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Biomass production and yield of soybean grown under converted paddy fields with excess water during the early growth stage

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ABSTRACT

Soybean production in converted paddy fields is generally impacted by excess soil water condition which typically occurs during the early stage of vegetative growth in Japan. This study attempted to identify how the excess water stress in this stage affects light components involved in crop production processes (biomass accumulation and seed yield). The Enrei cultivar was grown in three experiments under optimum soil moisture throughout the season (Opt) and with excess water at only the early vegetative growth stage (Ex-Wt). The excess water was imposed from 11 to 15 days after emergence (DAE) by water stagnation between ridged rows or raising the water table by sub-soil irrigation. Biomass accumulation was analyzed based on periodical harvesting and its relationship with the light components such as intercepted radiation (IR), radiation use efficiency (RUE) and light extinction coefficient (*K*). In all experiments, Ex-Wt produced fewer yields than Opt by 25–31%. The accumulation of total dry weight (TDW) before beginning of seed filling (R5) was less in Ex-Wt by 24–51%, while the harvest index was changed only slightly. In the Ex-Wt fields, the restricted leaf area resulted in 13–27% less intercepted radiation (cum IR) and exhibited a 13–33% lower RUE from emergence to R5. On average, the difference in yield between conditions was lesser in the dense planting than the sparse planting, and a similar trend was seen for cum IR. Thus, dense planting would ameliorate yield reduction to a limited extent. The results suggest that a 2-week period of excess water would reduce yield by reducing TDW, attributed to reduction in less cum IR and low RUE, even if the water condition is maintained at a preferable level for the remaining time.

1. Introduction

An excess soil water condition is one of the major problems in the production of soybean (*Glycine max* (L.) Merrill) in converted paddies in Japan (Sugimoto et al., 2000) The clayey nature of the soils favorable for paddy cultivation makes them prone to short term excess moisture because of their poor drainage. This problem typically occurs during the early stage of vegetative growth because of the frequent rainfall during the rainy season (June–July). And the circumstances are more-or-less common in the areas of East Asia.

It is well known that the full potential of the soybean yield cannot be realized when the plants are grown under an excess soil water environment. Oosterhuis et al. (1990) and Scott et al. (1990) found a yield reduction of 17–43% and 50–56% when water logging was imposed at the vegetative and reproductive stages, respectively. Rhine et al. (2010) reported an increase of yield by short-term flooding in the vegetative stage presumably with insufficient irrigation for the control without flooding, but there was a significant decline when it was continued for a longer duration in the reproductive stage. The effects of a high water table on yield were studied by Shimada et al. (1997), who showed a 50% reduction, in seed yield when the water table rose to −15 cm because of heavy precipitation.

In soybean, N_2 fixation is considered to be more sensitive to flood conditions than biomass production (Bacanamwo and Purcell, 1999; Buttery, 1987; Youn et al., 2008).This suggests that the enhancement of nitrogen (N) availability in the soil may help to ameliorate growth reduction by excess water. Also, inhibited leaf area development seems to be a primary factor that causes reduced biomass accumulation under excess water during the early stages of plant growth (Sugimoto et al., 1988; Furuhata et al., 2011). And, thus the establishment of a greater plant population can be one

Abbreviations: Ex-Wt, excess water; FOEAS, the Farm-Oriented Enhancing Aquatic System; Opt, optimum; DAE, days after emergence; Cum IR, cumulative incident radiation; F, fraction of light intercepted; RUE, radiation use efficiency; SMC, soil moisture content.

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measure to maintain productivity in fields that are prone to excess water. Nitrate reduction activity also is affected by excess water stress (Sung, 1993). Sugimoto and Sataou (1990) reported, from a study conducted under a converted paddy condition, a greater seed yield reduction by flooding in a non-nodulating soybean than its nodulating near-isogenic line. Also, leaf gas exchange activity is negatively affected by excess water stress (Oosterhuis et al., 1990; Shimada et al., 1997), which would cause a decline of physiological activity of canopy gas exchange and biomass accumulation. The previous studies have outlined the varied causes for seed yield reduction in soybean under excess water condition. However, to our knowledge there is not any studies regarding how the excess water environment in soybean interact with the light components such as amount of absorbed solar radiation and the efficiency of utilizing absorbed radiation to drive photosynthesis for biomass accumulation and seed yield. Studies available on soybean response to excess water stress had focused mostly on the stress at the late vegetative or reproductive phases (Rhine et al., 2010; Sal1am and Scott, 1987; Sugimoto et al., 2000). Despite the fact that an excess soil water environment at early stage is a common problem in the soybean-growing areas of the Asian monsoon region, very few studies have been conducted to explore early growth stage excess water impacts on yield. The research gap existed is that the fundamentally important correlation between the plant growth and biomass production with the amount of absorbed solar radiation under excess water condition at early vegetative growth has not been considered as the research objectives.

Therefore, the overall goal of the study is to determine the effects of early growth stage (V4) excess water stress on soybean yield performance, occurring on converted paddy fields (low permeable clay soils). More specifically, the study was conducted to quantify the reduction of light interception and radiation use efficiency under excess water condition attributed to the soybean yield reduction compared to soybean grown under optimum field condition.

