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The relationship between remotely sensed canopy surface temperature and canopy structure for crop fields

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Abstract

Various thermal phenomena on the surface of the earth have been analyzed by using surface temperature measurements from aircraft or satellites, because the preservation of the global environment recently has become an issue. However, few basic studies on vegetation surface temperatures for such analysis have been performed. Therefore, lack of knowledge regarding surface temperatures is an obstacle to analyzing data from aircraft or satellites.

The purpose of this study is to analyze the characteristics of canopy surface temperature of crop fields, to clarify the relationship between various thermal phenomena and these surface temperatures.

Study was performed for two different types of canopy structure, soybeans (planophile) and corn (erectophile). The arrangements of leaves in the canopies were obtained for both crop fields, and canopy surface temperatures and leaf temperatures were measured by IR-thermometer which uses the same measuring principle as aircraft or satellite radiometers. The results of this study are summarized as follows :

1) Canopy surface temperatures of the planophile crop (soybeans) as measured by IR thermometer are affected by the leaf temperatures of leaves in the upper portion, because most of such canopies leaf area is near the upper portion of the canopy.
2) In contrast, canopy surface temperatures for the erectophile crop are affected by the leaf temperature from the upper to the lower portion of the canopy.
3) Therefore, in later stages of growth (dense vegetation cover), the maximum canopy surface temperature of the erectophile crop (corn) is lower than that of the planophile crop (soybeans).
4) Also, the directional variation and hourly variation of leaf surface temperature are larger for the planophile crop (soybeans) than for the erectophile crop (corn), because wind and solar radiation strongly influence the planophile crop.
5) At low intensities of solar radiation, however, surface temperature of leaves facing skyward is lower for the planophile crop (soybeans) than for the erectophile crop (corn).

I. INTRODUCTION

Artificial satellites have recently been developed, and the surface temperature of the earth is measured regularly by launched radiometers. Furthermore, various thermal phenomena such as heat budget and radiation budget on the earth have been analyzed by using surface temperature measurements from these satellites or aircraft, because the preservation of the global environment recently has become an issue. Also, crop field surface temperature measurement by satellites is useful for many agricultural applications including evapotranspiration models, soil moisture detection, plant stress detection and yield prediction. Most studies have focused on remotely sensed canopy surface temperature to infer the water status of the vegetation for soil moisture detection and plant stress detection. However, few basic studies have been performed on the relationship between remotely sensed canopy surface temperatures and canopy structures for the analysis of thermal phenomena.

The purpose of this study is to obtain fundamental knowledge of remotely sensed surface temperature with regard to the canopy structure and ground measurements by IR thermometer. The radiometric measurement of canopy surface temperature over a crop field is affected by thermal radiance emitted from soil and vegetation and is sensed as a composite surface temperature (we call this "canopy temperature") by the IR thermometer. Kimes *et al.*[1], Kimes[2] and Heilman *et al.*[3] have evaluated the canopy temperature by using vegetation surface temperature, soil surface temperature and the probability of gap or percent vegetation cover. However, this canopy temperature is a function of the geometric structure of the plant canopy, such as spatial distribution of leaves within canopy and frequency distributions of leaf orientation and angle. Hatfield *et al.*[4] reported about changing the canopy temperature due to change morphological structure of the canopy, that is the canopy temperatures of wheat with panicles are cooler than those without panicles. It is important to understand the effects of the canopy's geometric structure on the remotely sensed surface temperature.

The study was performed for two different types of canopy structure, soybeans (planophile) and corn (erectophile)[5]. The canopy structures, such as involves distributions and orientations of leaves, and temperatures of leaves in the canopies, were measured for both crop fields in order to understand the relationship between canopy structure and canopy temperature.

II. MATERIALS AND METHODS

Field experiments were conducted at Hokkaido University Farm during crop seasons from 1992 to 1994. R adiative surface temperatures were measured with an IR thermometer (OPTEX HR-1P), which had a 4° field of view, a stated

accuracy of ±0.5℃, a resolution of ±0.1℃, and a spectral band of 10.5~12.5μm. The three items, comparison of canopy structures, comparison of leaf temperatures, and comparison of canopy temperatures, for fields of corn and of soybeans were analyzed.

A. Items for analysis

a. Canopy structures

De Wit[5] distinguished four major kinds of plant canopies by the arrangement of leaves : planophile, erectophile, plagiophile, and extremophile. Corn belongs to the erectophile type of canopy and soybeans to the planophile type. The arrangement of leaves in a canopy, that is, spatial distribution, leaf area facing skyward, and azimuth distribution, influences the canopy temperature measured by the IR thermometer. The following elements of the corn fields and the soybean fields were measured.

① Distribution of fresh weight with height, ② Distribution of leaf area facing skyward with height, and ③ Number of leaves for each azimuthal direction

b. Leaf temperatures

Leaf temperatures of both corn and soybeans that affected canopy temperature were compared. It is known that each crop has a characteristic leaf temperature[6]; therefore, leaf temperature differs by species and variety of crop and affects the canopy temperature. The following measurements were performed for leaf temperature of corn and soybeans.

① Difference of surface temperatures for the upper-most leaves and ② Difference of leaf temperatures for each azimuthal direction.

c. Canopy temperatures

Canopy temperatures of the corn field were compared to those of the soybean field. The following analyses were performed.

