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Original Research Article

Effects of Controlled Drainage Systems on Soybean (*Glycine max* L.) Growth and Soil Characteristics in Paddy Fields

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ABSTRACT Crop production in rice paddy fields is of great importance because of declining rice consumption and the low self-sufficiency ratio for field crops in Korea. A controlled drainage system (CDS) is recognized as an effective means to adjust water table (WT) levels as needed and control soil water content to improve the soil environment for optimum crop growth. The present study evaluated the effects of a CDS on soil characteristics, including soil water distribution and soybean development in paddy fields. The CDS was installed with two drain spacing (3 m and 6 m) at the experimental paddy field at the National Institute of Crop Science, Miryang, Korea. It was managed with two WT levels (0.3 m and 0.6 m) during the growing season. Soil water content, electrical conductivity and plant available nitrogen content in the soil were significantly greater in the 0.3 m WT management plots than in the 0.6 m plot and the control. At the vegetative stage, chlorophyll content was significantly lower with higher WT control because of excess soil moisture, but it recovered after the flowering stage. Soybean yield increased with WT management and the 0.6 m WT treatment produced the greatest grain yield, 3.38 ton ha^{-1}, which was 50% greater than that of the control. The CDS directly influenced outflow through the drains, which significantly delayed nutrient loss. The results of this study indicated that WT management by CDS can influence soil characteristics and it is an important practice for high yielding soybean production in paddy fields, which should be considered the crop growth stages for stable crop production.

Keywords : controlled drainage system, paddy field, soil water, subsurface drainage, water table

Due to the industrialization and changes of agricultural circumstances, arable land area in Korea is decreasing by 0.96% per year and arable land utilization rate is also being decreased from 140.4% in 1975 to 120.4% in 1985, 110.5% in 2000, and 106.7% in 2015 (KOSIS, 2016). Rice productivity has been increasing in Korea, but rice consumption has been declining to 65.1 kg per capita per year in 2014. Furthermore, self-sufficiency ratio of rice was maintaining more than 90 percent while other grain crops have very low self-sufficiency (23.8% in 2015). Therefore, field crops have been encouraged to cultivate in paddy fields to control rice production and improve food self-sufficiency ratio in Korea.

Generally, paddy fields in Korea have high clay contents that result in high water holding capacity and poor drainage properties. Based on drainage conditions for Korean paddy field areas (1,288 thousand ha), they were classified into ‘poor’ grade in 180 thousand ha and ‘somewhat poor’ class in 625 thousand ha, while the ‘somewhat good’ and ‘good’ classes are taken in 461 thousand ha and 20 thousand ha, respectively (RDA, 1992). Furthermore, due to the climate changes the numbers of both torrential rain events and drought periods have increased in frequency. Under these circumstances of climate changes and crop production conditions, the agricultural infrastructures are great importance to reduce the crop damages and yield losses caused by flooding and excessive water stress.

In poorly drained fields, soil water management is an important way to increase crop yield by minimizing crop water stress. Many studies in Korea have been conducted to adjust the soil water table (WT) levels, which are focused on improving excessive water in poorly drained

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paddy soil, salt removal in greenhouse cultivation soil, and acceleration of desalination in reclaimed tidal lands (Jung *et al*., 2012; Kim *et al*., 2006; Lee *et al*., 2015; Shin *et al*., 2008). Jung *et al*. (2012), for example, compared the drainage methods for improving soil physical conditions in poorly drained sloping paddy fields and found that subsurface drainage by pipe drainage improved crop productivity of poorly drained soils by lowering the WT and improving root zone layer condition. The result in reclaimed tidal land also showed that subsurface drainage system lowered the WT level, which improved soil salinity and crop production (Lee *et al*., 2015). However, most of the study related to WT control system conducted in Korea are the water managements that remove excessive water using by subsurface drainage system and there are little information on controlled drainage system (CDS) for field crop production. On the other hands, CDS have widely adapted in poorly drained fields in other countries. For example, the CDS in Japan, called the Farm Oriented Enhancing Aquatic System (FOEAS), was developed in 2005 to control WT level at desirable depths, which has been adapted more than 10,000 ha for field crop production in paddy fields by farmers (Wakasugi & Fujimori, 2009). Shimada *et al*. (2012) have shown that soil moisture content was less fluctuated by CDS, which resulted in higher SPAD value, stomatal conductance, root nodule and photosynthetic rate of soybean grown in paddy fields.

