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Photosynthetic Characteristics of Resistance and Susceptible Lines to High Temperature Injury in *Panax ginseng* Meyer

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In this study, photosynthetic parameters such as the net photosynthesis rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate were examined in selected ginseng varieties and/or lines that are resistant (Yunpoong, HTIR 1, HTIR 2, and HTIR 3) and susceptible (Chunpoong) to high temperature injury (HTI). The net photosynthesis rate increased with the increase in the light intensity in all the HTI-resistant and -susceptible ginseng lines with a light saturation point of 200 μmol $m^{-2}s^{-1}$, except for Yunpoong that had a light saturation point of 400 μmol $m^{-2}s^{-1}$. At the light saturation point, the net photosynthesis rate in July was highest in HTIR 3, at 4.2 μmol CO_2 $m^{-2}s^{-1}$, and was lowest in Yunpoong, HTIR 1, Chunpoong, and HTIR 2, in that order, at 1.9 to 3.7 μmol CO_2 $m^{-2}s^{-1}$. The net photosynthesis rate in August was highest in Yunpoong at 5.9 μmol CO_2 $m^{-2}s^{-1}$, and lowest in HTIR 1 and HTIR 3 (4.5 μmol CO_2 $m^{-2}s^{-1}$) and in other lines, in that order, at 2.8 to 2.9 μmol CO_2 $m^{-2}s^{-1}$. The stomatal conductance in July was highest in HTIR 3 (0.055 mol H_2O $m^{-2}s^{-1}$) and Yunpoong, Chunpoong, HTIR 1, and HTIR 2 were 0.038, 0.037, 0.031, and 0.017 in that orders. In August, meanwhile, HTIR 1 showed the highest as 0.075, and followed by HTIR 3, Chungpoong, and HTIR 2 with 0.070, 0.047, and 0.023, respectively. The intercellular CO_2 concentration at the light saturation point in July and August was much lower in HTIR 2 at 139 and 185 μmol mol^{-1} than in the other ginseng lines at 217 to 257 and 274 to 287 μmol mol^{-1}, respectively. The transpiration rate in July and August was higher in the HTI-resistant lines of Yunpoong, HTIR 1, and/or HTIR 3 at 0.83 to 1.03 and 1.67 to 2.10 mol H_2O $m^{-2}s^{-1}$ than in the other ginseng lines at 0.27 to 0.79 mol H_2O $m^{-2}s^{-1}$ and 0.51-1.65 mol H_2O $m^{-2}s^{-1}$, respectively. Conclusively, all the photosynthetic parameters that were examined in this study were generally higher in the HTI-resistant ginseng lines than in the HTI-susceptible lines, except for HTIR 2, and were much higher in August than in July, especially in the resistant ginseng lines. All these results can be used to provide basic information for the selection of HTI-resistant ginseng lines and the application of cultural practices that are efficient for ginseng growth, based on the photosynthetic characteristics of the lines.

Keywords: *Panax ginseng*, High temperature injury, Photosynthesis, Stomatal conductance, Transpiration

INTRODUCTION

Plants produce chemical energy through photosynthesis using light and CO_2 under favorable temperature conditions. Such chemical energy is used to synthesize and accumulate organic materials such as starch, proteins, and lipids for plant growth. Ginseng (*Panax ginseng* Meyer) is a semi-shade perennial plant whose photosynthetic capability is reduced at a light intensity and temperature that are beyond the optimum conditions, which adversely affects the growth and development of the plant's aboveground and underground parts. This requires the shielding of ginseng plants from direct sunlight by shading them during their growth in fields. In this sense, scattered

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indirect light, which dominates in somewhat cloudy days, would be better for the photosynthesis of ginseng than intensive direct light in sunny days [1,2].

Temperature and light intensity are very significantly correlated in the photosynthesis of ginseng, and show the optimum light intensities of 11,000 Lux at 15°C to 20°C and 9,500 Lux at over 25°C for maximum photosynthesis. The net photosynthesis of the ginseng plant is higher when it is shaded with a light transmission rate of 15% than with 5% and 30%. The duration of the CO_2 absorption increases with the increase in the light transmission rate under shading; CO_2 absorption occurs at 9:00 a.m. under shading with a light transmission rate of 5% to 15%, but occurs longer at 7:00 to 9:00 a.m. with a light transmission rate of 20%. The CO_2 saturation point is 600 ppm, and the compensation point is 130 ppm. The respiration rate increases with temperature increase. Especially for ginseng, the efficiency of the optimum photosynthesis is not influenced by either the temperature or the light intensity alone, but also by the interactions of the two factors [3].

