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The growth and yield changes of foxtail millet (*Setaria italic* L.), proso millet (*Panicum miliaceum* L.), sorghum (*Sorghum bicolor* L.), adzuki bean (*Vigna angularis* L.), and sesame (*Sesamum indicum* L.) as affected by excessive soil-water

Hyen Chung Chun*, Ki Yuol Jung, Young Dae Choi, Sang Hun Lee, Hang Won Kang

Crop Production Technology Research Division, National Institute of Crop Science, RDA, Miryang 50424, Korea

*Corresponding author: hyen2010@korea.kr

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Abstract

The objectives of this study were to investigate the effects of excessive soil-water on crop growth and to predict decrease of yields caused by excessive soil-water. The following five crops were selected for investigation: foxtail millet, proso millet, sorghum, adzuki bean, and sesame. These were planted in pots and a soil-water table was set to 10cm for 10 days. Crop susceptibility (CS) factors and stress-day indexes (SDI) were calculated for each crop to estimate effects of excessive soil-water. SDI models were calculated using CS and SDI data for each crop and predicted the yields of crops cultivated in paddy fields. All crops were cultivated in paddy fields with different soil water contents to evaluate the yield-SDI models. Results showed that yields decreased most when crops were affected by excessive soil-water at the early development stage. Decrease of yields was the greatest when the excessive soil-water treatment was applied at early growth stage. In the field experiment, crops from soils with the greatest soil-water content had the smallest yield, while ones from soils with the smallest soil water contents showed the greatest yields. Observed yields from the field and predicted yields from SDI models showed the least correlation for proso millet, foxtail millet, and adzuki bean and the greatest correlation for sesame . In conclusion, proso millet, foxtail millet, and adzuki bean were more susceptible to soil water than other crops, while sorghum and sesame were more suitable to cultivation in paddy fields.

Keywords: crop susceptibility, excessive soil-water, stress-day index

Introduction

Accurate and optimal water supply to cereal crops is critical in growing and producing maximum yields. Excessive soil-water can cause nutrient and oxygen deficiency (Cannel et al., 1980), limit the germination of seeds (Fausey et al., 1985), induce the dying of young plants (Lee et al., 2010), reduce root growth/plant height (Lee et al., 2010), reduce yields (Belford et al., 1985), and increase susceptibility to disease (Belford et al., 1992). These effects are caused by the depletion of oxygen or oxygen diffusion in soils. In addition, microbial growth increases, which can cause the formation of sulfides and butyric acid that are toxic to plants, and the potential for root diseases is increased (Ashraf and Rehman, 1999). These negative effects by excessive soil-water result in a reduced yield reliability and suboptimal production.

In Korea, many paddy fields have generally high groundwater levels or greater soil-water contents compared to general uplands because rice requires flooded conditions during cultivation. The area of paddy fields in Korea is 934,000 ha, which is more than 55% of total arable lands (NSO, 2015). Most of these paddy field soils have low infiltration rates and poor drainage properties (Jung et al., 2011). Recently, the Korean government decided to support cereal crop cultivation in paddy fields to reduce overproduction of rice. Crops cultivated in paddy fields have shown physiological stress caused by excessive soil-water or high groundwater level (Jo et al., 1996; Ji et al., 2009). There is a need to overcome excessive soil-water problems for cereal crops. Therefore, it is necessary to fully understand crop responses to excessive soil-water conditions in paddy field soils.

In case of excessive soil-water conditions, Hiler (1969) introduced the stress day index (SDI) to quantify the cumulative stresses imposed on crops by water. Researchers studied yield-SDI relationships in several crops: corn (Hiler and Clark, 1971; Ahmad and Kanwar, 1989; Mallikarjunaswamy et al., 1999), soybean (Purwanto et al., 1993), and cotton/wheat (Kandil et al., 2001). This yield-SDI relationship is based on crop susceptibility (CS) factors (Lewis et al., 1974; Howell and Hiler, 1975; Hardjoamidjojo et al., 1982). CS factors describe the plant’s susceptibility (or response) to environmental stresses and depend upon the species and the stage of development of a given crop. CS factors have been investigated for various physiological growth stages of corn and soybean under excessive soil-water or flooded conditions in various studies (Evans and Skaggs, 1984; Mukhtar et al., 1990; Evans et al., 1990; Purwanto et al., 1993). Evans et al. (1990) proposed the concept of NCS (Normalized Crop Susceptibility) factors to eliminate the effects of environmental elements other than flooding, such as, genotype, soil type, fertility, and temperature. NCS values were applied to yield-SDI relationships instead of CS factors and determined the reduction degree of corn and soybean yields and effects on crop growth under excessive soil water stress (Evans et al., 1990). CS and SDI concepts have been applied to soybean cultivated in paddy fields in Korea (Jung et al., 2011), but there has been no attempt to use the yield-SDI model to predict yields under excessive soil-water conditions.

