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Microclimate and Rice Production

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水稻作의 微氣象과 生産性

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ABSTRACT

Fluctuating climate is still most important environmental constrain, although improved modern agricultural technology has succeeded to increase crop production in the world. To stabilize the food production under fluctuating weather conditions, it is very needed to obain the quantitative information of interactions between crops and climate.

The main purpose of this paper is three hold. Using the JIBP-data, the dry matter accumulation of rice crops is studied in relation to weather indexes (ΣTa and ΣSt). Temperature dependence of the yield index of rice is analyzed as to air temperature and water temperature. ΣT_{10}-fluctuations are studied using meteorological data at various stations. The possible shift of ΣT_{10}-isopleths due to climate fluctuation is evaluated.

The second interest is in the plant climate of rice crops. Using results of canopy photosynthesis, it is pointed that the canopy structure has most important implication in plant climate. Leaf-air, stomatal, and mesophyll resistances of rice crops are described in relation to weather conditions. The change in light condition and aerodynamical property of rice crops with the growth is illustrated. The energy partition is also studied at different growing stages.

Third point is to show in more detail effective countermeasures against cold irrigation water and cool summer. Heat balance of warming pond and polyethylene tube as a heat exchanger is studied to make nomograms for evaluating the necessary area and necessary length. Effects of windbreak net on rice crops are illustrated by using experimental and simulation results.

INTRODUCTION

As well known, rice plants are indigenous to tropical and subtropical humid regions. Thus, rice plants need enough thermal resources and abundant water supply to yield good crop. Crop breeding and development of irrigation systems have succeeded to expand its boundary into the northern part of the middle latitude and into semiarid regions. At present, the rice cultivation has reached the region of about 50°N under continental conditions.

According to the FAO Production Yearbook, world acreage of rice planted in 1978 was about 145 million hectars. The world rice output (unhulled) exceeded 370 million tons. About 90 percent of the such vast rice production was produced in the Far East and southeast Asian countries, indicating that most inhabitants of these countries live on rice. Since rice plants are usually raised in flooded water

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and protected by water from the direct influence of unfavorable weather, the variability of rice yield is known to be small comparing with that for upland crops such as wheat, barley, soybean and so on.

However, statistical data show that the variability of rice yield reaches about 10 percent in the coefficient of variance. This is mainly because good crop needs a long growing season, air temperatures within physiological limits, sufficient solar radiation, and a large volume of rainfall evenly distributed over the growing season. On the other hand, it is recently asserted that climate or weather is becoming more variable, giving adverse effects on crop production. The above facts indicate clearly that climate is still an important environmental constraint to which rice crop respond closely. In order to prevent adverse effects of unfavorable weathers on rice crop and to stabilize the rice production under fluctuating climate, it is very important to understand quantitatively the interactions between rice plants and weather.

The main purpose of this report is three hold. The first point is to make clear the influence of weather factors on the growth and yield of rice crops, using the data mainly obtained through the JIBP. The variability of rice yield in Japan is studied in relation to weather conditions. Secondary, the interest is in the plant climate of rice crop, particularly in the mechanisms of exchange processes of energy and mass. The partition of solar energy in rice crop is also presented. The third point is to study in more detail countermeasures against unfavorable weather conditions for rice crop.

RICE PRODUCTION AND WEATHER CONDITIONS

Modern improved agricultural technology has made it possible to increase continuously the crop production in many countries, particularly in developed countries. However, crop production is still fluctuating year to year. This is cheafly because good crop needs specific combination and sequences of temperature, rainfall and solar radiation. In this chapter, the weather dependence of rice production is described with special reference to the climate fluctuation.

1. Influence of weather on growth and yield of rice crop

The data obtained during the period of the JIBP were analyzed in order to relate the dry matter production with weather conditions throughout its growing season (Uchijima, 1975).

In that study, the sum of daily solar radiation and the sum of daily mean of air temperature over the period after the transplanting of rice crops were adopted as weather indexes. Figure 1 is an example showing the dependence of the dry matter yield of rice crops on these climatic indexes. The dry matter accumulation over the growing period can be well approximated by

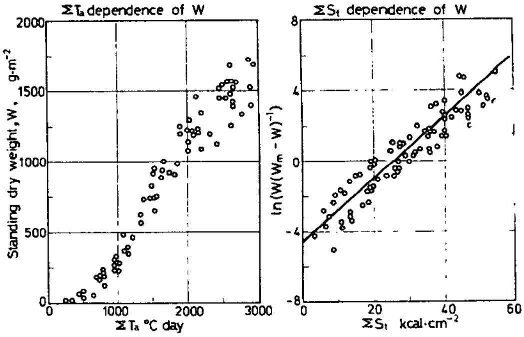


Fig. 1. Weather dependence of standing dry weight of rice crops (Uchijima, 1975)

$$W = 1.02 \exp (0.0033 \Sigma T_a)$$

$$\ln \left[\frac{W}{Wm-W}\right] = -4.23 + 0.00017 \Sigma St \quad ......(1)$$

where W is the dry matter yield of the rice crop measured at days after the transplanting (g/m^2),

Wm is the maximum dry matter yield to be achieved at the final stage of rice growth (g/m^2),

Ta is the daily mean of air temperature

(°C),

St is the daily solar radiation (cal/cm^2).

In a $\sum$ Ta range above 1,000°C day, the accumulating rate of dry matter of rice crop was nearly equal to 66 g/m^2/100°C · day. This accumulating rate was found to be between soybean (about 50 g/m^2/100°C day) and maize (about 90 g/m^2/100°C day).

Eq. (2) shows clearly that the relationship between the accumulation of dry matter of rice crops and solar radiation can be approximated by a S-shaped curve. This is presumably due to both extremely poor leaf area in the first stage and the decrease of photosynthetic activity of leaves and leaf area in the final stage. The following relation was found between CGR of rice crops and photosynthetic capacity index of the canopy ($I = S_t \cdot E_c \cdot (N/N_m)$, where S_t is the daily solar radiation (cal/cm^2), $Ec = (1 - \exp(-k \cdot f))$ is the absorptivity of radiation energy of rice canopy, N and Nm are respectively the total nitrogen content and its maximum in rice leaves, k is the extinction coefficient to be 0.65, F is the leaf area index of rice canopy) (Uchijima, 1975)

$$CGR = 0.7\exp(0.0069 \cdot I) \quad \text{......................} \quad (2)$$

The empirical relations deduced by analyzing the JIBP-data enble us to evaluate the dry weight of rice crops at the end stage of its vegetable growth from climatic data over the growing season, Murata (1971) pointed out that the dry weight at the end stage of its vegetable growth can be converted to its economic yield with acceptable error. Therefore, the empirical relations described above make it possible to evaluate the economic yield of rice crops from the climatic data.