Although the CDS has been reported to increase yield of field crop production as compared to conventional cultivation in other countries (Luo *et al*., 2008; Shimada *et al*., 2012; Tan *et al*., 2002), conflicted results have shown on the depth of WT. For example, Shimada *et al*. (1995) stated that WT depth of 0.7 m had greater soybean yields and yield components as compared to depths of 0.4 m. However, the results of Sarwar (2002) have shown that photosynthetic rates was significantly decreased with the rise in WT treatment from 0.60 m to 0.15 m, and average soybean yield in 0.15 m WT treatment was 48% lower than 0.60 m treatment. The effects of CDS are usually characterized by various environmental and physiological factors including crop cultivars and growth stage (Matsuo *et al*., 2013). However, there is limited information available on changes of soil properties and crop response to controlled drainage system in paddy fields in Korea. Therefore, the objectives of this study were to investigate 1) the effects of controlled drainage system as a method of WT management on soil water distribution and soybean growth, and 2) give water management practice information for stable field crop production at rice paddy fields.

MATERIALS AND METHODS

Study field characteristics

Field experiment was carried out to investigate the effect of controlled drainage systems on soil characteristics and soybean (*Glycine max* L.) growth at paddy fields. Experiment was conducted at a research farm (35°29'N, 128°44'E) at the National Institute of Crop Science, Miryang and the field has been used for rice cultivation last decades. Its dominant soil series was Pyeongtaeg series, which was classified as fine silty, mixed, nonacid, mesic family of typic endoaquepts. The top soil (Ap horizon) has dark grayish brown (10YR 4/2), silty loam texture, organic matter content of 24.5 g kg^{-1} and pH of 5.9. Soil profile was composed of B horizon (11-26 cm), Bg horizon (27-40 cm) and C horizon (40-83 cm) and clay content was about 20% throughout the soil profile. Bg horizon has low organic matter content (2.9 g kg^{-1}) and exchangeable Ca and Mg content. Soil characteristics in the pre-experimental stage were shown in Table 1.

Controlled drainage system and crop cultivation

Controlled drainage systems were installed on 20 m wide by 54 m long field plot in April, 2016. Drains (diameter 80 mm) were installed without any slope throughout the plot using inclinometer (Leica, Wild NA-20). The treatments included two drain spacing (3 m and 6 m) and two water table (WT) levels (0.3 m and 0.6 m). Applied treatments used in this experiment are as following; 1) drain spacing 3 m and 0.3 m WT level (CDS1), 2) drain spacing 6 m and 0.3 m WT level (CDS2), 3) drain spacing 3 m and 0.6 m WT level (CDS3), and 4) no drainage system (control). Each of the plots was hydraulically isolated by a vinyl sheet barrier which was buried up to 0.6 m depth. The WT level was maintained with WT controller and collected water were automatically pumped out to the ditch. To

Table 1. Physico-chemical properties of experimental soils in the pre-experimental stage.

Horizon	Depth	pH	OM	Avail. P	Exchangeable cations				PSD			Texture
					K	Ca	Mg	Na	Sand	Silt	Clay	
	cm	*1:5, H_2O*	*g/kg*	*mg/kg*	----------------- *cmolc/kg* -----------------				--------------- % ---------------			
Ap	0-11	5.9	24.5	27.3	0.12	4.0	0.67	0.11	11.7	71.6	16.7	SiL
B	11-25	6.0	21.5	30.3	0.10	4.1	0.77	0.12	10.9	70.5	18.6	SiL
Bg	26-40	7.0	2.9	4.5	0.08	6.0	1.42	0.11	13.6	63.0	23.4	SiL
C	40-	6.9	10.6	5.4	0.09	4.0	1.07	0.09	35.0	50.5	14.5	SiL

PSD, particle size distribution; SiL, silty loam.

investigate the effect of WT level on soybean root development a lysimeter (0.3 m diameter by 1 m in length) study was carried out. The levels of WT were constantly maintained at 0.2, 0.4, and 0.6 m from soil surface using by a mariotte bottle method.

