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Comparison of Interior Canopy Air Temperature and Humidity among Sugar Beet Genotypes (*Beta vulgaris* ssp. *vulgaris*)

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Abstract

We investigated differences in interior canopy microclimate between first filial generation (F_1) plants and their parental lines. Our findings suggested genotype-dependent variations in the interior canopy air temperature (T_{a_in}), interior canopy relative humidity ($RH_{_in}$), and interior canopy vapor pressure deficit ($VPD_{_in}$). The magnitude and patterns of these differences varied annually and seasonally, with F_1 plants demonstrating lower T_{a_in}, higher $RH_{_in}$, and lower $VPD_{_in}$ than their parental lines. Similarly, we investigated the interior canopy absolute humidity ($AH_{_in}$) and interior canopy humidity deficit ($HD_{_in}$). $AH_{_in}$ showed no clear difference between the F_1s and parental lines, but the F_1 plants exhibited a lower $HD_{_in}$. Consequently, heterosis may have indirectly influenced sugar beet growth. We hypothesized that these microclimatic factors were associated with differences in the leaf area index (*LAI*) among genotypes. We assessed the relationships between *LAI* and T_{a_in}, $AH_{_in}$, and $HD_{_in}$ and found a significant correlation ($p < 0.05$) between $HD_{_in}$ and *LAI* at 78 d after transplanting (DAT), but not for T_{a_in} ($p = 0.11$) or $AH_{_in}$ (*ns*) at 79-81 DAT in 2017. No significant relationships were observed between any of these parameters at 97-99 DAT in 2018; however, T_{a_in} showed a slight correlation ($p = 0.12$). Two factors may explain this year-to-year difference. First, the *LAI* at 97 DAT in 2018 was lower than that at 78 DAT in 2017, suggesting differences in canopy closure, which likely made vertical exchange easier in 2018. Second, it is possible that wind speeds differed on the observation days. Analysis of wind speeds during the same period suggested that the average wind speed in 2018 was higher than that in 2017. Further research is required to explore the interrelationships among the other factors.

Discipline: Agricultural Environment
Additional key words: relative humidity, F_1 plants

Introduction

Sugar beet is cultivated worldwide. In Japan, it is a regional specialty crop suitable for cooler regions and primarily grown in eastern Hokkaido, where it contributes significantly to the local economy by providing employment in related industries. However, global warming and other climate-change-related events are expected to substantially affect land use in Hokkaido (Usui et al. 2021a). For example, in 2010, the temperature anomaly was +2.3°C in summer (June-August), heavy rainfall occurred in July and August (198% and 116% of normal, respectively), and unusually low temperatures occurred in early spring (–0.8 °C and –0.5 °C deviation from the 1971-2000 mean in April and May, respectively) (Hirota et al. 2011). Takahashi et al. (2011) reported that total sugar production in Hokkaido during a 2010/11 campaign was 466,487 t from a total field area of 62,559 ha, which was the lowest yield in 25 years, with an average yield of 49.4 t/ha roots and a 15.3% sugar content. Three factors likely contributed to this low yield. The first is delayed growth caused by low temperatures in the early stage (i.e., late April-early May). The second is widespread and severe outbreaks of two major diseases, *Cercospora* leaf spot and *Aphanomyces* root rot, caused by high temperatures from the middle of June to

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harvesting time (beginning of October) and a large amount of rainfall. The third was the low sugar content caused by the high minimum temperature, which continued until harvest time. These authors emphasized the need to develop sugar beet varieties with tolerance to both high and low temperatures, and resistance to various pests, diseases, and extreme weather. Kajiyama (2011) noted that, while global warming may increase yields (i.e., root weight), high temperatures after summer could significantly reduce the sugar content. Furthermore, the onset of diseases, such as *Cercospora* leaf spot and *Aphanomyces* root rot, along with increased feeding damage by armyworms, is expected to occur earlier and more frequently in sugar beets under global warming. Iketani (2024) reported that extremely high temperatures led to a significant *Cercospora* leaf spot outbreak, which would have affected the sugar content in 2023.

One focus of sugar beet breeding in Japan has been the development of stable varieties that are resistant to major diseases, high temperatures, and humidity (Taguchi 2017). The development of varieties that can respond to climate change is a critical research priority. Breeding sugar beet varieties involves a three-way hybrid system that effectively utilizes hybrid vigor (heterosis). This approach produces hybrids between lines that exhibit superior performance and lines of different lineages, thereby selecting hybrids with the optimal productivity and other desirable traits (Taguchi et al. 2006).

Clarifying the genetic relationship between the first filial generation (F_1) and its parental plants is crucial for efficient variety development. In addition, indices are required to select varieties and lines adapted to environmental changes (Usui et al. 2021a). Therefore, development of novel selection and cultivation methods is required. Previous studies focused on the canopy surface temperature using proximity sensing, which is a key parameter in understanding crop physiology. Previous studies have evaluated the effects of the canopy surface temperature on crop transpiration and gas diffusion resistance (Homma et al. 1999, Homma & Shiraiwa 2009). Differences between the canopy surface and air temperatures have been used to validate drought avoidance estimates (Idso et al. 1977; Blum et al. 1982, 1989; Stark et al. 1991; Rashid et al. 1999; Fukuoka et al. 2003, 2006). Variations in canopy surface temperatures among sugar beet genotypes have also been reported (Usui et al. 2020a, 2021b, 2022). To understand the factors causing these variations, in previous studies we measured stomatal conductance in several sugar beet genotypes and found differences between them (Usui et al. 2020a, 2021a, 2021b, 2022). These differences between genotypes can be used for selection and disease detection during plant variety development (Usui et al. 2021a). Canopy surface temperature can be continuously and remotely measured using infrared thermometers and thermal imaging cameras.

In contrast, the recently developed integrated micrometeorology model (IM^{2}PACT) for rice can estimate panicle temperature, leaf temperature, inside canopy temperature, and relative humidity (*RH*) from microclimate data above the canopy (Yoshimoto et al. 2011, Yoshimoto 2020). Maruyama et al. (2023) and Kuwagata et al. (2024) formulated a model that estimates dew formation in rice plant canopies using a theoretical method based on a one-layer energy-balance model; however, these values are not based on observational data in the interior canopy, and varietal differences have not been confirmed.