The objectives of this study were to evaluate excessive soil-water stress to cereal crops by using CS factors at various growth stages and evaluate the use of the yield-SDI model to predict cereal crop yield from paddy fields with various soil-water contents or groundwater table levels.

Materials and Methods

Yield-SDI (Stress-Day Index) model

The SDI concept is determined from the stress day (SD) factor and the CS factor. The SD factor is a measure of the intensity and duration of stress. The CS factor is a measure of the crop susceptibility to a unit of stress and is a function of the crop species and its stage of development. Hiler (1969) defined the SDI as

$$\mathrm{SDI} = \sum_{i=1}^{n} \mathrm{SD}_i \times \mathrm{CS}_i \qquad (1)$$

where n is the number of growth stages and SD and CS are the stress day and crop susceptibility factors, respectively, for period *i*. The SD values can be replaced by SEW_{30} values. SEW_{30} (cm-day) represents the sum of groundwater level differences when it exceeds a depth of 30 cm, because Sieben (1964) considered the depth of 30 cm to be the critical excessive groundwater level for crops.

Sieben (1964) proposed crop yields to changes of groundwater table depths as

$$SEW_{30} = \sum_{i=1}^{n}(30 - X_i) \quad (2)$$

where x_i is the groundwater table depth below the soil surface on day *i,* and n is the number of days in the period being considered. The CS*i* is defined as the yield reduction ratio per unit of SD*i* at a given excessive soil water stress in *i* −the growth stage. Hiler (1969) expressed CSi as

$$CS_i = \frac{x - x_i}{x} \quad (3)$$

where X*i* is the yield from a treatment subjected to a unit water stress during *i* −the growth stage, and X is yield when a crop is kept under no water stress throughout the season. Later, Evans and Skaggs (1984) suggested the concept of NCS factor by normalizing CS factors to reduce the sensitivity of the CS factors to stress duration.

$$NCS_i = \frac{CS_i}{\sum_{i=1}^{n} CS_i} \quad (4)$$

where n is the number of growth stages. The relationship between crop yield and SDI can be determined based on CS factors using regression analysis. The generalized yield-SDI relationship determined from simple linear regression by

$$Y_j = Y_p - a \times SDI_j \quad (5)$$

where Y*j* is the absolute yield (kg·ha-1) observed in year *j*, Y*p* is the potential or base maximum yield that would occur in the absence of any soil-water related stress, a is the yield reduction per unit of SDI (slope of regression line), and SDI*j* is computed from eq.(1) using CS or NCS values. The relative yield (RY) was calculated by

$$RY_j = \frac{Y_j}{Y_p} = 1 - b \times SDI_j \quad (6)$$

where RY*j* is the relative yield, which is expressed as a percent of potential yield and b is the RY reduction per unit of SDI. Experimental site

The pot and field experiments were conducted to investigate responses of five crops to excessive soil-water conditions at National Institute of Crop Science, Crop Production Technology Research Division in Miryang, Gyeongnam, Korea. Foxtail millet (*Setaria italica L.*), proso millet (*Panicum miliaceum L.*), adzuki bean (*Vigna angularis L.*), and sorghum (*Sorghum bicolor L.*) were tested in 2013, and sesame (*Sesamum indicum L.*) was tested in 2015.

1) CS factor experiments

The CS experiments were conducted to investigate the response of excessive soil-water at five growth stages; tillering, booting, flowering, milk development, and ripening (Zadoks growth scale, Zadoks et al., 1974). Each crop was planted in a wagner pot ($1 \cdot 5000^{-1}$) filled with silt loam soils with chemical fertilizer as a basal manure. Each crop was planted in a pot with five replicates for each growth stage. A total of 30 pots for one crop were prepared including five pots with no stress treatments. All pots were managed with adequate watering, and growth stages were observed. Five pots were placed in bigger pots (1·2000-1) filled with water when the plants achieved each growth stage. Excessive soil-water treatment was applied by keeping the water level in these pots at a 10 cm depth for 10 days (Fig. 1). After 10 days, pots with crops were pulled out from water and the crops grew until harvest. The growth characteristics and yield components were measured from every pot.