As described already, rice crops are most sensitive to temperature and water supply throughout the growing season. The year to year fluctuation of temperature conditions during the growing season is most important factor affecting the rice yield. Statistical data of rice yield and weather conditions were analyzed to obtain the relationship between the rice yield and temperature conditions (Div. of Meteorol., NIAS, 1975).

The results were grouped for the each region as shown in Figure 2. As the average July and August air temperature [$T_{7,8}$] falls below a critical value, the yield index goes down rapidly independently of the regions. The critical temperature, at which the yield reduction starts, becomes large southwards from the Hokkaido to the Hokuriku. This is mainly because of the difference in the tolerance of rice varieties to low temperature among them. Namely, rice cultivars raised in the Hokkaido region are more tolerable to low air temperature compared them raised in the other regions.

Since young panicles of rice crops in its early stage are in the flooded water, the temperature of flooded water is an determinate factor of the growth and yield of rice crops. In Japan, many crop scientists have attempted to find out a critical water temperature below which the rice yield dimi-

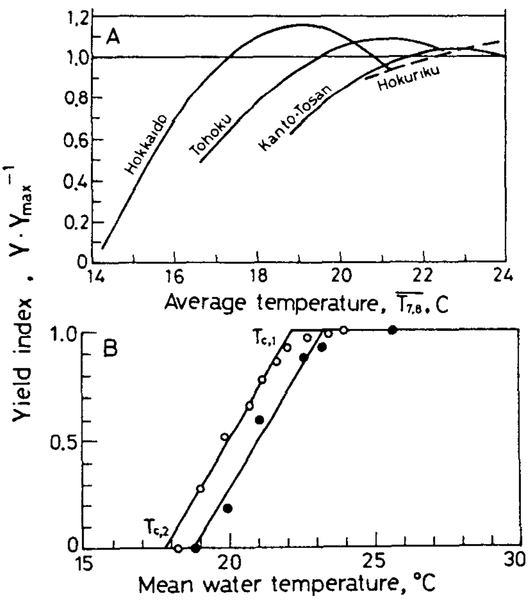


Fig. 2. A: Mean curve showing relationships between temperature conditions and yield index (Div. of Meteorol., NIAS, 1975),

B: Dependence of relative rice yield on mean water temperature.

nishes. One example showing the change in the rice yield with water temperature is illustrated in Figure 2-B. From this figure, we can define the two kinds of critical water temperature as follows:

$$T_{c,1} \leqq T_w \qquad IY = 1.0$$

$$T_{s2} \geqq T_w \qquad IY = 0.0$$

Therefore, the yield index in a range of water temperature between $T_{c,1}$ and $T_{c,2}$ can be expressed as follows:

$$IY = \frac{T_w - T_{c,2}}{T_{c,1} - T_{c,2}} \qquad T_{c,2} \leqq T_w \leqq T_{c,1} \text{..........} (3)$$

The critical water temperatures for the cultivars presented in Figure 2 are respectively as follows:

High tolerance cultivar

$T_{c,1} = 22.2$, $T_{c,2} = 17.8$°C

Middle tolerance cultivar

$T_{c,1} = 23.2$, $T_{c,2} = 18.8$°C

The information of critical water temperature for rice crops plays an important role in determining the necessary surface area of water warming pond and the necessary lengths of polyethylene tube and in evaluating the reduction rate of rice crop yield due to the application of cold irrigation water. Recently, rice breeders have concentrated their efforts into breeding rice cultivars with further lower $T_{c,1}$ and $T_{c,2}$

2. Variability of rice yield

As already pointed out by many researchers (e.g. Rauner, 1981; Uchijima, 1981), rice yield has a strong non-linear trend and large year to year fluctuation. It is possible to assume that the non-linear trend of rice yield is cheafly due to imporved agricultural technology and that the year to year fluctuation is because of weather fluctuation. To eliminate the influence of the non-linear trend upon the yield fluctuation, the following time series of yield index (IY(t)) were calculated.

$$IY(t) = \frac{Y(t)}{Y_T(t)} \text{ ....} (4)$$

where Y(t) is the original time series of rice yield (t/ha),

$Y_T(t)$ is the non-linear trend of rice yield (t/ha).

Uchijima(1981) approximated that original time series of the rice yield by polynomial to evaluate the non-linear trend.

Secular change in the rice yield index of representative Prefectures of Japan is presented in Figure 3. This illustrates clearly there is somewhat

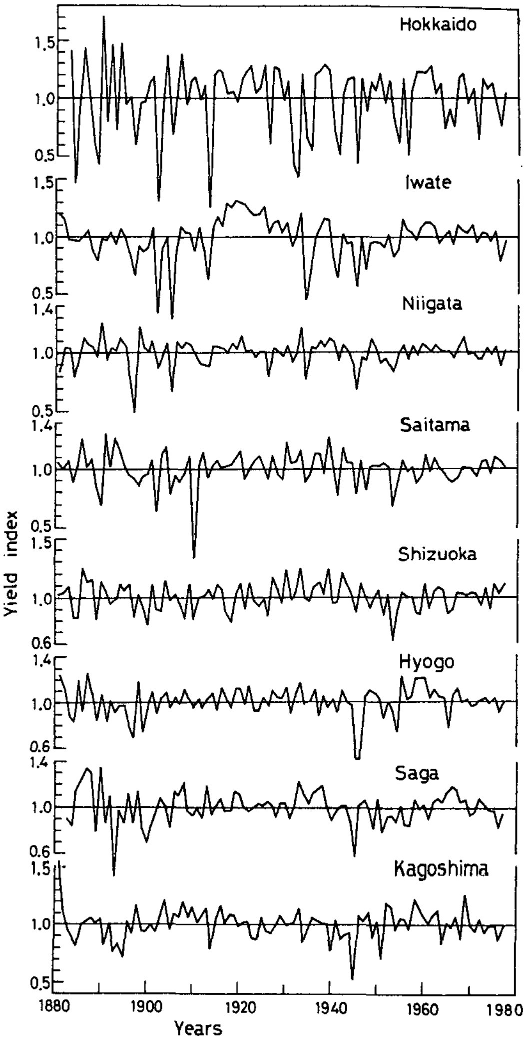


Fig. 3. Secular change in rice yield index of representative Prefectures (Uchijima, 1981).

large difference of rice yield variability among the Prefectures. In the Hokkaido and Iwate where thermal resources are somewhat insufficient for the stable rice cultivation and the rice production has been often affected by cool summer damage, IY(t) is considerably irregular with very distinct and sharp depressions. The magnitude of the irregularity of IY-time series was found to diminish considerably southwards from the northern part of Japan to the southern part. The standard deviation of IY-time series (σ_{IY}) is calculated to assess the magnitude of its irregularity and the results so obtained are presented as a function of both normal $[T_{7,8}]$ and standard deviation σ_T of average air temperature July to August in Figure 4.

