1. Summaries of Doctor Theses

Contribution of pre- and post-anthesis assimilates to the grain yield of two wheat cultivars differing in drought resistance

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Hongmangmai is a typical local wheat cultivar cultivated under rainfed conditions in the southern Loess Plateau, which is known to be drought resistant. It has been reported that drought resistance of Hongmangmai was closely related to the deep sowing tolerance. However, the relationships between its drought resistance and assimilation or accumulation of assimilates are still unknown. Grain filling of wheat depends on remobilization of pre- and post-anthesis assimilates. Although drought increases the proportion of assimilates originating from pre-anthesis assimilates, the relationship between the contribution of pre-anthesis assimilates to grain yield and drought resistance is not well understand. In order to characterize the drought resistant mechanisms of Hongmangmai, the relative importance of pre- and post-anthesis assimilates to grain yield, and flag leaf and ear photosynthesis were investigated and compared with Haruhikari. Haruhikari was bred in Hokkaido where climatic conditions are similar to the Loess Plateau except for precipitation; annual precipitation in Hokkaido is twice as much as in the Loess Plateau. Pot and field experiments were conducted for 1 and 3 years, respectively. The experimental field was covered with transparent sheets to prevent rain. In the field experiments, soil moisture was maintained near field capacity for the irrigated treatment throughout the growing season, while in the non-irrigated treatment water was withheld from seedling stage until maturity. In the pot experiment, however, soil water content was maintained at 7.0 % and 3.5 % in well watered and water stressed treatments, respectively.

The results obtained from this study were as follows:

Water stress reduced grain yield of the two cultivars, but Hongmangmai was less affected by water stress than Haruhikari in all experiments. This is firm evidence that Hongmangmai is a drought resistant cultivar and Haruhikari is a drought sensitive one. The pot experiment limited the root growth, but not the field experiment. Hence the trends observed for grain yield of the two cultivars under water stress were similar in both field and pot experiments, indicating that the drought resistance of Hongmangmai was not influenced by root growth. In all experiments, water stress hastened anthesis and physiological maturity of both cultivars, while Hongmangmai did not mature earlier under water stress compared to Haruhikari. Thus the drought resistant mechanism of Hongmangmai was not drought escape.

In the field experiment, remobilization of pre-anthesis assimilates and its contribution to the grain yield were decreased by water stress in Hongmangmai but increased in Haruhikari. This indicated that under water stress grain filling of Hongmangmai depended more on the post-anthesis assimilates, while the drought sensitive Haruhikari mostly relied on the remobilization of pre-anthesis assimilates to the grain. This may result from the differences in total shoot DM accumulation from anthesis to maturity between the two cultivars; there were no differences between the treatments in Hongmangmai, while in Haruhikari total shoot DM accumulation from anthesis to maturity markedly increased under irrigated condition and was little changed under non-irrigated condition.

Under drought stress, the P_N and leaf area of penultimate leaf during post-anthesis decreased similarly in both cultivars. This implied that net photosynthetic rate per penultimate leaf under water stress was not related to the drought resistance of Hongmangmai. The P_N of Haruhikari was close to zero but that of Hongmangmai was higher under water stress. The effect of water stress on the flag leaf area was more pronounced in Hongmangmai than in Haruhikari. Thus, this clearly demonstrated that Hongmangmai had higher net photosynthetic rate per flag leaf than Haruhikari. Under non-irrigated condition, Hongmangmai showed fairly higher P_N of ear than Haruhikari, while water stress similarly reduced the areas of ear in both cultivars. Therefore, Hongmangmai showed fairly higher net photosynthetic rate per ear than Haruhikari under non-irrigated condition. These results indicated that the higher P_N of ear and flag leaf under water stress could be associated with the drought resistance of Hongmangmai.

There were no differences in the stress-induced reduction in the g_s of the flag leaf of the two cultivars. However, c_i of the flag leaf was decreased by water stress in Hongmangmai but increased in Haruhikari. This implied that chloroplast activity to fix CO_2 was higher in Hongmangmai than in Haruhikari. Also, no

differences were observed in the ψ_l and osmotic adjustment of the flag leaf of the two cultivars. Therefore, the higher P_N of flag leaf in Hongmangmai may be attributed to the greater chloroplast activity under low leaf ψ_l. This also indicated that the drought resistant mechanism of Hongmangmai was dehydration tolerance. In this study, the dominant factor responsible for stress-induced reduction in ear P_N was not easy to be identified.

This study has demonstrated that root development and deep rooting in terms of water absorption may not be related to the drought resistance in Hongmangmai. Hongmangmai maintained a relatively high flag leaf and ear P_N under the low leaf ψ_l during post-anthesis, which induced higher post-anthesis assimilation and hence, grain yield. The observed higher contribution of post-anthesis assimilates to grain yield in Hongmangmai was contradictory to the previous reports that remobilization of pre-anthesis assimilates contributed to the grain yield under water stress. Further research is needed to demonstrate the relationship between the drought resistance and the parameters related to the chloroplast activity, such as PS2 and RuBPC activities, and RuBP regeneration capacity. Higher chloroplast activity in flag leaf seems to be of advantage in breeding drought resistant cultivars in rainfed agriculture.