In this study variety Daewonkong was selected due to the wide adoption rate by farmers in Korea. Soybean was planted with 50 kg ha^{-1} seeding rate in a single row, with 0.7 m row spacing and 0.2 m interval between plants within each row. Before planting, fertilizers were applied at the rate of 30-30-34 kg (N-P_2O_5-K_2O) ha^{-1} as a urea, super phosphate, and potassium chloride, respectively and weed and pest control managements were performed to maximize the yield during the growing season according to the recommended practices by RDA (2012). Soybean was harvested on November 4, 2016 and had 121 growing days.

Analysis of soil and plant

Soil samples were taken by a hand spiral auger at growing season. Volumetric soil water content was determined by using frequency domain technology (Decagon, EC5) and data were recorded to data logger (Decagon, EM50). In this study soil physical and chemical analysis were conducted based on the standard methods by RDA (2000). Collected soil samples were air-dried at room temperature for chemical quantification. Soil pH and EC were determined from the 1:5 of soil/water suspension using a pH/conductivity meter (Horiba, F-54). Available phosphorus was analyzed by Lancaster method using continuous flow spectrometer (Bran+ Luebbe Analytics, AutoAnalyzer 3). The 1N-NH_4OAC (adjusted pH 7.0) was used to extract exchangeable cations (K, Ca, Na and Mg) and quantified by inductively coupled plasma spectroscopy (PerkinElmer, Optima 3300DV).

The SPAD value and normalized difference vegetation index (NDVI) was measured using by chlorophyll meter (Konica-Minolta, SPAD-502Plus) and hand-held NDVI sensor (NTech Industries Inc., Greenseeker, USA), respectively, with 30 replications from each plot. Plant height, stem length and stem thickness were recorded periodically. At maturity, the plants from sub-plot (14 m^2) with three replications were sampled to determine the soybean yield and yield components (i.e., the number of pods and the 100-seed weight etc.), which were oven-dried at 70℃ for 72 hour and then they were ground to pass through a 0.5 mm sieve for quantitative analysis. After wet digestion with H_2O_2-H_2SO_4, filtrate solution was quantified for N, P, K, Ca, and Mg.

Statistical analysis

Experimental data were statistically analyzed using analysis of variance (ANOVA) with the JMP program (SAS institute ver. 5.0, USA). Least significant difference was used to compare the mean between treatments and Tukey-Kramer HSD at the 95% level when the F-test was statistically significant.

RESULTS AND DISCUSSION

Climate condition

The experimental site has a temperate climate region with the annual mean temperature of 13.3℃ for long-term periods (1981-2010). The average long-term annual precipitation was 1,229 mm, on which, about 67% falls between

June and October. The mean temperature (23.4℃) and precipitation (1,015 mm) during the crop growth periods (between June and October, 2016) was greater than the long-term temperature (21.8℃) and precipitation (869 mm), respectively. In 2016, total precipitation between June and August was 381mm, which was about 55% of long-term average (693 mm). Especially, the temperature (27.5℃) of August in 2016 was 1.7℃ higher than those in long-term average, but the precipitation was only 20% (46.8 mm) of 30-year average (238 mm) (Fig. 1).

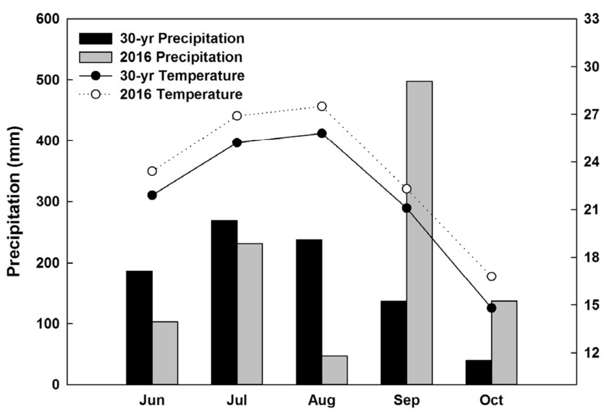


Fig. 1. Weather information in the experimental area during the experiment period.

