Evaluation of the potentialities of different soil types to yield response of soybean under deficit irrigation

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Abstract: An experiment was conducted in a vinyl house at Gifu University, Japan, from June to November 2007 to evaluate the potentialities of the three soil types under various water deficit conditions to yield of soybean. The soil type was the first factor with three different soil types, comprising of clay loam, sandy clay loam, and sandy loam soils, classified as Inceptisol, Ultisol, and Andisol, respectively. Water deficit (D) was the second factor with four levels including D_1 (0 – 25 %), D_2 (25 – 50 %), D_3 (50 – 75 %) and D_4 (75 – 100 %) water deficits of total available water (TAW).

The crop water requirement (CWR) of soybean in the three soil types significantly decreased with the increasing water deficit levels, and the highest was in Inceptisol, followed by Ultisol and then Andisol under all water deficit levels. Grain yield of soybean per unit area in Inceptisol was the highest, followed by Ultisol and then Andisol under all water deficit levels. The values of yield efficiency (YE), indicating the grain yield per unit CWR, was strongly influenced by water deficit level, and the maximum YE occurred at the water deficit level D_3 (50 – 75 %) in all the three soil types. However, there were no significant differences at 5 % level among the maximum values of YE in the three soil types. The lowest yield response factor (K_y), indicating the relative yield loss to relative water deficit, was seen in Inceptisol ($K_y = 0.42$), followed by Ultisol ($K_y = 0.64$) and then Andisol ($K_y = 0.87$) under the water stress lower than 50 – 75 % of TAW. These results indicate that deficit irrigation in Inceptisol contained the finest soil texture is the most effective for economic water usage among the three soil types under the water deficit lower than 50 – 75 % of TAW (D_3).
Key Words : deficit irrigation, soybean, crop water requirement, yield efficiency, yield response factor

1. Introduction

Soybean is economically an important crop with widespread consumption and utilization in vegetable oil and veterinary industries. Soybean crop seldom attains its full yield potential because of limitations on physiological processes imposed by environmental stresses. It is true that insects and diseases sometimes drastically reduce yields, but in the long run, such reductions are small compared with those caused by unfavorable weather. Shortage of available water is one of the most significant environmental stresses that cause yield reductions in a wide range of crops including soybean (Frederick and Hesketh, 1994).

Water resources in many areas of the world are limited but their demand is increasing. Irrigation agriculture is under economic and political pressure to improve the efficiency with which water is used. 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 can be reduced either through agronomic measures or use of deficit irrigation programs. The main approach in deficit irrigation practice is to increase crop water use efficiency by partially supplying the irrigation requirement and allowing water stress to planned plant with the least impact on crop yield. Deficit irrigation management requires optimizing the degree of plant stress within the restriction of available water.

Different soil types are known to influence the total available water to plants and, therefore, the time when crop water stress develops during a period of drying. This effect is incorporated in irrigation scheduling systems based on water balance estimates. However, it is generally assumed that the rate of transpiration from a crop with full canopy development and adequate water is controlled only by atmospheric condition and by physical and physiological properties of the canopy with soil type having little or no effect. There are few experiments on evapotraspiration from crop species grown on different soil types. Also, the reports of soil type effects on total water use by a well-watered crop exist, but the cause of water deficit effects is not known.

Therefore, the research was conducted with the objective to evaluate the potentialities of different soil types to yield response of soybean under water deficit conditions. This research can be used to determine water saving irrigation schedules for different soil types to ensure optimum production of soybean.

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Table 1 Physical properties of three soil types.

Soil types	Soil texture			Textural class	Particle density (g cm^{-3})	Textural density (g cm^{-3})	Total porosity (m^3 m^{-3})	Three phase distribution (m^3 m^{-3})		
	Sand (g g^{-1})	Silt (g g^{-1})	Clay (g g^{-1})					Solid phase	Water phase θ_{FC}(34.7 kPa)	Air phase
Inceptisol	0.40	0.27	0.33	clay loam	2.61	1.06	0.60	0.40	0.39	0.21
Ultisol	0.59	0.18	0.23	sandy clay loam	2.65	1.37	0.48	0.52	0.32	0.16
Andisol	0.63	0.20	0.17	sandy loam	2.49	1.07	0.57	0.43	0.35	0.22

Table 2 Moisture properties of three soil types.