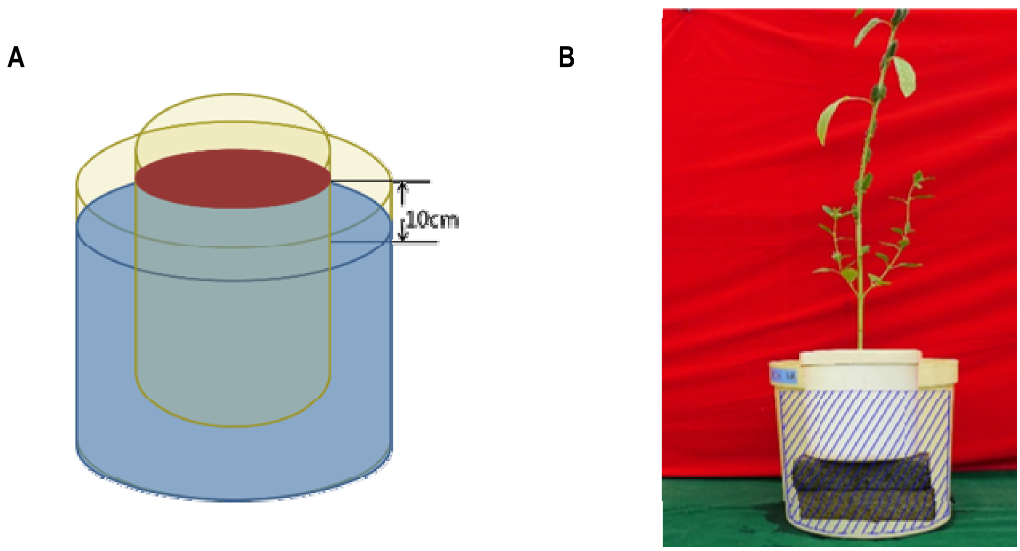

Fig. 1. Pictures of a CS experiment with groundwater level of 10 cm in wagner pots: (A) A diagram of the CS experiment, and (B) An actual picture of the CS experiment with sesame.

2) Field experiments

The field experiments were performed in paddy fields in Miryang, Gyeonam. The soil of the experimental field was classified as Gagog series (fine silty, mixed, nonacid, mesic family of Aeric Endoaquepts). The paddy fields were divided into two plots by drainage class; poorly and somewhat poorly drained (Fig. 2). The size of each plot was 30 m by 50 m. The characteristics of the soils from the two plots are shown in Table 1. Two different drainage systems were applied to alleviate effects of excessive soil-water in a plot: open ditch and pipe drainage system (Fig. 2). The open ditch was a 30 cm wide and 30 cm deep trench along one side of the plot and the pipe drainage was buried 50 cm deep along a side of the plot. A total of 4 subplots were placed in the site.

In 2013, sorghum, foxtail millet, proso millet, and adzuki bean were cultivated in each subplot of the experimental site as shown in Fig. 2. Sesame was cultivated in 2015 in each subplot. In each subplot, soil-water contents were measured by soil moisture probe (Easy AG, Sentek Pty. Ltd., Stepney, Australia) at 20 cm depth from the soil surface. Levels of groundwater were measured by sensors with automatic water level recorders (Remote Data Systems, Inc, NC, USA) from 0 cm to 150 cm. All measurements were applied for all four subplots and measured every hour during the growing seasons.