① Daily change of canopy temperature and ② Maximum canopy temperature

B. Cultural practices

Measurements of canopy structures were performed in 1993, measurements of leaf temperature in 1993 and 1994, and measurements of canopy temperature from 1992 to 1994. Agricultural practices and measurement periods for canopy temperature are shown in Table 1.

The rows for both fields were oriented north-south. In 1992, thinning was performed twice on July 3 and 24 in the soybean fields, and the resulting plant spacing was 40 x 20 cm.

Table 1. Study conditions in fields

Crop	Soybeans			Corn		
Year	1992	1993	1994	1992	1993	1994
Variety	Sapporo midori	Ezonishiki	Sirohana Taisetsu	Hany Bantam 36	Hany Bantam 36	Peter corn
Seeding Date	May 17	May 18	May 18	May 21	May 14	May 17
Plant Spaces	20×10 (cm) (5/17~7/03)	25×25 (cm)	25×25 (cm)	45×30 (cm)	40×30 (cm)	40×30 (cm)
	20×20 (cm) (7/04~7/24)					
	40×20 (cm) (7/25~9/22)					
Area of Field	11×8.5 (m)	18×8 (m)	13×8 (m)	9×8 (m)	11×8.5 (m)	13×8 (m)
Period of Measuring	Jun. 26~ Sep. 21	Jun. 12~ Aug. 27	Jun. 30~ Sep. 22	Jun. 26~ Sep. 21	Jun. 12~ Aug. 27	Jun. 30~ Sep. 22

C. Measurement methods

a. Canopy structures

1) Distributions of fresh weight with height : On September 5 and 8, 1993, the distributions of fresh weight at different plant depths within canopies were measured, while plant heights of corn and soybeans were 165 cm and 70 cm, respectively. During the measurement period the heights for both crops were approximately the maximum. The canopy was divided into 5 layers for corn, 0~31 cm, 31~60 cm, 61~90 cm, 91~120 cm and 121~165 cm, and 4 layers for soybeans, 0~15 cm, 16~30 cm, 31~45 cm and 46~70 cm. The above-ground fresh weight per layer was determined from samples in 1 m^2.

2) Distributions of leaf area facing skyward with height : The thermal radiance emitted from leaf areas facing skyward within the canopy was sensed by the IR-thermometer, while the canopy temperature was measured from above the canopy by the IR-thermometer. Ratio of leaf area facing skyward of each layer to area of ground cover with crop was measured on September 5 and 8, 1993. The sum of the ratios for leaf area facing skyward equals the percent ground covers of the vegetation. The percent ground covers for corn and soybeans were 80.6% and 95.9%, respectively. The layers adopted are the same as those of fresh weight, that is, 5 layers for corn and 4 layers for soybeans. Ratio of leaf area facing skyward was determined using infrared photos of each layer from a vertical position 1.5 m above the canopy, and the leaf area in the photo was scanned and calculated by a computer in the laboratory.

3) Number of leaves for each azimuthal direction : There is a specific azimuthal direction of leaves for each species, which affects the canopy surface temperature. Distribution of plant leaves for azimuthal directions was measured on September 2, 1993, and classified into one of eight different 45° intervals. Number of leaves

for each azimuthal direction was determined for the mean value of each 10 plants.

b. Leaf temperature

1) Difference of surface temperatures for the upper-most leaves : Surface temperatures for the upper-most leaves, that were artificially stretched to a horizontal orientation, for both crops were measured with the IR thermometer at the height of 1 m above the crop. The measurements of 10 leaf temperatures for each crop were taken at one-hour intervals from 08 : 30 to 15 : 45 on August 16, 1993, while the weather was partly cloudy and partly clear. Both crops were planted close to each other, so soil water and meteorological factors such as air temperature, wind speed and solar radiation were approximately the same.

2) *Difference of leaf temperatures for each azimuthal direction* : On September 2, 1993 of a clear day, temperatures for sunlit and horizontal parts of leaves at eight azimuthal directions were measured with the IR thermometer at one-hour intervals from 08 : 30 to 15 : 45. The measurements were taken for sunlit and horizontal parts of leaves, that were located from the No. 1 layer (the upper-most) to the No. 4 layer within the corn canopy, and only the No. 1 layer (the upper-most) within the soybean canopy. The leaf temperatures of 10 plants were averaged for each azimuthal direction.

c. Canopy temperature

Canopy temperatures for the corn field and the soybean field were measured with an IR thermometer mounted at 2 m above the top of the vegetation and scanned over the canopies with a 45° viewing angle. Also, the temperature measurements of a horizontal reference plate (painted black) were used to correct readings of the IR thermometer for skyward longwave radiation[7]. The following items were compared between the corn field and the soybean field.

① Daily change of canopy temperature and ② Maximum canopy temperature.

d. Measurements of other meteorological factors.

The data of air temperature and solar radiation were obtained during measurement periods as Table 1 by a thermocouple thermometer 1.5 m above the ground and with a pyrheliometer.