The values of σ_{IY} decrease very rapidly, reach a minimum of about 0.1 at 25°C, and increase again very slowly with increasing $[T_{7,8}]$. This is mainly because the variability of $[T_{7,8}]$ time series is larger in the district with poor temperature resources than in the district with sufficient temperature resources. The dependence of σ_{IT} on the magnitude of σ_T is also presented in Figure 4. In a range of σ_T higher than 1.0°C, σ_{IT} goes up drastically with increasing σ_T. Similar results have been also reported by Hanyu and Ishiguro (1972) using the data of rice yield in the Hokkaido district. The relationships presented in Figure 4 are well given by

$$\sigma_{IY} = 2.752\text{-}0.1993\,[T_{7,8}] + 0.0000376\,[T_{7,8}]^2$$

$$\sigma_{IY} = -0.703 + 0.328\sigma_T - 0.0423\sigma_T^2 + 0.01776\,\sigma_T^3 \quad \cdots\cdots (5)$$

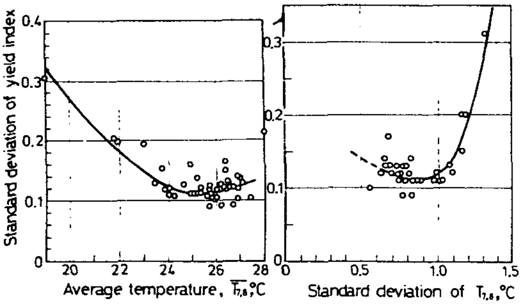


Fig. 4. Yield index fluctuation as a function of temperature conditions during rice growing period (Uchijima, 1981).

As seen in Figure 3, the secular change in rice yield index shows a slight difference in the pattern among the each Prefecture. To ascertain quantitatively the difference or similarity of the pattern of yield index fluctuations, the yield index data of the 47 Prefectures were processed by Maximum Enthropy Method for spectral analysis (Uchijima, 1981). Comparing the each spectral density curve so obtained, it was found that the spectral density patterns can be classified into the five groups such as the Hokkaido type, Tohoku type, Japan Sea coast type, southwest Japan type, and Okinawa type. The typical spectral density curves for the each type are reproduced in Figure 5.

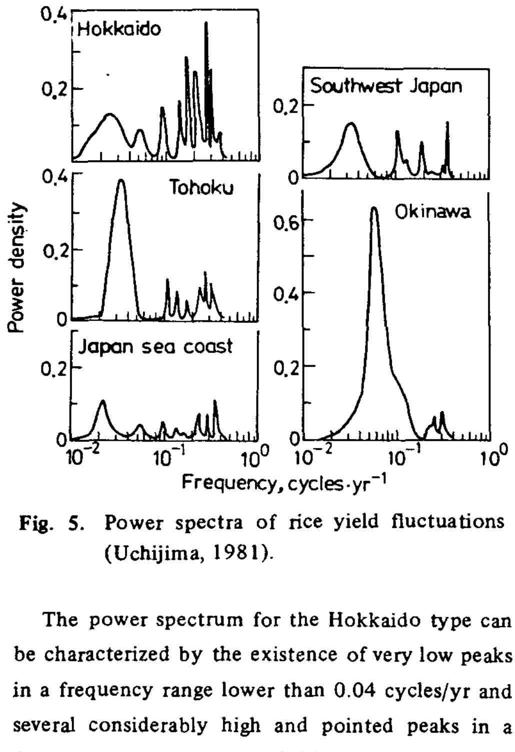


Fig. 5. Power spectra of rice yield fluctuations (Uchijima, 1981).

The power spectrum for the Hokkaido type can be characterized by the existence of very low peaks in a frequency range lower than 0.04 cycles/yr and several considerably high and pointed peaks in a frequency range between 0.05 and 0.4 cycles/yr. A highest peak with the period of about 4.3 years seems to correspond to cool summer damages of rice production at an interval of 4 or 5 years. The spectrum of IY-fluctuation for the Tohoku type has a distinct large peak in a frequency range lower than 0.05 cycles/yr. The spectrum density curve in a high frequency range above 0.1 cycles/yr has low and pointed peaks. The spectral curve of IY-fluctuation in the Prefectures located along Japan Sea coast are characterized by low density compared with them in other districts. The lowering of the spectral density implies evidently that climate prevailing in the Japan Sea coast during summer season is more favorable and stable for the rice cultivation.

Although the spectral curve in the southwest part of Japan has certain points of likeness to that of the Japan Sea coast type, the peak centered on the period of 30 years is two or three times as large as that for the Japan Sea coast type. The Okinawa type is observed only in the Okinawa Prefecture in which climate is subtropical and typhoon attacks frequently. Its spectral density curve can be distingished by the existence of a very pronounced paek at the period of about 19 years. It is reasonable to assume that the difference in the pattern of spectral density curve is closely related to the difference in climate variability among these regions. To investigate the interaction between climate and rice yield fluctuation, futher studies are needed in the fields of crop science and agrometeorology.

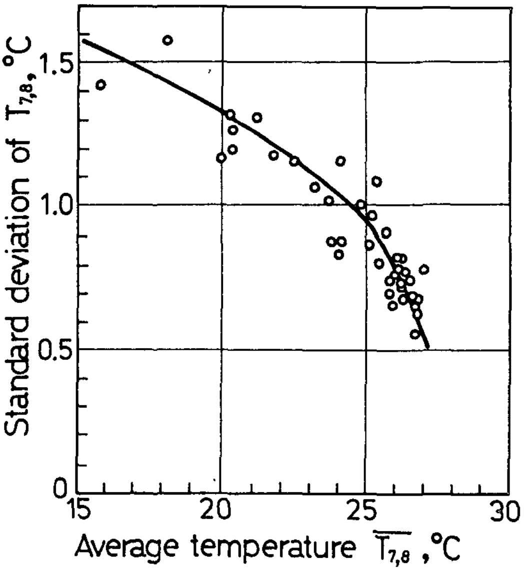


Fig. 6. Temperature fluctuation as a function of average temperature (Uchijima, 1981).

