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Microclimate of Rice Fields

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Introduction

Microclimate of rice fields affects the growth of rice through its physiological and ecological processes. Microclimate itself is also altered by the growth of rice, cultivation, soil conditions and water management.

The objectives of this report were to study the seasonal change of microclimate of rice field and to investigate the relation between the microclimate and cultivation, water managment and plant temperature of rice.

CHAPTER Ⅰ. **Seasonal change of the microclimate in a rice field**

Section 1. *Method*

Measurements were made in a rice field of the Yamagata University Farm located in the Shonai plain, Yamagata prefecture from 1965 through 1969. The rice (*Oriza sativa* L. var. Norin 41) was planted at a plant population of 64 plants per 3.3 m^2. Microclimatological factors measured were summarized in Table 1. These factors were measured in different growth stages.

Table 1. Microclimatological factors measured.

Factor	Measurement position
Water tomperature	2.5 cm above soil-surface (Water depth 5 cm)
Air temperature	5 cm, 10 cm, 20 cm, 50 cm, 100 cm, 150 cm (Above water surface)
Soil temperature	Soil-surface 5 cm depth 10 cm depth 20 cm depth
Solar radiation	10 cm, 40 cm, 130 cm, (Above water surface)
Reflectance	130 cm above water surface
Wind speed	150 cm above water surface

An additional measurement of direct solar radiation at noon was made, using NDR photo-copy paper. The directly radiated area near water surface was calculated. The plot was surrounded by the wind shelter when the measurements were taken, to prevent the rice plants from moving by wind.

Section 2. *Results and discussion*

1) Radiation balance for a rice field

Radiation balance for a rice field can be expressed as

$$R_N = =(1-a)R_S+R_e \qquad (1)$$

where R_N is the net radiation, R_S the incident short wave radiation, R_e the effective long wave radiation and 'a' the reflectance (albedo). R_e can be estimated from theoretical calculations, and R_S and 'a' can be measured.

The seasonal change of 'a' due to the development of vegetative cover has not been yet fully disclosed. Figure 1 shows the changes in the daily mean value of transmittance and the portion of direct solar radiation measured at the water surface as the rice grew. The daily average transmittance was 100% immediately after the transplanting. It decreased as the rice grew, becoming smaller than 50% when LAI was about 2 and being about 10% at the heading stage. It then increased in the period of grain-filling stage, as the lower leaves died to fall off. The portion of direct solar radiation changed in a similar manner to the daily mean transmittance.

Daily average reflectance of short wave radiation increased with the growth of rice plants, reaching the maximum value of 20% in the period of panicle pregnancy in the end of July. It declined after the heading. Diurnal change of the reflectance exhibits its maximum at noon, the trend being reverse of that of transmittance.

2) Air temperature between plants

The profiles of air temperature for each growth stage are given in Figure 2. The maximum temperature 3°C greater than the screen temperature, was observed near the water surface in the period of transplanting. In the period of panicle initiation (July 17) the maximum temperature, 3-4°C greater than the screen temperature, appeared both in the layer of 20-30 cm above the water surface and in the layer near the surfaces in the plant canopy.

Table 2. Correlation coefficients between the temperature at soil-surface or 10 cm depth and the screen temperature or the solar radiation.

Correlation coefficints between the soil temperature and the screen temperature.				Correlation coefficints between the soil temperature and the solar radiation.	
Soil surface		10 cm depth		Soil surface	10 cm depth
Maximum	Minimum	Maximum	Minimum	Maximum	Maximum
+0.706**	+0.968***	+0.957***	+0.967***	+0.483*	+0.509*

The maximum plant materials were attained in the period of panicie formation (July 27). In this period the high temperature region near the water surface

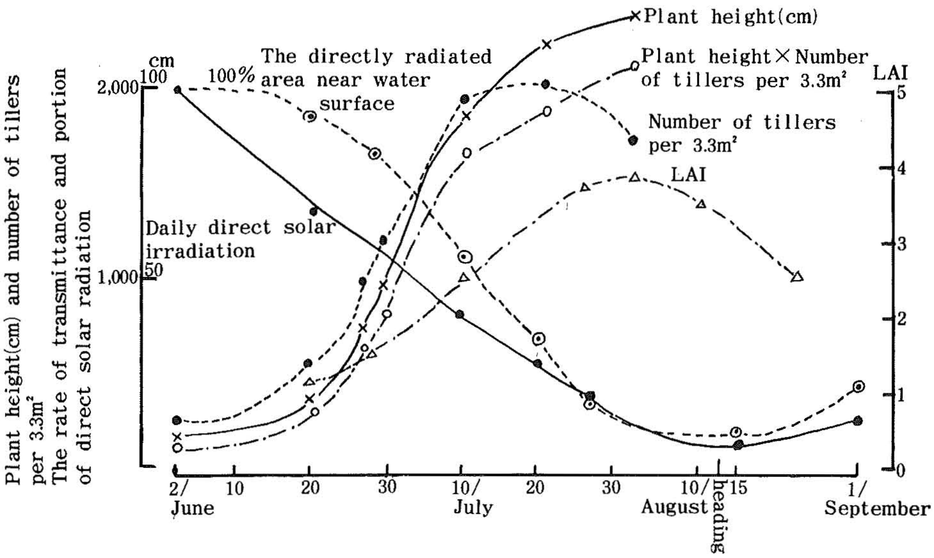

Fig. 1. The changes in the daily mean value of transmittance and portion of direct solar radiation measured at the water surface as the rice grew.

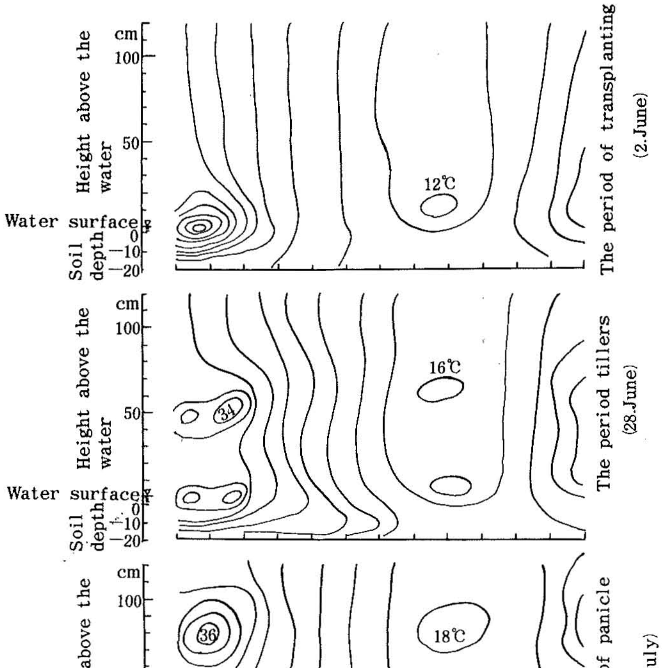

Fig. 2. Profiles of air temperature for each growth stage.

disappeared and the maximum temperature was seen only in the layer of 50-60 cm above the water surface where the canopy had its maximum plant materials. This means that less heat was received at the water surface. The high temperature region was formed near the heads, about 90 cm above the water, in the period of grain-filling stage (Sept. 2). The maximum temperature was only 1°C higher than that of screen temperature. This is the result from the lower solar altitude, with less solar radiation received.

The minimum air temperature between plants was 1°C lower than the screen temperature in each period. Its height observed was the same as the maximum air temperature.

The height of the largest amplitude of the air temperature was the same as that of the maximum temperature. It shifted upward, which indicates that the heat exchange at the water surface decreased as the canopy developed.

The vertical change in the amplitude of the air temperature is at first governed by the amount of solar radiation absorbed by the canopy and by the intensity of long wave radiation exchange at night. Absorption of solar radiation in the daytime and suppression of the long wave radiation exchange by the canopy increase with the development of the canopy. Secondly, it is influenced by the irrigation water which lessens the decrease of night time air temperature. Thirdly, the groth of the rice may affect the amplitude of the temperature, as the heat capacity and the heat exchange coefficient of rice changes with the plant materials above the ground.