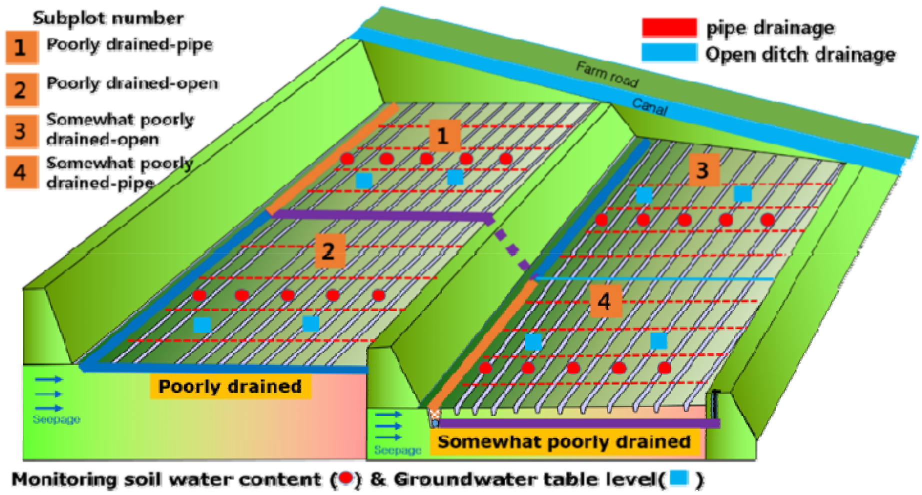

Fig. 2. Layout of drainage systems and measuring points of soil water content and groundwater level at each plot.

Table 1. Soil properties of the experimental field by soil horizon.

Horizon	Depth (cm)	Bulk density (Mgm^{-3})	Porosity (%)	Texture class
Ap1	0 - 10	1.18	55.5	loam
Ap2	10 - 20	1.55	41.4	loam
Ag	20 - 24	1.62	38.8	loam
Bg	24 - 35	1.60	39.7	sandy loam
BCg	35-	1.60	39.6	sandy loam

Statistical analyses

All data from experiments were analyzed statistically by analysis of variance (ANOVA) and Duncan's multiple range test at 90% using SPSS v20 (SPSS Inc., Chicago, IL, USA).

Results and Discussions

CS and NCS factors

The CS and NCS factors were determined from the yields of sorghum, foxtail millet, proso millet, adzuki bean, and sesame according to the controlled excessive soil-water condition (Table 2). The crops had the greatest decreases in yields when the excessive soil-water was applied at the tillering stage and the least yield decrease when the excessive soil-water was applied at the ripening stage. The CS and NCS factors from the five crops were calculated from Equations (3) and (4) and the results are shown in Table 2 & 3. The CS and NCS factors had similar trends across growth stages for all the crops, except sesame. The yields decreased statistically less than the yields in no water stress treatments ($p < 0.1$) where the excessive soil-water was applied at the later growth stage. The yields and CS factors of sesame from the milk development and ripening stages showed opposite results to other crops'. However, there was no statistical difference in the values between the milk development and ripening stages ($p > 0.1$).

Evans et al. (1986) discussed that NCS factors are more insensitive to crop variety or to environmental factors. NCS

Table 2. Yields of five crops with excessive water stress at five growth stages (Zadoks growth scale) and no water stress. Relative yields (RY) were calculated using yields from each growth stage and yields from no water stress.

Crop	Growth stage	Yield ($g \cdot pot^{-1}$)	RY
Sorghum	Tillering	18.94 ± 3.87f	0.43 ± 0.09f
	Booting	24.84 ± 0.50e	0.56 ± 0.01d
	Flowering	27.71 ± 0.64d	0.63 ± 0.01c
	Milk development	34.33 ± 0.77c	0.77 ± 0.02b
	Ripening	37.22 ± 0.02b	0.84 ± 0.04a
	No stress	44.32 ± 1.77a	1
Foxtail millet	Tillering	10.64 ± 1.71f	0.27 ± 0.04f
	Booting	15.17 ± 2.36e	0.39 ± 0.06d
	Flowering	19.58 ± 0.64d	0.50 ± 0.02c
	Milk development	27.48 ± 1.65c	0.71 ± 0.04b
	Ripening	33.20 ± 0.82b	0.85 ± 0.02a
	No stress	38.96 ± 0.82a	1
Proso millet	Tillering	2.72 ± 0.36f	0.16 ± 0.02c
	Booting	4.99 ± 0.52e	0.30 ± 0.03b
	Flowering	5.82 ± 0.40d	0.35 ± 0.02b
	Milk development	7.85 ± 1.43c	0.47 ± 0.09b
	Ripening	12.05 ± 0.83b	0.72 ± 0.05a
	No stress	16.63 ± 2.62a	1
Adzuki bean	Tillering	1.67 ± 0.81b	0.29 ± 0.14
	Booting	2.78 ± 1.35b	0.48 ± 0.23
	Flowering	3.13 ± 0.79b	0.54 ± 0.14
	Milk development	3.44 ± 0.50a	0.60 ± 0.26
	Ripening	4.14 ± 0.85a	0.72 ± 0.15
	No stress	5.76 ± 0.46	1
Sesame	Tillering	2.19 ± 0.61c	0.61 ± 0.03d
	Booting	2.81 ± 0.39c	0.71 ± 0.02c
	Flowering	3.18 ± 0.26b	0.87 ± 0.05b
	Milk development	3.48 ± 0.23b	0.95 ± 0.01a
	Ripening	3.70 ± 0.28a	0.94 ± 0.08a
	No stress	3.75 ± 0.54a	1