Sugar beets are particularly suited to cooler climates and are more difficult to grow when higher air temperatures occur more frequently during the growing season. In addition to high air temperatures, high *RH* may also increase the risk of *Cercospora* leaf spot infection in sugar beets. In the United States of America the daily infection index (DIV) model was developed using meteorological data (Shane & Teng 1984, 1985); however, the interior canopy microclimate is estimated using meteorological observation data. Ikeda (2004) investigated *Cercospora beticola* dispersal in sugar beet fields and found that spores were trapped at a 10-cm height before an outbreak; however, 16 d after the outbreak, the spores were trapped at a 20-cm height, reflecting the dispersal of spores from lesions on sugar beet leaves. Because the 20-cm zone from the ground surface is within the sugar beet canopy, it is necessary to further clarify the details of the canopy interior microclimate environment. Therefore, it is important to comprehensively examine air temperature (T_a) and *RH* around the canopy. However, to the best of our knowledge, no previous studies have examined interior canopy microclimate environments based on detailed observations. Considering previous studies (Usui et al. 2020a, 2021a, 2021b, 2022), there may be differences in the interior canopy microclimate among genotypes because several sugar beet genotypes have differences in plant architecture and physiological properties.

In this study, we performed temporal measurements of the interior canopy air temperature (T_{a_in}) and *RH* for six genotypes, comprising three F_1s and their parents, during the 2017 and 2018 sugar beet growing seasons in Hokkaido. We assessed differences in the interior canopy microclimate between the F_1s and their parents.

Materials and methods

1. Site description and growing conditions

Field experiments were performed at the Memuro Experiment Station of the Hokkaido National Agricultural Research Center (NARO/HARC) in 2017 (42° 88′ N, 143° 05′ E; 110-m above sea level) and 2018 (42° 88′ N, 143° 07′ E; 99-m above sea level) in Memuro, eastern Hokkaido, Japan. In 2017 and 2018, subsoil plowing (approximately 50 cm) and harrowing (approximately 30 cm) of the Andosol soil were performed in mid-October of the previous year. We prepared the field in mid-April in 2017 and 2018, and applied fertilizers in late April for all plots at rates of 15.0 g m^{-2} nitrogen (N), 31.5 g m^{-2} phosphorus pentoxide (P_2O_5), and 21.0 g m^{-2} potassium oxide (K_2O). The experiment was conducted in five replicates with a 60-cm row width, 22.5-cm row spacing, 6.75-m row length, and two rows per plot, using a randomized block design. We measured the T_{a_in} and relative humidity ($RH_{_in}$) in one of these plots (no replication), and conducted growth surveys in four replicates of the productivity test plot.

Six genotypes, comprising three F_1s and their parents, were developed by NARO/HARC in Japan. The three inbred lines were NK-195BRmm-O (high yield combining ability), NK-235BRmm-O (high sugar content), and NK-388mm-O (disease resistance). These lines were self-fertilized for more than six generations to increase the degree of genetic fixation. The genotypes NK195BR, NK235BR, and NK388 were used as experimental materials. Three F_1s were obtained using the genotype combinations of NK195BR×NK388, NK235BR×NK195BR, and NK235BR×NK388.

Seeds were sown in paper pots (19-mm diameter and 13-cm height; Nippon Beet Sugar Mfg. Co., Ltd., Tokyo, Japan) on March 16, 2017 and March 15, 2018. One month later (April 25, 2017, and April 26, 2018, respectively), the seedlings were transplanted to the field.

Meteorological data (T_a, RH, total solar radiation [SR], and precipitation) were collected at the weather station of the HARC Memuro Research Station, located at the same site as the experimental field. The shortest distances between the weather station and experimental field were approximately 2,200 m in 2017 and 650 m in 2018.

The vapor pressure deficit (VPD [hPa]), absolute humidity (AH [g m^{-3}]), and humidity deficit (HD [g m^{-3}]) were calculated using the following equations:

$$VPD = \left(1 - \frac{RH}{100}\right) \times e_{\mathrm{sat}}(T_{\mathrm{a}}), \quad (1)$$

$$AH = \left(\frac{217 \times e_{\mathrm{sat}}(T_{\mathrm{a}})}{273.15 + T_{\mathrm{a}}}\right) \times \left(\frac{RH}{100}\right), \ and \quad (2)$$

$$HD = (100 - RH) \times \left(\frac{217 \times e_{\mathrm{sat}}(T_{\mathrm{a}})}{273.15 + T_{\mathrm{a}}}\right) / 100, \quad (3)$$

where RH is the relative humidity (%), e_{sat} (T_{a}) is the saturated water vapor pressure (hPa), and T_a is the air temperature (°C).

e_{sat} (T_{a}) was calculated as previously described (Tetens 1930):

$$e_{\mathrm{sat}}(T_{\mathrm{a}}) = 6.1078 \times 10^{\frac{7.5 \times T_{\mathrm{a}}}{237.3 + T_{\mathrm{a}}}}. \quad (4)$$

2. Measurement of T_{a_in} and $RH_{_in}$

Interior canopy air temperature ($Ta_{_in}$) and relative humidity ($RH_{_in}$) were measured. Interior canopy vapor pressure deficit ($VPD_{_in}$), absolute humidity ($AH_{_in}$), and humidity deficit ($HD_{_in}$) were calculated using Equations (1)-(4). To measure T_{a_in} and $RH_{_in}$, we installed a temperature and humidity sensor (HMP60; Vaisala, Helsinki, Finland) inside a forced ventilation tube, as described by Okada & Nakamura (2010) and Usui (2024). The sensors were placed between each genotype row, such that the intake port was set at a 10-cm height above the soil surface. Temperature and humidity were measured every 10 s using a data logger (CR1000; Campbell Scientific, Inc., Logan, UT, USA) and recorded as average values over 10 min. The measurement period was from June 10, 2017 (46 days after transplanting [DAT]) to September 19, 2017 (147 DAT), and from May 30, 2018 (34 DAT) to September 19, 2018 (146 DAT).

3. Growth survey

Plant length and the total number of leaves were measured using the method described by Usui et al. (2020b). Briefly, in the test plots where productivity tests were conducted (4 replicates), 10 individuals (5 individuals per row, excluding those that died during the growth survey period) were selected for each replicate, and the same individuals were continuously monitored approximately once per week for approximately 5 months from the start of measurement after transplanting. The plant length was measured as the distance from the ground to the tip of the longest mature leaf. The total number of leaves refers to the total number of true leaves that emerged during the growth period, rather than the number of leaves remaining at the time of measurement.

For each surveyed plant, all leaves that emerged a few days after transplanting were numbered with markers, and the number of the newest true leaves was counted on the survey date.

