.8 and crop coefficient (K_c) of soybean being 0.75 (the average value for the whole period). The values of K_{pan} and K_c were referred from Doorenboos and Kassam (1979). The emerged seedlings were pruned to maintain only two healthy seedlings per seedling hole. Fertilizer application of urea at 50 kg/ha, triple super phosphate at 75 and 75 kg/ha muriate of potash were applied. The soybean plants were sprayed with insecticide to protect them from insect attack at least twice a month. The growth period of soybean plant was 85 days, and 2 weeks before harvesting, the irrigation was stopped.

The soil water content was monitored by porous blocks placed at 15 cm depth in each plot. These porous blocks were made by two circles of brass plate; the diameter of small one was 1 cm and the big one was 2 cm, and both the brass plates had extension wires to make easier in measuring the resistance by multitester. All brass plate were in side of gypsum cylinder with 3 cm diameter and 4.5 cm high. Before using them to measure the soil water content, the porous blocks had been calibrated in the laboratory by making the relationship between the soil water resistance and the soil water content. The soil water resistance was measured by multitester daily, and using the relationship as mentioned above the data was converted to the soil water content.

Agronomic variables evaluated in this research were plant height, leaf, flower and pod numbers, wet weight of total biomass and yield, WUE, and yield efficiency (YE). WUE (g/mm) was calculated as the ratio of total biomass (g/plant) to the total irrigation (TI), and YE (g/mm) was calculated as the ratio of yield (g/plant) to TI (mm). Statistical analysis using *F*-test at 5% significant level, followed by LSD (Least Significant Different) test at the same level was carried out.

Results and discussion

Plant growth

The effects of water deficit on plant growth indicators are shown in Table 1. It can be observed from this table that based on plant height and leaf number at week II, the soybean experienced stress throughout the growth period except ET_2 treatments. ET_2 treatment started to be stressed at week V and continued to be stressed until week VI, which was shown by the pod number of ET_2 treatment. This stress condition was continued until the end of growth, which was shown by the total biomass and yield at ET_2, which were significantly different compared to ET_1. The plant height at ET_1 (43.9 cm) was the highest at week VII, and significantly different compared to ET_3 (37.2 cm), ET_4 (28.5 cm), and ET_5 (17.1 cm). Similarly the leaf number at ET_1 (61.0) was the greatest at week VII, and significantly different compared to ET_3 (48.0), ET_4 (42.5), and ET_5 (15.1).

Yield

Table 2 provides information that the flowering and pod formation were significantly affected under ET_2, ET_3, ET_4, and ET_5 treatments. The flower numbers at ET_1 (10.46 pieces) was the highest at week V, and significantly different compared to ET_3 (8.83 pieces), ET_4 (4.75 pieces), and ET_5 (1.13 pieces). The flower numbers at ET_1 (13.4 pieces) was the greatest at week VI, and significantly different compared to ET_2 (11.18 pieces), ET_3 (6,18 pieces),

Table 1 The effect of water stress at vegetative phase on the plant height, and leaf number

Water stress level	Week						
	I	II	III	IV	V	VI	VII
Plant height (cm)							
ET_1	5.1 a	8.8 a	17.2 a	21.9 a	30.1 a	35.6 a	43.9 a
ET_2	5.0 a	8.4 ab	15.1 ab	19.2 ab	27.6 b	32.6 b	41.8 a
ET_3	5.0 a	7.4 bc	13.1 b	17.4 b	22.5 c	26.9 c	37.2 b
ET_4	5.0 a	7.6 c	10.2 c	12.4 c	16.3 d	20.5 d	28.5 c
ET_5	5.0 a	5.6 d	7.8 d	8.5 d	9.7 e	13.1 e	17.1 d
Leaf number (pieces)							
ET_1	4.0 a	8.50 a	11.9 a	17.8 a	30.3 a	50.9 a	61.0 a
ET_2	4.0 a	8.58 a	10.8 ab	16.4 ab	25.4 b	44.8 b	58.5 a
ET_3	4.0 a	8.04 b	10.5 bc	16.2 b	22.5 b	38.6 c	48.0 b
ET_4	4.0 a	6.91 c	9.2 c	12.0 c	16.8 c	32.2 d	42.5 c
ET_5	4.0 a	4.75 d	4.9 d	5.7 d	8.3 d	11.4 e	15.1 d