III. RESULTS AND DISCUSSION

A. Comparison of canopy structures

a. Distribution of fresh weight with height

Distributions of fresh weight within canopies of both corn and soybeans are given in Fig. 1. Corn canopy has a △-shape structure in which there is much vegetation in the lower part of the canopy, but the soybean canopy has a ▽-shape

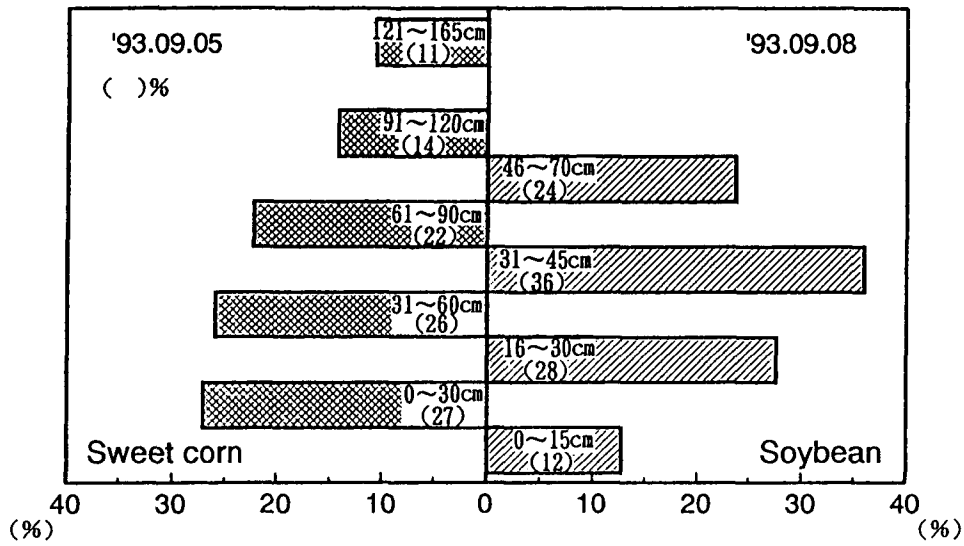

Fig. 1. Distributions of fresh weight within canopies of both corn and soybeans.

structure. Fifty percent of the total fresh weight within the corn canopy was located in the lower one-third of the plant height, and 60% within the soybean canopy in the upper one-third. Similar results were reported by Shaw *et al.*[8] and Nakaseko *et al.*[9]. These characteristics affect canopy temperature in both fields.

b. Distributions of leaf area facing skyward with height

Temperatures of leaves facing skyward within the canopy and soil surface temperature are sensed by an IR thermometer when measurements are taken from above the canopy, and the weighted mean temperature of leaves facing skyward and soil surface temperature is called the canopy temperature of canopy. Therefore, distribution of leaf area facing skyward within the canopy is important for canopy temperature measured by the IR thermometer.

The ratio of leaf area facing skyward to the area of total vegetation cover is shown in Fig. 2. The corn canopy has 41% of the leaf area facing skyward in the upper-most layer, and the soybean canopy has 72%. Up to the second layer, the ratio is 53% for the corn canopy and 96% for the soybean canopy. This is important for canopy temperature measured by IR thermometer, because leaf temperatures of lower parts within the canopy strongly influence the measured composite surface temperature of the corn canopy. On the other hand, only the upper-most part of leaf temperatures influences the measured canopy temperature for the soybean canopy.

Transpiration from leaves of each layer is different because there are air

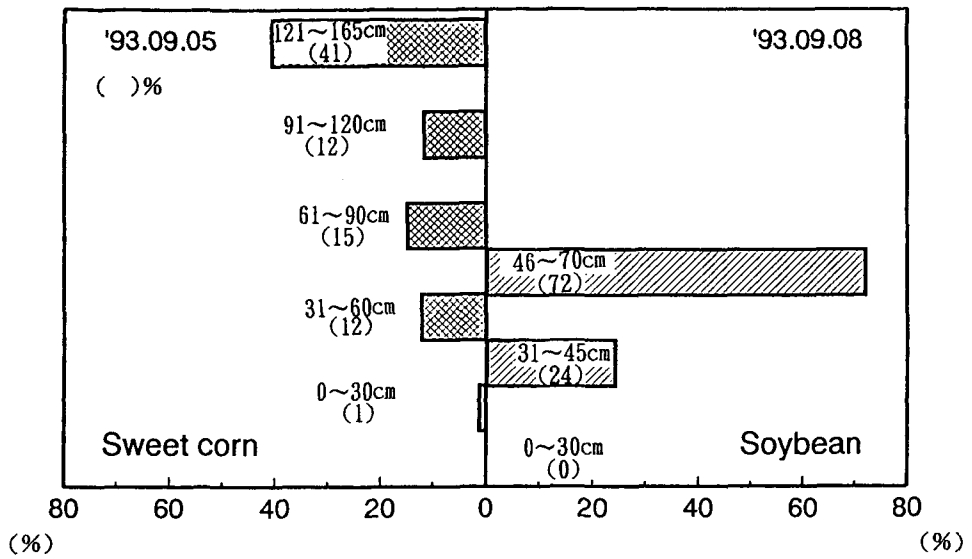

Fig. 2. The ratio of leaf area facing skyward to the area of total vegetation cover.

temperature and vapor pressure profiles within canopies, that is, the leaf temperatures for each layer are different. Therefore, canopy temperatures, that measured temperature of leaves facing skyward, depend on plant canopies that have the different ratios of leaf area facing skyward.

c. Number of leaves for each azimuthal direction

Leaf orientation of eight azimuthal directions for both plant leaves are shown in Fig. 3. Azimuthal direction data for corn leaves show an unhomogeneous distribution, that is, the highest percentage is in the northwest and southeast, and the lowest percentage is in the southwest and northeast. Also, south directions (southeast, south, and southwest) have fewer leaves than do the opposite directions : northeast, north, and northwest. The percentages of both directions for total leaves are 33.3% and 45.8%, respectively.