3) Seasonal change of water and soil temperature

Water temperature was higher than both the air temperature between plants and the screen temperature in the early growth stages, by 4-7°C for the maximum temperature and by 2°C for the minimum temperature. Both heat loss and gain were small. However, the water temperature became lower than the air temperature between plants in daytime according to the growth of plants accompained by the incrase in LAI (leaf area index), except for a short period around noon. At night it was slightly higher than the air temperature between plants as the radiative cooling was depressed by the leaf canopy.

Figure 3 shows the ratio of water temperature to the maximum screen temperature for clear days (with solar radiation above 500 ly/day) of each growth stage. The ratio was 1.4, i. e., the water temperature was higher than the air temperature at the period immediately after transplanting. It decreased as the plants grew, being 1 after LAI became larger than 3. This trend corresponds to that of the protion of direct solar radiation at the water surface. The ratio decreases as the direct solar radiation at the water surface decreases.

Soil temperature both at the surface and at 10 cm depth increased as the canopy developed, reaching the maximum in August. The maximum temperature was higher than the screen temperature at the surface and it was lower at 10 cm depth. The difference of the screen temperature from the soil was larger for the surface in the early stages of growth and for 10 cm depth in later stages.

Correlation coefficients between the soil surface or 10 cm deep temperature and the screen temperature or the solar radiation are given in Table 2. The maximum temperature of both soil sufrace and 10 cm depth was more highly correlated to the screen temperature than to the solar radiation. This is particulary so for the temperature of 10 cm depth. Thus, the linear regression was obtained between these two quantities, which enables us to estimate the temperature of 10 cm depth from the screen temperature.

Correlation and linear regression coefficients between the water temperature and the screen temperature for days of different radiation level are summarized in Table 3. Minimum water temperature was more closely correlated to the screen temperature than the maximum one. The correlation coefficient between the maximum water temperature and the screen temperature was larger when the radiation level was low.

Table 3. Correlation and linear regression coefficients between the water temperature and the screen temperature for days of different radiation level.

Solar radiation	Temperature	Maximum temperature	Minimum temperature
≧5001 y/day	Water Soil	$Y=33.2+0.49(x-29.4)$ $Y=25.9+0.41(x-29.4)$	$Y=21.5+0.83(x-18.6)$ $Y=23.0+0.60(x-18.6)$
≦500≧300	Water Soil	$Y=28.5+0.60(x-27.1)$ $Y=24.2+0.36(x-27.1)$	$Y=21.3+0.69(x-18.0)$ $Y=22.7+0.40(x-18.0)$
≦300	Water Soil	$Y=25.8+0.82(x-25.1)$ $Y=23.0+0.47(x-25.1)$	$Y=20.9+0.78(x-18.6)$ $Y=22.0+0.62(x-18.6)$

Note : Y : Water temperature or soil temperature at 10 cm depth.
x : The screen temperature. (°C)

4) Seaeonal change of thermal properties and the soil heat flux of the rice field soil

The change of thermal diffusivity, soil heat flux and the soil temperature gradient with the growth of rice were studied.

PATTEN (1948) stated that the thermal diffusivity is more important in the heat exchange processes in the soil than the thermal conductivity. For a undisturbed soil layer with the volumetric heat capacity of C and the density of δ, the heat capacity C_r is given by

$$C_r=C\cdot\delta$$

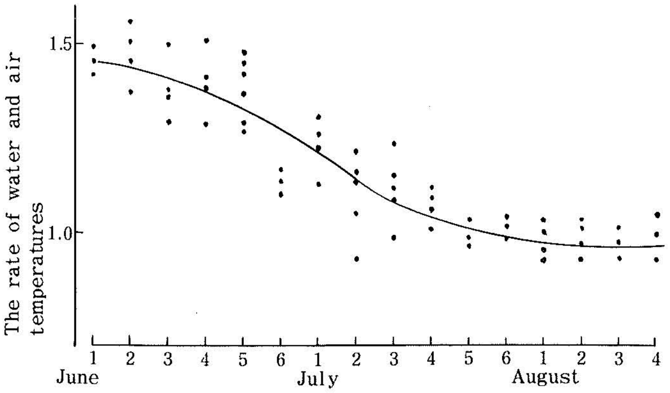

Fig. 3. The ratio of water temperature to the maximum screen temperature for clear days. (with solar radiation above 500 ly/day and concerning each 5 days mean temperatures.)

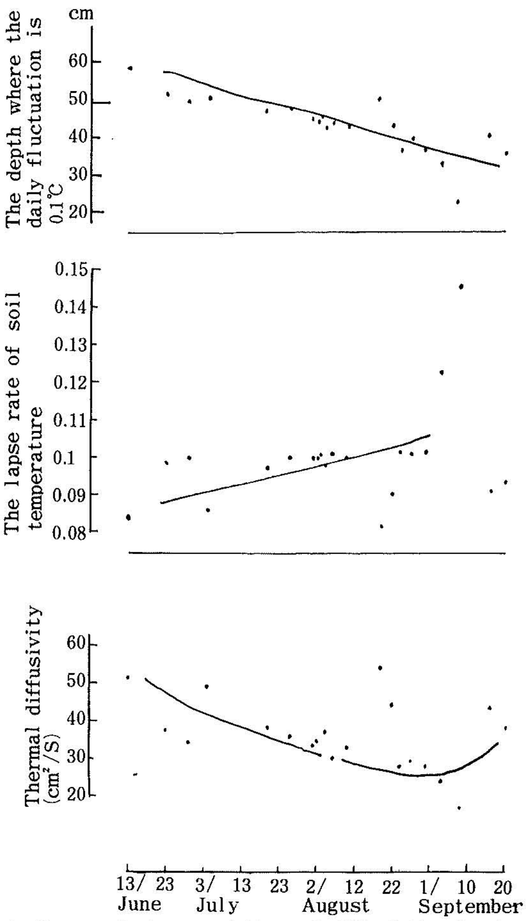

Fig. 4. Seasonal change of thermal diffusivity, the lapse rate of soil temperature and the daily fluctuation is 0.1℃.

Thus, the thermal diffusivity (α^2) is

$$\alpha^2 = k/C_r = R/C \cdot \delta$$

where K is the conductivity of the soil. There are many methods for calculating thermal diffusivity. SATO (1960) compared two methods, one using the amplitude and the other using the thermal properties and soil constituents. He concluded that the results from two methods for a rice field agreed.

In this investigation the following formula to calculate the thermal diffusivity (α^2) from the amplitude was used :

$$\alpha^2 = x^2M^2(\pi/T)/(\log R_o - \log R_x)^2$$

Where R_o is the amplitude of surface temperature, R_x the amplitude of the soil temperature at X cm depth, T the period of time (=one day 81,400 sec), and M the constant (=0.4343).

The soil heat flux G was calculated from the next equation :

$$G = \frac{C\delta H(\theta_2 - \theta_1)}{T_2 - T_1} \tag{3}$$

where θ_1 and θ_2 are the average temperature over H cm deep layer at the time T_1 and T_2 respectively, and C the average specific heat capacity, δ the density, and H the depth at which the temperature is constant for a day. The upward flux is defined as heat loss (−) and the downward flux as heat gain (+).

The daily amplitude of soil temperature decreases as the depth increases. The relation between the amplitude and the depth for a homogeneous soil layer can be expressed as

$$R_x = R_o \exp(-\beta x) \tag{4}$$

where R_x is the amplitude at X cm depth, R_o the amplitude at the surface and β the lapse rate of soil temperature. Figure 4 shows seasonal change of thermal diffusivity, soil heat flux and β calculated from eq. (2) through eq. (4). The thermal diffusivity at first decreased as the rice grew, increasing after grain-filling stage, so did the soil heat flux.

The increase in both thermal diffusivity and soil heat flux at the late grain-filling stage may be resulted from the increase of penetrated solar radiation due to the loss of lower leaves and from the decrease of soil water content brought about by draining water. β increased and the depth where the daily fluctuation is 0.1°C became smaller as the rice grew.

CHAPTER II. The influence of cultivating conditions on the microclimate of the rice field

Section 1. *Cultivating conditions and light environment*

The influence of leaf inclination, the amount of leaf and the plant type on the light environment was studied.

1) Methods

(a) Measurements in 1965

The measurements were taken in a field of Experimental Farm of Tohoku University Agricultural Research Institute, Kashimadai, Miyagi Prefecture. Two plots of rice (var. Fujisaka 5-go), one planted at a density of 64 plants per 3.3 m^2 and the other of 121 plants per 3.3 m^2 were used.