Silicon-Induced Enhancement of Drought Tolerance in Sorghum and Its Physiological Mechanisms

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Crop production in arid and semi-arid areas is most limited by insecure water supply. In these areas improvement in the drought tolerance of crop has been recognized as one of the most important factors to increase and stabilize production. Previous studies have revealed that various minerals such as phosphates, potassium salts and silicates are related with plant drought tolerance. Because of the comparatively few and fragmentary studies on silicates, their effects on drought tolerance have remained unclear. The objectives of the present study were to determine how silicon could enhance drought tolerance in sorghum, and to monitor the physiological responses of sorghum to silicon application under water stress. To meet these objectives, three experiments were conducted.

In the first experiment, drought tolerant and sensitive sorghum cultivar, cv. Gadambalia and Tabat, were grown under drought stress with or without silicon fertilizer application to verify the effects of silicon on their drought tolerance based on dry matter production, water use efficiency and water uptake. Regardless of their drought susceptibility, both sorghum cultivars showed almost similar responses to silicon application. Silicon application ameliorated the reduction in dry matter production under drought stress but had no effect under wet condition. Under drought stress, silicon-applied sorghum had a lower shoot/root ratio, indicating facilitation of root growth and maintained a higher photosynthetic rate and stomatal conductance than plants grown without silicon application. Water use efficiency was not influenced by silicon application. Diurnal determination of transpiration rate indicated that the silicon-applied sorghum could extract a larger amount of water from a drier soil to support a higher stomatal conductance. These results suggested that silicon application could be useful to improve the dry matter production of sorghum under drought stress by enhancing water uptake.

In the second experiment, solution-cultured sorghum plants (cv. Gadambalia) grown with or without silicon were subjected to osmotic stress and the effects of silicon on their transpiration rate, hydraulic resistance to water flow and water uptake rate were investigated. Under osmotic stress, silicon application alleviated the reduction in dry weight depending on application levels. In contrast, no silicon effect was observed when sorghum plants were grown without osmotic stress. Regardless of silicon application levels or osmotic stress, the photosynthetic rate increased in proportion to increasing stomatal conductance which also changed depending on leaf water potential. Thus, growth promotion by silicon application was likely attributed to the higher leaf water potential due to silicon. Comparison of the hydraulic resistance to water flow between silicon-applied or silicon-deficient sorghum revealed that silicon application could ameliorate stress-induced increases in hydraulic resistance. Without silicon application the hydraulic resistance increased under osmotic stress. Data on water uptake rate and transpiration rate indicated that the latter changes in response to former. Silicon application had no effects on cuticular transpiration rate in sorghum unlike in the case of rice as previously reported. These results indicated that 1) the ameliorative effect of silicon on the reduction in dry matter production under osmotic stress was attributed to the higher leaf water potential following the acceleration of water uptake caused by silicon, and that 2) silicon accelerated water uptake by maintaining a lower hydraulic resistance under osmotic stress.

In the third experiment, the effects of silicon on cell wall physical properties related with root elongation rate and mechanical reinforcement of stele for the protection of its conductive function in water-stressed conditions were investigated. Sorghum seedlings (cv. Gadambalia) were grown in a nutrient solution with or without silicon. The mechanical properties of cell walls were measured in 3 separate root zones: basal, apical and subapical. Silicon treatment decreased cell wall extensibility in the basal zone of isolated stele tissues covered by endodermal inner tangential walls. The silicon treatment increased cell-wall extensibility in the apical and subapical zones with a concomitant decrease in elastic moduli (E) and viscosity coefficients (η). In contrast to the apical zone, the silicon-induced hardening of cell walls was also measured with an increase in E and η. The

silicon-enhanced cell wall extensibility in the growing zone may be one of the causal factors for the silicon-promoted root elongation. In addition, silicon deposition might protect the stele as a mechanical barrier by hardening the cell walls of stele and endodermal tissues.

The overall results of the present study revealed that silicon application to sorghum ameliorated stress-induced reduction in leaf water potential, leading to grater dry matter production under water stress. This advantageous effect of silicon is attributed to the increase in water uptake by sorghum due to improved plant hydraulic resistance and accelerated root elongation. There are possibilities that silicon-induced changes in cell wall extensibility might affect these factors.