3. Variation in temperature resources

The year to year fluctuation of temperature resources is a most important factor affecting the fluctuation of rice yield in rice producing area located in high middle latitude and in mountainous regions. Iwakiri (1967) studied the year to year fluctuation of average air temperature July and August $[T_{7,8}]$ and found that CV of $[T_{7,8}]$ is larger in the Hokkaido (about 9%) than in the Kyushu (about 2%). By reprocessing Iwakiri's data, Uchijima (1981) obtained the results shown in Figure 6.

Standard deviation of average July and August air temperature σ_T decreased drastically with increasing $[T_{7,8}]$ from 1.5°C at $[T_{7,8}]$ of 15°C to 0.5°C at $[T_{7,8}]$ of 26°C. The dependence of σ_T on $[T_{7,8}]$ was well approximated by

$$\sigma_T = 0.679 + 0.124\,[T_{7,8}] - 0.0046\,[T_{7,8}]^2 \quad \cdots\cdots (6)$$

This has the implication that the northern district with poor temperature resources is also unfavorable from the standpoint of the stable production of rice. σ_T in the southern district of Japan with temperature resources as ample as those in the tropical or subtropical zone is one-third as large as that in the Hokkaido. However, the variability of rice yield seems to began to increase again slowly as indicated in Figure 4. This is presumably due to that an excess in temperature resources is associated with intensive loss of water during the rice growing season. This means that in these regions the timing, duration, and amount of rainfall becomes critical for rice crops.

Analysis of weather data is recently asserted that climate or weather is becoming more variable. Adverse effects of fluctuating climate on crop production is one of the biggest problems in applied meteorology in every country of the world. Uchijima (1976 a,b ; 1978) studied the secular change and the variability of accumulated effective air temperature, ΣT_{10}, representing the heat supply for crop growth. ΣT_{10} is defined as the total number of degrees over the period with daily mean temperature above 10°C.

To make clear characteristics of the secular change in ΣT_{10} in relation to the general change in climate, ΣT_{10}-time series at selected stations compared with the secular change in annual mean temperature, averaged over the Northern Hemisphere. The results are presented in Figure 7.

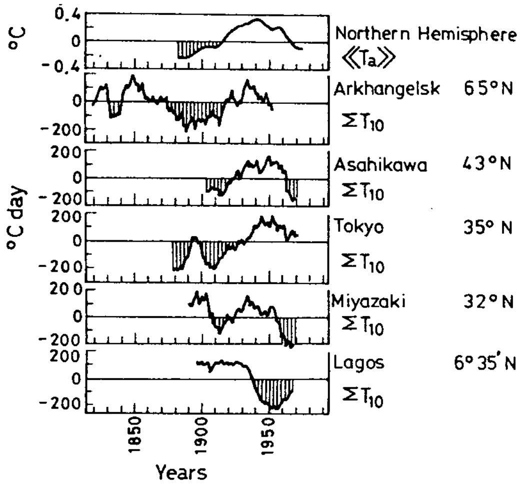


Fig. 7. Secular change in annual mean temperature $[[T_a]]$ (after Budyko, 1974) and in ΣT_{10} (Uchijima, 1978).

The each time series was smoothed by adopting 10 year running mean method to eliminate unnecessarily fine fluctuations and to visualize the general trend.

The distinct feature of this figure is that there have been clear systematic fluctuations in temperature resources for the past century. Although the secular change in ΣT_{10} of the latitudes polewards of latitude 30°N is in phase with that of $[[T_a]]$ reported by Budyko (1974), the secular change in ΣT_{10} in the equatorial zone is quite opposite to the fluctuation of $[[T_a]]$ in the phase. The temperature resources in all latitudes changed about 300 to 400°C day for the past century. In the latitudes polewards of latitude 30°N, ΣT_{10} has decreased clearly from the 1950's to the first half of the 1960's. Recent weather data, however, indicate that the decrease of temperature resources seems to cease or to start to increase in the 1970's.

To eliminate errors relating to the topographical conditions, ΣT_{10} data from meteorological stations with the altitude above 150m were excluded from the analysis. The data so obtained were used to study the latitudinal change in ΣT_{10} (Uchijima, 1976 a, 1978). The latitudinal change in ΣT_{10} was well approximated by

$$[\Sigma T_{10}] = 10663 + 41.1\varphi - 9.0\varphi^2 + 0.096\ {}^3$$
$$0 < \varphi < 60° \quad \cdots\cdots (7)$$

where $[\Sigma T_{10}]$ is the zonal mean of ΣT_{10} (°C day),
φ is the latitude on the Northern Hemisphere (degree).

Eq. (7) shows that $[\Sigma T_{10}]$ decreases drastically with increment of the latitude from about 10,000°C day in the equatorial zone to about 1,500°C day in the higher middle latitude zone.

In order to assess the shift of the isopleths of ΣT_{10} with fluctuations of climate, the following relation was deduced from Eq. (7) (Uchijima, 1976 a)

$$\Delta\varphi = A\,(1 - Z)\,[\Sigma T_{10}] \quad \cdots\cdots (8)$$

where $\Delta\varphi$ is the shift of isopleths of ΣT_{10},
τ_0 is the return period (years),
$CV_{\Sigma T}$ is the coefficient of variation of ΣT_{10} -fluctuations,
A and Z are respectively given by

$$A = -1.96 \cdot 10^{-2} + 5.16 \cdot 10^{-6}\,[\Sigma T_{10}] - 3.96 \cdot 10^{-10}\,[\Sigma T_{10}]^2$$

$$Z = 1 \pm \frac{\tau_0}{370 + 40.8\tau_0}\,CV_{\Sigma T}$$

The results calculated from Eq. (8) are presented in Figure 8. The value of Z larger than unity implies that climate becomes warm and the isopleths of ΣT_{10} shift northwards, while a value of Z below unity causes a southward shift of isopleths of ΣT_{10}. Use of Figure 8 makes it possible to predict a northward or southward shift of ΣT_{10}-isopleths due to change in general climate. As shown in Figure 8, the possible shift of ΣT_{10}-isopleths with climate fluctuations is lowest between 25° and 32°N, implying that the influence of change in ΣT_{10} upon