2. Material and methods

Field experiments were conducted in 2010 and 2011 at two different locations: the Experimental Farm of Kyoto University at Takatsuki, Japan (34°52′N), and the Shiga Prefecture Agricultural Technology Promotion Center at Azuchi, Japan (35°07′N). In both years, a determinate type cultivar Enrei (maturity group IV) was grown under optimum soil moisture conditions throughout the season (Opt) and with excess water only at the early vegetative growth stage (Ex-Wt).

On 9 July 2010 (Exp I) at Takatsuki, soybean seeds were sown after fertilizer (N:P:K = 3:10:10 $g m^{-2}$) application in a clay loam soil (Typic Fluvaquent) with 0.17% total N and 2.7% total C. The inter-row and intra-row distances were 70 cm and 15 cm, respectively maintaining nine plants m^2 after thinning. At the early plant stage, 20 days after emergence, water stagnation (15–20 cm) imposed by irrigating frequently to the ridged row-intervals and stopping drainage, so that water level was kept at 15–20 cm. This treatment was conducted for 12 days, with an optimum condition for rest of the period by regular drainage and irrigation. The Opt was maintained optimally for the whole growing season. Three replicate plots were established in each condition. The soil moisture content (SMC) was monitored continuously by using EC5 soil moisture sensors set at the depth of 15 cm from the soil surface.

In 2011 at Azuchi, two experiments were conducted: June sowing (Exp II) and July sowing (Exp III). Fertilizers (N:P:K = 2:6:6 $g m^{-2}$) were applied prior to sowing to the silty clay loam soil (Typic Hydraquent; Total N = 0.18%, C = 3.2%), which had been used for paddy cultivation for last two years. The experimental field was divided into 4 sections (8 × 80 m each) facilitated separately with the Farm-Oriented Enhancing Aquatic System (FOEAS) system (Shimada et al., 2012; Wakasugi and Fujimori, 2009). The seeds were sown on 14 June in two sections and on 11 July in the remaining two sections. For the respective sowing dates, one section was designated as Opt, with the water table maintained at approximately 50–60 cm throughout the season. The other section was subjected to an excess water soil condition as the Ex-Wt section, with the water table being raised to approximately 10–20 cm from the soil surface after 12 days of emergence. The treatment lasted approximately 15 and 10 days for the June and July sowing, respectively. This water table was decided based on Kitagawa et al. (1984), who indicated that the water table in a poorly drained paddy field of Japan ranged from 5–20 cm from the soil surface, which was sufficient for a 50% reduction in crop productivity. In each field condition of both experiments, three replicate blocks were established and two planting densities were settled in each block: Sparse (70 × 15 cm) and Dense (70 × 7.5 cm), with 9.5 and 19.2 plants per m^2, respectively by thinning. To record the depth of the water table maintained by the FOEAS system (a groundwater level control system consisting of underdrain and sub irrigation system and can control the water table at desired depth), one vinyl chloride tube of 70 mm inner diameter was set in each block, and the water level inside the tube was measured periodically. Additionally, one tube for each sowing was placed for measuring the water table continuously with a water table gauge (S&DL mini, Oyo Chishitsu, Tokyo). SMC was monitored in the same way as in 2010 experiment.

In both years, the plants were sampled prior to excess water treatment and at the end of the treatment, and periodical harvesting was performed at different growth stages including maturity from a 1.2 m^2 area to determine the leaf area index (LAI) and dry weight of aboveground plant parts (fallen leaves not included). Total leaf area, one plant per replicate block was measured by a leaf area meter (LI-COR, LI-3000). The LAI was calculated as the ratio of leaf area divided by total ground area occupied by each plant. Seed yield was expressed with 14% moisture content.

The radiation intercepted (F) is generally calculated based on photosynthetically active radiation (PAR) below the canopy (I_0) and incident radiation above the canopy (I) using the line-source quantum sensor (Kiniry et al., 2005; Sadras and Wilson, 1997) by the equation:

$$F = 1 - (I/I_0) \quad (1)$$

However, in this study we estimated the light interception using digital image techniques as described by (Purcell, 2000). Fractional canopy coverage (F) was determined by using the digital images taken above canopy. Daily solar radiation (R_s) ($MJ/m^2/day$) was recorded at the respective experimental sites, and daily incident radiation (DIR) above the canopy was computed as the product of R_s and F. Cumulative incident radiation (Cum IR) at a particular day was computed by adding DIR. The mean radiation use efficiency (RUE) was determined for the periods from emergence (EMG) to the beginning of seed filling (R5) and from R5 to 30 d after R5 as the slope of linear regression between TDW (above ground) and Cum IR (Monteith, 1994). Light extinction co-efficient (K) is generally estimated using the exponential function of LAI and radiation levels at above and below canopy using modified Beer–Lambart law as described by Monsi and Saeki (1953):

$$F = 1 - \exp^{-K \times \mathrm{LAI}} \quad (2)$$

The slope between the natural logarithm of F computed from digital image analysis and LAI is referred as K (Campbell and Norman, 1989) in our study.

Statistical analysis was performed using cropstat software. Analysis of variance (ANOVA) and standard error of means (SE) were used when testing the effects of treatments. Graphs were