Soil Types	Field Capacity θ_{FC} (31 kPa) (m^3 m^{-3})	Wilting Point θ_{PWP} (1553 kPa) (m^3 m^{-3})	Total Available Moisture $\theta_{FC} - \theta_{PWP}$ (m^3 m^{-3})
Inceptisol	0.390	0.228	0.162
Ultisol	0.323	0.182	0.141
Andisol	0.350	0.185	0.165

2. Materials and Methods

This research was conducted in a vinyl house with open surrounding sides, located in the experimental farm of Gifu University, Japan, from June to November 2007. A factorial experiment was arranged in randomized block design with three replications.

The first factor was the soil property with three different soil types namely; Inceptisol, Ultisol and Andisol. The physical properties of the three soil types are shown in Tables 1 and 2. The Inceptisol, which was taken from a paddy field in Yanagido farm of Gifu University, was clay loam. It had the highest fine particles consisting of clay and silt, and the highest water content at field capacity and wilting point. The Ultisol also taken from Yanagido farm of Gifu University, was sandy clay loam with the highest bulk density and the lowest total available moisture. The Andisol, taken from Minokamo farm of Gifu University, was sandy loam, locally named as “Kurobku soil” with the highest total available moisture.

The second factor was the water stress (D) with four levels of water deficit treatments imposed as D_1 (0 – 25 %), D_2 (25 – 50 %), D_3 (50 – 75 %) and D_4 (75 – 100 %) of available water deficit. The water deficit level D_2 (25 – 50 %), for example, meant that the available water was maintained between 25 % and 50 % of total available water (TAW) throughout the growing season. When the maximum allowable depletion of available water got close to 50 % of TAW, water was applied to restore the available water to the deficit level of 25 % of TAW. TAW is defined as the water content between field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}).

Plastic pots of 10 liters volume and 23.8 cm diameter were filled with 10 kg air-dried soil and then five soybean seeds were planted in each pot. The soybean cultivar used was *Glycinemax* L. Merrill. One week later, the seedlings were thinned to only 2 seedlings, and maintained until the end of the growth period. Basal fertilizers were applied just once during the seedling stage at the rate of 20 N, 180 P_2O_5 and 100 K_2O kg ha^{-1}. The period of irrigation lasted for 22 weeks from June 9 to November 9. The average temperature was 22.4°C and the relative humidity was 67.5 % for the duration of the experiment. Data were analyzed using Tukey’s multiple comparison test ($p < 0.05$) (Nagata and Yoshida, 1997). The PC software ‘Excel Statistics’ (Version 5.0, Esumi Co. Lts., Japan) was used for the calculations.

Agronomic variables evaluated in this research were crop water requirement (CWR, g/pot), oven dry (at 65°C for 96 h) weight of total biomass including roots (TDB, g/pot) and air-dried grain yield of soybean (Y, g/pot), and leaf area index (LAI, m^2 m^{-2}). LAI was measured at 84 DAS according to Fehr and Cavines (1977) using a portable leaf area meter (Model LI 3000A; LI-COR Inc. Lincoln, NE, USA) from each pot. Crop water requirement (CWR, g/pot) was calculated from the evapotranspiration during the irrigated period of soybean according to Allen et al. (1998). Daily evapotranspiration (ET) was measured by weighing the pot every day.

3. Results and Discussions

3.1 Crop water requirement (CWR) and water stress coefficients (K_S)

Table 3 shows that crop water requirement (CWR) in each soil type significantly decreased with the increasing water deficit levels imposed. Furthermore, when the CWR under each of the corresponding water deficit levels was compared among the three soil types, the following trend was observed; Inceptisol > Ultisol > Andisol in that order. Therefore, the above CWR relationship indicates that plants can undergo water stress quickly in Andisol which is coarse textured (sandy loam) soil, whereas plants in the

Table 3 The effect of water deficit level on crop water requirement (CWR), leaf area index (LAI), total dry biomass, grain yield, water use efficiency (WUE) and yield efficiency (YE) of soybean under different soil types.