Hyun et al. [4] reported that the photosynthetic capacities differed depending on the light intensity and the ginseng leaf temperature, which showed the maximum CO_2 absorption at a light intensity of 250 μmol $m^{-2}s^{-1}$ and a leaf temperature of 18°C, which was optimal for photosynthesis. Lee et al. [5] reported that, in their study to compare the photosynthetic characteristics of *P. ginseng* and *P. quinquefolium*, the optimum temperature for photosynthesis and the light saturation point were similar, at around 20°C and 15,000 Lux, respectively. The photosynthesis rate in *P. quinquefolium* (7.8 mg [CO_2/dm^2/h]) was higher than in *P. panax* (6-7 mg [CO_2/dm^2/h]), though. In the examination of photosynthetic characteristics by Lee [6], the light saturation point and the optimum temperature for photosynthesis were similar at around 15,000 Lux and 20°C in all the tested ginseng varieties and/or lines (Chunpoong, Yunpoong, Gopoong, and Jakyungjong). The net photosynthetic rates, however, were 6.0 mg (CO_2/dm^2/h) for Yunpoong, 5.0 mg (CO_2/dm^2/h) for Chunpoong, and 5.0 mg (CO_2/dm^2/h) for Gopoong, which were somewhat higher than the 4.5 mg (CO_2/dm^2/h) in Jakyungjong. Under the controlled light intensity of 500 μmol $m^{-2}s^{-1}$ in Jakyungjong, the net photosynthesis rate, stomatal conductance, and intercellular CO_2 concentration at different growth stages showed that all these parameters were related to the increase in the net photosynthesis rate in August rather than in July [7]. Oh et al. [8] reported that the net photosynthesis rate and stomatal conductance were higher in the front and middle rows than in the rear rows of ginseng beds, regardless of the ginseng growth stage. All these show that the net photosynthesis rate in ginseng is related to environmental conditions, shading materials, and cultivation methods, and these suggest that proper ginseng growth should be governed by cultural conditions for the plant's optimum net photosynthesis.

In this study, the net photosynthesis rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate in selected ginseng lines that were resistant and susceptible to high temperature injury (HTI) were examined during their cultivation in the hot-temperature season (July to August) to provide basic information on the photosynthetic characteristics of the ginseng lines.

MATERIALS AND METHODS

Experiments were conducted in the experiment fields of the Natural Resources Research Institute of Korea Ginseng Corporation in Boeun, Korea, using ginseng varieties and/or lines that were resistant (Yunpoong, HTIR 1, HTIR 2, and HTR 3) and susceptible (Chunpoong) to HTI. On March 5, 2008, one-year-old seedling roots of these ginseng lines were transplanted in the main experiment field at a density of 54 plants (6 columns × 9 rows) in a 1.62 m^2 plot, and were cultivated under a shading sheet with a light transmission rate of 20% (80% shade). A two-layered black polyethylene net was not additionally installed during the 2- to 3-year ginseng growth. Photosynthetic parameters such as the net photosynthesis rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate were measured twice, on July 11 and August 14, 2009, with an LI 6400 Portable Photosynthesis System (Li-Cor, Lincoln, NE, USA) using the same leaves in the third rows of the plots. The conditions inside the leaf chamber were controlled by an air influx rate of 500 μmol s^{-1}, a CO_2 concentration of 400 $μmol^{-1}$, a relative humidity of 30% to 40%, and a temperature of 20°C. To examine the effects of the light intensity on the photosynthetic parameters, they were measured by adjusting the photosynthetically active radiation to 0, 200, 400, 600, and 800 μmol $m^{-2}s^{-1}$ using an LI-6400-02 LED light source (LI-COR).

RESULTS AND DISCUSSION

The net photosynthesis rates in the HTI-resistant and -susceptible ginseng lines increased with the increase in the light intensity and peaked at the light intensity of 200 μmol $m^{-2}s^{-1}$, without a significant increase in the net pho-