In contrast, the soybeans has less directional preference than does the corn, i.e., the percentages of number of leaves for south directions (southeast, south, and southwest) and for north directions (northeast, north, and northwest) are 39.3% and 39.8%, respectively.

Soybean leaves have a regular leaf orientation and corn leaves have an irregular leaf orientation that grows toward spaces within the canopy. Numbers of leaves for each azimuthal direction of both crops affect the canopy temperature. It can be assumed that the canopy temperature for the corn field is lower than that for the soybean field, because the corn leaves develop to have a higher vegetation cover ratio than that of the soybean leaves.

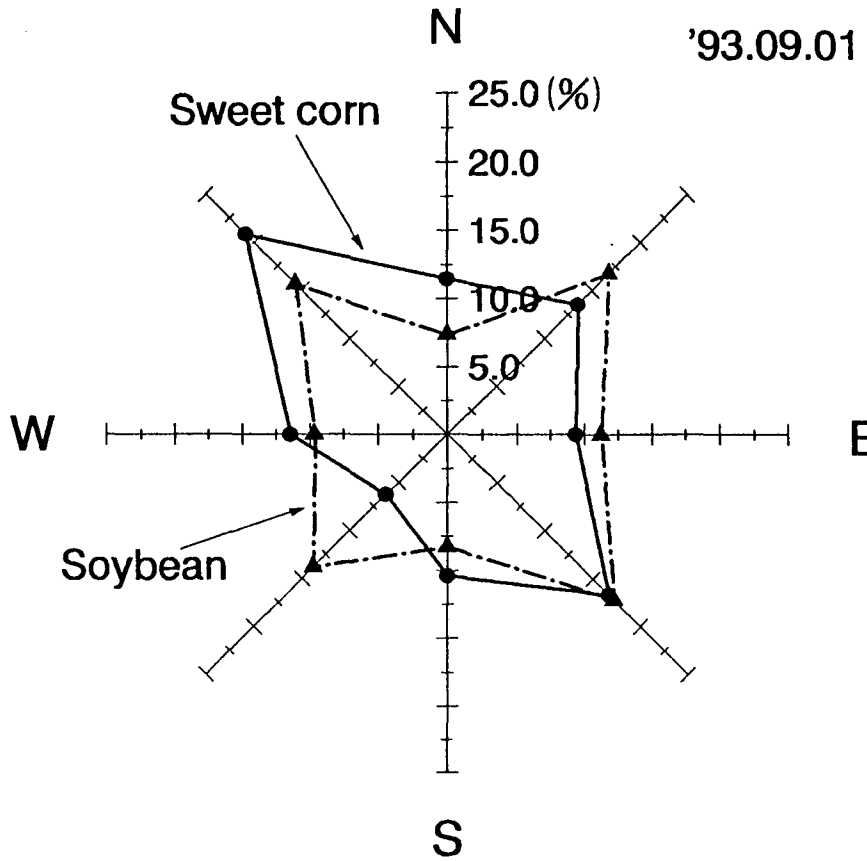

Fig. 3. Leaf orientation of eight azimuthal directions for corn and soybeans.

B. Comparisons of leaf temperature

a. Comparisons of leaf temperature between corn and soybeans

The results of surface temperature at the upper-most leaf that was artificially stretched to a horizontal orientation are shown in Fig. 4. At a high intensity of solar radiation, leaf temperature for soybeans is higher than that for corn, and at a low intensity of solar radiation, leaf temperature for soybeans is lower than that of corn. This tendency is the same for all directions of leaves.

Takechi[6] has done detailed studies on leaf temperature. According to his studies, the difference between leaf temperature and air temperature depends on leaf absorption of solar radiation and transpiration. It is assumed that soybean leaves transpired more than corn leaves in the case of strong solar radiation.

b. Comparisons of leaf temperatures for each azimuthal direction between corn and soybeans