Soil Types	Water Deficit Level (%)	CWR (g/pot) ①	LAI (m^2 m^{-2}) ②	Total dry biomass (g/pot) ③	Grain yield (g/pot) ④	WUE (g g^{-1}) ⑤ = ③ / ①	YE (g g^{-1}) ⑥ = ④ / ①
Inceptisol	D_1 (0 – 25)	116,504 A a	5.1 A a	214 A a	31.8 A a	0.00184 AB c	0.000273 B c
	D_2 (25 – 50)	92,949 A b	4.7 A b	176 A b	29.5 A b	0.00189 A b	0.000317 A b
	D_3 (50 – 75)	76,794 A c	4.1 A c	146 A c	26.7 A c	0.00190 A a	0.000348 A a
	D_4 (75 – 100)	60,608 A d	3.1 A d	121 A d	18.8 A d	0.00200 A a	0.000310 A b
Ultisol	D_1 (0 – 25)	90,034 B a	4.6 B a	172 B a	27.4 B a	0.00191 A b	0.000304 A b
	D_2 (25 – 50)	77,877 B b	4.2 B b	151 B b	25.4 B b	0.00194 A b	0.000326 A a
	D_3 (50 – 75)	63,442 B c	3.3 B c	124 B c	21.4 B c	0.00195 A b	0.000337 A a
	D_4 (75 – 100)	51,980 B d	2.3 B d	106 B d	14.8 B d	0.00204 A a	0.000285 B c
Andisol	D_1 (0 – 25)	88,883 B a	4.4 B a	160 C a	26.6 B a	0.00180 B a	0.000299 A a
	D_2 (25- 50)	68,961 C b	3.5 C b	128 C b	21.5 C b	0.00186 A a	0.000312 A a
	D_3 (50 – 75)	54,355 C c	2.5 C c	102 C c	17.5 C c	0.00188 A a	0.000332 A a
	D_4 (75 – 100)	40,919 C d	0.8 C d	74 C d	6.7 C d	0.00181 A a	0.000164 C b

Means followed by different small letters (a – d) in the same column in each soil types under different water deficit levels are significantly different according to Tukey's multiple comparison test ($p < 0.05$). .
Means followed by different capital letters (A – C) vertically at same water deficit level among the three soil types are significantly different according to Tukey's multiple comparison test ($p < 0.05$).

finer textured Inceptisol (clay loam) have ample time to adjust to low soil water matric pressure, and may remain unaffected by water stress. Tables 1 and 2 support the above explanation.

Fig. 1 shows that CWR linearly correlated with leaf area index (LAI) without differences among the three soil types. Based on this result, it can be said that among all the agronomic factors, LAI as a growth indicator was the most sensitive in the control of evapotranspiration rate. This result agrees with Setiyono et al. (2008) who found the same phenomenon that transpiration is directly controlled by leaf area index.

According to Allen et al. (1998), evapotranspiration under water stress condition is referred to as the adjustment evapotranspiration (ET_{cadj}, mm d^{-1}) which can be calculated by the following equation.

$$ET_{cadj} = K_s ET_c \quad (1)$$

where ET_c (mm d^{-1}) is the crop evapotranspiration under standard condition, K_s is water stress coefficient (no dimension).

The value of K_s is important for estimating ET_{cadj}, and can be used for deficit irrigation scheduling. K_s describe the effect of water stress on crop transpiration (Allen et al. 1998). Assuming that the evapotranspiration at D_1 (0 – 25 %) occurred under the ideal condition for plant growth in which the soil water content is near the field capacity, the actual evapotranspiration (ET_a) at D_1 is crop evapotranspiration (ET_c), which means the evapotranspiration of plant under standard conditions (Allen et al., 1998). Water stress coefficient (K_s) is calculated as the ratio between the actual evapotranspiration (ET_a) at each water deficit level and the crop evapotranspiration (ET_c). The ratio of water deple-