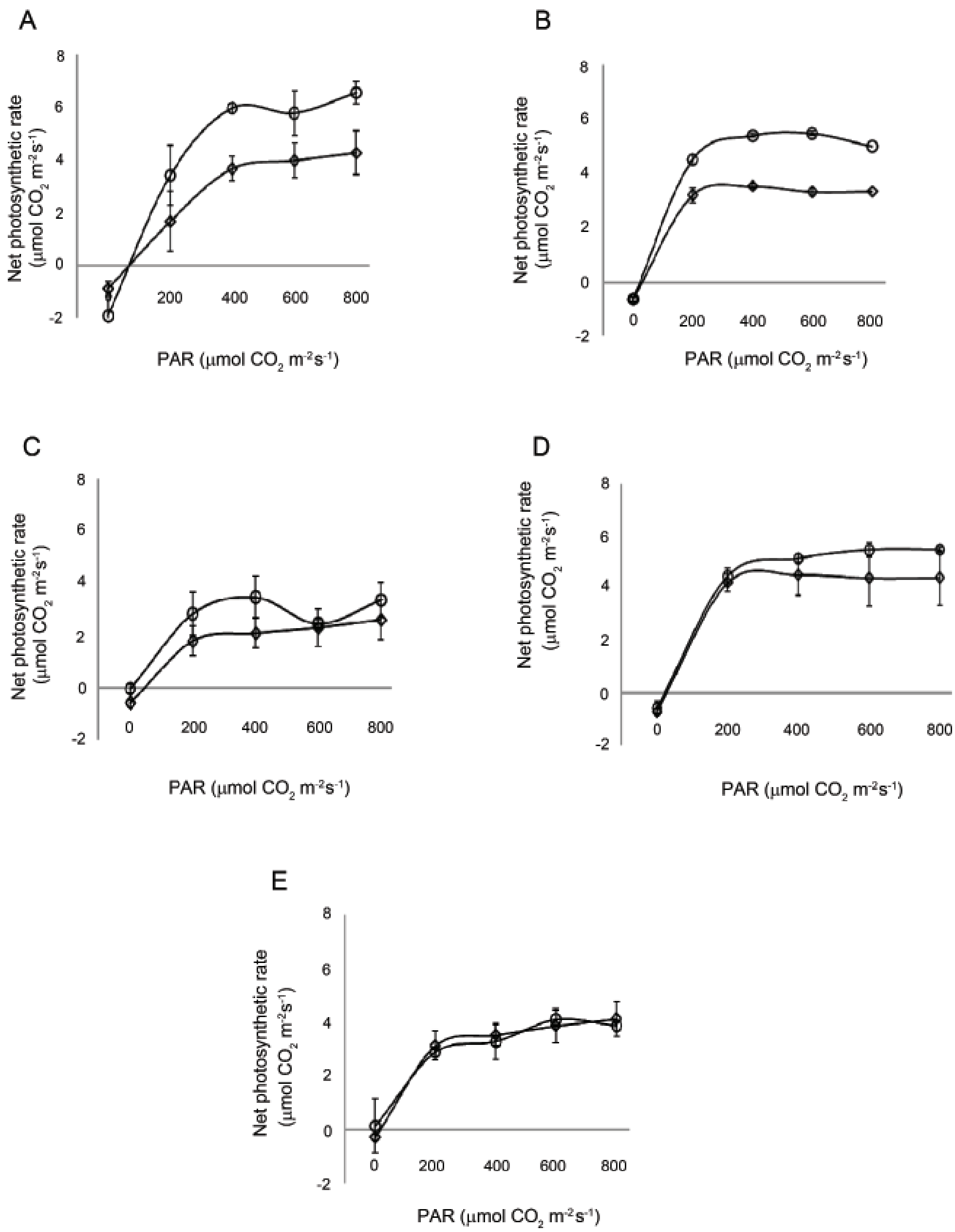

Fig. 1. Monthly net photosynthesis rates in the high temperature injury-resistant (A: Yunpoong, B: HTIR 1, C: HTIR 2, and D: HTIR 3), susceptible (E: Chunpoong) lines. The bars represent the means±SE (*n*=3). Investigation days: ◇ 11 July, ◯ 18 August). PAR, photosynthetically active radiation.

tosynthesis rate with the increased light intensity except in Yunpoong, which suggests that it is the light saturation point (Fig. 1). The light saturation point in Yunpoong was around 400 μmol $m^{-2}s^{-1}$. These results are consistent with those of previous studies [7-9], in which the light intensity for optimum net photosynthesis was around 200 to 400 μmol $m^{-2}s^{-1}$ and the light saturation point in Yunpoong was 400 μmol $m^{-2}s^{-1}$, whereas that for the other HTI-resistant and -susceptible Chunpoong was 200 μmol $m^{-2}s^{-1}$. Among the ginseng lines with the same light saturation point of 200 μmol $m^{-2}s^{-1}$, the net photosynthesis rate at the light intensity of 200 μmol $m^{-2}s^{-1}$ in July was highest in HTIR 3 (4.2 μmol CO_2 $m^{-2}s^{-1}$) and lowest in HTIR 1 (3.2 μmol CO_2 $m^{-2}s^{-1}$), Chunpoong (3.1 μmol CO_2 $m^{-2}s^{-1}$), and HTIR 2 (1.9 μmol CO_2 $m^{-2}s^{-1}$), in that order. The net photosynthesis rate at the light saturation point in July was 3.7 μmol CO_2 $m^{-2}s^{-1}$ in Yunpoong, with a light saturation point of 400 μmol $m^{-2}s^{-1}$. In August, the net photosynthesis rate at the light intensity of 200 μmol $m^{-2}s^{-1}$ was highest in HTIR 1 and HTIR 3 (4.5 μmol CO_2