The leaf area index (*LAI*) was measured using a portable photosynthetically active radiation sensor (AccuPAR LP-80; Decagon Devices Inc., now METER Group, Inc., Pullman, WA, USA) as the canopy analyzer. Measurements began on June 6, 2017 (42 DAT) and May 29, 2018 (33 DAT). The sensor was configured for two rows per plot, with measurements taken at two locations within each plot. Measurements were taken approximately once per week in 2017 and once every 10 d in 2018 (note: surveys were not conducted during some weeks due to weather conditions).

4. Statistical analysis

Statistical analysis was performed using one-way analysis of variance, in which genotypes were treated as the main factor. Regarding statistical significance levels, $p < 0.001$ indicated significance at the 0.1% level, $p < 0.01$ indicated significance at the 1% level, $p < 0.05$ indicated significance at the 5% level, and *ns* indicated no significant difference. Additionally, Scheffé's method ($p < 0.05$) was used to test for significant differences between groups of F_1s and their parental lines (Ps) using R version 4.3.3 (2020-10-10) (R Core Team 2020).

Results

1. Weather overview from April to August in 2017 and 2018

The monthly mean values of T_a, *RH*, *SR*, and monthly precipitation from April to August in 2017 and 2018 are presented in Table 1.

In April, June, and August 2017, the monthly mean T_a values were 0.8, 0.3, and 0.1°C lower than those in 2018, respectively. However, in May and July 2017, monthly mean T_a values were 1.1 and 2.4°C higher, respectively, than those in 2018 for the same period. As a result, the mean T_a in 2017 was 0.4°C higher than that in 2018. The monthly mean *RH* in 2018 was slightly higher than that in 2017, whereas the monthly mean *RH* in August 2017 was significantly higher than that in 2018. The monthly mean *SR* in 2017 was higher than that in 2018, with a value of approximately 8%. In June and July 2017, the monthly mean *SR* was approximately 13% and 35% higher, respectively, than those in 2018.

2. Plant growth

We selected three consecutive days that exhibited typical diurnal variations in T_{a_in} and $RH_{_in}$ during the measurement period. For example, we examined three consecutive days, from July 13, 2017 (79 DAT) to July 15, 2017 (81 DAT), and from August 1, 2018 (97 DAT) to August 3, 2018 (99 DAT).

The growth status at the time of measurement, as well as the plant length, leaf number, and *LAI* on July 12, 2017 (78 DAT) and August 1, 2018 (97 DAT) are shown in Figure 1. The plant lengths of the six genotypes ranged from 46 cm to 70 cm in 2017 and from 48 cm to 71 cm in 2018. Plant length differed significantly among genotypes ($p < 0.001$), and that of F_1s was greater than that of Ps ($p < 0.001$) in both years (Figs. 1a, b). Leaf numbers ranged from 30 to 39 in 2017 and from 36 to 44 in 2018. The leaf number differed significantly among genotypes ($p < 0.001$), however F_1s and Ps showed no significant difference in either year (Figs. 1c, d). The *LAI* ranged from 2.8 to 3.9 in 2017 and from 2.3 to 3.4 in 2018. The *LAI* differed significantly among genotypes ($p < 0.01$), and significant differences were observed between F_1s and Ps ($p < 0.01$ in 2017 and $p < 0.05$ in 2018) (Figs. 1e, f).

Table 1. Monthly mean air temperature, monthly mean relative humidity, monthly mean total solar radiation, and monthly precipitation from April to August in 2017 and 2018

Month / year	Monthly mean air temperature (°C)		Monthly mean relative humidity (%)		Monthly mean total solar radiation (MJ m^{-2} day^{-1})		Monthly precipitation (mm)	
	2017	2018	2017	2018	2017	2018	2017	2018
April	5.6	6.4	68.6	67.2	18.8	18.0	63	39
May	12.9	11.8	70.1	73.3	18.1	18.6	68	122
June	14.3	14.6	80.6	81.2	17.7	15.6	159	105
July	21.3	18.9	80.8	88.2	18.0	13.3	89	157
August	18.5	18.6	84.8	83.7	12.6	13.1	38	197
Mean	14.5	14.1	77.0	78.7	17.0	15.7	83	124

Adapted and translated from Usui et al. (2021b, 2022)

3. Diurnal variations of interior canopy air temperature (T_{a_in}), relative humidity ($RH_{_in}$), and vapor pressure deficit ($VPD_{_in}$)

Diurnal variations in the hourly mean values of T_a, RH, T_{a_in}, and $RH_{_in}$ for the six genotypes are presented in Figures 2a-f. Variations in VPD, SR, and $VPD_{_in}$ from July 13, 2017 (79 DAT) to July 15, 2017 (81 DAT) are shown in Figures 2g-i. The corresponding data for 2018, i.e., from August 1, 2018 (97 DAT) to August 3, 2018 (99 DAT), are presented in Figures 3a-i.

In 2017, the highest T_{a_in} values for most genotypes were observed at approximately 13:00, whereas the highest T_a values at the weather station occurred between 14:00 and 15:00 (Figs. 2a-c). As T_{a_in} increased, a T_{a_in} range of approximately 1°C or more began to appear among the genotypes from approximately 6:00. The maximum difference in the T_{a_in} (ΔT_{a_in}) range between genotypes was approximately 2.7°C at around 8:00 and 9:00 at 81 DAT. The highest T_{a_in} value was observed for NK195BR, and the lowest value was observed for NK235BR×NK388 at 9:00 at 81 DAT. However, the maximum ΔT_{a_in} between the genotypes at 79 and 80 DAT generally occurred at approximately 14:00 and 15:00. Subsequently, the ΔT_{a_in} among genotypes decreased, with the maximum ΔT_{a_in} being less than approximately 1°C from 16:00 to 18:00 or later. The lowest $RH_{_in}$ values for most genotypes were observed between 13:00 and 15:00, and the lowest RH values at the weather station