Solar radiation was measured by a tube solarimeter on the water surface, and the incident short wave radiation by a Noshidenshitype solarimeter set up at 2 m height above the water. The reflected solar radiation was measured by a Noshidenshi-type solarimeter facing downward.

All outputs were recorded on a recorder. Three points on a chart, taken in a period of 10 min, before the hour, were averaged to obtain the value in ly/min for each hour. Daily solar radiation was calculated by averaging hourly values over 6 JST (Japan Standard Time) through 18 JST.

To study the relation between the plant type and light environment, 5 varieties (Sasanishiki, Sasashigure, Fujisaka 5-go, Rikuu 132-go, and Kamenoo), Planted at a density of 64 plants per 3.3 m^2, were used in the experiment. Number of stems for each variety was equalized.

(b) Measurements in 1966-1968

The measurements were made in a rice field of Yamagata University Farm. Three plots of different canopy structures were prepared by applying three levels of nutrition : a low level, a standard and a high level plot.

Leaf area was measured by the photo-copy method and the angle of leaf inclination by the method of MATSUSHIMA (1965). Both long and short diameters of a cross section, assumed as an ellipse, at the heights of 10 cm and 30 cm above the base of top were measured as an indicater of the opening of a plant.

The penetrated direct light through a leaf was measured by a cadomium photocell attached to the lower surface of the leaf which was held parpendicular to the solar beam. The transmittance was then calculated by dividing it by the incident light above the leaf surface.

The thickness of the leaf was measured in terms of leaf area-fresh weight ratio. Absorptance of an 80% aceton solution, made by extracting chlorophyl out of 5 g flag leaf on the main stem, was measured at 665 mμ Wavelength by a Hitachi spectrophotometer and used as an index of chlorophyl content of the leaf.

2) Results and discussion

(a) 1965 experiment

The plant in the plot of 121 plants/3.3 m^2 (plot A) was 7 cm higher in average than the one in the plot of 64 plants/3.3 m^2 (plot B). The number of spikes were

1584 and 1533 per 3.3 m^2 in plot A and plot B, respectively. The LAI of plot A (4.19) was slightly higher than that of plot B (3.90).

Figure 5 shows the transmittance and reflectance of light around the heading stage. Daily average transmittance was smaller in the dense plot, about 13–15% at the heading stage, decreasing there-after. In the sparse plot (plot B) it was about 33% at the stage of heading, also decreasing there-after. MURATA et al. (1965) suggested that the decrease in transmittance after heading was caused by the presence of ears that change the structure of the canopy surface.

Daily mean reflectance tended to be smaller as the planting density increased ; 3 to 5 percents for plot A and 20% for plot B. Both reflectance and transmittance of plot A with larger LAI were smaller than those of plot B with smaller LAI, which means the dense canopy absorbs more energy than the sparse one.

The length and the inclination of three leaves from the top are given in Table 4, and the degree of opening of the plant in Table 5, both for the panicle pregnant period. The leaf inclination of plot A was smaller than that of plot B, particularly so for the flag leaf. Each leaf in plot A was shorter than that in plot B. The degree of opening, measured in terms of long diameter and short diameter of the ellipse at the heights of 10 cm and 30 cm adove the base of the top was smaller for plot A with fewer stems per plant than for plot B. The difference at two heights was also small for plants in plot A. The smaller

Table 4. The length and the inclination of three leaves from the top of rice plants.

		I	II	III
Inclination angle (o)	Plant population of 64 plants per 3.3 m^2	45.5	24.1	55.8
	Plant population of 121 plants per 3.3 m^2	23.3	14.7	40.7
Length of leaf (cm)	Plant population of 64 plants per 3.3 m^2	24.3	28.5	30.6
	Plant population of 121 plants per 3.3 m^2	23.6	27.6	30.3

Table 5. The degree of opening of the plant. (The panicle pregnant period)

	At the height of 10 cm above the base of tpo.		At the height of 30 cm above the base of top.	
	Short diameter (cm)	Long diameter (cm)	Short diameter (cm)	Long diameter (cm)
The plot of 64 plants/3.3 m^2	4.7	8.4	5.5	11.4
The plot of 121 plants/3.3 m^2	3.7	6.2	4.3	6.7

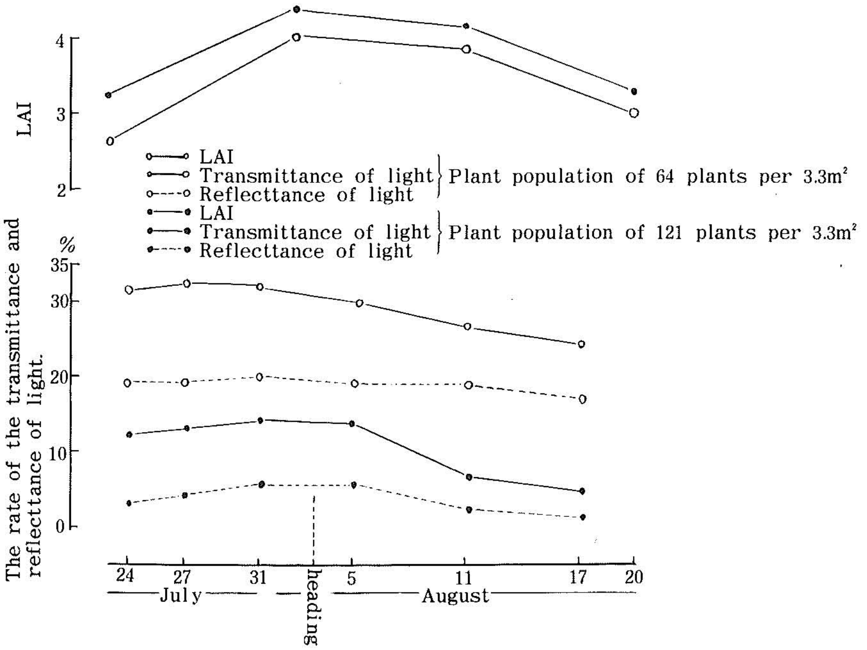

Fig. 5. LAI and the transmittance and reflecttance of light around the heading stage.

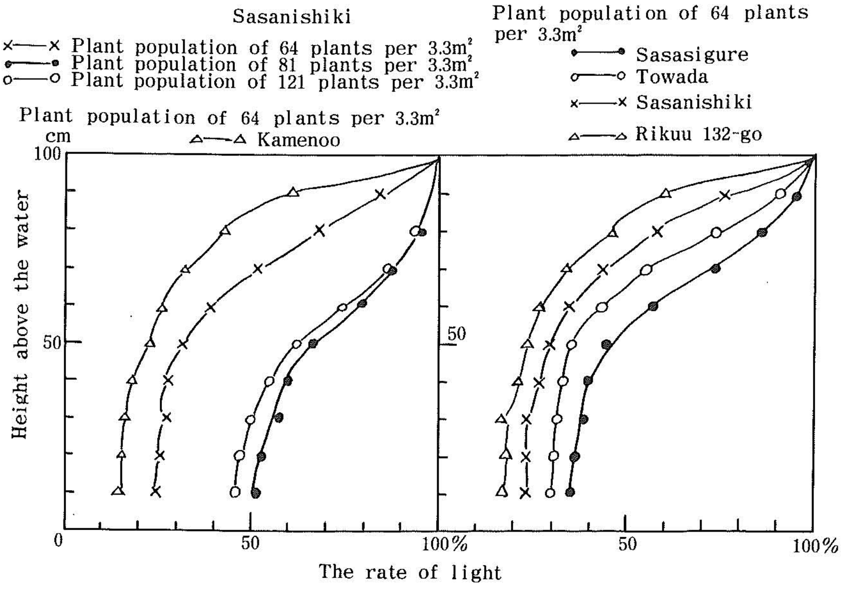

Fig. 6. The trnsmittance of light for each variety and plant population.

reflectance of plot A was, therefore, caused by the fact that the plant in plot A had more erect leaves and thus lower degree of opening.

Table 6. The reflectance for each variety.