$m^{-2}s^{-1}$) among the ginseng lines with the light saturation point of 200 μmol $m^{-2}s^{-1}$, and was similar in Chunpoong (2.9 μmol CO_2 $m^{-2}s^{-1}$) and HTIR 2 (2.8 μmol CO_2 $m^{-2}s^{-1}$). The net photosynthesis rate at the light saturation point in August was 5.9 μmol CO_2 $m^{-2}s^{-1}$ in Yunpoong, with a light saturation point of 400 μmol $m^{-2}s^{-1}$. In the HTI-resistant ginseng (Yunpoong and HTIR 1), the net photosynthesis rate in August increased remarkably compared to that in July, and only slightly increased in the other HTI-resistant lines (HTIR 2 and HTIR 3). On the other hand, no or little difference in the net photosynthesis rate was noted in the HTI-susceptible variety (Chunpoong) between July and August. These results indicate that photosynthesis may occur more readily at a high temperature in the HTI-resistant ginseng lines than in the HTI-susceptible lines whose photosynthesis rates between July and August did not differ. HTI occurs on ginseng plants that grow under a shade in which the canopy temperature remains at over 30°C for about a week [10]. The net photosynthesis rate in the HTI-resistant ginseng lines is not expected to decrease significantly at this temperature, however, because it was confirmed that the photosynthesis rate increased during the hot season. An [7] reported that the photosynthesis rate under the light intensity of 500 μmol $m^{-2}s^{-1}$ increased in August rather than in July, regardless of the shading material such as the shading sheet, polyethylene net, and rice straw. This is consistent with the results of the authors' study in which the photosynthesis rate was higher in August than in July at the light intensity of 200 μmol $m^{-2}s^{-1}$. On the other hand, Oh et al. [8] reported that the net photosynthesis rate in three-year-old Jakyungjong was highest in June and decreased thereafter toward July and August, regardless of the planting position (row). This seems to be similar to the result of the authors' study that the photosynthesis rate did not increase in August, unlike in July, in the HTI-susceptible variety (Chunpoong).

The changes in the stomatal conductance due to the light intensity are shown in Fig. 2. Among the ginseng lines with a light saturation point of 200 μmol $m^{-2}s^{-1}$, the stomatal conductance at the light intensity of 200 μmol $m^{-2}s^{-1}$ in July was highest (0.055 mol H_2O $m^{-2}s^{-1}$) in HTIR 3, and decreased in Chunpoong (0.037 mol H_2O $m^{-2}s^{-1}$), HTIR 1 (0.031 mol H_2O $m^{-2}s^{-1}$), and HTIR 2 (0.017 mol H_2O $m^{-2}s^{-1}$), in that order. In Yunpoong, which had a light saturation point of 400 μmol $m^{-2}s^{-1}$, the stomatal conductance at the light intensity of 400 μmol $m^{-2}s^{-1}$ in July was 0.038 mol H_2O $m^{-2}s^{-1}$. The stomatal conductance at the same light intensity of 200 or 400 μmol $m^{-2}s^{-1}$ was significantly higher in HTIR 1 (0.075 mol H_2O $m^{-2}s^{-1}$), HTIR 3 (0.070 mol H_2O $m^{-2}s^{-1}$), and Yunpoong (0.106 mol H_2O $m^{-2}s^{-1}$) in August than in July. No significant difference was noted in the stomatal conductance values in the HTI-resistant HTIR 2 line (0.023 mol H_2O $m^{-2}s^{-1}$) and the HTI-susceptible Chunpoong (0.047 mol H_2O $m^{-2}s^{-1}$) between July and August. The stomatal conductance is similarly elevated with the increase in the net photosynthesis rate, which is enhanced up to the light saturation point and sustained thereafter in the stationary phase [7,8,11]. On the other hand, the stomatal conductivity in *Chloranthus glaber* continued to increase steadily above the light saturation point [12].