The values of plant height and leaf number were measured at the last day of each week

Numbers followed by the same letters vertically were not significantly different using LSD-test at 5% significant level

Table 2 The effect of water stress at vegetative phase on the flower and pod number

Water stress level	Flower number (pieces)		Pod number (pieces)	
	Week V	Week VI	Week VI	Week VII
ET_1	10.46 a	13.40 a	15.96 a	21.39 a
ET_2	9.83 ab	11.18 b	12.00 b	17.88 b
ET_3	8.83 b	6.18 c	8.03 c	18.16 b
ET_4	4.75 c	5.21 c	2.58 d	7.26 c
ET_5	1.13 d	1.31 d	0.00 e	1.22 d

The values of flower and pod number were measured at the last day of each week

Numbers followed by the same letters vertically were not significantly different using LSD-test at 5% significant level

Table 3 The effect of water stress at vegetative phase on the biomass, yield, TI, WUE, and YE

Water stress level	Wet biomass (g/plant)	Yield (g/plant)	TI (mm)	WUE (g/mm)	YE (g/mm)
ET_1	51.5 a	35.2 a	220.0	0.187 a	0.16 a
ET_2	44.5 b	31.0 b	200.4	0.181 a	0.15 a
ET_3	33.3 c	18.1 c	181.0	0.132 b	0.10 b
ET_4	14.3 d	7.6 d	161.5	0.058 c	0.05 c
ET_5	8.7 e	3.3 e	142.1	0.037 d	0.02 d

TI total irrigation, *WUE* water use efficiency, *YE* yield efficiency

Numbers followed by the same letters vertically were not significantly different using LSD-test at 5% significant level

ET_4 (5.21 pieces), and ET_5 (1.31 pieces). The pod numbers at ET_1 (15.96) was the greatest at week VI, and significantly different compared to ET_2 (12.00), ET_3 (8.03), ET_4 (2.58), and ET_5 (0.00). The pod numbers at ET_1 (21.39) was the highest at week VII, and significantly different compared to ET_2 (17.88), ET_3 (18.16), ET_4 (7.26), and ET_5 (1.22). Furthermore, in Table 3 it can be seen that the total biomass and yield were also significantly affected under ET_2, ET_3, ET_4, and ET_5 compared to ET_1. The total biomass at ET_1 (51.5 g/plant) was the highest at week VII, and significantly different compared to ET_2 (44.5 g/plant), ET_3 (33.3 g/plant), ET_4 (14.3 g/plant), and ET_5 (8.7 g/plant). The yield at ET_1 (35.2 g/plant) was the highest at week VII, and significantly different compared to ET_2 (31.0 g/plant), ET_3 (17.1 g/plant), ET_4 (7.6 g/plant), and ET_5 (3.3 g/plant).

Based on the explanation above, it is clear to understand that the soybean plant experienced initial stress from week V at ET_2, and from week II at ET_3 to ET_5, and remained in the stress condition until harvest time.

Water use and yield efficiencies

Table 3 shows that the effects of RDI at vegetative phase on the WUE and YE were significantly different. RDI treatments of ET_3–ET_5 showed significant difference compared to ET_1 (as a control).

The value of TI in Table 3 was assumed to be same with the total irrigation for the whole growing period (see Table 4). It can be seen from Table 3 that even though there is no significant difference between ET_2 and ET_1 treatments in WUE and YE, there is significant difference in yield per plant. So the ET_1 treatment is the greatest in yield per plant, WUE and YE.

Daily soil moisture contents

The daily soil moisture contents measured by porous block were shown in Fig. 2. It can be seen that the soil moisture content of all treatments decreased at the first week, and

Table 4 The weekly irrigation (mm)

Water stress level	Week I	II	III	IV	V	VI	VII	VIII	IX	X	Total
ET_1	22.7	26.7	25.4	22.4	19.6	17.8	15.3	18.2	25.4	26.3	219.8
ET_2	18.4	21.4	20.4	17.9	19.6	17.8	15.3	18.2	25.4	26.3	200.7
ET_3	13.6	16.0	15.3	13.4	19.6	17.8	15.3	18.2	25.4	26.3	180.9
ET_4	9.1	10.7	10.2	9.0	19.6	17.8	15.3	18.2	25.4	26.3	161.6
ET_5	4.5	5.3	5.1	4.5	19.6	17.8	15.3	18.2	25.4	26.3	142.0