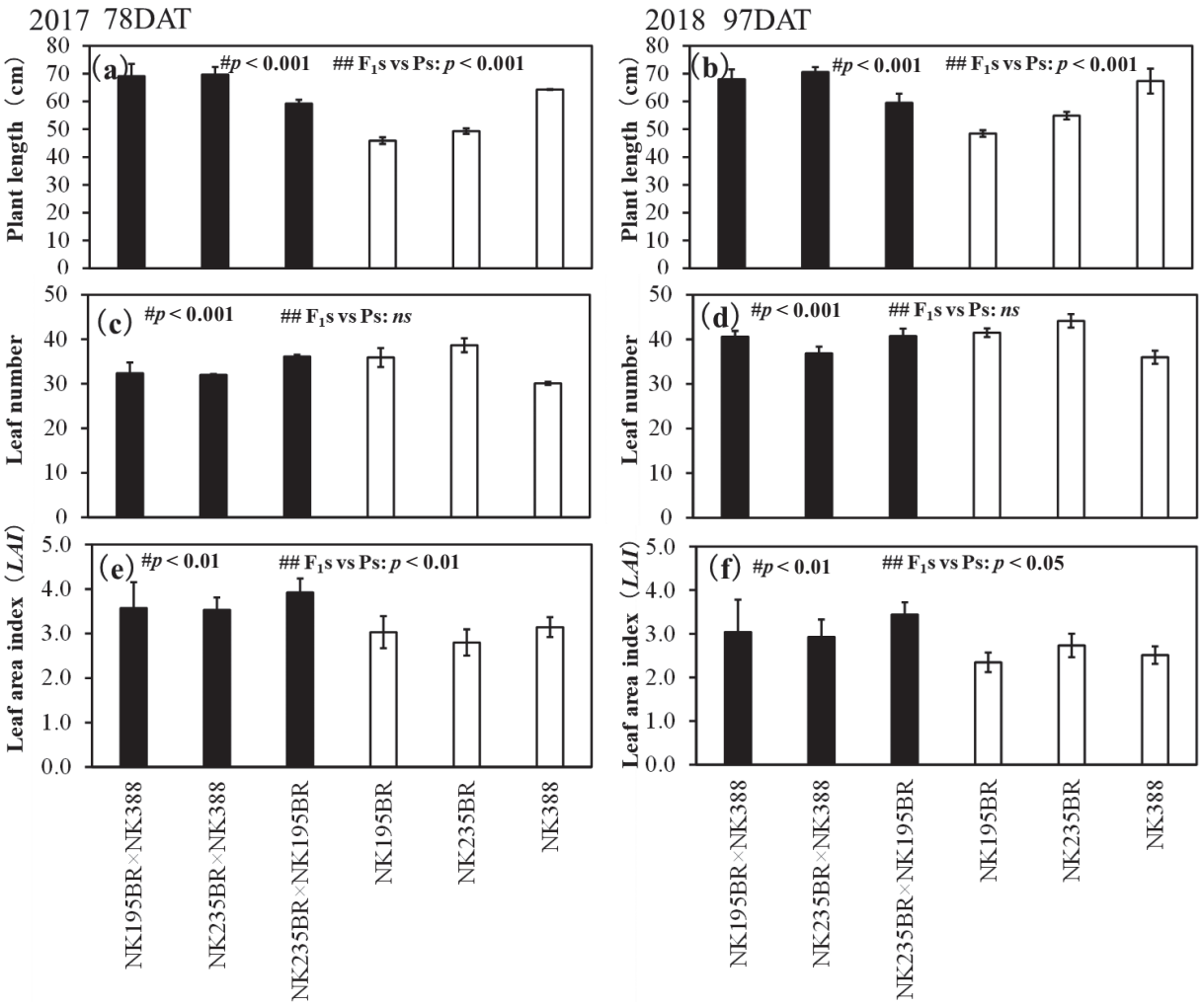


Fig. 1. Plant length, leaf number, and leaf area index (*LAI*) of the six tested genotypes on 12 July 2017 (78 DAT) and 1 August 2018 (97 DAT)

Vertical bars represent the standard deviations (SD) of the means. #: One-way ANOVA indicated significant differences at $p < 0.001$ (0.1%) and $p < 0.01$ (1%) (N = 24, with four replicates for each of the six tested genotypes). ## Scheffé's method ($p < 0.05$) and comparisons between the F_1s group and the parental line (Ps) group (F_1s vs. Ps). The p values indicate significant differences at $p < 0.001$ (0.1%), $p < 0.01$ (1%), $p < 0.05$ (5%), and ns (not significant).

was observed between 13:00 and 14:00. The maximum difference in $RH_{_in}$ ($\Delta RH_{_in}$) was observed between 13:00 and 14:00 (Figs. 2d-f). The highest $VPD_{_in}$ values for most genotypes were observed between 13:00 and 15:00, whereas the highest $VPD_{_in}$ values at the weather station occurred between 13:00 and 14:00. The maximum difference in $VPD_{_in}$ ($\Delta VPD_{_in}$) was observed between 13:00 and 14:00 (Figs. 2g-i).

In 2018, the highest T_{a_in} values for most genotypes were observed between approximately 12:00 and 13:00, and the highest T_a values at the weather station occurred between 11:00 and 13:00 (Figs. 3a-c). As T_{a_in} increased, a range of approximately 1°C or more among genotypes appeared starting at approximately 7:00 (10:00 in the case of 97 DAT). The variation at 97 DAT may have been attributed to different *SR* variations (Fig. 3g) compared to that on other days (Figs. 3h, i). The maximum ΔT_{a_in} range between genotypes was approximately 1.7°C at 12:00 at 98 DAT. The highest T_{a_in} value was observed for NK388, and the lowest value was observed for NK195BR×NK388. Subsequently, the ΔT_{a_in} among genotypes decreased, with the maximum difference being < 1°C from approximately 14:00 to 16:00 or later. The lowest $RH_{_in}$ values for most genotypes and at the weather station were observed between 12:00 and 14:00. The maximum $\Delta RH_{_in}$ value was observed between 8:00 and 11:00 (Figs. 3d-f). The highest $VPD_{_in}$ values for most genotypes were observed between 12:00 and 14:00, and the highest $VPD_{_in}$ values at weather stations were observed between 11:00 and 14:00. The maximum $\Delta VPD_{_in}$ value was observed at approximately 12:00 (8:00 in the case of 99 DAT) (Figs. 3g-i).

4. Diurnal variations of interior canopy absolute humidity ($AH_{_in}$) and humidity deficit ($HD_{_in}$)

Because we investigated parameters within the interior canopy environment in this study, we also examined the $AH_{_in}$ and $HD_{_in}$.