The intercellular CO_2 concentration influenced by the light intensity is related to the stomatal opening and closing; the lowered intercellular CO_2 concentration causes the entry of K^+ and water into the guard cells from the mesohphyll cells, as a result of which the stoma opens so that the leaves absorb the atmospheric CO_2 that is used for photosynthesis. Among the ginseng lines with a light saturation point of 200 μmol $m^{-2}s^{-1}$, the intercellular CO_2 concentration in July decreased most significantly to 139 μmol mol^{-1} in HTIR 2, and increased in HTIR 1 (217 μmol mol^{-1}), Chunpoong (251 μmol mol^{-1}), and HTIR 3 (257 μmol mol^{-1}), in that order (Fig. 3). In Yunpoong that had a light saturation point of 400 μmol $m^{-2}s^{-1}$, the intercellular CO_2 concentration decreased to 225 μmol mol^{-1} in July. Among the ginseng lines with the light saturation point of 200 μmol $m^{-2}s^{-1}$, the intercellular CO_2 concentration in August decreased most significantly to 185 μmol mol^{-1} in HTIR 2 and increased in HTIR 3 (274 μmol mol^{-1}), Chunpoong (276 μmol mol^{-1}), and HTIR 1 (278 μmol mol^{-1}), in that order. In Yunpoong that had a light saturation point of 400 μmol $m^{-2}s^{-1}$, the intercellular CO_2 concentration decreased to 282 μmol mol^{-1} in August. These results indicate that the CO_2 concentration at the light saturation point decreases more significantly in HTI-resistant ginseng lines than in HTI-susceptible ginseng line. This is probably because the HTI-resistant ginseng lines sustain photosynthesis even at above 25°C, thus depriving the intercellular spaces of CO_2 for photosynthesis, whereas photosynthesis is inhibited beyond such temperature in HTI-susceptible ginseng line.

The changes in the transpiration rate according to the light intensity are shown in Fig. 4. The transpiration rate in July was 0.83-0.96 mol H_2O $m^{-2}s^{-1}$ in Yunpoong, 0.50-0.52 mol H_2O $m^{-2}s^{-1}$ in HTIR 1, 0.27-0.65 mol H_2O $m^{-2}s^{-1}$ in HTIR 2, 0.85-1.03 mol H_2O $m^{-2}s^{-1}$ in HTIR 3, 0.51-0.56 mol H_2O $m^{-2}s^{-1}$ in Chunpoong, respectively. The transpiration rate in August was 1.79-2.10 mol H_2O $m^{-2}s^{-1}$ in Yunpoong, 1.67-1.78 mol H_2O $m^{-2}s^{-1}$ in HTIR 1, 0.84-