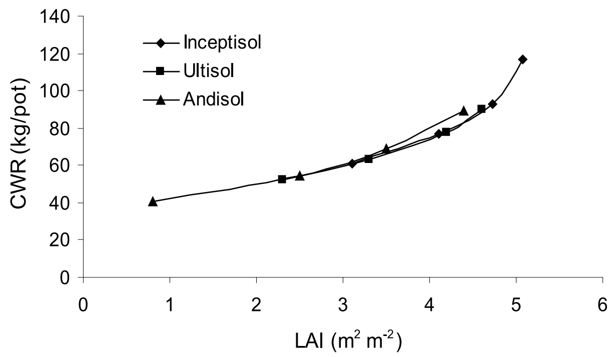

Fig. 1 The relation between crop water requirement (CWR) and leaf area index (LAI).

tion to the total available water in the root zone, referred to as "p", is an indicator of the water deficit level. For example, the average value of "p" under the water management of D_2 (25 – 50 %) treatment is calculated as "p" $= (0.25+0.50)/2 = 0.38$.

Fig. 2 shows that the K_s value decreased linearly with the increase of available water deficit level "p". It indicates that the K_s value (water stress coefficients) in Andisol is more sensitive to water deficit than the other two soil types. This is mainly due to the coarse textured nature of Andisol (Table 1).

3.2 Total dry biomass (TDB) and water use efficiency (WUE)

Table 3 shows that total dry biomass (TDB, g/pot) of soybean in each of the three soil types significantly decreased with the increase of water deficit levels. Furthermore, the TDB of soybean in the three soil types under each of the corresponding water deficit levels, significantly decreased in the order of Inceptisol > Ultisol > Andisol. The TDB of the three soil types linearly correlated with CWR under the water deficit levels (Fig. 3). This result indicated that the decrease in total dry biomass was due to the considerable reduction in plant growth and canopy structure caused by the water stress conditions. This phenomenon agrees with Shao et al. (2008) who found that the biomass of soybean plant was reduced by the water stress imposed.

Water use efficiency (WUE, g g^{-1}) is defined as the ratio of total dry biomass (TDB, g/pot) to the crop water requirement (CWR, g/pot). Table 3 shows that the WUE value slightly increased with the increase of water deficit level, except water deficit level D_4 in Andisol. Consequently, the highest WUE value was obtained at the water deficit level D_4 in Ultisol and Inceptisol, while the highest WUE in Andisol was at water deficit level D_3. However, there was no difference at 5 % significant level among the WUE values of the same water deficit level from D_2 to D_4 in the three soil types. This result indicated that there was little influence of the soil types on WUE value at the same water deficit level.

3.3 Grain yield and yield efficiency (YE)

The grain yield of soybean in the three soil types decreased with the increase of water deficit levels (Table 3). Similar to TDB, the grain yield of soybean in the three soil types under each of the corresponding water deficit levels, significantly decreased in the order of Inceptisol > Ultisol > Andisol. Figs. 4 and 5 shows that the grain yield of soybean was strongly influenced by both CWR and LAI among the three soil types. These results indicated that the reduction in CWR by water stress caused the decrease of soil water uptake with soluble nutrients and consequently the decrease of soybean grain yield through reduction in photosynthesis.

Yield efficiency (YE, g g^{-1}) is defined as the ratio of grain yield (Y, g/pot) to crop water requirement (CWR, g/pot). There was an effect of water deficit (D) on the YE value in the three soil types at 5 % significant level (Table 3). Table 3 shows that the YE value slightly increased with

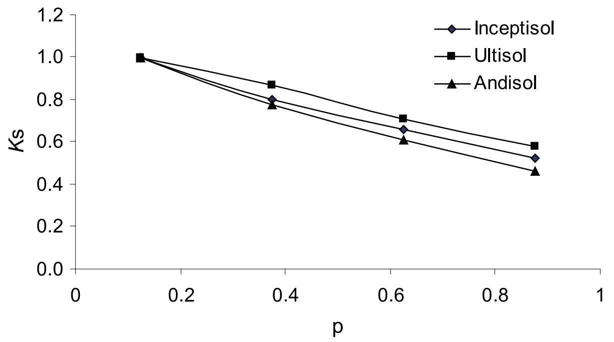

Fig. 2 The effect of available water deficit (p) on water stress coefficient (K_s).