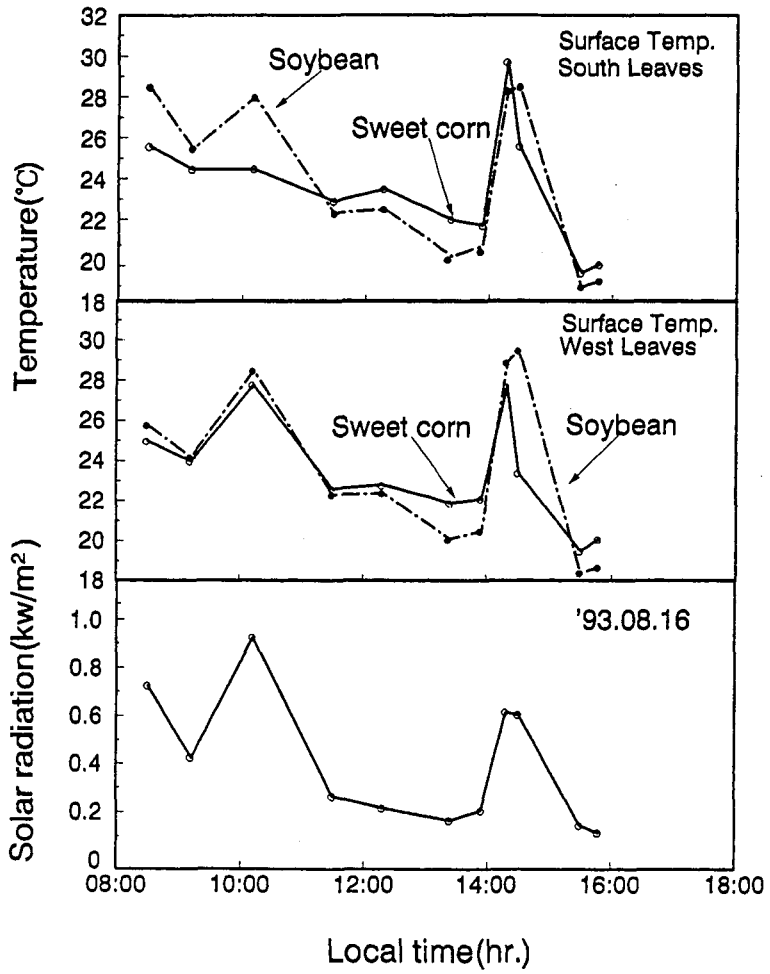

Fig. 4. Surface temperature at the upper-most leaf.

Daily changes of leaf temperature and the daily mean leaf temperatures for sunlit and horizontal parts of leaves at four azimuthal directions within canopies are shown in Fig. 5 and Fig. 6. Leaf temperature for soybeans has larger variations at each hour of four azimuthal directions than that for corn. Also, the variation of daily mean leaf temperature at four azimuthal direction for soybeans is large in comparison with that for corn.

The mean leaf temperature and standard deviation of eight azimuthal directions for each hour are calculated in Table 2. The mean leaf temperatures of soybeans for each hour are higher than those for corn except at 08 : 30 and 13 : 30. This is explained by the fact that the lower is the location within the canopy for corn, the lower is air temperature in the daytime, and the lower part of leaves within the canopy is affected by the low air temperature and results in a low leaf

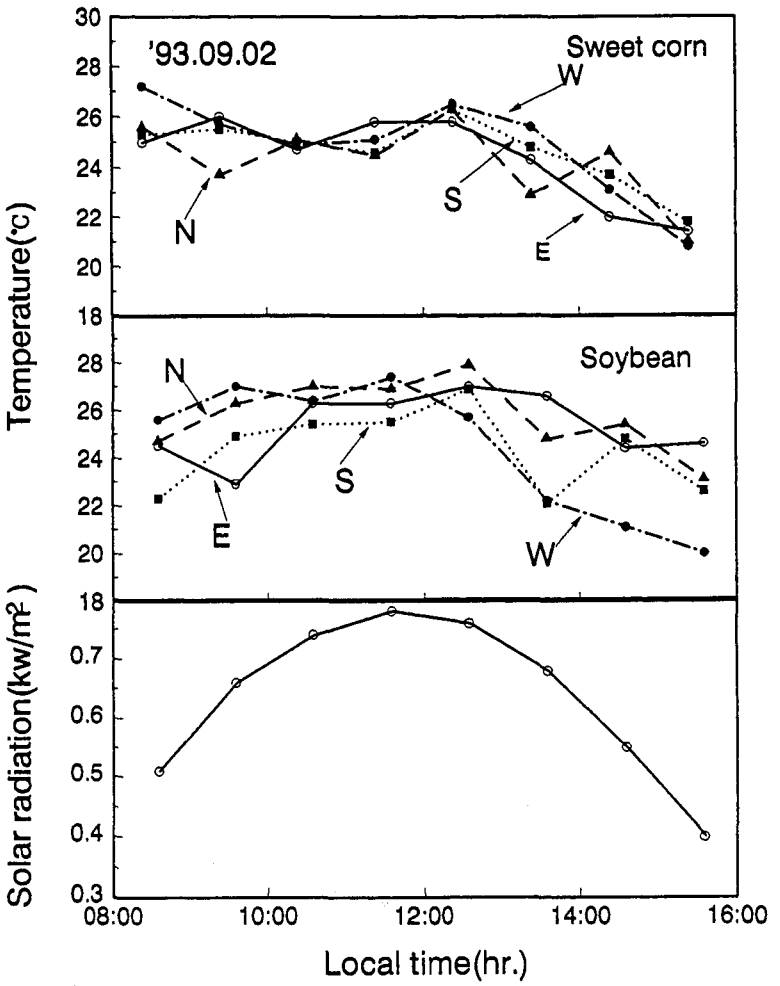

Fig. 5. Daily changes of leaf surface temperature for sunlit and horizontal parts of leaves at four azimuthal directions and solar radiation.

temperature that is included in the canopy temperature for corn.

Also, the standard deviations for soybeans are larger than those for corn except at 11 : 30. This is due to the fact that leaves are affected strongly by wind and air temperature above the canopy because the leaves of soybeans are located in the upper part of the canopy. Those facts, i.e., that the leaf temperature for soybeans has a large deviation in azimuthal directions and is higher than that of corn in the daytime, were confirmed by the measurements in 1994.