In 2017, the highest $AH_{_in}$ values for most genotypes were generally observed at approximately 12:00, and all genotype values and variations (except for NK235BR, which had the lowest $AH_{_in}$ value), were generally similar (Figs. 4a-c). However, differences in $HD_{_in}$ values among genotypes emerged during the daytime, and the $HD_{_in}$

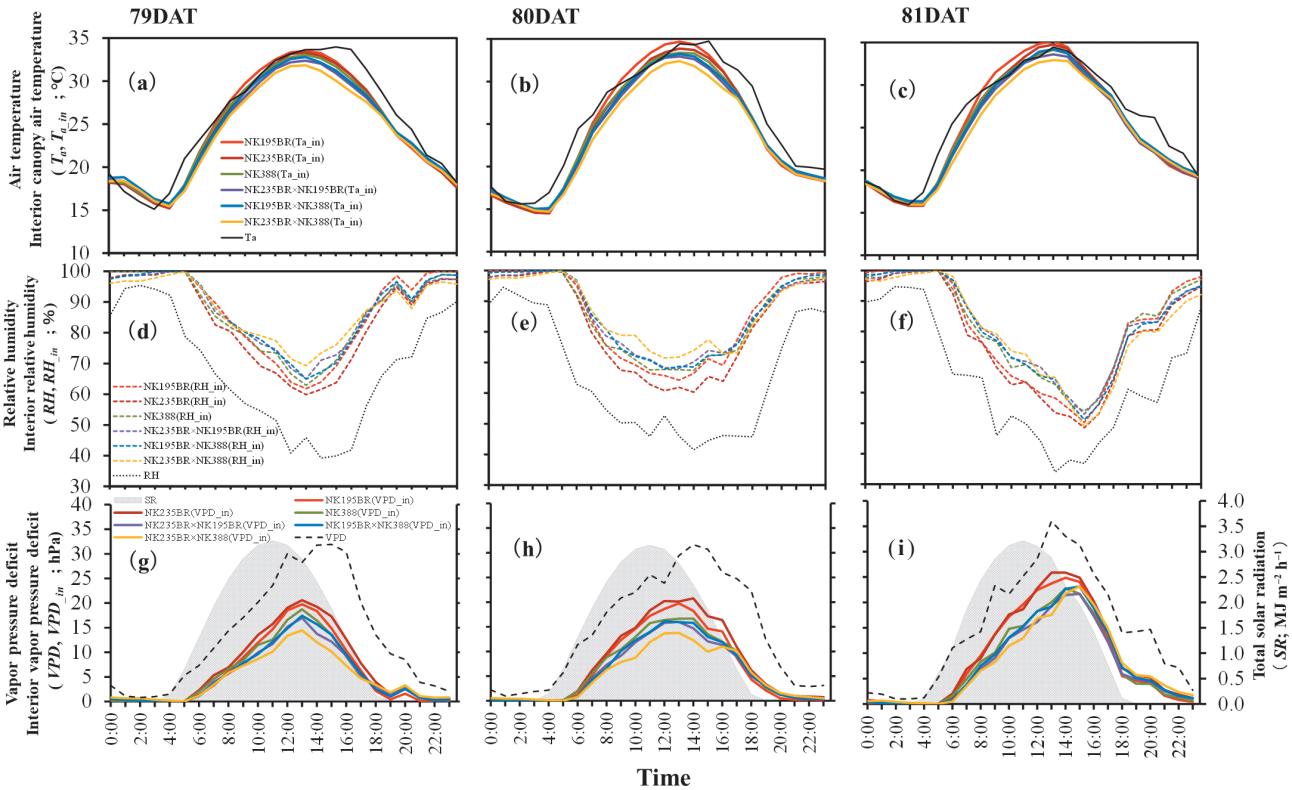


Fig. 2. Diurnal variations in hourly mean values for air temperature (T_a) and interior canopy air temperature (T_{a_in}) of the six tested genotypes (a-c); relative humidity (*RH*) and interior canopy relative humidity ($RH_{_in}$) of the tested six genotypes (d-f); vapor pressure deficit (*VPD*) , interior canopy vapor pressure deficit ($VPD_{_in}$) of the six tested genotypes and total solar radiation (*SR*) ; from 13 July (79 DAT) to 15 July (81 DAT) in 2017