Soybean development

Controlled drainage systems (CDS) significantly influenced the height of soybean plant (Fig. 2a). The highest plant height was observed from 6m drain spacing treatment at 33 days after plant (DAP) stage, and the 0.3 m water table (WT) treatment had a greater plant height than other treatments. Similar trends were observed in the stem length and stem thickness (Fig. 2b & 2c). These results are probably due to the high availability of soil water and

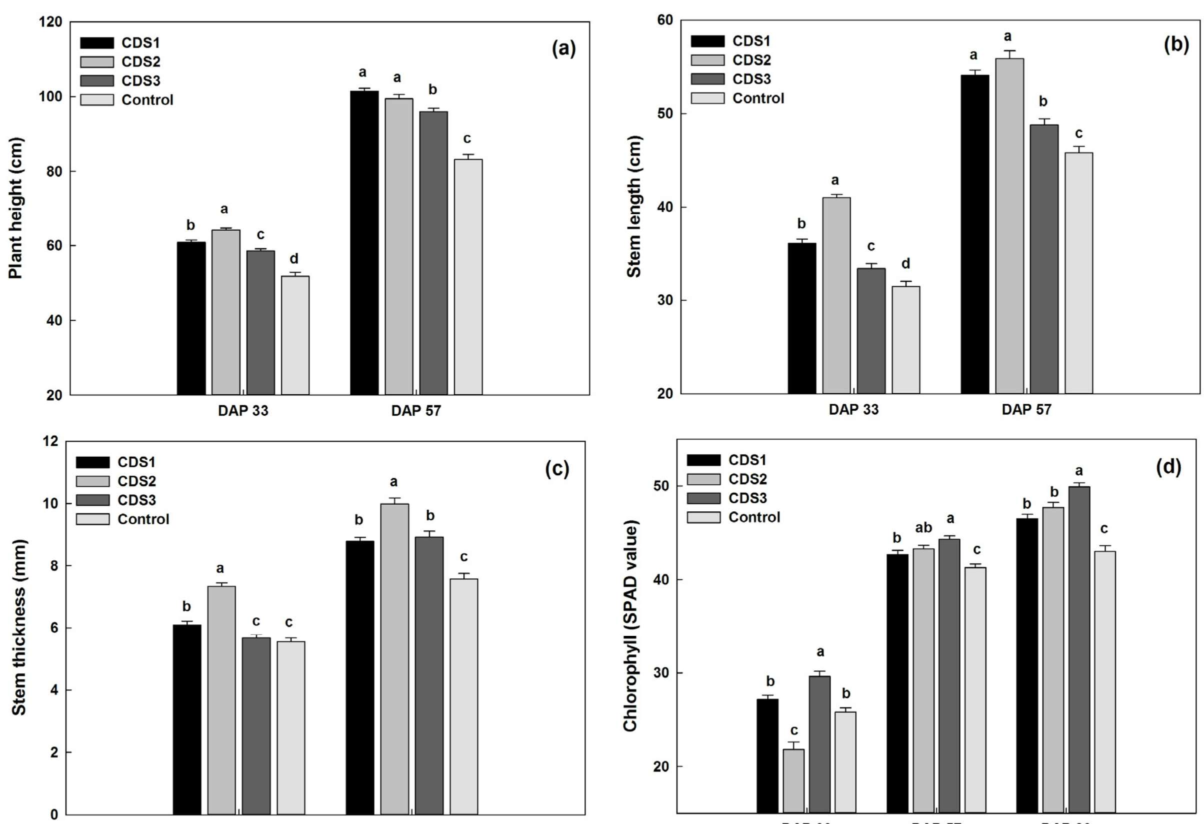


Fig. 2. Soybean response to controlled drainage systems grown in a paddy field. CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3 m water table level, and CDS3: 3 m drain spacing and 0.6 m water table level and control: no drainage. Bars with different letters within the same day after planting (DAP) indicate significant difference at the 95% level.