Variety	Reflectance (%)
Towada	13.45
Fujiminori	14.30
Sasashigure	14.10
Sasanishiki	16.14
Konnoikusei	16.24
Rikuu 132-go	17.48
Kamenoo	17.68

The transmittance and reflectance for each variety, measured at solar noon on calm and clear days, are given in Table 6 and Figure 6. The transmittance decreased as the height from the water surface decreased. The difference in the transmittance among varieties can be appreciable at 10 cm height above the water surface where the transmittance of Sasanishiki, Towada, Rikuu 132-go and Kamenoo. The reflectance of Towada with short stems and erect leaves was smaller than that of Rikuu 132-go or Kamenoo with longer leaves of large curvature. Thus, the erect leaves let more light from the sky penetrate, compared to horizontal leaves.

The fact that the reflectance increases and the transmittance decreases as the leaf becomes more horizontal enables us to judge the canopy structure for light from the values of transmittance.

(b) Experiments in 1966-1968

To obtain rice stands of different canopy structure, plots of three nutrient levels, i. e., a low (L), a standard (S) and a hith (H) level plot, were made.

Both plant height and stem number were large in plots of higher nutrient level. Three leaves in the top were larger for the higher nutrient level plots. The LAI in the heading period was 5.3 in plot H, 3.5 in plot S and 2.3 in plot L.

The vertical distribution of the leaf area was measured. The layer of the maximum leaf area was 70-80 cm above the ground for plot H, 50-60 cm for plot S and 40-50 cm for plot L. This result may be attributable to the difference in the leaf length at each height caused by the difference of nutritions applied.

Light penetration after the heading declined as the grain-filling proceeded, decreasing rapidly especially in the plots of higher nutrient level.

Diurnal variation of the reflectance is shown in Figure 7. The reflectance was the smallest at noon when the solar elevation is the highest, being 13% in plot L and 22% in plot H. It was larger either in the morning or in the evening.

The transmittance of the leaf at the heading stage was lower as the nutrient level was higher. It was smaller for the leaves in the lower leaves. The transmittance reached its maximum at noon, being less affected by both the nutrient level and the leaf position. In the morning or in the evening when the solar energy received is less, the transmittance become smaller associated with more

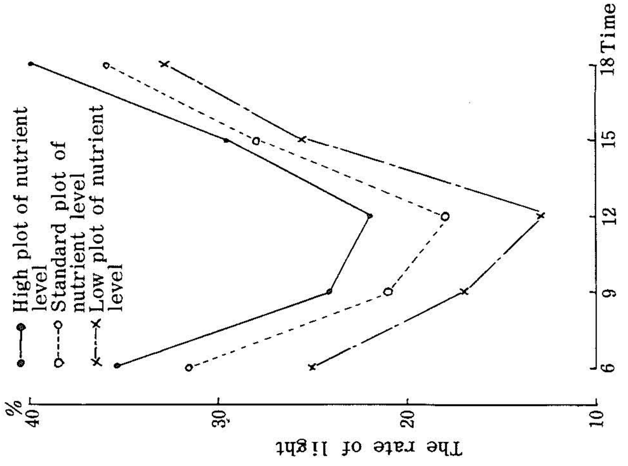

Fig. 7. Diurnal variation of the reflectance.

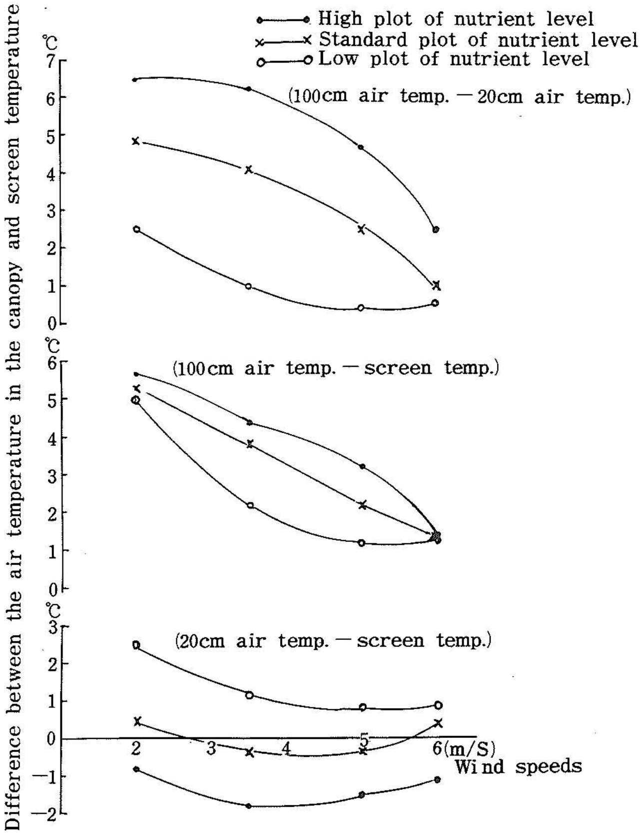

Fig. 8. Influences of the wind speeds upon the difference in the maximum temperature between the air temperature in the canopy and the screen temperature.
Note : Temp. : Temperature

differences among plots and leaf positions.

The transmittance of the leaf is affected by the amount of pigment content, thickness of the leaf and the structure of the leaf tissue. The lower transmittance in higher nutrient level plots may be resulted from higher chlorophyl content, since the chlorophyl content increased and the thickness of the leaf was reduced as the nutrient level increased.

Section 2. *Temperature environment as affected by the cultivation conditions*

Air temperature in canopies with different plant populations and nutrient levels were measured.

1) Methods

Three rice plots with plant population of 64 plants, 81 plants and 121 plants per 3.3 m^2 were used. The rice in all plots was planted in square. The temperature was measured at the heights of 10 cm, 30 cm, 40 cm, 60 cm and 80 cm above the water. Another three plots of high, standard and low nutrient levels were used to measure temperature at the height of 20 cm and 100 cm. The temperature was measured with a high sensitive thermometer (Iio Denki) in the early panicle formation period and in the heading period.

2) Results and discussion

The layer of the minimum and maxinmum temperature in the plots of different planting density was about 60 cm height above the water. This is the level just above the layer of maximum leaf, forming the second active layer for the temperature.

Comparison of the air temperature in the canopy with the screen temperature shows that the difference was lagest for the maximnm temperature. The difference in the minimum temperature was only 1°C. The difference in the maximum temperature among plots was greater at high wind speeds. The maximum temperature for the dense plots was higher at the of 100 cm, while it was lower at the height of 20 cm. The height of maximum temperature was near the top of the layer with the maximum leaf. The larger the leaf amount was, the higher the maximum air temperature was. The difference in the maximum temperature between the air temperature in the canopy and the screen temperature was on days of higher wind speeds, being about 6°C in the plot of largest leaf area (see Figure 8).

This temperature difference is close to the one measured by SATO (1960) in a rice field in Chikugo, Fukuoka Prefecture. The minimum temperature was less affected by the denseness of the canopy.

Heat balance is expressed as

$$R_N = L_O + lE_O + B_W \tag{5}$$

Each component of the above epuation is given as

$$R_N=(1-a)\,R_S-(1-c\bar{n}^2)\,\{\sigma T_a{}^4\,(0.39-0.058\sqrt{e}\,)\}$$

$$L_O=-(R_N+B_W)/(1+r),\ r=2\,\{e_Z-e\,(\theta_W)\}\,/(\theta_Z-\theta_W)$$

$$B_W=C\rho H\,(\theta_{W1}-\theta_{W2}),\ lE=-(R_N+B_W)r/1+r$$

in which R_N=net radiation, lE_O=latent heat flux, L_O=sensible heat flux, B_W=storage heat, 'a'=reflectance (albedo), R_S=total short wave radiation, T_a=air temperature in dgree K, e=water vapor pressure of atmosphere, $\bar{n}$=average cloud amount, c=0.6, σ=Stefan Boltzman's constant (=8.14×10^{-11} ly/min/°K^4), θ=water or soil temperature, H=depth of the water, $c\rho$=volumtetrice heat capacity of the water, e_Z=the vapor pressure at the height Z, $e\,(\theta_W)$=saturation vapor pressure at temperature θ_W.

The results calculated from the above equation are given in Table 7. Heat gain in the net radiation exceeded heat loss for the plots with larger leaf area. The same is true for the storage heat (B_W), but with smaller magnitude.