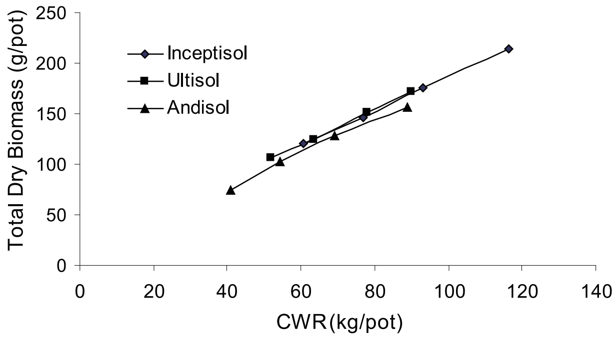

Fig. 3 The relation between total dry biomass (TDB) and crop water requirement (CWR).

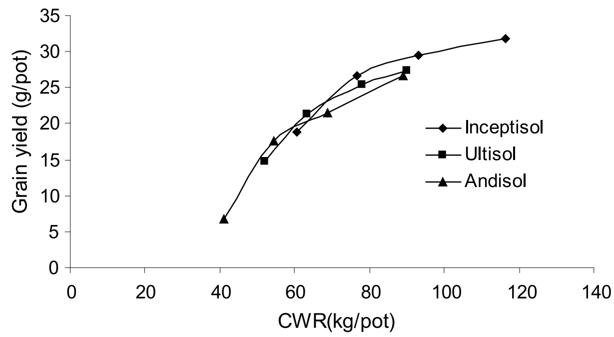

Fig. 4 The relation between the grain yield (Y) and crop water requirement (CWR).

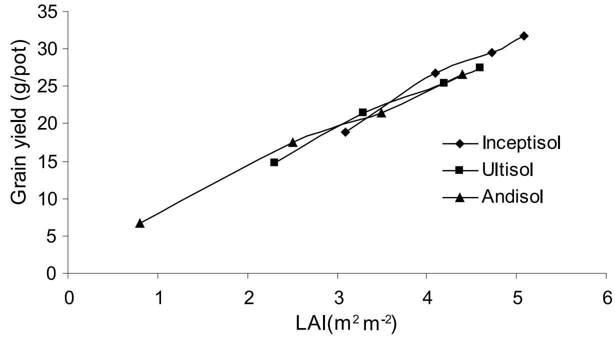

Fig. 5 The relation between the grain yield (Y) and leaf area index (LAI).

Table 4 The effect of water deficit level on water stress coefficient (K_s) and yield response factor (K_y) of soybean under different soil types.

Soil Types	Water deficit level (%)	Yield (g/pot)	ET_a (g/pot)	$K_s = \frac{ET_a}{ET_m}$	$1-\frac{Y_a}{Y_m}$	$1-\frac{ET_a}{ET_m}$	K_y
Inceptisol	D_1 (0 – 25)	31.8	116,504	1	0	0	-
	D_2 (25 – 50)	29.5	92,949	0.80	0.07	0.20	0.36
	D_3 (50 – 75)	26.7	76,794	0.66	0.16	0.34	0.47
	D_4 (75 – 100)	18.8	60,608	0.52	0.41	0.48	0.85
Ultisol	D_1 (0 – 25)	27.4	90,034	1	0	0	-
	D_2 (25 – 50)	25.4	77,877	0.86	0.07	0.14	0.54
	D_3 (50 – 75)	21.4	63,442	0.70	0.22	0.30	0.74
	D_4 (75 – 100)	14.8	51,980	0.58	0.46	0.42	1.09
Andisol	D_1 (0 – 25)	26.6	88,883	1	0	0	-
	D_2 (25 – 50)	21.5	68,961	0.78	0.19	0.22	0.86
	D_3 (50 – 75)	17.5	54,355	0.61	0.34	0.39	0.88
	D_4 (75 – 100)	6.7	40,919	0.46	0.75	0.54	1.39

Y_a : actual yield, Y_m : maximum yield = yield under no water stress condition (D_1), ET_a : actual evapotranspiration,
ET_m : maximum evapotranspiration = evapotranspiration under no water stress condition (D_1)).