nutrients by crop from the 0.3 m ground water. Chlorophyll content of soybean leaves was determined at 33, 57 and 83 DAP using SPAD values (Fig. 2d). Results indicated that the average chlorophyll content was significantly increased as crop develops on before the leaf and petiole change color and loss. At 33 DAP stage, soybean in 0.3 m WT treatment had statistically lower SPAD values than 0.6 m WT treatment, and 6 m drain spacing had less chlorophyll content than in 3 m drain spacing treatment. The previous study (Haque *et al*., 2014) reported that vegetative stage the leaf chlorophyll content was lower than that in other treatments due to excess soil moisture. Overall chlorophyll content was significantly higher in 0.6 m WT treatment than other three treatments, indicating that WT management had the adverse effect on chlorophyll content of soybean leaves in the early stage. These results are in agreement with results reported by Sarwar (2002) who observed that lower chlorophyll content in soybean leaves was found in shallow WT treatment in earlier part of the growing season, but the highest values of chlorophyll content were found for lower (0.6 m) WT treatment in the later part of the growing season. Normalized difference vegetation index (NDVI) value provides a crude estimate of vegetation health because healthy vegetation reflects very well in the near-infrared part of the electromagnetic spectrum. Fig. 3 shows that the plants in the CDS treatment had statistically greater NVDI value as compared to the control, indicating that the CDS resulted in improving the plant vigor such as leaf greenness and photosynthesis.

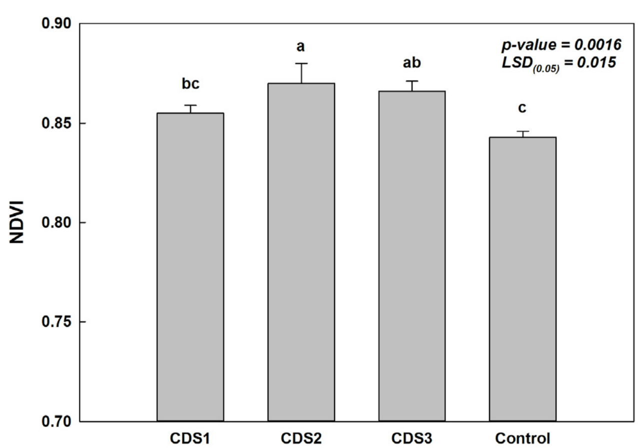


Fig. 3. Normalized difference vegetation index (NDVI) for soybeans at the DAP 41 stage grown in a paddy field. CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3 m water table level, and CDS3: 3 m drain spacing and 0.6m water table level and control: no drainage. Bars with different letters were significantly different at the 95% level.

The numbers of root nodules were lowest in 0.6 m WT treatment and plants in CDS treatment had significantly lower root nodules as compared to those in the control (Table 2). This result is probably related to the soil nitrogen content because the development and nitrogen fixation activity of soybean root nodules are known to be suppressed when roots are exposed to a high presence of combined nitrogen (Imsande, 1986). In this study, nitrate content (6.8 mg kg^{-1}) in CDS treatment at post-harvesting time was significantly higher than the control (3.1 mg kg^{-1}). Significant differences in root and shoot biomass were also observed among the treatments. Plants in the 0.6

Table 2. Root nodules and root growth of soybean grown in a paddy field at harvesting stage as affected by controlled drainage systems (CDS).