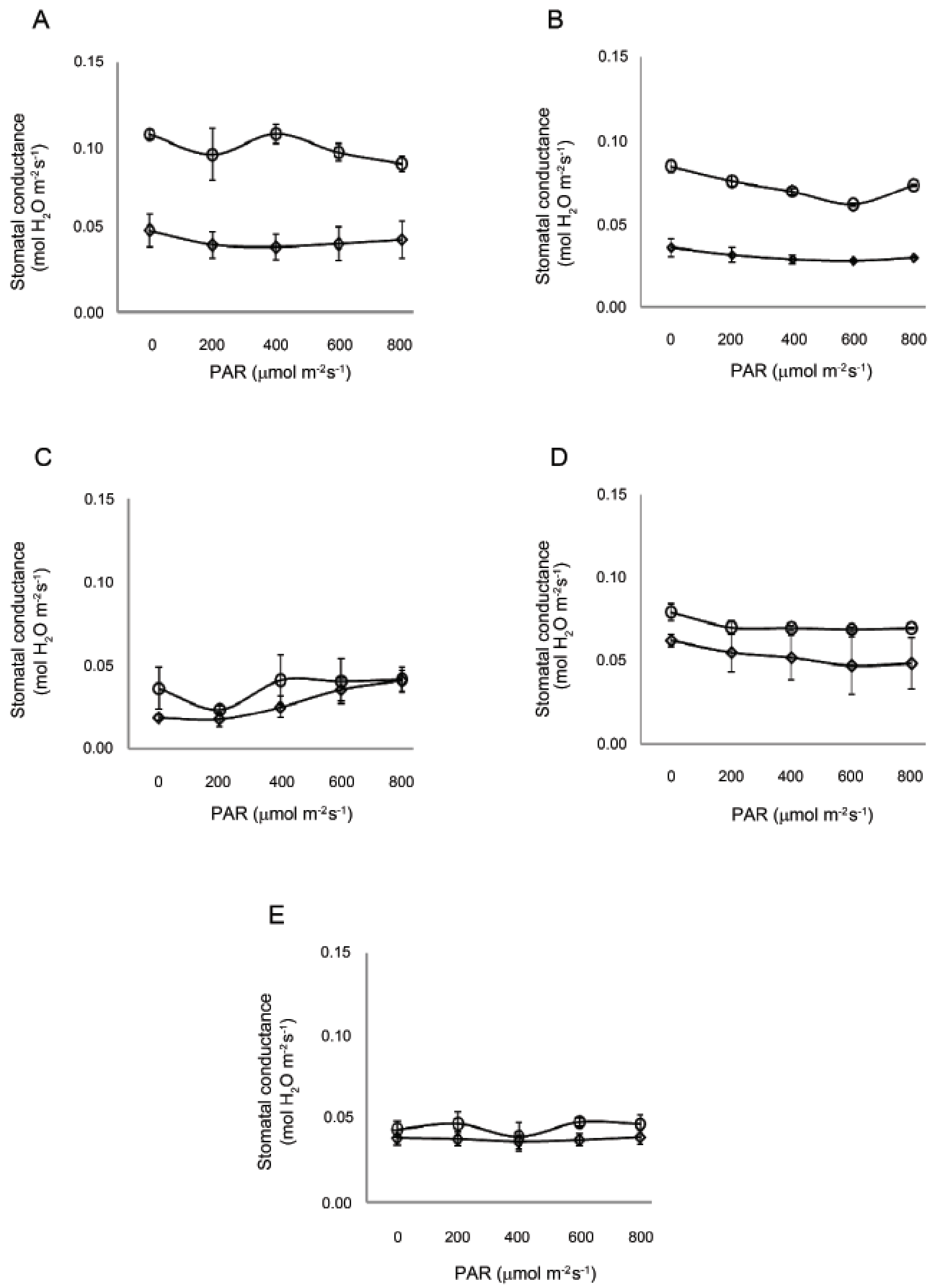

Fig. 2. Monthly stomatal conductance in the high temperature injury-resistant (A: Yunpoong, B: HTIR 1, C: HTIR 2, and D: HTIR 3), susceptible (E: Chunpoong) lines. The bars represent the means±SE (*n*=3). Investigation days: ◇ 11 July, ○ 18 August). PAR, photosynthetically active radiation.

1.02 mol H_2O $m^{-2}s^{-1}$ in HTIR 2, 1.47-1.65 mol H_2O $m^{-2}s^{-1}$ in HTIR 3, 1.15-1.35 mol H_2O $m^{-2}s^{-1}$ in Chunpoong. These results show that the transpiration rates in all the tested ginseng lines were higher in August than in July, except in Yunpoong and HTIR 3, in which the transpiration rate was high both in July and August. The transpiration rate was increased remarkably in August in HTIR 1 but only slightly in HTIR 2. In Chunpoong, the transpiration rate was also higher in August than in July, but was not as high as in the HTI-resistant lines. The higher increase in the transpiration rate in August than in July may be related to the cooling of the ginseng leaves under the shade with a high canopy temperature due to the evaporation of water molecules from the surface openings (stomata) [7].

In this study, it was confirmed that the light saturation point in Yunpoong was 400 μmol $m^{-2}s^{-1}$, and 200 μmol