The results of leaf temperature are summarized as follows; ① leaf temperature for soybeans is higher than that for corn, when solar radiation is high, ② when solar radiation is low, leaf temperature for soybeans is lower than that of

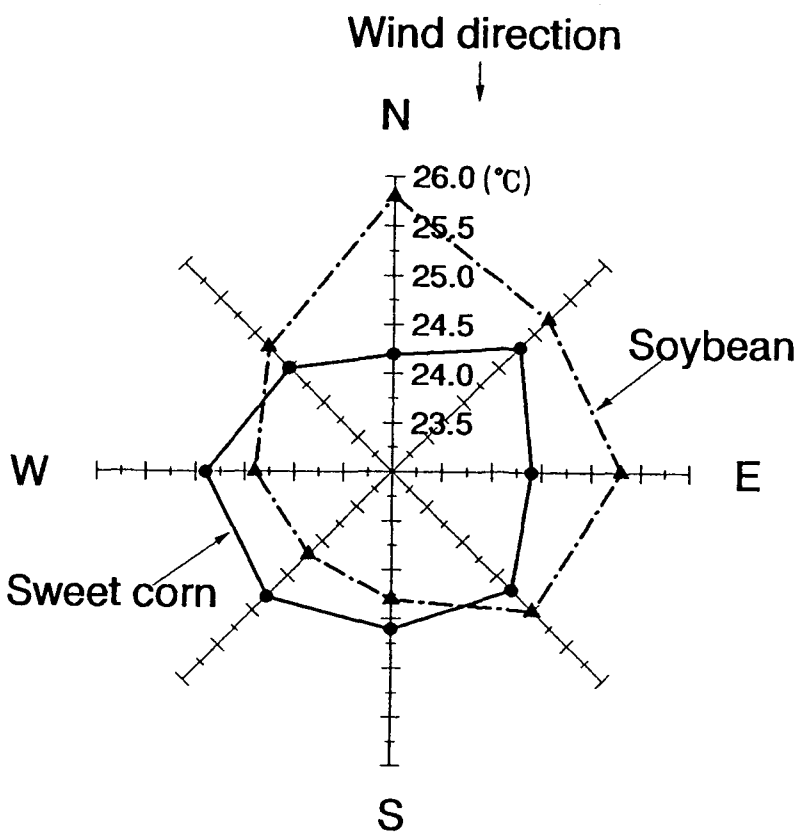

Fig. 6. Daily mean surface temperature for sunlit and horizontal parts of leaves at eight azimuthal directions.

Table 2. The mean leaf temperatures of eight azimuthal direction and standard deviations for each hour

Crop	Time (JST)	08 : 30	09 : 30	10 : 30	11 : 30	12 : 30	13 : 30	14 : 30	15 : 30
Corn	Mean temp.(°C)	25.3	25.4	25.0	25.6	26.1	24.6	23.4	21.5
	Stand. dev.(°C)	±1.1	±0.8	±0.3	±0.9	±0.2	±1.0	±1.1	±0.4
Soybeans	Mean temp.(°C)	24.6	25.5	26.5	26.3	26.5	24.0	23.6	21.9
	Stand. dev.(°C)	±0.3	±1.5	±1.1	±0.7	±1.3	±1.7	±1.4	±1.7

corn, ③ leaf temperature for soybeans has large variations for each azimuthal direction and at each hour, and ④ the variation of daily mean leaf temperature for azimuthal directions for soybeans is large. The characteristics of leaf temperature must influence the canopy temperature.

C. Comparisons of canopy temperature

Daily changes of canopy temperature and maximum canopy temperature were compared between the corn fields and the soybean fields.

a. Daily change of canopy temperature

Daily changes of canopy temperature are shown in Fig. 7. The vegetation cover ratios for the corn fields and the soybean fields were 70.1% and 83.4% on August 30, 1992 (Fig.7(a)), 28.4% and 26.3% on June 30, 1993 (Fig.7(b)), and 81.9% and 49.1% on July 24, 1993 (Fig. 7(c)), respectively.

According to Fig. 7(a), there is a large difference of canopy temperature

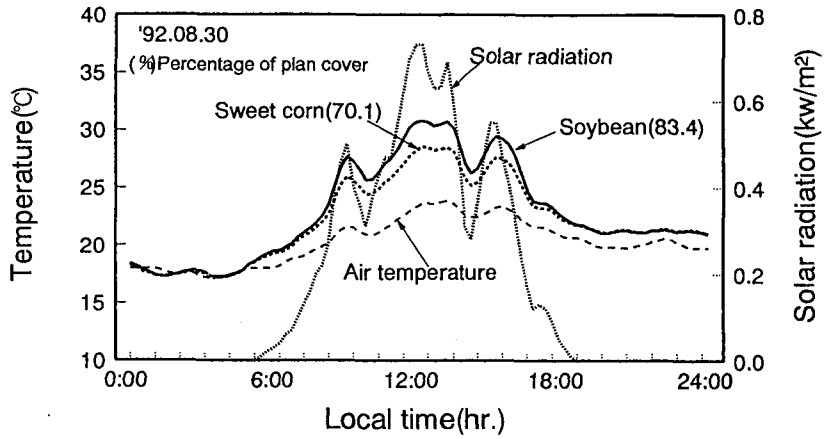

Fig. 7(a). Daily changes of canopy temperature, air temperature and solar radiation for crop fields (on August 30, 1992).