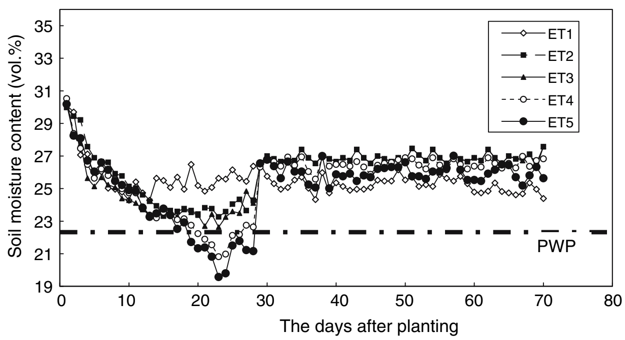

Fig. 2 The daily soil moisture content measured by porous block

Table 5 The yield response factor (K_y) of soybean

Water stress level	Yield (g/plant)	ET_a (mm)	$1 - Y_a/Y_m$	$1 - ET_a/ET_m$	K_y
ET_1	35.23	97.2	0.00	0.00	0.00
ET_2	31.04	78.1	0.118	0.20	0.59
ET_3	18.10	58.3	0.486	0.40	1.21
ET_4	7.55	39.0	0.786	0.60	1.30
ET_5	3.29	19.4	0.907	0.80	1.13
Average					1.05

Y_a actual yield, Y_m maximum yield, ET_a actual evapotranspiration at vegetative phase, ET_m maximum evapotranspiration of ET_a, K_y yield response factor

after that, since week II, the change of soil moisture content depended on each treatment. It is easy to understand that at the first week the soil moisture of all treatments decreased because on the day before planting, the soil was saturated and the gravitational water in soil continued to percolate deeper for a week. In week II, it can be seen that the soil moisture contents of ET_3, ET_4, and ET_5 were lower than ET_1, but that of ET_2 was quite closed to ET_1 treatment. Based on growth indicators (plant height and leaf number), it is known that soybean plants started to be stressed at week II at ET_3, ET_4, and ET_5 treatments. It means that the critical water content (θ_c) of soybean at week II was reached at the ET_3 treatment, and the θ_c was 0.24 m^3/m^3 on the average. The ET_4, and ET_5 still were continuing to be stressed at week III and IV, and soil water contents of those treatments were under the permanent wilting point.

Figure 2 shows that the soil moisture content of ET_1, which is a full irrigation treatment ($1.0 \times ET_c$), was relatively constant since week II until the end of irrigation period at 0.243–0.266 or 0.253 m^3/m^3 in average. It means that the actual evapotranspiration of soybean at ET_1 was balanced with the amount of irrigated water estimated using the value of $K_c = 0.75$.

Figure 2 also shows that after stopping the treatments (week V), the soil moisture content of ET_2, ET_3, ET_4, and ET_5 treatments hovered constant values, which were more than that of ET_1 treatment. It means that the stress condition of the soybean plant at ET_2, ET_3, ET_4, and ET_5 treatments still continued until the end of irrigation period, which indicates that the evapotranspiration rates of those treatments were less than that of ET_1.

Yield response to water stress

Using Eq. 3, the K_y values of ET_2, ET_3, ET_4, and ET_5 shown in Table 5 are 0.59, 1.21, 1.30, and 1.13, respectively, with an average value of 1.05. The value of evapotranspiration at ET_1 was assumed as maximum evapotranspiration (ET_m), and the evapotranspiration at ET_2–ET_5 were assumed as a actual evapotraspiration (ET_a). The relationship between relative yield decrease ($1 - Y_a/Y_m$) and relative evapotranspiration deficit ($1 - ET_a/ET_m$) was not linear as shown in Fig. 3. The result of this experiment was almost same with that of pot experiment by Bustomi Rosadi et al. (2005).

According to Doorenboss and Kassam (1979), the K_y values are derived on assumption that the relationship between relative yield decrease and relative evapotranspiration deficit is linear and is valid for water deficits of up to about 50% or $1 - ET_a/ET_m = 0.5$, in which the K_y of soybean for the vegetative period of water deficit is 0.59. According to Doorenboss and Kassam (1979), the K_y values of soybean at early vegetative was 0.45. The differentiation between those K_y values was due to the different period in applying the RDI. In this research RDI was applied at the whole vegetative phase, whether Doorenboss and Kassam at the early vegetative phase.