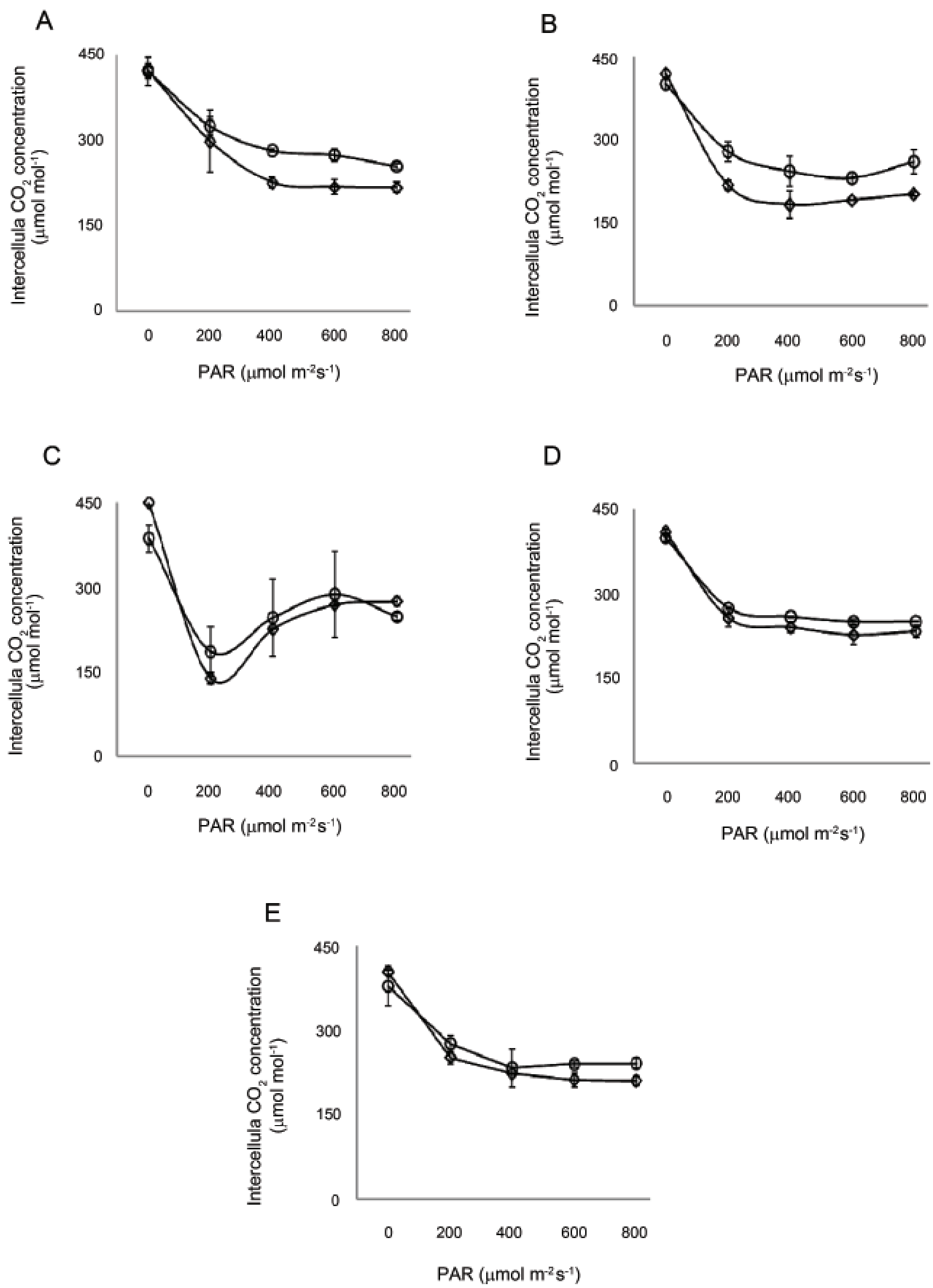

Fig. 3. Monthly intercellular CO_2 concentration in the high temperature injury- resistant (A: Yunpoong, B: HTIR 1, C: HTIR 2, and D: HTIR 3), susceptible (E: Chunpoong) lines. The bars represent the means±SE (*n*=3). Investigation days: ◇ 11 July, ○ 18 August). PAR, photosynthetically active radiation.

$m^{-2}s^{-1}$ in the other tested ginseng lines. These suggest that to properly growth the ginseng plant in Yunpoong, the net photosynthesis rate there should be enhanced by increasing the light transmission rate there before the hot season. Lee [6] reported that the net photosynthesis rate was highest in Yunpoong among the ginseng cultivars, presumably because of its more efficient CO_2 exchange ability due to the greater stomatal distribution on its leaves, even though they were smaller than those in the other ginseng lines. Also, Yunpoong has a large leaf area per plant because of its many leaflets, so it could efficiently produce organic materials (by photosynthesis), unlike other ginseng varieties and/or lines, which contributes to its heavier ginseng root weight. Plant respira-