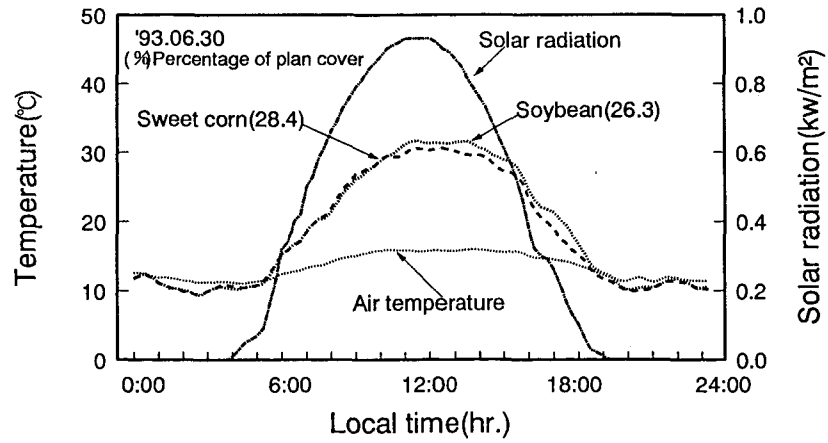

Fig. 7(b). Daily changes of canopy temperature, air temperature and solar radiation for crop fields (on June 30, 1993).

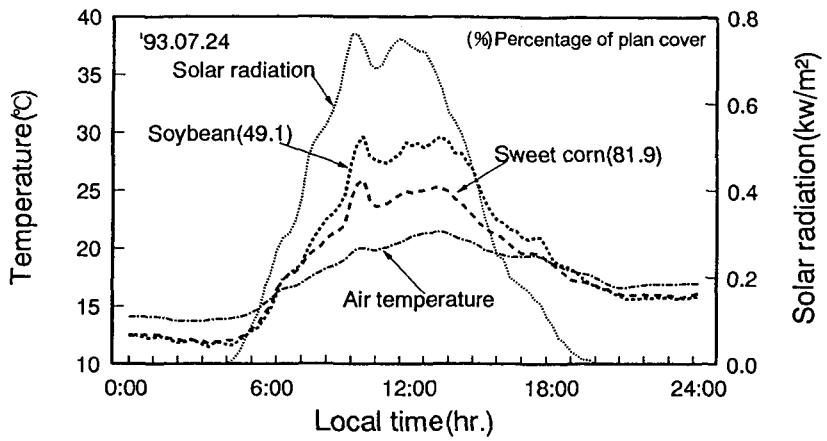

Fig. 7(c). Daily changes of canopy temperature, air temperature and solar radiation for crop fields (on July 24, 1993).

between the corn field and the soybean field when solar radiation is high, and a small difference when solar radiation is low. There is no difference of canopy temperature between the corn canopy and soybean canopy at night.

In an early growth stage, on June 30, 1993 (Fig. 7(b)), canopy temperature of the corn field that had approximately the same vegetation cover ratio as a the soybean field was slightly higher than that of the soybean field or the nearly same as the soybean field in the daytime. On July 24, 1993 (Fig. 7(c)), however, the vegetation cover ratio of the corn field became larger than that for the soybean field, and the canopy temperature of the corn field became lower than that of the soybean field. This phenomena that the canopy temperature of the corn field was lower than that of the soybean field, in spite of nearly the same vegetation cover ratio at a latter growth stage in 1992 (Fig. 7(a)).

Though those results are for the daytime, the vegetation cover ratio insignificantly influences the canopy temperature for both crops at a latter growth stage.

b. Maximum canopy temperature

The maximum canopy temperature that characterizes daytime canopy temperature, was analyzed in relation to vegetation cover ratio and growth stage. The mean maximum canopy temperatures for four clear days of each growth stage in 1992 and 1993 are shown in Fig. 8. In the latter growth stage of both years, the maximum canopy temperature of the corn field became lower than that of the soybean field.

In an early growth stage, however, the maximum canopy temperature of the corn field was higher than that of the soybean field or was nearly the same as the

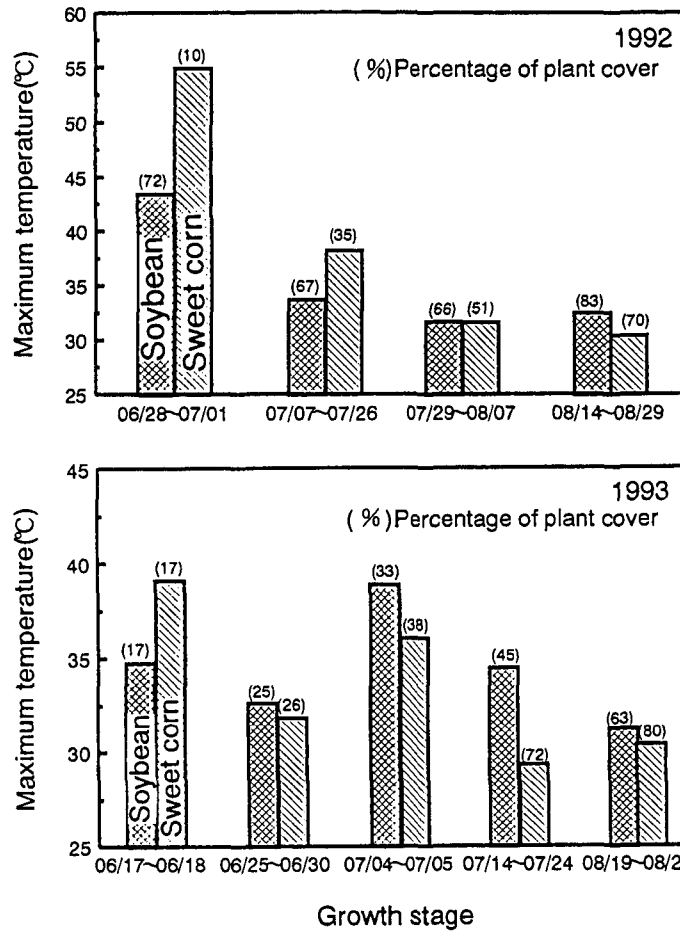

Fig. 8. Comparisons of the mean maximum canopy temperatures for each growth stage.

soybean field. There is a large difference in both years for the differences of maximum canopy temperature between the corn field and the soybean field. It may be caused by soil background temperature, which changes with soil moisture.