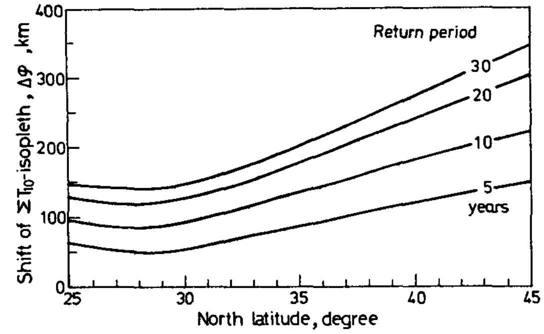


Fig. 8. Shift of ΣT_{10}-isopleth with climatic change characterized by different return period (Uchijima, 1976 a, 1978).

rice production is not very large. In latitude polewards of 32°N, the possible shift of ΣT_{10}-isopleths increases linearly with increasing the latitude. Independently of the latitude, the possible shift of ΣT_{10} isopleths becomes large considerably with the increment of the return period characterizing an unusual weather to be expected once in years. If an unusual weather with the return period of 30 years occurred, the isopleths of ΣT_{10} in southern, middle, and northern parts of Japan should shift southward or northward by about 150, 200, and 300 km from its normal positions, respectively. The southward shift of ΣT_{10}isopleths implies the decline of temperature resources at any station. In the regions northern than 35°N, such a decline of temperature resources should have adverse effects on the growth and yield of rice crops, particularly in the Hokkaido, Tohoku, and mountainous regions.

MICROLIMATE OF RICE CROPS

During the growing season, rice crops exchange vigorously energy and mass through its leaves and root systems with the sourrounding environment. Absorption and reflection of solar radiation energy by the leaves play an most important role in the energy exchange. Air mixing in the surface air layer including the rice canopy layer has a decisive influence on the exchange of carbon dioxide, oxigen, and water vapor closely relating to the physiological activity of rice plants (Inoue and Uchijima, 1979; Inoue, 1981).

With the growth of rice plants, the numbers of the stems and leaves of rice increase, resulting the continuous increment of the canopy height and leaf area index. Since plant leaves act to air flow as an obstacle by which absorbs strongly the momentum, the aerodynamical characteristics of rice crops change necessarily gradually with the growth of rice plants. The change in the aerodynamical characteristics gives in turn substantial influence upon the exchange processes. From the above description, it is easily understood that the rice crops and the surrounding environment are associated with the each other through so-called the action and reaction coupling, building up the plant climate. The following factors have most important implication in building up the rice plant climate:

1 : canopy structure,.
2 : vertical distribution of solar energy in the canopy,
3 : vertical distribution of turbulent transfer coefficient in the canopy.

1. Canopy structure of rice crops

Since Monsi and Saeki's epoch-making paper (Monsi and Saeki, 1953), the relationships between photosynthesis and canopy structure have been one of the important subjects in plant ecology. A great number of both theoretical and experimental studies have been done on this problem and brought about the plant type concept in the crop breeding (e.g. Tsunoda, 1964).

Ito, Udagawa, and Uchijima (1973) and Udagawa, Ito, and Uchijima (1974 a, b) measured comprehensively the canopy structure of rice crops at the different growing stages. Figure 9 shows the change in the layer's leaf inclination-density function of rice crops with the development of plants. In this figure, x represents the "leaf-area inclination index" characterized by

$$x = 0.5\ [\,(0.13 - g_1) + (0.37 - g_2) + (0.50 - g_3)\,]$$

where g_1, g_2, and g_3 are respectively the leaf area fraction of the inclination angle intervals, 0° - 30°, 30° - 60°, and 60° -90°

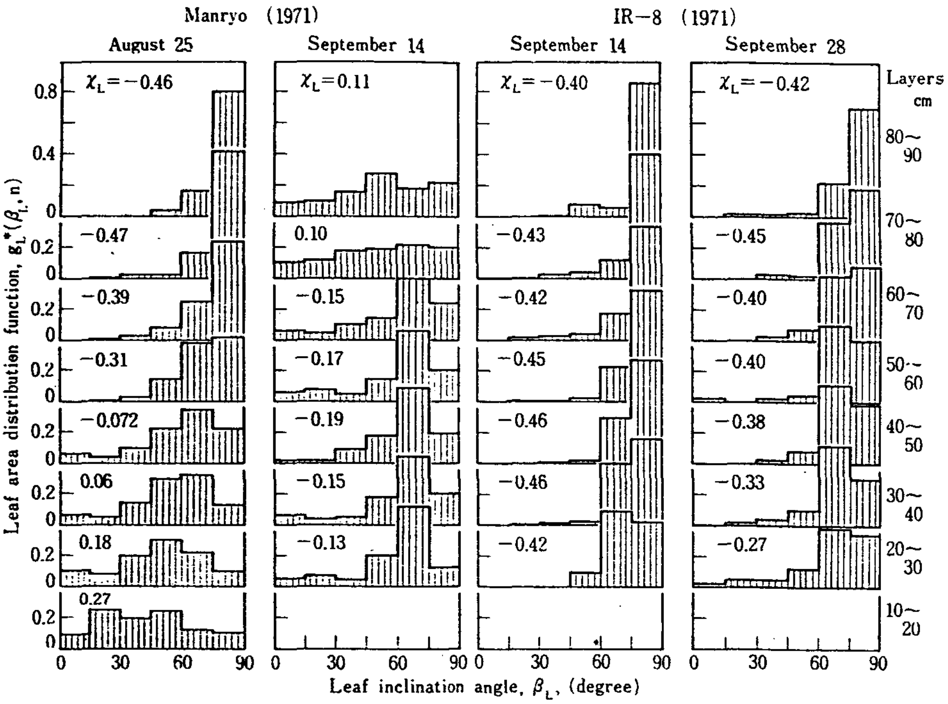


Fig. 9. Layer's leaf inclination-density function of rice cultivars (Ito, Udagawa and Uchijima, 1973).

Negative value of x indicates that a plant canopy mainly consists of erect leaves, while positive denotes a plant canopy composing of horizontal leaves. As shown in Figure 9, the cultivar IR-8 retained an erect leaved canopy throughout the whole growing season, while the canopy structure of the Manryo cultivar changed from the typical erectophile structure to the plagiophile type. Particularly, the leaf arrangement in the upper layer of the canopy changed from the erect type to the horizontal one. This was mainly due to the development of the flag leaves and ears.

They calculated extinction coefficients for direct solar radiation, diffuse solar radiation and total short-wave radiation, respectively, using the data of layer's leaf inclination density function of the two cultivars. The results showed that the extinction coefficient for total shortwave radiation (Kt) is not very different between the two cultivars and decreases monotonically from about 0.9 at sun elevation of 10° to some 0.3 at sun elevation of 70°.