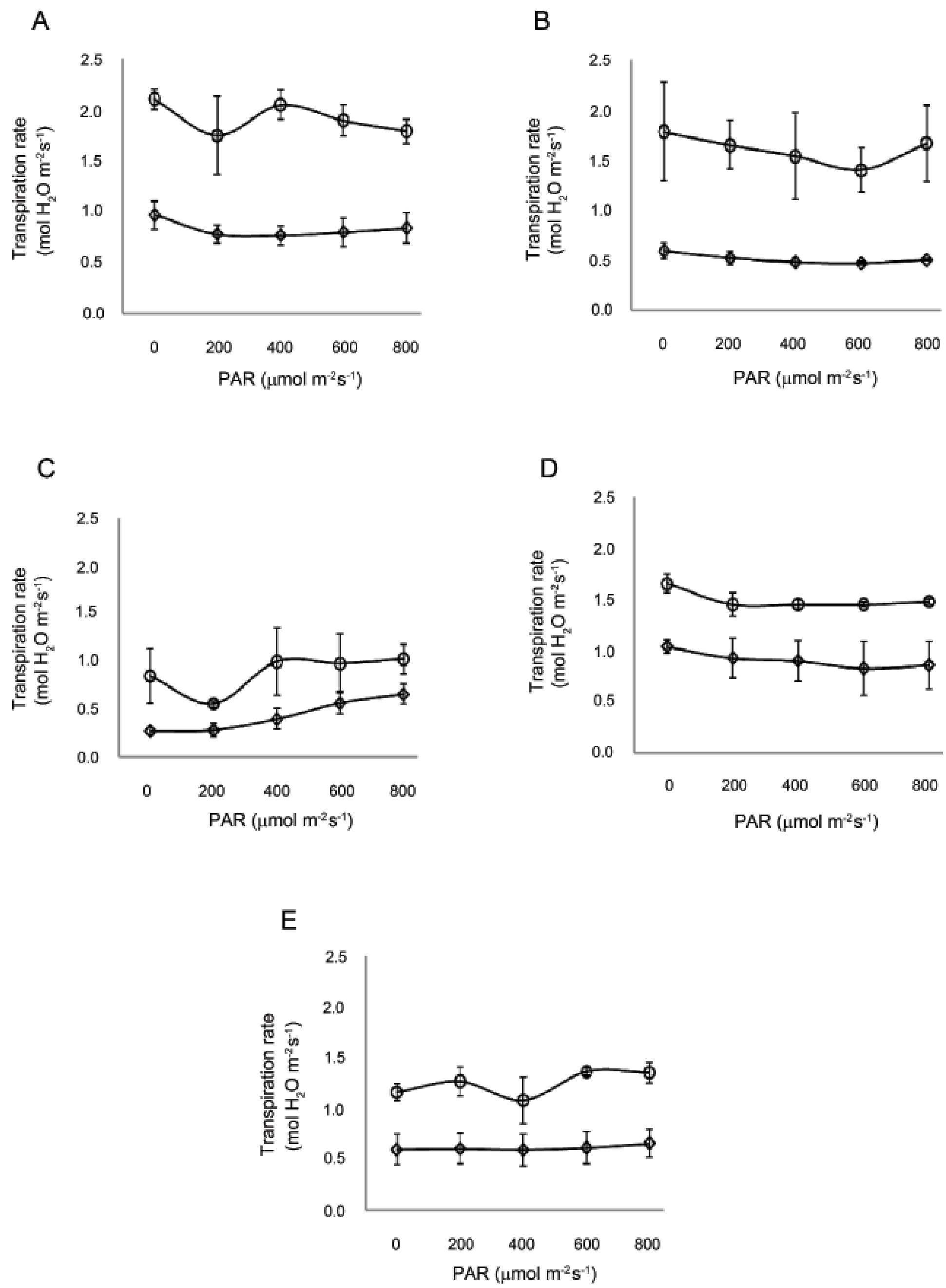

Fig. 4. Monthly transpiration rates in the high temperature injury-resistant (A: Yunpoong, B: HTIR 1, C: HTIR 2, and D: HTIR 3), susceptible (E: Chunpoong) lines. The bars represent the means±SE (*n*=3). Investigation days: ◇ 11 July, ○ 18 August). PAR, photosynthetically active radiation.

tion involves the oxidation of organic materials such as carbohydrates to produce chemical energy, which is used for growth respiration and maintenance respiration for the plant's growth and survival, respectively. Especially, the remarkable increase in the maintenance respiration due to the excessive development of non-photosynthesizing organs such as stems decreased the plant yield [13]. Yunpoong is a ginseng variety with multiple stems attached to numerous leaflets that overlap, so they receive insufficient light for full photosynthesis. This may lead to the poor accumulation of nutritional substances, which has been suggested as one of the reasons why Yunpoong has a high percentage of inside cavities in the red ginseng that is manufactured from raw ginseng [14].

Lee et al. [10] and Lee et al. [15] reported that the relative light maximum in the HTI-resistant ginseng lines used in this study increased more significantly in August than in July, but decreased in the HTI-susceptible such as Chunpoong. The maximum relative light is high with low photo inhibition in the HTI-resistant ginseng lines, and low with high photo inhibition in Chunpoong, which inhibit photosynthesis. Also, the distribution of cuticle layers, thickness of cuticles on adaxial and abaxial surfaces, and longitudinal stomatal lengths are more profoundly developed on the lines resistance such as HTIR 1, 2 and 3 than on the susceptible line Chunpoong.

In this study, the net photosynthesis rate of the HTI-resistant line HTIR 2 was lower in July and slightly higher in August than in Chunpoong; but the decrease in the intercellular CO_2 concentration in HTIR 2 was fastest among the tested ginseng lines. This suggests that this ginseng line may utilize atmospheric CO_2 most efficiently under continuous irradiation of the optimum light intensity, thus preventing transpiration via stomatal closing due to the increase in the intercellular CO_2 concentration with the irradiation of excessive light intensity. Therefore, all these results can be used to provide basic information for the selection of HTI-resistant ginseng lines and the application of cultural practices that promote the efficient growth of ginseng lines based on their photosynthetic characteristics.

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