Different letters within the same column are statistically different at 90%.

factors reduced variations of the CS factor values across growth stages and crops. Therefore, the NCS factors were applied instead of CS factors in this study. The SDI values for five crops were calculated by Equation (1) (Table 4). The RY values were calculated using yields with no water stress and yields at each growth stage. Previous studies calculated the yield-SDI model from field data, but model accuracy was lower than 80% (Ahmad and Kanwar, 1989; Evans et al., 1991; Purwanto et al., 1993; Kandil et al., 2001). In this study, CS factors and yield-SDI models were calculated from the indoor and fully controlled experiment (pot experiments) to improve the precision of model predictions. All data from CS experiments were applied to the yield-SDI models using Equation (5) and. (6). The fit and results of model calculations are shown in Fig. 3. The r^2 values of the models were greater than 80% except the one for adzuki bean. This result showed better fit results than the previous studies that calculated the yield-SDI models from actual field data.

Shaw (1974) and Sudar et al. (1979) proposed zero threshold stress levels which means no yield from crops under drought condition. Evans et al. (1991) applied this concept to yield-SDI model under excessive soil-water condition and

Table 3. CS and NCS factors of five crops with excessive water stress at five growth stages and no water stress.

Crop	Growth stage	CS	NCS
Sorghum	Tillering	0.57 ± 0.09a	0.32 ± 0.05a
	Booting	0.44 ± 0.01b	0.25 ± 0.01b
	Flowering	0.37 ± 0.01c	0.21 ± 0.01c
	Milk development	0.23 ± 0.02d	0.12 ± 0.01d
	Ripening	0.16 ± 0.04e	0.09 ± 0.02e
Foxtail millets	Tillering	0.84 ± 0.02a	0.28 ± 0.01a
	Booting	0.70 ± 0.03b	0.23 ± 0.01b
	Flowering	0.65 ± 0.02c	0.22 ± 0.01b
	Milk development	0.53 ± 0.09d	0.18 ± 0.03b
	Ripening	0.28 ± 0.05e	0.09 ± 0.02c
Proso millets	Tillering	0.73 ± 0.04a	0.32 ± 0.02a
	Booting	0.61 ± 0.06b	0.27 ± 0.03a
	Flowering	0.50 ± 0.02c	0.22 ± 0.01b
	Milk development	0.29 ± 0.04d	0.13 ± 0.02c
	Ripening	0.15 ± 0.02e	0.06 ± 0.01d
Adzuki bean	Tillering	0.71 ± 0.14	0.30 ± 0.06
	Booting	0.52 ± 0.23	0.22 ± 0.10
	Flowering	0.46 ± 0.14	0.19 ± 0.06
	Milk development	0.40 ± 0.26	0.17 ± 0.09
	Ripening	0.28 ± 0.15	0.12 ± 0.06
Sesame	Tillering	0.41 ± 0.02a	0.39 ± 0.02a
	Booting	0.28 ± 0.04b	0.27 ± 0.04b
	Flowering	0.18 ± 0.02c	0.17 ± 0.02c
	Milk development	0.08 ± 0.03d	0.07 ± 0.03d
	Ripening	0.11 ± 0.02d	0.10 ± 0.02d

Different letters within the same column are statistically different at 90%.