Treatment	Root nodule (No.)	Weight of Root (g)	Weight of Shoot (g)	Length of Primary root (cm)	R/S ratio
CDS1	30.0ab	2.54b	33.4bc	26.3	0.081bc
CDS2	19.4b	3.60a	42.3ab	26.5	0.085ab
CDS3	18.5b	3.79a	52.8a	28.5	0.072c
Control	37.2a	2.35b	24.7c	22.2	0.095a
$LSD_{(0.05)}$	13.9	0.97	12.3	ns	0.011

CDS1: 3 m drain interval and 0.3 m water level, CDS2: 6 m drain interval and 0.3 m water level, CDS3: 3 m drain interval and 0.6 m water level and control: no drainage. Mean values followed by the different letters are significantly different at the 95% level. ns indicates not significant.

m WT treatment had the greatest shoot (52.8 g) and root biomass (3.79 g), followed by plants in the 6 m drain spacing treatment (42.3 g shoot, 3.6 g root biomass). Shoot and root biomass in the control were reduced substantially. The longest length of primary root was observed in the 0.6 m WT treatment, but it was not significantly different with other treatments because the values had considerable variation among plants. To clarify the effect of WT levels on soybean root development a lysimeter experiment were conducted and have shown that the length of the primary root and the total weight of soybean root were significantly increased with increasing the WT level (Fig. 4). This result is agreement with the review by Ayars *et al*. (2006) who stated that soybean root growth did not extend the below the WT level and increased with the depth of WT level. The results of these data indicate that soybean plants in CDS treatments had more favorable cultivation conditions than in the control because root dry weight and primary root length is usually decreasing under water stress conditions and have resulted in decreasing water and nutrient uptake. The R/S ratio of the control was the greatest than other treatments. This result agrees with Ahmed *et al*. (2010) who found that the R/S ratio of soybean increased under water stress conditions.

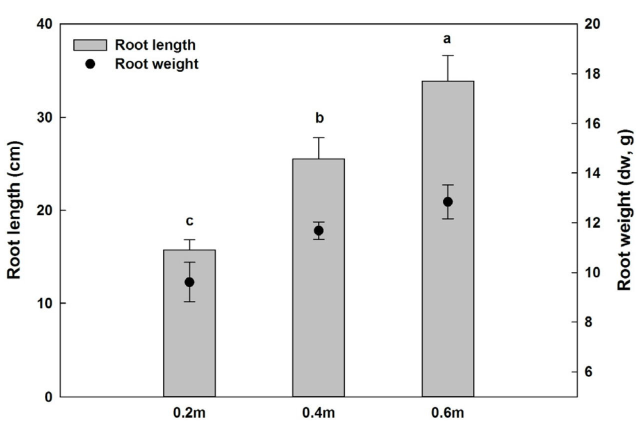


Fig. 4. Comparison of soybean root development at the harvesting stage in response to water table levels (0.2, 0.4, and 0.6 m) in a lysimeter study.

Grain yield

At harvesting stage, grain yield components were generally greater in 0.6 m WT treatment, although the length of stem and the length of the first pods were higher with 0.3 m WT treatment than in 0.6 m WT treatment (Table 3). Plants in the 0.6 m WT treatment had the greatest number of branches (5.7 branches per plant), which were reduced to 4.9 per plant in plants in the 0.3 m WT level and the control. Although the weight of 100-seed was non-significant by CDS treatments, the increased numbers of seeds per plant were directly influenced on grain yield. The result shows that the grain yield was significantly influenced by CDS treatment (Table 3). The average soybean yield obtained for 0.6 m WT treatment was 3.38 ton ha^{-1}, which was about 50% higher than mean grain yield (2.26 ton ha^{-1}) for the control, followed by the plants with the 0.3 m WT treatment that had a grain yield of 3.11 and 3.23 kg ha^{-1} for 3 m and 6 m drain spacing, respectively. The effects of WT treatment on crop yield have been investigated by many researchers and shown the conflicted results on the optimum WT depth for highest crop yields (Luo *et al*., 2008; Shimada *et al*., 1995). For example, Shimada *et al*.

Table 3. Grain yield and yield components of soybeans grown in a paddy field as affected by controlled drainage systems.