To confirm the results, the variations of the maximum surface temperature minus the maximum air temperature for the measurement periods are calculated and shown in Fig. 9. The same results were indicated in Fig. 9.

In the latter growth stage of an erectophile crop, the canopy temperature includes the low leaf temperature of the under part within the canopy. However, leaves of the planophile crop receive much energy and the canopy temperature becomes high.

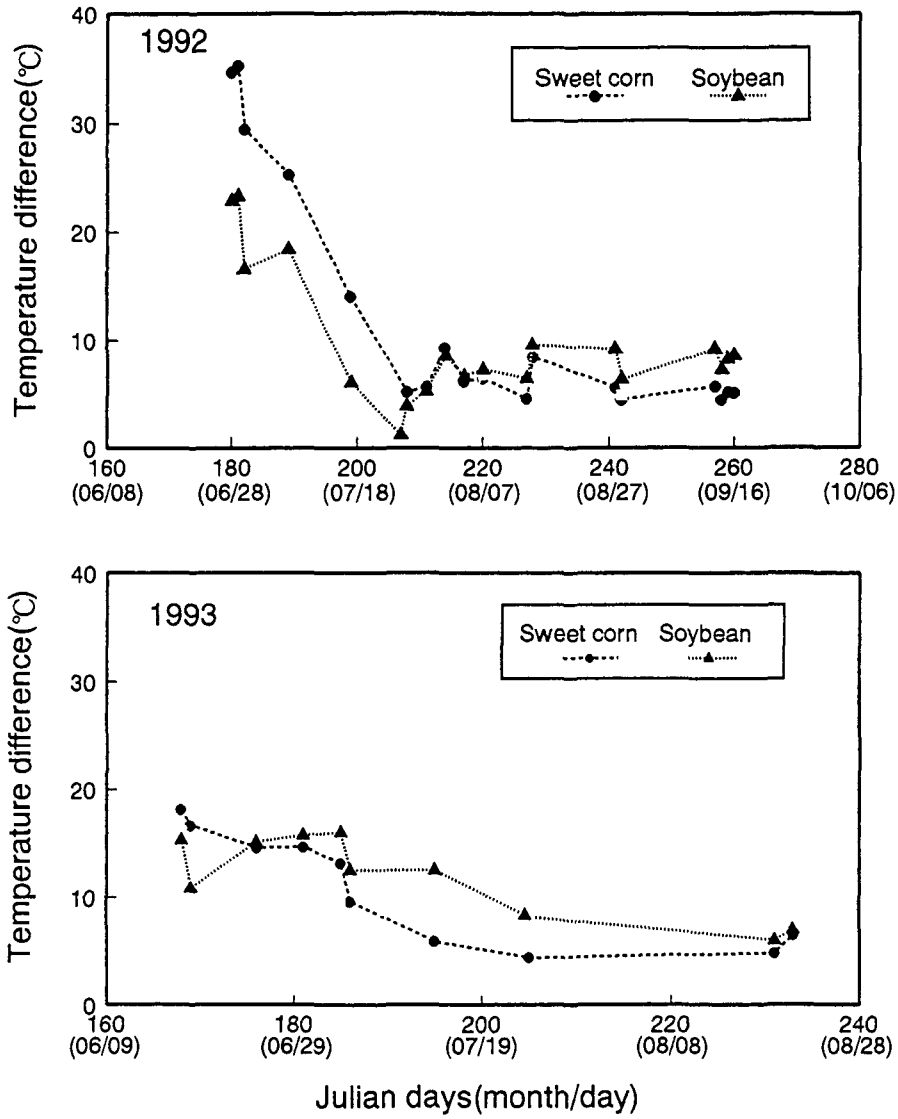

Fig. 9. The variations of the maximum canopy temperature minus the maximum air temperature for the measurement period.

IV. CONCLUSIONS

The results of this study are summarized as follows :

1) Canopy surface temperatures of the planophile crop (e.g. soybeans) are affected by the leaf temperatures in the upper portion.

2) In contrast, canopy temperatures for the erectophile crop (e.g. corn) are

affected by the leaf temperature from the upper to the lower portion of the canopy.

3) Therefore, in latter stages of growth (dense vegetation cover), the maximum canopy temperature of the erectophile crop (corn) is lower than that of the planophile crop (soybeans).

4) Also, magnitudes of the directional variation and hourly variation of leaf surface temperature are larger for the planophile crop (soybeans) than for the erectophile crop (corn), because wind and solar radiation influence more on the planophile crop.

5) At low intensities of solar radiation, however, surface temperatures of leaves facing skyward are lower for soybeans than for corn.

These results suggest that canopy temperatures vary due to canopy structure : especially orientation and distribution of leaves within canopies, and crop spaces. Therefore, in the latter growth stage of crops, vegetation cover ratio is not an important factor for canopy temperature. In the latter growth stage (dense vegetation cover), the canopy temperature of the erectophile crop is lower than that of the planophile crop in daytime. This is important for analyzing thermal phenomena using canopy temperature measured by IR thermometer.

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