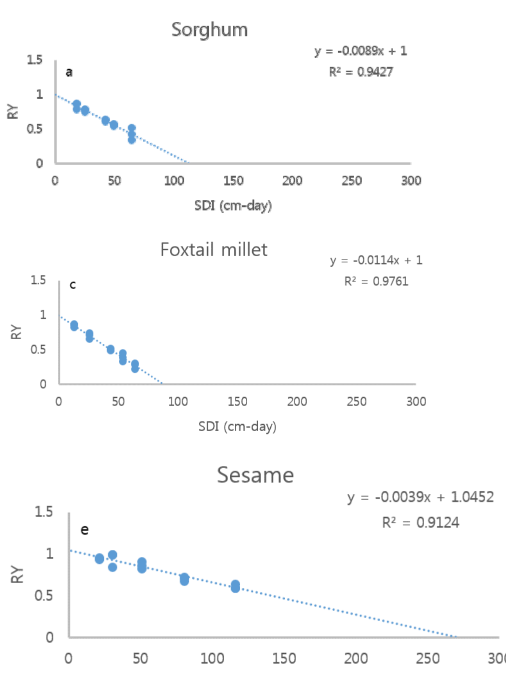

Fig. 3. Yield-SDI models from five crops: a. sorghum, b. foxtail millet, c. proso millet, d. adzuki bean, and e. sesame.

Table 4. Stress-day indexes (SDI) of five crops with excessive water stress at five growth stages and no water stress.

Crop	Growth stage	SDI
Sorghum	Tillering	64.60
	Booting	49.57
	Flowering	42.29
	Milk development	25.45
	Ripening	18.09
Foxtail millets	Tillering	63.83
	Booting	53.61
	Flowering	43.69
	Milk development	25.88
	Ripening	12.99
Proso millets	Tillering	56.00
	Booting	46.87
	Flowering	43.34
	Milk development	35.35
	Ripening	18.43
Adzuki bean	Tillering	59.97
	Booting	43.74
	Flowering	38.54
	Milk development	33.96
	Ripening	23.78
Sesame	Tillering	116.34
	Booting	80.72
	Flowering	50.88
	Milk development	21.63
	Ripening	30.41

set the SDI value at yield = 0 (SDI_0) as a threshold of excessive water stress in yields. Evans et al. (1991) suggested the SDI_0 value for corns was 141 cm-day and SDI_0 value of soybeans was 154 cm-day. If SDI values for corn were greater than 141 cm-day, yield-SDI model were set as y = 0. In this study, SDI_0 values were calculated from the yield-SDI model (Fig. 3). The sorghum SDI_0 values was 112 cm-day, proso millet was 67 cm-day, foxtail millet was 87 cm-day, adzuki bean was 78.6 cm-day, and sesame was 270 cm-day. This result meant that proso millet was more vulnerable to excessive soil-water compared to other cereal crops, followed by Foxtail millet. On the other hand, sesame was most tolerant to the excessive soil-water condition.

Evaluation of the yield-SDI model

Jung et al. (2014) reported the same results from their wet injury tests of crop cereals in paddy fields. They concluded that the degree of wet injury of five cereal crops were proso millet > foxtail millet > adzuki bean > sorghum. In this study, proso millet was most vulnerable to wet injury followed by adzuki bean.

The yield-SDI model from each crop was applied to actual yields from paddy fields for evaluation. Average values of groundwater levels and soil-water from the paddy field of all treatments are shown in Table 5. In 2013 and 2015, somewhat poorly drained paddy fields with a pipe drainage treatment had the lowest groundwater level and soil-water throughout the growing seasons. The poorly drained paddy field with an open drainage treatment had the highest groundwater level and soil-water (Fig. 4). These conditions led to the greatest stress of excessive soil-water to crops in the poorly drained paddy field with an open drainage treatment while they led to the smallest stress to crops in the somewhat poorly drained paddy field with a pipe treatment.

Table 5. Hydrological properties from paddy fields of two drainage classes and two drainage treatments.

	Drainage class	Drainage treatment	Groundwater Level (-cm)	Soil-water (mm·m^{-1})
2013	Poorly	open	14.08 ± 7.45ab	34.0 ± 5.59ab
		pipe	42.19 ± 29.37a	29.7 ± 3.25a
	Somewhat poorly	open	31.94 ± 12.30b	30.4 ± 4.24b
		pipe	76.15 ± 22.38ab	26.7 ± 2.57ab
2015	Poorly	open	28.80 ± 24.36ab	31.98 ± 7.37a
		pipe	58.37 ± 23.84a	29.43 ± 9.25a
	Somewhat poorly	open	37.03 ± 27.00ab	24.23 ± 6.69ab
		pipe	68.33 ± 22.97a	23.54 ± 5.57ab

Different letters within the same column are statistically different at 90%.