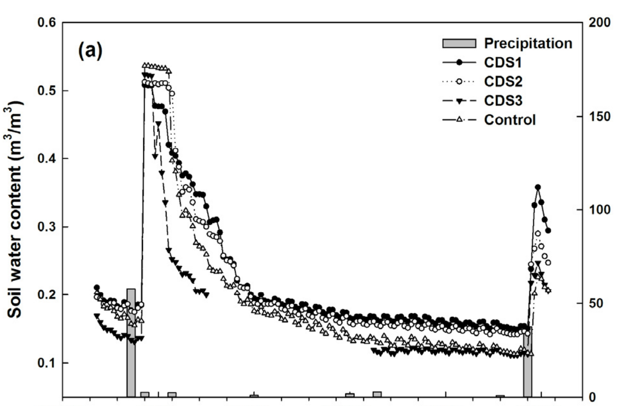
Treatment	No. branch (ea. $plant^{-1}$)	No. Pod (ea. $plant^{-1}$)	No. Seeds (ea. $plant^{-1}$)	100-seed weight (g)	Yield (ton ha^{-1})	Yield Index
CDS1	4.8b	55.7b	73.4b	27.5	3.11a	138
CDS2	5.0b	55.2b	79.2b	27.0	3.23a	143
CDS3	5.7a	66.1a	107.4a	27.7	3.38a	150
Control	4.9b	45.6c	67.0b	27.8	2.26b	100
$LSD_{(0.05)}$	0.4	3.9	17.4	ns	0.53	-

CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3m water table level, and CDS3: 3 m drain spacing and 0.6 m water table level and control: no drainage. Mean values followed by the different letters are significantly different at the 95% level. ns indicates not significant.

(1995) have shown that the higher grain yield for soybean was obtained from lower WT treatment (0.7 m WT) in high precipitation season, but the plants in higher WT treatment (0.4 m WT) had the higher grain yield in low precipitation season, concluding that the depth of WT management to get the highest yield may varies according to the precipitation during the growing season. As mentioned earlier, the precipitation during the growing season in this study was greater as compared to the long-term average, and these climate conditions may influenced on the higher grain yield in lower WT treatment though the yield differences among CDS treatments were non-significant. To clarify the effect of climate variation on crop yield and optimum depth of WT, further studies need to be conducted.

Soil water and nutrient content

Soil water content and water potential were significantly influenced by CDS treatments and fluctuated by rainfall events (Fig. 5). Soil water content in 0.6 m WT treatment was lower than other treatments and 0.3 m WT treatment had the greater soil water content. Our results agree with Shimada *et al*. (2012) who stated that the volume water content at the upper soil layer (0-20 cm) was significantly greater in shallow (0.2 m) WT treatment than lower (0.32 m) WT treatment. This result is probably due to the upward movement of water from the WT in the 0.3 m WT treatment and residual soil moisture in soil profile in control plot. On the other hand, soil water in 0.6 m WT treatment was not supplied water to the surface layer from the WT. These results are supported by the volume of drainage outflow during the soybean growth period, which showed that drainage outflow of 2.4 mm d^{-1} was observed for 0.3 m WT treatment (Table 4). But the values were dramatically increased to 22.2 mm d^{-1} for 0.6 m WT treatment under the same drain spacing condition. Soil water potential at surface layer showed the similar trends to soil water contents, which showed that the average water potential was significantly different among the CDS.



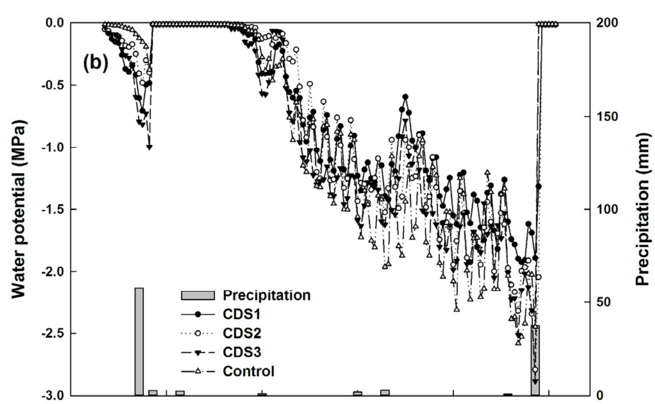


Fig. 5. Temporal changes in soil water content (left) and water potential (right). CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3 m water table level, and CDS3: 3 m drain spacing and 0.6 m water table level and control: no drainage.