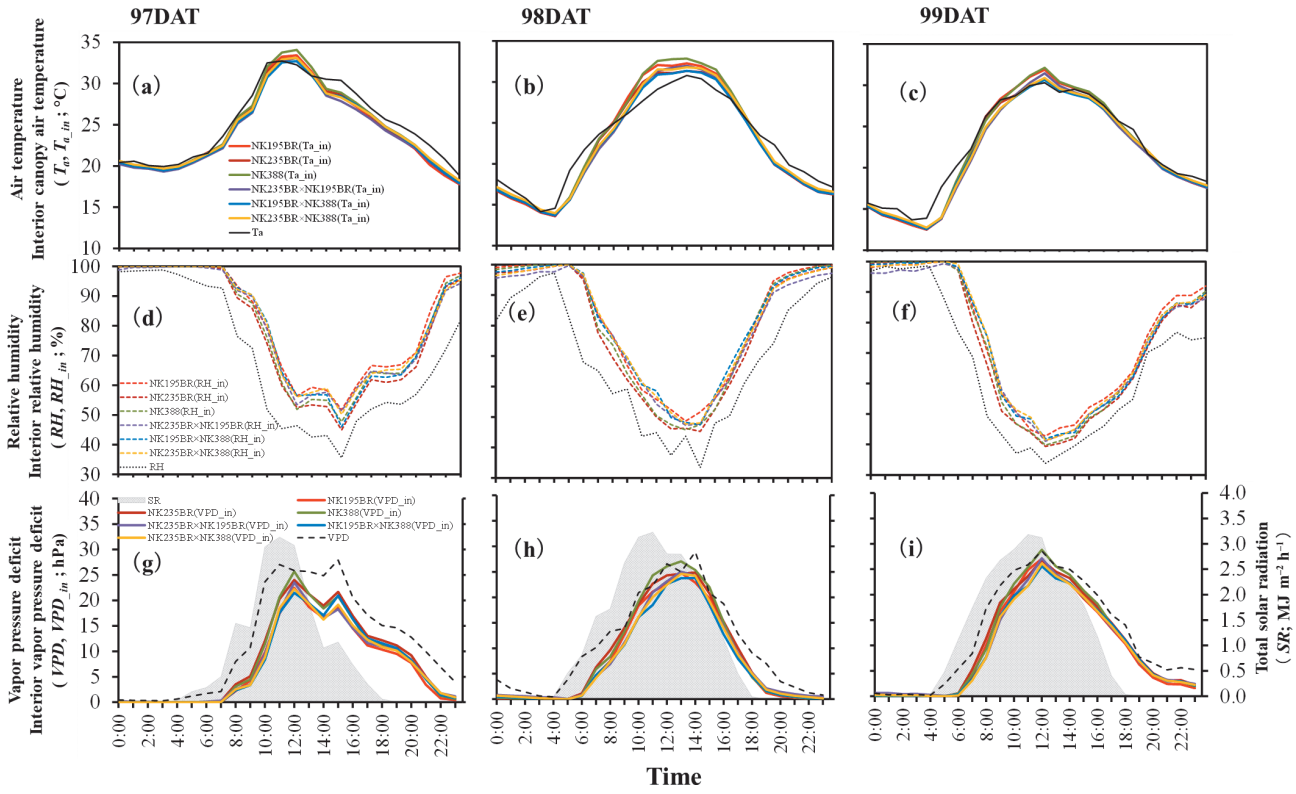


Fig. 3. Diurnal variations in hourly mean values for air temperature (T_a) and interior canopy air temperature (T_{a_in}) of the tested six genotypes (a-c); relative humidity (RH) and interior canopy relative humidity (RH_{in}) of the tested six genotypes (d-f); and vapor pressure deficit (VPD), interior canopy vapor pressure deficit (VPD_{in}), and total solar radiation (SR) from 1 August (97 DAT) to 3 August (99 DAT) in 2018

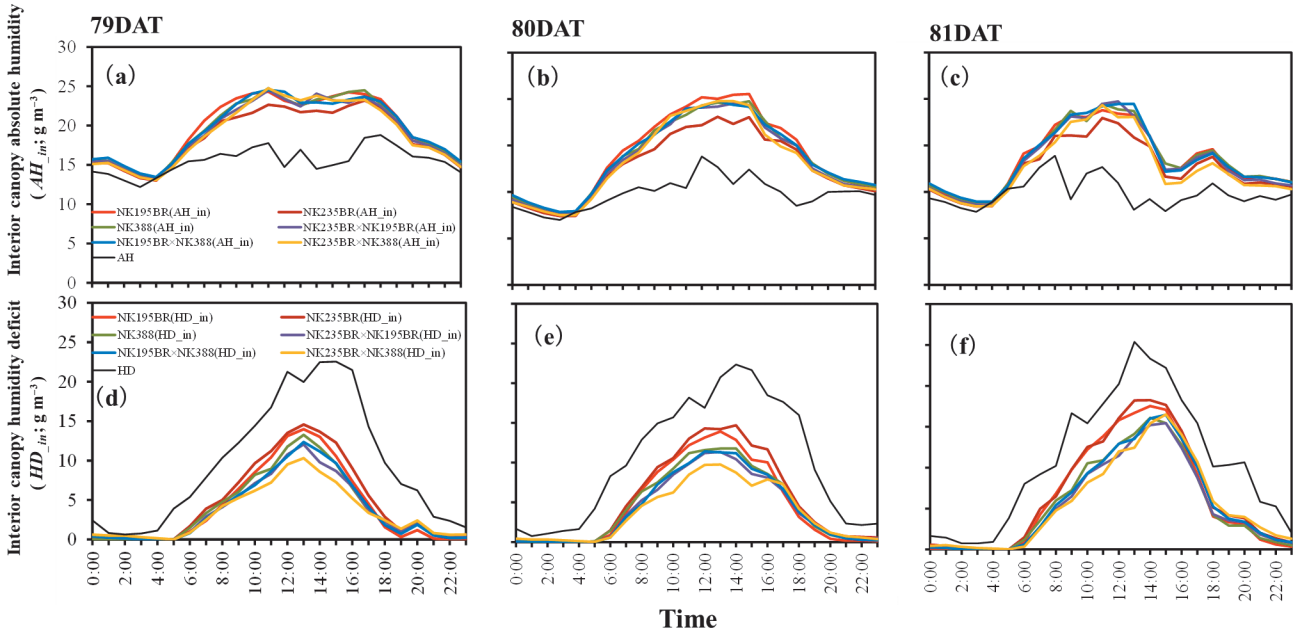


Fig. 4. Diurnal variations in hourly mean values of absolute humidity (AH) and interior canopy absolute humidity (AH_{in}) of the six tested genotypes (a-c); humidity deficit (HD) and interior canopy humidity deficit (HD_{in}) of the six tested genotypes (d-f), from 13 July (79 DAT) to 15 July (81 DAT) in 2017

value of NK235BR was the highest (Figs. 4d, e).

In both 2017 and 2018, there was a tendency for $AH_{_in}$ values and differences among genotypes to increase during the daytime, but the extent of these increases was small (Figs. 5a-c). $HD_{_in}$ values and variations in 2018 were similar to those in 2017, although the values and differences among genotypes were smaller than those in 2017 (Figs. 5d-f).

5. Differences in T_{a_in}, $AH_{_in}$, and $HD_{_in}$ among genotypes

To investigate the differences in T_{a_in}, $AH_{_in}$, and $HD_{_in}$ among genotypes, we analyzed the 6-h mean values from 10:00-16:00 over 3 d (79-81 DAT in 2017 and 97-99 DAT in 2018) (Fig. 6). This period was selected because the genotypic differences were the most pronounced.

The maximum difference in T_{a_in} among genotypes was approximately 2°C in 2017 and approximately 1.2°C in 2018. In general, T_{a_in} was higher in the parent genotype than in the F_1s (Figs. 6a, d).

All $AH_{_in}$ were higher than AH. The maximum difference in $AH_{_in}$ ($\Delta AH_{_in}$) among genotypes was approximately 1.8 g m^{-3} in 2017 and approximately 2.1 g m^{-3} in 2018. The highest $AH_{_in}$ was exhibited by NK195BR, and the lowest $AH_{_in}$ was exhibited by NK235BR (Figs. 6b, e).

The maximum difference in $HD_{_in}$ ($\Delta HD_{_in}$) among the genotypes was approximately 4.3 g m^{-3} in 2017 and 1.9 g m^{-3} in 2018 was higher in the parental lines than in the F_1s (Figs. 6c, f).

Discussion

In this study, we compared the interior canopy environment among six sugar beet genotypes and suggested the differences and variations among them. The results showed that T_{a_in} and $HD_{_in}$ differed between F_1s and their parental lines, whereas no clear difference was observed for $AH_{_in}$. The differences observed between F_1s and their parental lines were thought to have been influenced by differences in canopy structure due to heterosis. Usui et al. (2020b) reported that the *LAI* of F_1s was higher than that of parental lines. Ogata et al. (2010) reported that diploid F_1 hybrids with a greater number of leaves and longer plant lengths led to earlier development of monohybrids with vigorous initial growth and earlier covering dates. In general, F_1s obtained through intra- or interspecific hybridization showed increased biomass compared to their parents. Heterosis was observed in plant length and *LAI* in the present study because a clear significant difference existed between the F_1s and parental lines (Fig. 1). Therefore, we investigated the correlations between canopy structure, particularly *LAI*, and various parameters within the interior canopy (Fig. 7).