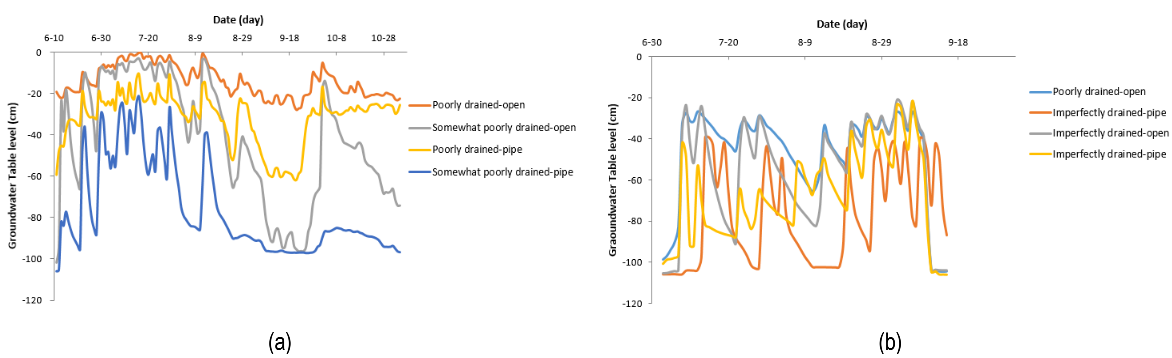

Fig. 4. Groundwater levels from paddy fields for all treatment in 2013 (a) and 2015 (b); poorly drained-open was a poorly drained field with open ditch drainage treatment, poorly drained-pipe was a poorly drained field with pipe drainage treatment, somewhat poorly drained-open was a somewhat poorly drained field with open ditch drainage treatment, and somewhat poorly drained-pipe was a somewhat poorly drained field with pipe drainage treatment.

There was no significant difference across drainage treatments in crop yields from foxtail millet, proso millet, and adzuki bean ($p > 0.1$, Table 6). Sorghum and sesame showed a significant difference between poorly drained fields with open drainage and somewhat poorly drained fields with pipes ($p < 0.1$). The average yield of each crop from no water stress cultivation in uplands was 330 kg·10 a^{-1} for sorghum, 298 kg·10 a^{-1} for foxtail millet, 257 kg·10 a^{-1} for proso millet, 104 kg·10 a^{-1} for adzuki bean, and 90 kg·10 a^{-1} for sesame (NSO, 2013). Foxtail millet from paddy fields resulted in a 20% to 50% reduction of yields and proso millet to a 40 % to 60% reduction compared to the average yields from uplands. However, sorghum and sesame did not show a reduction in yields compared to the average yields from uplands. As discussed above, foxtail millet and proso millet were more vulnerable to excessive soil-water conditions than sesame and sorghum. In table 7, SDI values for each crop were calculated as per Equation (1). Proso millet and adzuki bean from all drainage classes and drainage treatments had greater SDI values than the SDI_0 value. Foxtail millet had only one SDI value which was greater than SDI_0. Therefore, the yield-SDI model of proso millet, foxtail millet, and adzuki bean expected no yield under this condition. Based on SDI values, proso millet, foxtail millet, and adzuki bean had the most significant damage from excessive soil-water. The yield results also confirmed that there was no difference from proso millet, foxtail millet, and adzuki bean ($p > 0.1$). They all had wet injury across all treatments. Sorghum and sesame yield data were applied to calculate the relative yield (actual RY) and the yield-SDI models calculated expected relative yield (expected RY).

Table 6. Average and standard deviation values of yields from five crops from all treatments.

Drainage class	Drainage treatment	Yield ($kg\cdot10a^{-1}$)				
		Sorghum	Foxtail millet	Proso millet	Adzuki bean	Sesame
Poorly	open	277.46 ± 18.30b	235.66 ± 63.58	148.43 ± 62.58	133.96 ± 73.8	83.5.02 ± 19.89b
	pipe	319.41 ± 13.67	272.05 ± 30.97	178.19 ± 39.05	212.52 ± 58.04	91.73 ± 17.86
Somewhat poorly	open	331.16 ± 20.21	242.70 ± 39.52	158.72 ± 65.50	139.26 ± 36.78	85.59 ± 17.05
	pipe	334.48 ± 16.96a	279.21 ± 47.97	183.80 ± 36.57	197.56 ± 32.78	106.10 ± 20.32a

Different letters within the same column are statistically different at 90%.