Table 4. Comparison of drainage outflows as affected by a controlled drainage system (CDS) during the soybean growth period (between July 6 and November 3).

	CDS1	CDS2	CDS3
Total drainage (mm)	285.5	68.6	2,667
Average drainage (L/day)	881	212	8,231
Average drainage (mm/day)	2.4	0.6	22.2

CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3 m water table level, and CDS3: 3 m drain spacing and 0.6 m water table level.

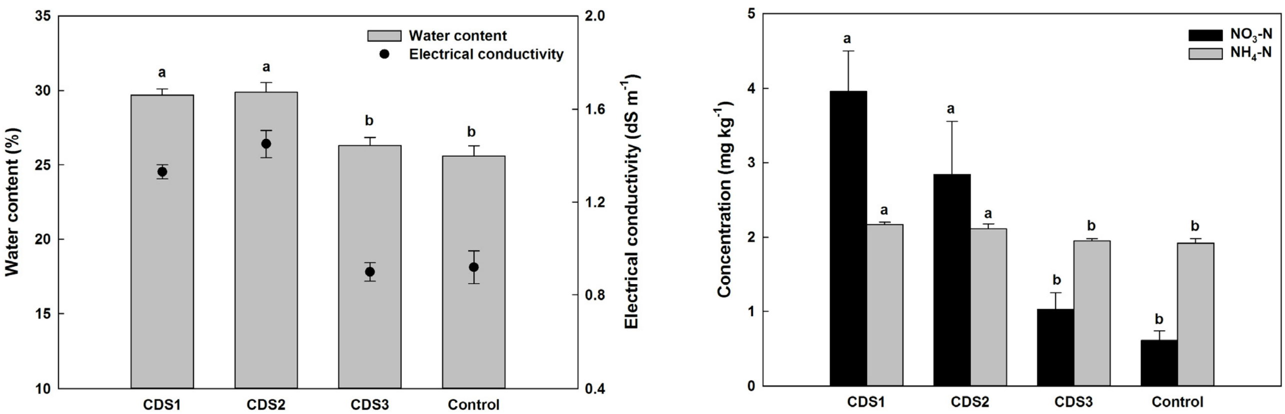


Fig. 6. Soil water, electrical conductivity (left), and nitrogen content (right) of soil in response to controlled drainage systems. CDS1: 3 m drain spacing and 0.3 m water table level, CDS2: 6 m drain spacing and 0.3 m water table level, and CDS3: 3 m drain spacing and 0.6 m water table level and control: no drainage. Bars with different letters are significantly different at the 95% level.

After 50mm rainfall event on July 30, water potential had maintained 0 MPa for 7 days and it was decreased until the next rainfall event.

Electrical conductivity (EC) in soil was significantly greater with 0.3 m WT treatment as compared to other treatments (Fig. 6). Also, plant available nitrogen (nitrate and ammonium form) content in surface layer was significantly higher with 0.3 m WT treatment than other treatments. This result is probably due to the reduction of drained outflow volumes which pass through soil profile. Controlled drainage outflow during the crop growing season were significantly different among three drainage treatments (Table 4). The average outflow of the CDS was dramatically greater from the 0.6 m WT management plot than other treatments. In 0.3 m WT treatments, drainage outflow was greater with 3 m drain spacing as compared to 6 m spacing, indicating that the narrow drain installation has more efficiency to drain the soil water. These results agree with the result by Luo *et al*. (2008) who showed that the reduction of the drain depth by CDS from 1.0 to 0.4 m resulted in a reduction of drainage discharge by 50-60%.

In conclusion, this study demonstrated that the CDS influenced soil water and nutrient content in root zone, which affected on soybean growth and grain yield. However, the effect of CDS on soybean growth was different in response to soybean growth stage and design of CDS. Therefore, the WT management as the method of CDS should permit the maximum use of soil water by the crop root and it would be considered crop development stages and climate conditions.

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