We compared *LAI* and T_{a_in}, and observed that as

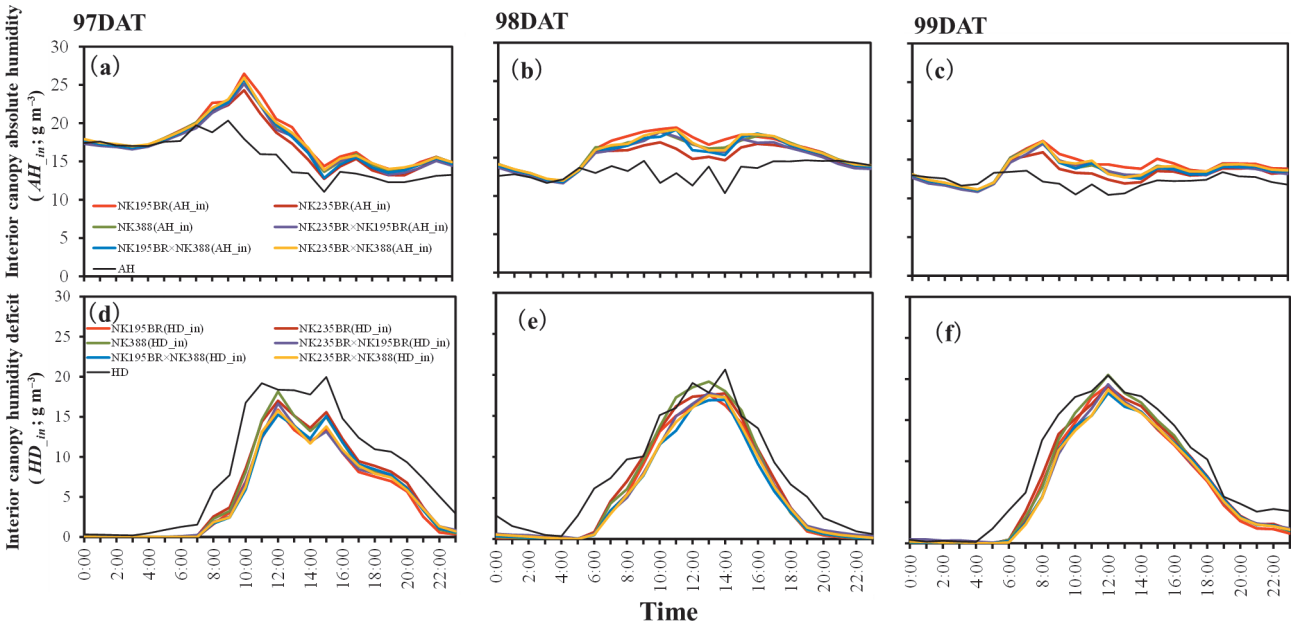


Fig. 5. Diurnal variations in hourly mean values of absolute humidity (*AH*) and interior canopy absolute humidity ($AH_{_in}$) of the six tested genotypes (a-c); humidity deficit (*HD*) and interior canopy humidity deficit ($HD_{_in}$) of the six tested genotypes (d-f), from 1 August (97 DAT) to 3 August (99 DAT) in 2018

LAI increased, T_{a_in} decreased ($P = 0.11$ in 2017; $P = 0.12$ in 2018) (Fig. 7a). Given that temperature and *RH* are generally inversely proportional, both of these relationships, as well as the influence of the growing environment, likely contributed to these differences. However, in the case of $AH_{_in}$, *LAI* and $AH_{_in}$ showed no significant correlation in either year (Fig. 7b). Although the order of the genotypes varied depending on the year, $HD_{_in}$ of the F_1s was consistently lower than that of their parents. *LAI* and $HD_{_in}$ showed a significant linear correlation in 2017 ($P < 0.05$), but no significant correlation was observed in 2018 (Fig. 7c).

The following two factors may explain why the relationship between *LAI* and $HD_{_in}$ was stronger in 2017 than in 2018: First, the *LAI* in 2018 was lower than that in 2017, suggesting differences in canopy closure, which likely facilitated vertical air exchange in 2018. Second, it is possible that wind speeds differed on the observation