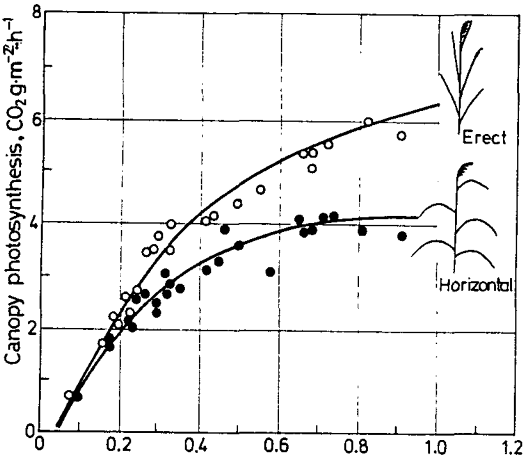


Fig. 10. Effect of canopy structure on canopy photosynthesis of rice crop (Tanaka, 1972).

Theoretical study of canopy photosynthesis has revealed that photosynthesis of plant canopy with leaf area index above 3.0 is higher for an erect-leaved canopy than for a horizontal leaved canopy Tanaka et al. (1968) reported that a recent high yielding variety of rice crops has smaller extinction coefficient compared with old varieties with low yield capacity. Tanaka (1972) has demonstrated, by mechanically manipulating the leaf arrangement of a rice canopy, how the leaf inclination angle influences canopy photosynthesis. Figure 10 shows his interesting results. An artificially horizontal leaved canopy shows a plateau type response of photosynthesis to solar radiation, while an originally erect leaved canopy has higher photosynthesis. The yield of the mechanically manupulated canopy was about 70 percent of that of the erect leaved rice canopy, agreeing well with theoretical results (76%) proposed by Tooming (1977).

2. Diffusion resistance of rice crops

In analogue to Ohm's law in electricity, the flow of carbon dioxide and water vapor between the surrounding air and plant leaves can be expressed as follows:

$$P = \frac{Ca - C\iota}{r_a + r_s + r_m}$$

$$E = \frac{a(T\iota) - a_a}{ra + rs'} \quad \text{.......................................} \quad (9)$$

where P and E are respectively the flux densities of carbon dioxide and water vapor (g CO_2/cm^2s, g H_2O/cm^2 s),

Ca and Cι are the carbon dioxide concentration in the air and in the photosynthetic center of leaves, respectively (g CO_2/cm^3),

a_a and a(Tι) are the absolute humidity in the air and the leaves, respectively (g H_2O/cm^3),

r_s and r_s' are the diffusion resistance for carbon dioxide and water vapor through stomatal opening (s/cm),

r_m is the mesopyll resistance in leaves (s/cm).

Although a great number of studies have been made to elucidate the relationships between these resistances and affecting factors, study of relationships between diffusion resistances of rice crops and environmental conditions seems to be not as comprehensive as might be desired. Recent attempts in making the working models of photosynthesis and transpiration of rice crops have facilitated the study

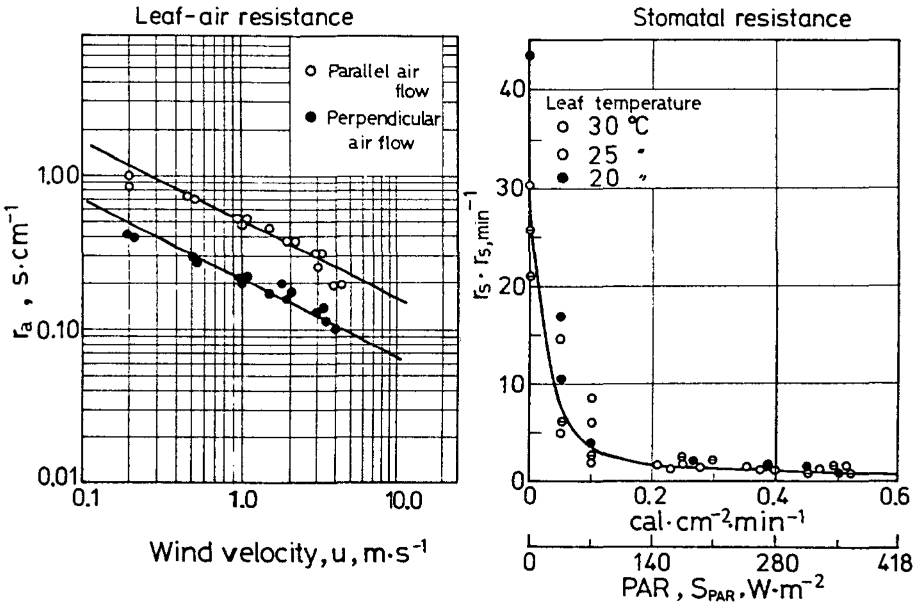


Fig. 11. Left: Wind dependence of leaf-air resistance,
Right: PAR dependence of stomatal resistance (Horie, 1981).

of diffusion resistances of rice crops.

Horie (1981) carried out comprehensive measurements of diffusion resistances of rice crops in relation to environmental conditions. He used the results to make the simulation models of photosynthesis, transpiration and growth of rice crops. Using the ordinary method for determining leaf-air resistance (r_a) and stomatal resistance (r_s), Horie studied the dependence of the resistances upon wind velocity and photosynthetically active radiation flux density (PAR). His results are reproduced in Figure 11. The leaf-air resistance of rice leaves decreased with increasing wind velocity, indicating that the thickness of the boundary layer over the leaves becomes thin. The wind dependence of r_a was found to be approximated by

$$r_a = k\,U^{-\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where U is the wind velocity (cm/s).
k is a proportionality constant to be 2.1 and 5.3 respectively for leaves perpendicular and parallel to wind flow.

Since wind is blowing generally horizontally, the leaf-air resistance of erect rice leaves is expected to be smaller than that of horizontal leaves. As already described, stomatal resistance of plant leaves is mainly controlled by the magnitude of stomatal opening. Stomatal opening of plant leaves is known to change with water potential in plants and radiation flux density impinging on leaves. It is reasonable to assume for rice crops raised usually in flooded water that radiation flux density is a most important factor controlling the stomatal opening of rice crops, consequently the stomatal resistance. The dependence of r_s on PAR-flux density is presented in the right hand side of Figure 11. r_s decreased firstly very drastically with increasing the PAR-flux density and approximated to minimum in a PAR-range over 0.3 cal/cm^2 min. This relationship between r_s and PAR-flux density was well approximated by the following exponential relation (Horie, 1981).

$$r_s = r_{s,\,min} + (r_{s,\,max} - r_{s,\,min})\exp(15.2 \cdot S_{PAR}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

where $r_{s,max}$ is the maximum of r_s under dark conditions (s/cm),
S_{PAR} is the PAR flux density impinging on leaf surface (cal/cm^2 min).