Table 7. Heat balance for rice field (ly/min).

Nutrient level		High				Standard				Low			
		R_N	B_W	L_O	l_E	R_N	B_W	L_O	l_E	R_N	B_W	L_O	l_E
Stage of panicle pregnancy (8. Aug.)	Heat gain	0.030	0.074	0.146	0.466	0.380	0.110	0.137	0.373	1.431	0.141	0.131	0.336
	Heat loss	-0.621	-0.017	-0.030	-0.012	-0.569	-0.020	-0.182	-0.232	-0.505	-0.033	-0.158	-1.244
Ripening stage (25. Aug.)	Heat gain	0.002	0.022	0.236	0.523	0.267	0.040	0.190	0.401	1.251	0.053	0.146	0.369
	Heat loss	-0.746	-0.036	0.000	0.000	-0.594	-0.048	-0.060	-0.180	-0.565	-0.067	-0.515	-0.771

Heat gain as the sensible heat flux exceeded heat loss for the plot of high nutrient level with larger leaf area. The trend is more evident at the stage of panicle pregnancy than the ripening stage. This may be explained by the difference in leaf area of the canopy that strongly affects the heat exchange in rice fields. The water surface was more shaded as the heading proceeded in the plot due to the loss of lower leaves.

The latent heat flux was greater than the sensible heat flux. Heat gain as the latent heat flux was greater than the heat loss for the high nutrient level plot, and was smaller for the plot of low nutrient level. Heat gain increased from the panicle pregnancy stage to the grain-filling stage, while heat loss decreased.

The negative latent heat flux means the heat loss as the evaporation at the water surface, the positive meaning the heat gain as dew formation. Heat gain by net radiation and heat loss by the latent heat flux were predominant in the daytime for a sparse canopy. At night most of the heat was lost by the net radiation and gained by the latent heat transfer. On the other hand, for a dense canopy, more heat was lost by the net radiation both in the daytime and at night, and heat gain by the latent and sensible heats increased.

CHAPTER III. **Thermal properties of a paddy field with plants**

Microclimate of a rice field is primarily determined by the macroscale climate and modified by the irrigation water and the growth of rice plants. In this chapter the relation between the amount of irrigation water, percolation and thermal state of paddy field soil is presented.

NAKAHARA (1942) found that the correlation between the rice yield and the soil temperature at 10 cm depth was the maximum. FUJIWARA (1954) pointed out the importance of soil temperature from the viewpoint of nutrient physiology. Recently, TAKAMURA (1961) and MATSUSHIMA (1964) revealed that the growth and yield of rice is strongly affected by the soil temperature.

Section 1. *Apparatus*

This experiment requires the apparatus that has no leak of water horizontally and can adjust the rate of vertical percolation. There-fore, a lycimeter, 3.3 m^2 of cross sectional area and 1.8 m deep was used. A block of 10 cm bentnite was planted on side walls for reducing water leak and heat loss through the wall. Sandy loam was then filled in the lycimeter. Vertical percolation was adjusted by discharging the water from the bottom. Surface water in the lycimeter was drained from the outlet at the same height of the ground surface.

Section 2. *Soil heat flvx in the soil as affected by the planting density and nutrient level.*

1) Methods

Rice was planted at a plant population of 121 plants per 3.3 m^2 (plot D) and 64 plants per 3.3 m^2 (plot S). Three nutrient levels ; high, standard, and low were imposed.

The soil temperature was measured and recorded at the surface, 5 cm and 10 cm depths with a Yokogawa Potentiometric Thermometer.

2) Results and discussion

The stem number in plot D at the maximum tillers stage was 2580 and 1660 in plot S per 3.3 m^2. The LAI was 4.7 in plot D and 3.3 in plot S.

The soil heat flux and thermal diffusivity were calculated from equations (2) and (3) for days with solar radiation above 500 ly/day. Both heat loss and gain decreased as the rice grew, reaching the minimum at the panicle pregnancy stage at which the LAI was the greatest. Both heat loss and gain were greater for plot S with lower LAI. The heat loss and gain in the rice field with vegetation decreased rapidly after LAI became greater than 2.0. The thermal diffusivity was greater for the plot D as compared with plot S.

Less growth and LAI were attained in the plots of lower nutrient level Soil heat flux decreased with the growth of rice, and was smaller for the higher nutrient plots. The thermal diffusivity was the smallest for plot H with largest LAI. This result is different from the one obtained in plant density treatment.

Therefore, it is concluded that LAI is not only one factor that affects thermal status of the rice field soil.

Thermal diffusivity on cloudy days was larger for the plots of higher nutrient level with larger LAI, to the contrast with the result on clear days. The reason may be as follows. On cloudy days low evaporative demand induces less water uptake by roots, and thus less water movement in the soil. This is particularly so for the plot of small LAI. Therefore, the higher thermal diffusivity, brought about by the slower water movement in the soil, is obtained for the plot of smaller LAI. This reasoning is supported by the fact that the difference in thermal diffusivity due to the difference in the LAI was larger for the middle of tillers stage as compared with the panicle pregnancy period when the water uptake by rice plants is the maximum.

Accordingly, it may be concluded that the soil heat flux is not only influenced by the transmittance but also by the water uptake by rice plants.

Section 3. *Heat transfer in a rice field as affected by the depth of water flooded.*

1) Method

Rice was planted at a density of 64 plants/3.3 m^2 in three plots : one flooded in 1.5 cm, the other in 4 cm depth, and the third without flooded. Soil temperature was measured in each plot, and soil heat flux and thermal diffusivity were computed from equations (2) and (3).

2) Results and discussion

The amplitude of soil temperature was larger for the non-flooded plot, since the maximum temperature was higher and the minimum lower for this plot. The temperature difference between two plots in the early growth stages was small as the heat gain at the soil surface was large due to the high transmittance. The decrease in the transmittance with the increase of LAI caused to reduce the soil temperature rise particularly when the water that has the large heat capacity is flooded in the plots. Heat transfer either as gain or as loss decreased as the rice grew ; larger for the flooded plot in the early growth stages and for the non-flooded plot later.

Thermal diffusivity was less for the flooded plot because of the high water content in the flooded soil.

The maximum water temperature was the highest for the plot of 1.5 cm water, the minimum being the highest for the plot of 4.0 cm water. Both soil and water temperatures difference among plots declined as the rice grew, being accompanied by the reduced transmittance. Therefore, the soil and water temperature were raised and thus the temperature amplitude was held large by the shallow water management in the early growth stages when the transmittance was large.

Section 4. *The relation between percolation rate and heat transfer*

Heat transfer in tne soil of rice fields without vegetation is studied by SUZUKI (1951) and YABUKI (1951). There are few investigations on the heat transfer in the soil of rice field witn vegetation, since one should use the plot that has the measures for adjusting percolation and for preventing horizontal water loss. The method to satisfy the above conditions is by use of lysimeter.

1) Experimental method

A 3.3 m^2 lysimeter, its percolation rate being regulated by drainage pipes at 2 m depth in the ground, was used in this experiment. Three levels of percolation rate, 3.7 mm/hr, 2.5 mm/hr, and 0.7 mm/hr were imposed and the mesurements were taken in the middle of tillers and panicle pregnancy periods.

Soil temperature was measured at the soil surface, 5 cm, 10 cm and 20 cm depths with a Iio High Sensitive Thermometer.

Rice, variety Norin 41-go, was planted at a Planting density of 64 plants/3.3 m^2.

2) Results

Thermal diffusivity computed from eq. (2) increased with the increase of percolation rate up to 20 mm/day, declining thereafter.

Section 6. *Heat transfer in soils of different textures.*

1) Experimental method

Heavy loam and coarse sand were mixed according to the following relative proportions.

Heavy loam	Coarse sand
40%	60%
60	40
100	0
0	100

The mixture was contained in pots of 1/2000-a and the surfaces were covered with the same field soils of 3 mm thickness to eliminate the influence of soil surface color on the temperature. The water surfaces were also covered with OED (evaporation retardant) films to lesson the difference in the water temperature due to the difference in evaporation.

Each pot was covered with stylo-foam and buried up to 80% of its height in the soil in order to eliminate the temperature effect of surroundings.