the increase of water deficit level from D_1 to D_3. However, there was no significant difference at 5 % level among the YE values of the three soil types at the water deficit level D_3. These results indicated that soil moisture and aeration at the water deficit level D_3 were the most appropriate for maximizing the YE value, and the maximum values of YE were slightly influenced by the soil types. On the other hand, significant differences appeared among the YE values at the water deficit levels D_1 and D_4 of the three soil types. The smallest YE value at full irrigation (D_1) was shown in Inceptisol, which contained the finest soil texture, probably due to lack of aeration in the soil. On the other hand, the smallest YE value at the deficit irrigation which controlled soil moisture near the wilting point (D_4) was in Andisol with the coarsest soil texture probably due to excessive water stress.

3.4 Yield response factor (K_y)

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.

$$1-\frac{Y_a}{Y_m} = K_y \times \left(1-\frac{ET_a}{ET_m}\right) \qquad (2)$$

where $1-Y_a/Y_m$: relative yield decrease, Y_a: actual yield, Y_m: maximum yield (under no 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 conditions of limited water distributed equally over the total growing season, involving crops with different K_y values, the crop with higher K_y value will suffer a greater yield loss than the crop with a lower K_y value (Moutonnet, 2000). The K_y values for most crops are derived on the assumption that the relationship between relative yield (Y_a/Y_m) and relative evapotranspiration (ET_a/ET_m) is linear and valid for water deficit of up to about 50 percent or $1-ET_a/ET_m = 0.5$ (Kirda et al., 1999). According to a report by Doorenboss and Kassam (1979), the K_y of soybean under water deficit for the whole growing period was found to be 0.85.

The K_y values of soybean in the three soil types, calculated by using the above equation (2), are shown in Table 4. The smallest K_y value was in Inceptisol, followed by Ultisol and then Andisol under all water deficit levels. Deficit irrigation in Inceptisol was effective ($K_y < 1.0$) for economic water usage under all water deficit levels. On the other hand, the deficit irrigation in both Ultisol and Andisol was effective ($K_y < 1.0$) under the water deficits lower than 50 – 75 % of TAW (D_3).

The relative yield ($1-Y_a/Y_m$) linearly decreased with the relative water deficit ($1-ET_a/ET_m$) up to the D_3 water deficit levels (50 – 75 % of TAW) and thereafter, greatly

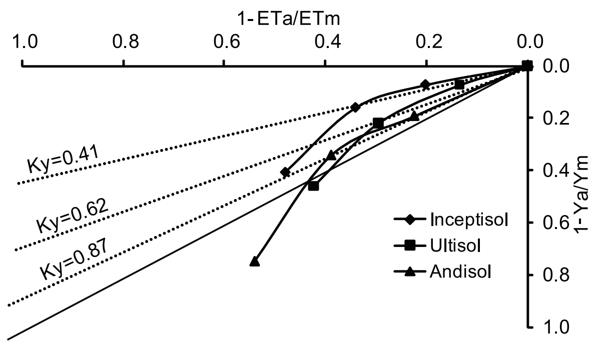

Fig. 6 Yield response factor (K_y) for water deficit of soybean under three soil types..

decreased form D_3 to D_4 water deficit level among the three soil types, and the mean value of K_y was 0.41, 0.62, and 0.87 in Inceptisol, Ultisol, and Andisol, respectively (Fig. 6). However, the above results indicated that the K_y values of soybean were strongly influenced by soil physical properties, especially soil texture. The response of water stress to soybean grain yield was the smallest in fine-textured soil like Inceptisol ($K_y = 0.41$), and was the greatest in coarse-textured soil like Andisol ($K_y = 0.87$). It can be concluded from these results that the effect of deficit irrigation for saving irrigation water was great in Inceptisol with fine soil texture, followed by Ultisol with medium soil texture, and then Andisol with coarse soil texture.