Eq. (11) can be applied for assessing the stomatal resistance of rice leaves, independently of leaf temperature.

Mesophyll resistance affecting the photosynthetic absorption of carbon dioxide by leaves is a complex quantity consisting of three components as follows:

$$r_M = r_m + r_e + r_c$$

where r_m is the diffusion resistance in parenchyma cells (s/cm),
r_e is the excitation resistance (s/cm),
r_c is the carboxylation resistance (s/cm).

By processing experimental data of rice leaves, Horie (1981) obtained the following relation.

$$r_M = \frac{\epsilon}{S_{PAR} - S_{PAR,C}} + r_{mo} \quad \ldots\ldots\ldots\ldots \quad (12)$$

where $S_{PAR,C}$ is the PAR-flux density at which photosynthesis becomes null (cal/cm^2 min),
r_{mo} is the minimum of r_m under extremely high PAR (s/cm).

Eq. (12) indicates evidently that r_M is a deterministic component on which the photosynthetic absorption of carbon dioxide depends closely. Horie (1981) showed that Eq. (12) can be also applied to sunflower and maize plants, with a little change in a constant

Because physical and chemical activities in leaves relate closely with leaf temperature, r_m of leaves should have a close correlation with leaf temperature. Using the leaf chamber method for determining photosynthesis and transpiration, Horie(1981) studied the temperature dependence of r_M. The results are reproduced in Figure 12. Although r_s is independent of leaf temperature, r_M shows a close

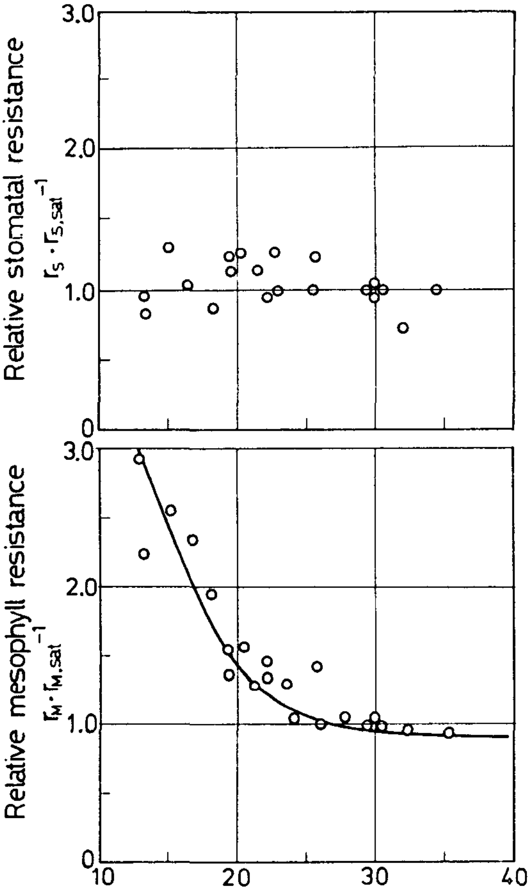


Fig. 12. Dependence of r_s and r_M on leaf temperature of rice crops (Horie, 1981).

correlation with the leaf temperature, particularly in a range below 20°C. In a leaf temperature range above 25°C, r_m is retained at a constant level of $R_{M,SAT}$. The above relation was well approximated by

$$r_M = r_{m,SAT}\;[\;1 + 47\exp(-0.23\cdot T_l)\;]\;........(13)$$

where T_l is the leaf temperature (°C).

It can be concluded from Eq. (13) that the photosynthetic activity of rice leaves goes down considerably with decreasing the leaf temperature in a range below 20°C.

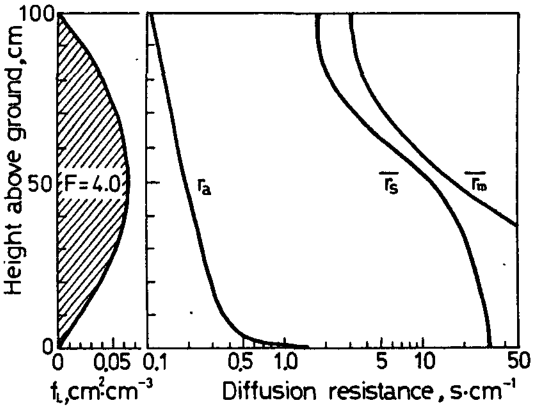


Fig. 13. Simulated profiles of three diffusion resistances in model rice canopy (Horie, (1981).

Since mean radiation flux density impinging on leaves decreases rapidly with the distance downward from the canopy top, giving the influence on the leaf temperature and the stomatal opening, it is easily expected that the each diffusion resistance should change vertically with the downward distance. Using the experimental results described above and the simulation models for radiation penetration into the rice canopy, Horie (1981) studied numerically the profiles of diffusion resistances and obtained the results shown in Figure 13. The leaf-air resistance increases nearly exponentially with increasing the downward distance with exception near the underlying water surface. $\bar{r}_s$ and $\bar{r}_m$ denote respectively the mean value among sunlit and shaded leaves in the each rice layer. The changing rate of $\bar{r}_s$ and $\bar{r}_m$ with the downward distance was the maximum in the 5th and 8th tenths of model rice canopy. As can be seen in this figure, the magnitude of the diffusion resistance in rice crops is the order of $r_a < r_s < r_m$. r_s is about ten times as large as r_a, and r_m is two and three times as large as r_s. The conclusion to be drawn from the simulated results is that the photosynthetic activity of rice leaves is more strongly controlled by the mean mesophyll resistance and stomatal resistance than by the leaf-air resistance.

3. Change in aerodynamical and light characteristics of rice crops with its growth

As pointed out in the top of this chapter, aerodynamical properties, as characterized by roughness z_0 and zeroplane displacement d, change gradually with the development of rice crops. The such change in z_0 and d gives in turn substantial effects on the air mixing controlling the transfer processes of momentum, carbon dioxide and water vapor in the surface air layer. Under neutral air conditions, the vertical profiles of wind velocity and turbulent transfer coefficient in the surface air layer can be expressed as follows:

$$u(z) = \frac{V_*}{\mathcal{K}} \ln \frac{Z-d}{Z_0}$$

$$K(z) = \mathcal{K}\, V_* (z-d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

where $V = \sqrt{\tau \cdot \rho}$ is the friction velocity (cm/s),
τ is the momentum flux density (dynes/ cm^2),
ρ is the air density (g/cm^3).