2) Restlts and discussion

Both the heighest maximum soil temperature and the lowest minimum temperature were obtained in the coarse sand plot. The amplitude of daily temperature cycle was the greatest at each depth in the coarse sand plot. Soil heat flux in the soil as both heat gain and as heat loss increased with the increasing proportion of coarse sand ; the same was true for the thermal diffusivity. The rate of soil temperature decrease, on the other hand, increased as the amount of heavy loam incresed (Fig. 9).

Thus the movement of heat in the rice field soil reaches deeper as the relative proportion of coarse sand increases.

CHAPTER IV. **Relation between the rice field microclimate and the plant temperature of rice**

There have been many studies on the influences of watter, soil and air temperatures on the growth and yields of rice. It has been reported that the soil and water temperature, particularly the temperature near the base of the stem where the growing poind locates, are the most important factor affecting the growth during the vegetative growth stages. However, few attempts have been made to measure the plant temperature itself. Since the plant temperature near the water and soil surfaces depends on net radiation exchange, sensible heat and latent heat exchanges and the conductive heat flow in the soil and water layers, it is closely related to the microclimate in the rice field.

Section 1. *Experimental methods*

Experiment 1 : Stem temperature of rice in natural conditions

Rice, var. Sasanishi, was grown in lysimeters under natural conditions. Two water treatments, a plot flooded with water of 1.5 cm depth (W) and a plot without flood (D) were prepared. Stem and air temperatures were measured at 1 cm above water surface for the plot W and above the soil surface for the plot D, when the 13th leaf and 15th leaf fully expanded. Additional stem temperature measurements were taken at 1 cm above the surface in shade and in sunlit for plot D.

Experiment 2 : Relation between the stem, soil, and water temperatures

Sasanishiki was grown in pots (1/5,000 a) during the period from transplanting time to 13th leaf stage. The pots were respectively placed in water tanks of which temperature were 30°C, 25°C, 20°C and 15°C in a glass house. The stem temperature was measured at 0.5 cm, 5 cm, 10 cm and 20 cm above the water surface. Pots were then placed in the water tank held constant at 25°C. The stem temperature at the height of 1 cm above the surface was measured for a flooded and non-flooded pots.

Experiment 3 : The corresponding change of plant temperature to the change in air temperature

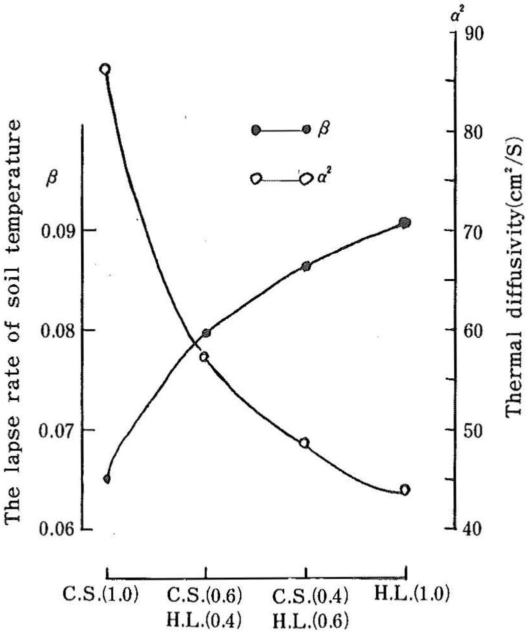

Fig. 9. Heat transfer in soil of different textures.
H.L. : Heavy loam C.S. : Coarse sand

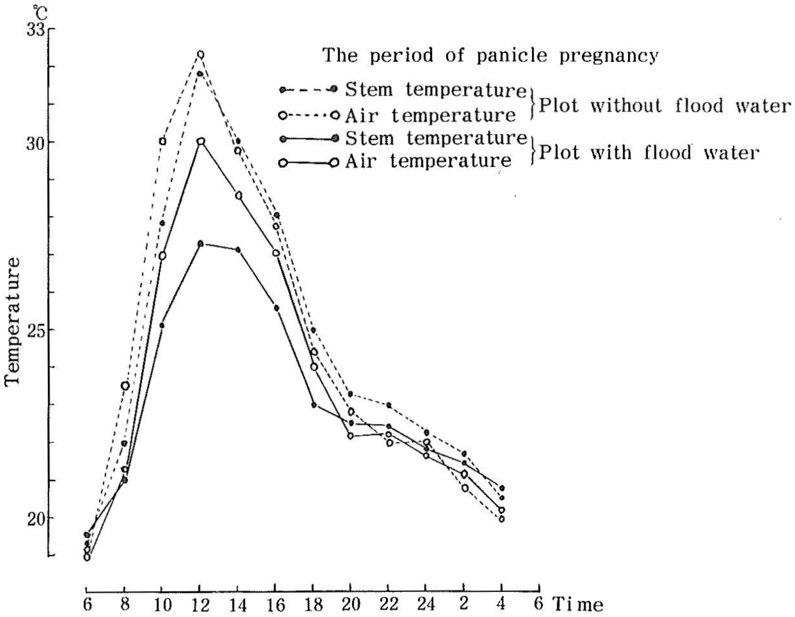

Fig. 10. The comparsion of the stem temperature at sunlit and under shade for the plot without flood water.

Leaf and stem temperatures on Sasanishiki, grown to the heading stage in pots (1/5,000 a) with sand, was measured by changing the air temperature from 15°C to 30°C at 10 minute intervals for three plots : a plot flooded, a plot not flooded, and a plot treated by wind of 2 m/sec.

Experiment 4 : Influence of transpiration suppression on the leaf and stem temperature

Sasanishiki at the 13th leaf stage was used. A part of the leaf and a stem up to 5 cm above the water was coated with 10% solution of OED Green. The temperature of the part coated by OED was measured in a phytotron. The stem of a field grown Sasanishiki was also treated likewise. The stem temperature was measured at 5 cm height above the water surface.

Experiment 5 : Influence of wind on the stem temperature

Stem temperature on the plant of panicle pregnancy stage was measured at 1 cm height above the surface at a windspeed of 2 m/sec and a light level of 50 klux. Two combinations of air temperature and humidity ; 29°C and 72%, and 17°C and 64%, were imposed. Temperature was measured by Cu-Co thermocouples of 0.1 mm diameter, with one junction inserted 1 cm deep in the stem, or taped on the middle of the lower surface of the leaf by a gam-tape of 2-3 cm long. This method gives close result to the one measured with infrared thermometers (NISHIYAMA, 1972). Assman psychrometer was used to measure air temperature and humidity.

Section 2. *Results and discussion*

Experiment 1 : Stem temperature of rice in natural conditions

Figure 10 shows the results obtained on clear days. Stem temperature in the plot D was higher than in plot H. The temperature difference between two plots was the greatest, about 1.7°C, when the air temperature reached maximum. Stem temperature was lower than the air temperature during midday period and slightly higher at night.

The comparison of the stem temperature at sunlit and under shade for the plot without flood water was given in Figure 10. The temperature of the sunlit stem was higher than the air temperature by about 2°C. In shade it was about 1°C lower than the air temperature. The difference was smaller both in the morning and in tne evening. It was concluded that the stem temperature in the day time is higher than the air temperature for the plot without flood water and for the plant in sunlit.

Experiment 2 : The relation between the stem temperature and soil or water temperature

Stem temperature was lower than the air temperature when the water temperature was lower than the air temperature, and it was higher than the air

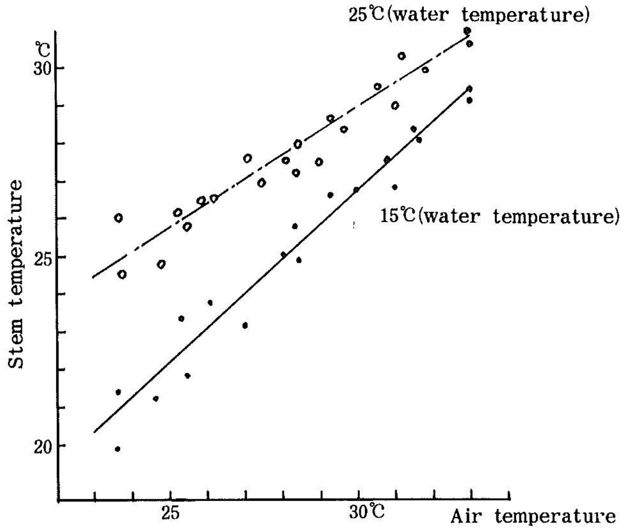

Fig. 11. The relation between the stem temperature at 5 cm above the water and the air temperature at 15℃ and 25℃ water temperatures.