Influences of Water Quality and Evapotranspiration on the Scheduling of Drip Irrigation

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Irrigation scheduling is the key factor for increasing irrigation efficiency and crop yield as well as the control of soil degradation under low quality water use. Strategies for irrigation scheduling include appropriate timing and intervals of irrigation according to soil water holding capacity, uniformity of irrigation system and evapotranspiration. Drip irrigation system (DIS) is designed for high-frequency irrigations to maintain soil moisture at an optimal or near optimal level for maximum yield during the whole growing season. The effectiveness of DIS depends as well on the quality of the water under use and the maintenance of the system. Water quality can considerably affect DIS scheduling and efficiency due to emitter clogging by sewage or saline water and the level of soil solution concentration in the crop root zone. A study on DIS scheduling as affected by water quality and evapotranspiration was carried out at the Arid Land Research Center, Tottori University, and the Tohaku irrigation project area, Tottori, Japan (35°32′N and 134°13′E) during 2002 and 2003. This study included the following three parts:

The first part of the study was on the estimation and forecast of ETo to improve irrigation scheduling and consequently water use efficiency. Six ETo estimation models were assessed statistically against experimentally determined values in a humid temperate environment. The ETo estimates were obtained using the Penman (PE), Penman-Monteith (PM), Wright-Penman (WP), Blaney-Criddle (BC), Radiation balance (RB), and Hargreaves (HG) models. The ETo forecasts were obtained using 5-yr or 8-yr weather data and 1- and 2-year return period approach. Compared with the lysimeter values, it was observed that all the six models over or under-estimated the ETo. Nevertheless the PE model produced the best ETo estimates as assessed by root mean square, mean bias error, and t-test statistics for the temperate environment. In general, the ETo forecasts obtained using 8-yr weather data were better than 5-yr. The 2-yr return period ETo forecasts were better than 1-yr return period, regardless of the duration of weather data.

The second part was to investigate the impact of selected water quality (chemical and biological) in effluents on water discharge rate and distribution uniformity from emitters with different orifice areas (OA), in-built filtration areas (FA), pressure compensation (PC) systems. The field experimental layout in the Tohaku irrigation project included 8 types of on-line and in-line emitters each on 50 m long laterals connected to the field irrigation line without filters. The results of Biological clogging agents (BCAs) count indicated that during 2002 it was highest at the beginning of irrigation in April, and decreased with time until September, while during 2003 it increased with time and peaked at the end of August. Emitter discharge rates increased with increasing OA, FA, and working pressure (WP) and decreased with increasing BCAs counts. Because BCAs were the only dynamic variables in the above relationship, we concluded that BCAs-induced clogging is a major reason for clogging when filters were not installed in field irrigation lines. Four selected emitters from the first year's experiment and another 2 new emitter types were used to assess the impact of chemical treatment on preventing or reducing emitter clogging induced by BCAs, and the performance of drip irrigation. Each of the 6 types of emitters was installed on two separate laterals, in two similar subunits of DIS, for two different management schemes of with and without chlorine injection into the irrigation water. The discharge from emitters increased with chlorine injection into the irrigation water and with increasing OA and FA, but decreased with increasing BCAs counts. The values of the mean discharge ratio variation (Dra) indicated that the cumulative impact of manufacturing variations (Vm) and that induced by BCAs and chlorine injection on emitter discharge was low during the irrigation season when chlorine was injected into the irrigation water. The values of the statistical uniformity coefficient (Uc)were more than 93 % for both managements, indicating that the uniformity of emitters discharge and consequently, clogging along a lateral were high.

In the third part of the experiments, the effects of (i) irrigation regimes, (ii) time after irrigation, and (iii) crop growth stages, on soil water content (θw) and soil solution salinity (ECw) was studied at different radial distance from the emitter (lateral pipe). The experiments were carried out in the sand dune field of the Arid Land Research Center, Tottori University. Three irrigation regimes were applied. The first irrigation regime (I_d) was based on daily crop water requirement. Two other irrigation regimes were based

on I_d and 20 % and 40 % leaching ($I_d \cdot 1.20$ and $I_d \cdot 1.40$). The simultaneous distribution of water and solute under drip irrigation was measured using Time Domain Reflectometry (TDR). The results indicated that θw and ECw increased in the order early stage (ES) < mid-stage (MS) < late stage (LS) for all irrigation regimes. The maximum θw and minimum ECw coincided at 10 cm radial distance from emitter (r_{10}) during all crop growth stages for all the irrigation regimes. The same trend was noted for 20 cm radial distance from emitter (r_{20}) under $I_d \cdot 1.40$, but only during the ES for I_d and during the ES and MS for $I_d \cdot 1.20$. The ECw increased significantly in the order $r_{10} < r_{20} < r_{30}$ (30 cm radial distance from emitter) during all the crop growth stages for all the irrigation regimes. Time elapsed after irrigation was terminated until θw attained its maximum level in the crop root zone changed with crop growth stages. It is therefore suggested that irrigation should commence at different times before noon, depending on the crop growth stage, so that maximum θw (minimum ECw) will coincide with maximum evapotranspiration (ETo). Interaction between θw and ECw for a given radius and the different crop growth stages showed that the influence of θw on ECw was restricted to a small radius of about 0-20 cm from the emitter. Beyond this range, increases in θw did not significantly affect ECw. The first irrigation regime (I_d) was found unsuitable for an irrigation regime involving use of saline water. A distance of about 25 and 30 cm was suggested for 2 consecutive emitters on a lateral pipe under $I_d \cdot 1.20$ and $I_d \cdot 1.40$ respectively, to minimize ECw along the lateral pipe. Moreover, a combined irrigation scheduling of $I_d \cdot 1.40$ for ES and MS, and $I_d \cdot 1.20$ for LS was suggested to increase the irrigation efficiency.