Table 7. Stress-day indexes (SDI) calculated from Eq. (1) for sorghum, foxtail millet, proso millet, and adzuki bean in 2013 and sesame in 2015. Relative yields (RY) were calculated from actual yields and optimum yields of sorghum, foxtail millet, proso millet, adzuki bean, and sesame grown in the experimental site.

Drainage class	Drainage treatment	SDI (cm-day)				
		Sorghum	Foxtail millet	Proso millet	Adzuki bean	Sesame
Poorly	open	119.74	677.09	1064.80	1388.56	116.14
	pipe	14.03	173.28	230.23	190.31	71.02
Somewhat poorly	open	27.68	254.14	304.20	342.01	36.76
	pipe	11.07	74.56	87.03	98.75	0
Drainage class	Drainage treatment	RY				
		Sorghum	Foxtail millet	Proso millet	Adzuki bean	Sesame
Poorly	open	0.84	0.50	0.45	0.58	0.83
	pipe	0.96	0.76	0.54	0.91	0.85
Somewhat poorly	open	0.93	0.53	0.48	0.59	0.91
	pipe	1.11	0.78	0.55	0.84	1.11

Sorghum and sesame showed a fit with $r^2 > 90\%$ between actual RY and the expected RY (Fig. 5). Evans et al. (1991) and Purwanto et al. (1993) evaluated the yield-SDI models of corns and soybeans compared to actual field yields. Their best fitting results were found to range between r^2 values of 60 and 80%. Both studies determined their models based on field data instead of controlled experiment data. Previous studies reported that sorghum is one of the most tolerant crops to excessive soil-water compared to other cereal crops (Jung et al., 2013). Wei et al. (2013) reported that sesame has a severe sensitivity to waterlogging condition. But in this study, sesame had a slope value of 0.0039 from yield-SDI model while sorghum had one of 0.0146. In other word, yield decrease of sesame was less than that of sorghum as SDI increased. This result meant that sesame was more tolerant to wet injury than sorghum.

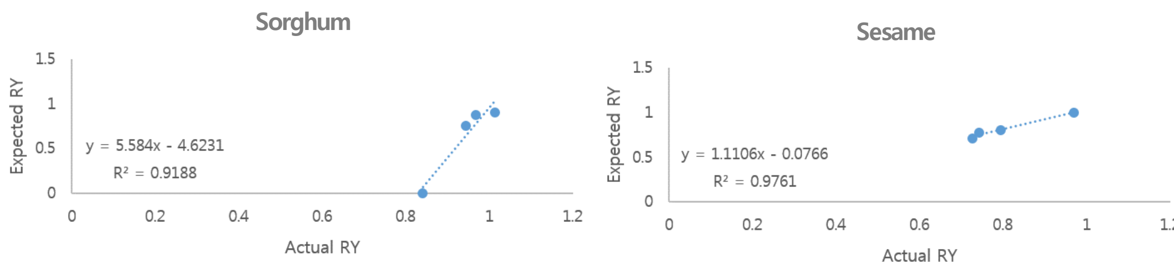

Fig. 5. Relations between expected yields calculated using Eq. (6) and actual RY (Table 7) of sorghum (top) and sesame (bottom).

Conclusions

This study evaluated the effect of excessive soil-water or high groundwater level conditions on yields of five cereal crops. The yield-SDI model was adopted to evaluate the effect of excessive soil-water and predict yields under excessive soil-water or high groundwater conditions. The model was useful for certain crops such as sorghum and sesame, which had relatively greater tolerance to excessive soil-water. However, the model was unable to predict yields of proso millet, foxtail millet, and adzuki bean from paddy fields in excessive soil-water condition. These results concluded that these three crops may not be suitable for cultivation in paddy fields. On the other hand, sorghum and sesame were more suitable to paddy filed cultivation and their yields can be easily predicted under various soil-water conditions or groundwater levels. More studies will be performed to obtain additional field data for cereal crops with various groundwater tables to test yield-SDI models and improve the models for proso millet, foxtail millet, and adzuki bean. This study may contribute to more precise water management for cereal crops in paddy fields and provide a guideline to manage water conditions in paddy field soils to cultivate cereal crops.

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