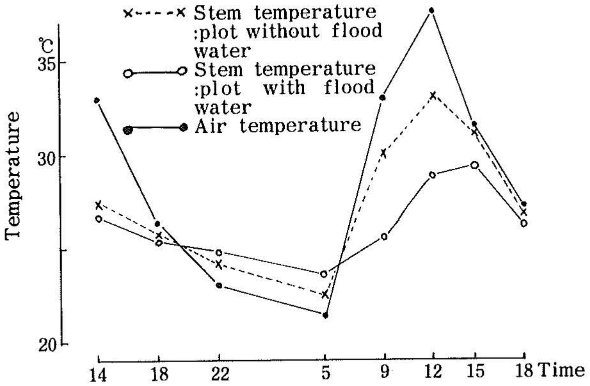

Fig. 12. Hourly change of the stem temperature for both plots with water and without at 25℃ water temperature.

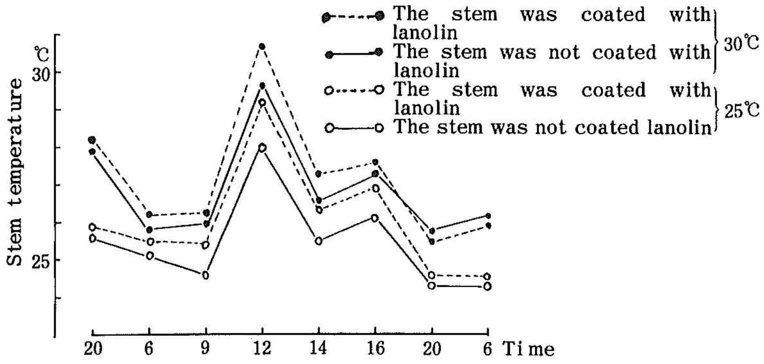

Fig. 13. The decrease in the stem temperature was reduced when the stem was coated with lanolin in the flooded plot.

temperature when the water temperature was higher than the air temperature. This trend was more evident near the water surface. The growing point of rice plant is located near the soil surface about 20 days before heading and thus being under direct influence of the water temperature. It then gradually moves upward to the above water surface, being influenced by the air temperature between plants. The results of this experiment may indicate that the growing point up to almost 10 cm above the water surface is under the influence of water temperature.

Figure 11 shows the relations between the stem temperature at 5 cm above the water and the air temperature at 15°C (L) and 25°C (H) water temperatures. The stem temperature in the plot H was always greater than in the plot L, the difference decreased when the air temperature was high.

Hourly change of the stem temperature for both plots with water and without at 25°C water temperature is depicted in Figure 12. the stem temperature at 1 cm height above the surface was higher for the plot without water as compared with the flooded plot. This result seems to suggest that the difference in the stem temperature between two plots (flooded and non-flooded) in experiment 1 was not resulted from the difference in soil temperature but was resulted from the difference in the heat exchange near the base of plant stem by flooding water.

Experiment 3 : The corresponding change of the plant temperature to the change in air temperature

Leaf and stem temperature was measured when the air temperature in the phytotron was varied rapidly from 30°C to 15°C.

Table 8. The temperature differences before and after treatments.

	A plot not flooded			A plot flooded			
	Temp. of the perpendicular leaf	Stem temp. (at 5 cm above the soil surface)	Soil-surface temp.	Temp. of the perpendicular leaf	Stem temp. (at 5 cm above the water surface)	Water temp.	Air temp.
Control plot	13.5	12.5	13.1	12.8	12.3	13.1	14.8
A plot treated by wind of 2 m/sec.	15.1	13.0	13.1	13.7	12.1	13.0	14.7

Note : Temp. : Temperature (°C)

The temperature differences before and after treatments were given in Table 8. The air temperature was quickly equated to the set temperature at 15°C. However, the change in the leaf and stem temperature was smaller than the change in the air temperature, the change of leaf temperature being less than that of stem temperature. This was more so for plot W as compared with plot D. It followed that the leaf temperature was more sensitive to the change of air temperature, particularly in plot D. The leaf responded more sensitively to the change of air temperature when wind existed. This may be due to the smaller heat capacity of the leaf accompained by the decreased water content of the leaf.

Experiment 4 : The influence of transpiration suppression on the leaf and stem temperatures

The results of OED Green treatment are given in Table 9. The leaf temperature increased as the light flux increased, especially so at low air temperature. In the dark, however, no effect of OED treatment was seen in both air temperature treatment. The stem temperature decreased witn decreasing light and air temperature. The decrease in the stem temperature was reduced by the OED treatment that decreased transpiration. The decrease in the stem temperature was reduced when the stem was coated with lanolin in the flooded plot (Figure 13). The decrease in the stem temperature was also reported by SATO et al). (1968). This phenomenon, in view of experimental results obtained here, may be explained from the latent heat loss both as transpiration of stem and as evaporation of water that ascended the stem by capillary.

Table 9. The influence of transpiration suppression on the leaf and stem temperatures.

	Illuminance (Klux)		Temp. of the horizontal leaf. (°C)	Stem temp. (°C)		Soil-surface temp. (°C)	Air temp. (°C)	Humidity (%)
				5 cm	1 cm			
				(At above the water surface)				
Control plot	High temp.	50	29.7	30.2	27.9	29.7	29.5	56
		30	28.6	29.7	25.0	28.7	29.5	57
		15	29.5	28.0	24.4	25.5	28.7	59
		0	27.6	27.3	23.7	25.0	27.0	62
	Low temp.	50	17.6	18.0	18.4	20.5	19.7	64
		0	13.7	13.7	13.7	15.0	14.0	58
A plot of OED Green treatment	High temp.	50	31.9	30.2	29.5			
		30	30.1	29.5	29.0			
		15	30.0	28.1	27.0			
		0	27.5	27.0	24.4			
	Low temp.	50	21.2	21.3	20.9			
		0	13.9	13.0	13.7			

Note : Temp : Temperature (°C)

Both the maximum and minimum temperature of the OED treated plant were 1-2°C higher than the plant without treatment in natural conditions.

Experiment 5 : The influence of wind on the stem temperature

The results from the experiments of wind treatment are given in Table 10. The decrease in the stem temperature was enhanced for both the high temperature/low humidlty plot and the low temperature/low humidity plot.

Table 10. (i) The influence of wind on the stem temperature.

			Stem temp. (°C) (At 1 cm above the water surface)	water temp. (°C)	Air temp. (°C)	Humidity (%)
Control plot	High temp. low humidity	A plot not flooded	27.2	29.3	28.0	72
		A plot flooded	26.0	28.7	28.7	
	Low temp. low humidity	A plot not flooded	16.7	17.5	17.2	64
		A plot flooded	16.1	17.0	16.6	
A plot treated by wind of 2 m/sec.	High temp. low humidity	A plot not flooded	28.2	28.1	28.8	
		A plot flooded	25.0	26.1	28.8	
	Low temp. low humidity	A plot not flooded	17.0	17.0	17.0	
		A plot flooded	15.1	16.8	17.1	

Table 10. (ii)

High humidity (92%)				Low humidity (50%)			
Control plot		A plot treated by wind of 2 m/sec		Control plot		A plot treated by wind of 2 m/sec.	
Stem temp.	Air temp.	Stem temp.	Air temp.	Stem temp.	Air temp.	Stem temp.	Air temp.
30.0	29.9	28.9	29.3	26.9	29.5	24.8	30.0

Note : Temp. : Temperature (°C)
Stem temp. : At 1 cm above the water surface.

The wind enhanced both evaporation and transpiration from the stem and thus lowered the temperature in the flooded plot. For the non-flooded plot the sensible heat exchange was enhanced, the stem temperature approching to the air temperature.

The decrease in the stem temperature was more profound for low humidity conditions as compared with high humidity conditions.

The growth stage in terms of LAI when the light level of 50 klux, used in this experiment, is attained in the field was determined as follows. The light level in rice canopies decrease as the canopy developes, according to the equation:

$$I = I_0 \exp(-0.42\,F) \tag{6}$$

where I is the light flux density on the ground below the canopy, I_0 the light flux density above the canopy and F the LAI.