3.5 Optimum deficit irrigation

The highest grain yield of soybean per unit area was produced under the full irrigation (D_1) in all the three soil types. The highest grain yield of soybean (Y, g/pot) at full irrigation was obtained in Inceptisol (Y = 31.8 g/pot), followed by Ultisol (Y = 27.4 g/pot), and then Andisol (Y = 26.6 g/pot). On the other hand, the optimum grain yield of soybean with the highest yield efficiency (YE) was obtained by the deficit irrigation, in which water deficit level was maintained at 50 – 75 % of TAW (D_3). The water stress coefficient (K_s) at D_3 was 0.66, 0.70, and 0.61 in Inceptisol, Ultisol, and Andisol, respectively. The YE value at water deficit level D_3 was 1.27 times as much as that under the full irrigation (D_1) in the Inceptisol, and 1.11 times those of both Ultisol and Andisol. It was observed that the grain yield of soybean per unit area under deficit irrigation at 50 – 75 % of TAW (D_3) was reduced by 16.0, 21.9, and 34.2 %, but could conserve 21.6, 9.8 and 9.9 % of irrigation water to produce the same yield compared to the full irrigation (D_1) in the Inceptisol, Ultisol and Andisol, respectively.

4. Conclusions

The present study indicates that the decrease of CWR by water stress resulted in a decrease of LAI, TDB and a subsequent decrease in soybean grain yield with significant differences among the three soil types. The soybean plants in Inceptisol could absorb and transport more water-soluble nutrients from soil through the roots with a subsequently higher grain yield due to its fine-textured properties that could retain much more water than the other two soil types.

Yield efficiency (YE) values indicated that soil moisture and soil aeration at the water deficit level 50 – 75 % of TAW (D_3) were the most appropriate for maximizing the YE values in the three soil types, and the maximum values of YE were slightly influenced by the three soil types.

The lowest yield response factor K_y under the water stress below 50 – 75 % of TAW was in Inceptisol (0.42), followed by Ultisol (0.64) and then Andisol (0.87). These results suggest that deficit irrigation in Inceptisol (clay loam) provided the most effective economic water usage among the three soil types, followed by Ultisol (sandy clay loam) and then Andisol (sandy loam) under the water deficit level lower than 50 – 75 % of TAW (D_3).

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要　　旨

土壌特性の違いが節水灌漑下におけるダイズ収量への影響を評価するために，2007 年 6 月から 11 月にかけて岐阜大学内のビニールハウス内で，次の二因子で三反復の栽培実験を実施した．第一因子は土壌特性の相違であり，Inceptisol（clay loam）, Ultisol（sandy clay），Andisol（sandy loam）の３つの土壌型に分かれる．第二因子は土壌水分管理の方法であり，圃場容水量からの土壌水分欠損量（D）によって処理した．すなわち，土壌水分欠損量が総容易有効水分量の 0~25 % (D_1)，25~50 % (D_2)，50~75 % (D_3)，75~100 % (D_4) の 4 レベルの試験区を設けた．

ダイズの総消費水量は，3 種類の土壌型とも土壌水分欠損レベルが増加するにつれて減少し，同じ土壌水分欠損レベルでは，Inceptisol の総消費水量が最大となり，次いで Ultisol，Andisol の順に大きい．単位面積当たりの穀物収量も，同じ土壌水分欠損レベルに対して Inceptisol が最大となり，次いで Ultisol，Andisol の順に大きい．収穫効率（単位消費水量当たりの収穫量）は，土壌水分欠損レベルによって強く影響され，その値は 3 種の土壌型とも D_3 レベルで最大となった．しかし、収穫効率の最大値は 3 種の土壌間で有意な差が見られなかった．収量反応係数（K_y：消費水量減少量に対する収穫減少量の比）は，土壌水分欠損量が総容易有効水分量の 50~75 % （D_3 レベル）以下の場合は，Inceptisol ($K_y = 0.42$) で最小となり，次いで Ultisol ($K_y = 0.64$)， Andisol ($K_y = 0.87$) の順に小さくなる．以上のことから，３種の土壌型の中で，土壌組成が最も細かい Inceptisol における節水灌漑が経済的な水利用の観点から最も有効であることが明らかになった．

キーワード：節水灌漑，ダイズ，水利用効率，収穫効率，収量反応係数