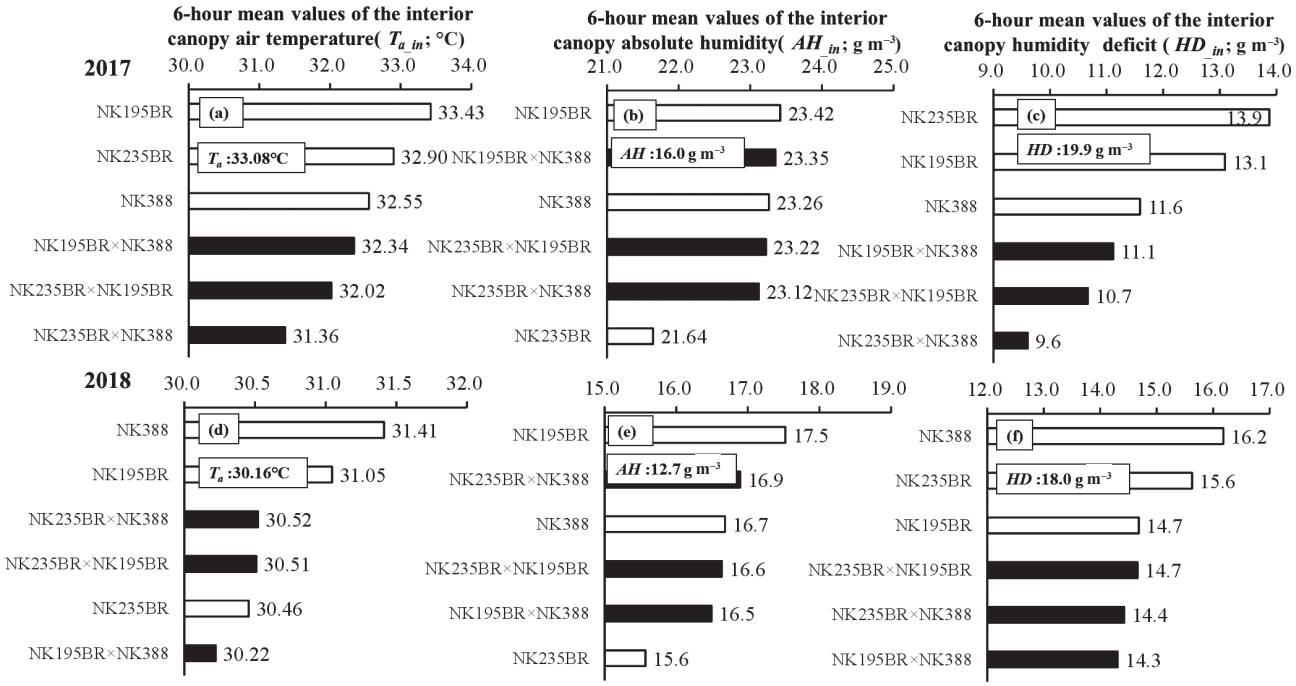


Fig. 6. Six-hour mean values from 10:00 to 16:00 over three days (79-81 DAT in 2017, 97-99 DAT in 2018) of interior canopy air temperature (T_{a_in}) in 2017 (a) and 2018 (d), interior absolute humidity ($AH_{_in}$) in 2017 (b) and 2018 (e), and interior humidity deficit ($HD_{_in}$) in 2017 (c) and 2018 (f) for the six tested genotypes

＊T_a, *AH*, and *HD* in the figure are the 6-h mean values from 10:00 to 16:00 during the same three-day periods at the weather station.

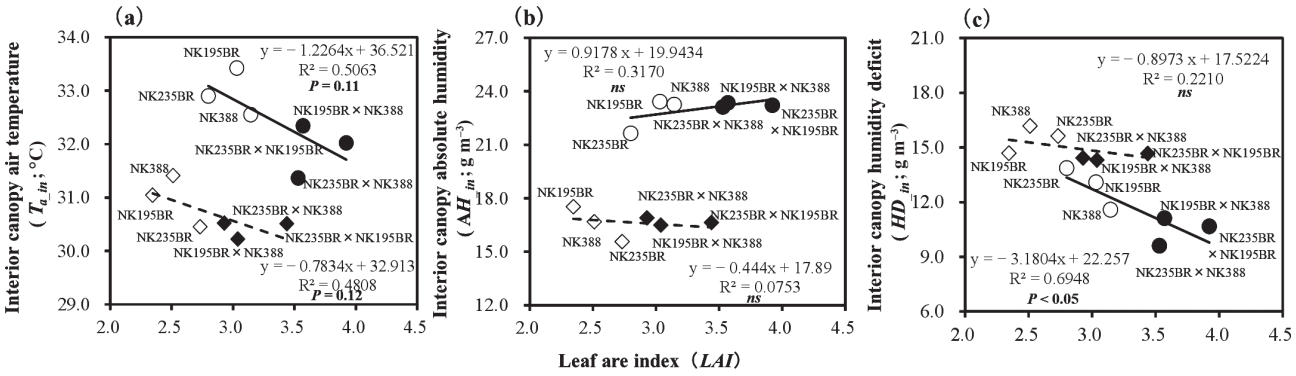


Fig. 7. Relationship between *LAI* and the 6-h mean values from 10:00 to 16:00 of interior canopy air temperature (T_{a_in}) (a), absolute humidity ($AH_{_in}$) (b), and humidity deficit ($HD_{_in}$) (c)

＊○ and ● indicate the year 2017; ◇ and ◆ indicate the year 2018.

days. Therefore, when examining wind speeds at the weather station of the HARC Memuro Research Station during the same period, the 3-d average daily wind speed was approximately 1.3 m/s in 2017, compared to 2.3 m/s in 2018. Similarly, the 3-d average maximum wind speed was approximately 2.9 m/s in 2017, compared to 5.9 m/s in 2018, indicating higher wind speeds in 2018. Therefore, disturbance within the interior canopy was greater in 2018 than in 2017.

A comparison of interior canopy environments among sugar beet genotypes, i.e., particularly T_{a_in} and $HD_{_in}$ values, suggested diverse trends among the lines, including differences between F_1s and their parents. Usui et al. (2021a, 2021b, 2022) reported that the canopy surface temperature of F_1s was lower than that of their parents and was correlated with variations in transpiration rates among genotypes; these studies also suggested that heterosis may contribute to these differences. Additionally, these authors found that the sugar yield and root weight of F_1s were higher than those of their parents. In the present study, F_1s consistently showed lower temperatures and $HD_{_in}$ values than their parents in the interior canopy, suggesting that heterosis may have indirectly influenced the sugar beet growth environment.

In addition, to adapt to high air temperatures (T_a) in summer under climate change conditions, it is essential to select cultivars that are tolerant of high temperatures and develop appropriate cultivation techniques. In this study, we investigated the interior canopy microclimate of several sugar beet genotypes using detailed observations. However, detailed observations are difficult because of the necessary labor and cost. Therefore, it is desirable to improve the interior canopy microclimate model based on the results of this study and develop prediction-based evaluation methods.

The causative pathogens of *Aphanomyces* root rot and *Cercospora* leaf spot thrive in high-temperature and high-moisture environments, posing significant challenges for sugar beet cultivation. Although no impact of disease on yield was observed in this study, particular attention should be paid to future climate change conditions.

The detailed interior microclimate observation data collected in this study may contribute to the refinement of this model. For example, in the USA, the DIV model was developed using meteorological data (Shane & Teng 1984, 1985). This model assigns values ranging from 0 to 7 within a 24 h period based on the leaf wetness duration and T_a, which were estimated from the *RH* above the plant canopy in the present study. It is widely utilized as an indicator of pest control timing across various regions of the USA (Kumazawa et al. 2017), although the DIV model partially accounts for temperature and humidity within the canopy. Given that environmental conditions within the canopy vary by genotype, as demonstrated in the present study, it is necessary to improve the model to account for differences in the canopy structure among different varieties. Maruyama et al. (2023) and Kuwagata et al. (2024) introduced multi-layer microclimate models to simulate dew formation in rice canopies. Integrating this multi-layer microclimate model with our findings on the microclimate within sugar beet canopies offers potential for accurately assessing interior canopy microclimate conditions. These data can serve as a guide for selecting cultivars that are adaptable to climate change and refining cultivation techniques. Additionally, an agrometeorological grid square data-based *Cercospora* leaf spot alert system has been developed (Ohno et al. 2016).

In this study, we determined that the differences in the interior canopy microclimate among genotypes could be partially explained by their relationship with the *LAI*. However, further research is required to explore the relationships between other factors.

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