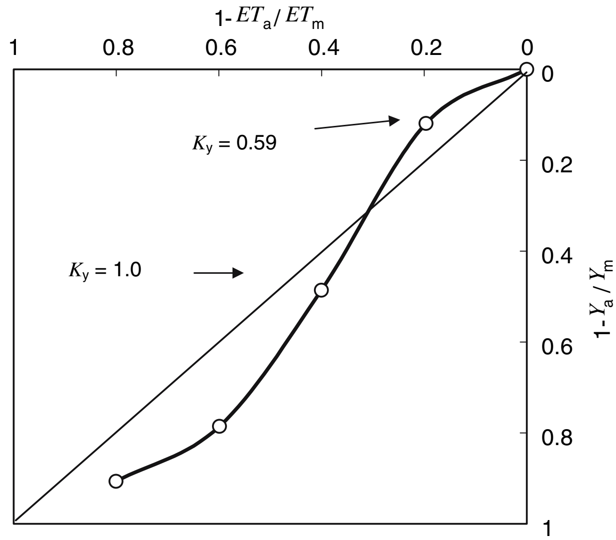

Fig. 3 The yield response of water deficit at vegetative phase to the yield

Optimum deficit irrigation

According to the result in Table 5, the K_y value of ET_2 treatment was 0.59, which meant that ET_2 treatment responded to deficit irrigation because of $K_y < 1$. Bustomi Rosadi et al. (2005) also showed that the optimum yield of soybean plant (var. *Willis*) with the highest efficiency was reached by deficit irrigation that maintained the soil water condition at the level of 40–60% of available water deficit with $K_y = 0.611$, and could conserve 10.1% of water. The K_y of the optimum yield of this laboratory experiment was almost same with the K_y of ET_2 treatment, which was 0.59. However, the effect of the treatment to the WUE and YE at ET_2 was not significantly different compared to ET_1. So, there remains question if the calculation of YE at ET_2 was right. Principally, if ET_2 treatment responded to the deficit irrigation, the YE of ET_2 must be higher than ET_1.

Based on Fig. 2, it was found that the soil water content at ET_2 was higher than ET_1 treatment. It was happened because the soybean plant really continued to be in stress condition after week V (see Tables 1, 2). So, if the plant was irrigated by the same volume with ET_1, some water could not be really used by plant and may be lost as gravitational water or still remained in the soil as shown in Fig. 2, and the value 200.4 mm at ET_2 in Table 3 is supposed to be more than the real crop water requirement. Those same phenomena were also happened at ET_3, ET_4, and ET_5 treatments.

So, if the ET_2 treatment was irrigated by the amount of water such as actual evapotranspiration since week V, there was a possibility that the total irrigated water could be decreased and the value of YE could become bigger than the results as shown in Table 3. It is important for completing optimal water management in RDI to estimate the actual evapotranspiration after vegetative phase without yield decrease.

However, this water management cannot be applied to the other fields with different soil and meteorological conditions, which could affect strongly soil moisture consumption by soybean plant. This research could propose how to determine the water stress coefficient in regulated deficit irrigation with the highest yield efficiency of soybean on the field.

Conclusion

1. At week II, the soybean experienced stress throughout the growth period except ET_2 treatments. ET_2 treatment started to be stressed at week V and continued to be stressed until harvest time.
2. The critical water content (θ_c) of soybean at week II was reached at the ET_3 treatment, and the θ_c was 0.24 m^3/m^3 on the average.
3. The water stress in RDI at vegetative period significantly affect the yield. The highest yield was ET_1 (35.2 g/plant), follows by ET_2 (31.0 g/plant), ET_3 (18.1 g/plant), ET_4 (7.6 g/plant), and ET_5 (3.3 g/plant).
4. The optimal water management of soybean with the highest yield efficiency was regulated deficit irrigation with water stress coefficient (K_s) of 0.80 for the vegetative phase. Furthermore, there is the possibility that the amount of total irrigated water could be decreased, if the actual evapotranspiration of ET_2 treatment after the vegetative phase could be estimated without decrease compared to full irrigation.

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