LAI is calculated to be 2.61 when I_0 is equal to 50 klux on clear days, and 1.65 on cloudy days. This LAI corresponds to the middle of tillering stage. It has been pointed out that temperature fluctuation near the growing point of plants strongly affects the growth of rice. Since the temperature fluctuation at the surface decreases with the growth of rice plant, it is important to increase the plant temperature fluctuation by drainage when the growing point is located near the ground surface. MATSUSHIMA et al. (1964) have proposed the irrigation method for the regions of cold water in that the water is drained in the daytime and irrigated at night. This method is considered to be reasonable from the view point of plant temperature control.

CHAPTER V. **The relation between the yield of rice and the temperature and evaporation in Shonai.**

MATSUSHIMA (1964) has disclosed that there are optimum daytime temperature and optimum night temperature in each growth stage, pointing out that it is not reasonable to use daily mean temperature only for predicting the yield. He has also found that the temperature fluctuation is closely related to the grain-filling of rice.

It is known that the evaporatio is not only an index of overall climatic conditions but also is closely related to the transpiration and assimilation by rice crops.

In view of above results, the relations between the maximum and minimum temperature, temperature fluctuation, evaporation and the yield were studied.

Section 1. *Methods*

Three areas ; Shonai (Fujishima), the Murayama Basin (Yamagata) and Iwanuma in Miyagi Prefecture located in the coastal region of the Pacific Ocean, were investigated in this study. Shonai is located on the coast of the Japan Sea in Yamagata Prefecture.

Data are those from the rice yield prediction experiments and the meteorological observations by the Agricultural Experiment Station of each prefecture.

Section 2. *Results and discussion*

The relation between the yield and temperature is given in Table 11. The yield is correlated to the daily temperature fluctuation averaged over a month and the monthly maximum air temprerature of July for the Shonai Area. There is no correlation found in Yamagata.

Table 11. The relation between the yield and temperature.

		Air temperature (monthly mean)											
		Maximum				Lange				Mean			
		June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.
Yamagata	Short-term	0.235	0.079	0.031	0.322	0.235	0.079	0.031	0.322	0.012	0.314	0.083	0.322
	Medium-term	0.268	0.277	0.164	0.243	0.268	0.277	0.164	0.243	0.018	0.359	0.191	0.303
	Long-term	0.389	0.196	0.143	0.276	0.389	0.196	0.143	0.276	0.226	0.281	0.102	0.363
Fujishima	Short-term	0.213	0.249	0.234	0.139	0.491*	0.681**	0.308	0.326	0.091	0.216	0.074	0.073
	Medium-term	0.215	0.430*	0.361	0.346	0.203	0.595**	0.249	0.296	0.088	0.374	0.246	0.291
	Long-term	0.346	0.278	0.434*	0.332	0.374	0.665**	0.385	0.446*	0.104	0.445*	0.263	0.091

Tables 12 & 13 show the correlation between the temperature averaged over 5 days and the rice yield. The correlation between the temperature maximum or the fluctuation and the yield is the highest for the fifth 5 day period of July in the Shonai Area. In Iwanuma the high correlation was obtained for the sixth 5 day period of July.

Consequently, the higher maximum temperature from the fifth 5 dayperiod of July to the second 5 day period of August may result in the increase of the

Table 12. The correlation between the temperature averaged over 5 days and rice yield on Fujishima. (≧0.3)

		Air temperature (monthly mean)								
		Maximum			Minimum			Lange		
		Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term
July	1									
	2									
	3	0.425**	0.463*	0.378				0.394		
	4	0.380	0.414*					0.379		
	5	0.495**	0.613**	0.693**				0.667**	0.673**	0.827**
	6	0.381*	0.340	0.444*		0.395*	0.454*			
Aug.	1		0.382	0.548**						
	2		0.368	0.427**			0.401*			
	3		0.389*	0.416*				0.391*	0.385	0.437*
	4		0.319	0.452*						
	5									
	6		0.327	0.452*	0.345		0.317			
Sept.	1		0.439*	0.309	0.336	0.413*				
	2	0.462*	0.565**	0.475*		0.392*				
	3	0.312	0.441*	0.304						
	4		0.303			0.312				

Table 13. The correlation between the temperature averaged over 5 days and rice yield on Iwanuma. (≧0.3)

		Air temperature (monthly mean)								
		Maximum			Minimum			Lange		
		Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term
July	4	0.320				0.577**	0.386*			0.510**
	5	0.345	0.353		0.439*	0.480**	0.333		0.529**	
	6	0.487**	0.704***	0.638***		0.369			0.456*	0.389*
Aug.	1				0.526**					0.345
	2	0.731***	0.585***	0.654***	0.405*					0.374

rice yield. This period corresponds to the growth stage of reduction division stage (15-20 days before heading) at which the number of panicle is determined. According to MATSUSHIMA (1965), the rice is highly influenced by both the air and water temperatures, attaining the higher yield under the temperature of 31℃. This is because the high water temperature brings about the increase in the number of spikelet per panicle, in the weight per 1,000 grains and in the percentage of ripened grains.

High positive correlation between the yield and evaporation was obtained in the fifth and sixth 5 day period of July for the coastal areas in both Yamagata and Miyagi Prefecture (Table 14). This means that the rice growth at the

Table 14. High positive correlation between the yield and evaporation.

		Fujishima (Yamagata prefecture)			Iwanuma (Miyagi prefecture)		
		Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term
July	1						
	2						
	3		0.380*				
	4	0.380*				0.448*	
	5	0.412*	0.522**	0.427*	0.507*	0.466*	0.440*
	6	0.383*	0.522**	0.452*	0.659**	0.605**	0.622**
Aug.	1	0.382*		0.452*	0.505*	0.424*	0.514*
	2						
	3	0.401*	0.417*				
	4						
	5						
	6				0.500*		0.434*
Sept.	1						
	2		0.392*				
	3				0.517*		

Note : The temperature averaged over 5 days.

stage of reduction division under dry conditions results in a higher yield for fields in marine climatics.

Late July is the early panicle formation period of rice. The transpiration of rice is also vigorous under the meteorological conditions of high evaporation. It is followed by the increase of CO_2 uptake by plants that may result in the increase of photosynthate to be utilized in the growth of panicles. It is, therefore, concluded that the high yield can be attained by increasing plant temperature in the plot being drained, since the high daytime temperature in the period of reduction division stage is favorable for the rice growth in the fields of marine climate.

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摘　要

水田微気象に関する研究

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本論文は水稲の生育経過にともなう水田微気象の推移を群落構造の相異と光および温度の面から明らかにすると共に，水田微気象に対する灌漑水の意義ならびに水稲の体温に及ぼす影響を究明したものである．

1） 群落内の光透過率は葉面積の増加にともなって減少し，一方，光反射率は葉面積の増加にともなって増加する．

また，両者は葉面積のみならず，葉身の傾きならびに，株の開張度，品種によって影響され，葉身が直立的なものは光透過率が高く，反射率は小さくなる．

2） 群落内の気温分布はLAI 2位から二面の熱的能動層が形成されるが，さらに生育が進むにつれて水面近くの第一能動層は消失する．LAIの多い水田での第二能動層の最高気温は露場におけるものよりも約6°C高温となり，最低気温は約1°C位低温となる．さらに，風速が強くなるにつれて群落内外の気温差は小さくなる．

3） 水温の推移を露場気温とLAIとの関係から解析した結果，水温はLAI 3.0位から露場気温とほぼ同温となる．地温は生育初期には浅水湛水によって，生育後期には無湛水が高温をもたらす．

4） 水田地中の熱学的解析において，栽植水田においては水稲の蒸散量の多少が地中の動水勾配に影響し，地中の熱拡散率を左右する．

5） 水稲の葉鞘基部の体温は水温によって影響されるが，一般に気温よりも低く，無湛水によって昇温が認められた．その原因は葉鞘基部を上昇する水の蒸発による潜熱放熱の結果であることが知られた．

6） 東北地方の海岸水田における水稲収量は，幼穂分化期の最高気温との相関々係が高くなる．従って，この時期の葉鞘基部体温の上昇を計ることは増収をもたらす一因となりうる．