It is apparent from Eq. (14) that the magnitude of K increases linearly with increasing the height above the zeroplance displacement and that its proportionality constant goes up with increasing wind velocity and the roughness.

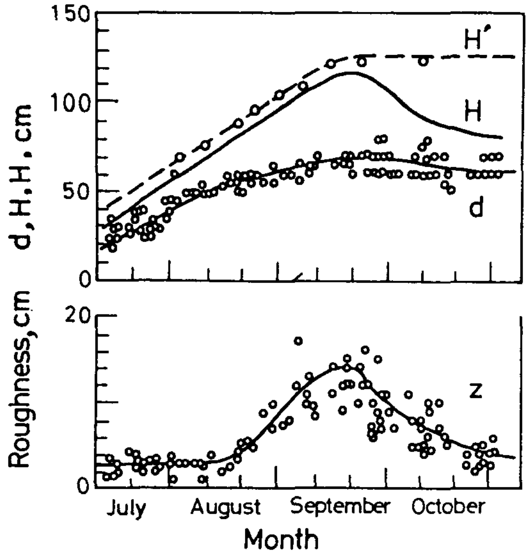


Fig. 14. Change in quantities relating to aerodynamical property of rice crops with its growth (Seo and Yamaguchi, 1963).

Figure 14 illustrates the change in d and z_0 of rice crops with its growth. The seasonal change in z_0 was in phase with that of the canopy height (H), while the seasonal change in d was in phase with that of the plant height (H'). As seen in Figure 14, the magnitude of z_0 was one tenth as large as the canopy height. The magnitude of d was about 60 percent of the plant height. The points of d and z_0, particularly z_0 scatter to somewhat large extent around the each general trend obtained by eye fitting. The scatter of points is mainly due to the wind dependence of the roughness and zero-plane displacement of rice crops (e.g. Uchijima, 1976 c,d). Turbulent transfer coefficient and friction velocity in the air layer near rice crops can be

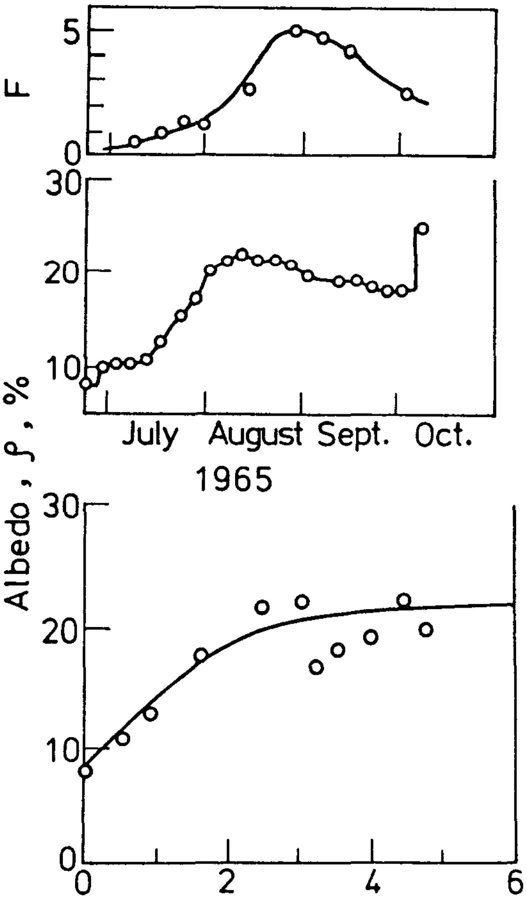


Fig. 15. Change in albedo of rice canopy with its growth (RGE, 1967 a).

easily determined by substituting the values of z_0 and d, and wind data in Eq. (14). It is expected that the turbulent transfer coefficient at the canopy top of rice crops increases with the development of rice crops. In daylight hours with high solar radiation, unstable temperature profile is usually observed in the surface air layer, Unstable profile of temperature enhances strongly the vertical mixing of air, leading to the increase of turbulent transfer coefficient.

Since the reflectivity (or albedo) of flooded water to solar radiation is less than that of plant leaves, the albedo of rice canopy is considerably influenced by the development of rice crops. Research group of evapotranspiration (RGE, 1967 a) made comprehensive measurements of radiation and evaporation of rice crops throughout the growing season. The results are summarized in Figure 15. The albedo of rice canopy (ρ) showed a plateau type response to leaf area index (F), as expressed as follows:

$$\rho = \rho_{max} - (\rho_{max} - \rho_w) \exp(-0.56 \cdot F) ....(15)$$

where ρ_{max} is the maximum albedo of fully grown rice crops,

ρ_w is the minimum albedo of flooded water.

Somewhat large deviation of points from the above relation during the ripening period seems to be due to the change in the leaf arrangement and to the appearance of ears in the period. The reflectivity of rice leaves in the wave band of PAR is about second as large as that of flooded water. The reflectivity of rice canopy in the PAR range should decrease with the development of rice crops. Kishida (1973) revealed experimentally that the reflectivity of rice canopy in the PAR range decreases gradually with its growth.

In the field of crop ecology and agrometeorology, many researchers have studied both experimentally and theoretically the radiation regime of plant canopies in relation to canopy photosynthesis. In these studies, the scattering and the absorption of radiation flux by plant elements have been taken into consideration (Udagawa, Ito and Uchijima, 1974; Horie, 1981). The results so obtained have been used in making clear the radiation environment in plant canopies and in building simulation models of plant climate. Excellent reviews have been published about this problems (e.g. Ross, 1975; Monsi, Uchijima, and Oikawa, 1973; and Uchijima, 1976 a, b).

4. Partition of solar energy in rice crops

Net radiation denoting the difference between influx and eflux of radiant energy is distributed as follows:

$$R_n = lE + H + B_p + B_w + B_s + \lambda P ....(16)$$

where R_n is the net radiation flux density (cal/cm^2 min),

lE and H are the latent and sensible heat flux densities, respectively (cal/cm^2 min),

B_p, B_w, and B_s are respectively the time change in heat stored in plant body, water layer and soil column (cal/cm^2 min),

λP is the solar energy absorbed in photosynthetic process (cal/cm^2 min).

In general, B_p and λP are little compared with other heat balance components, and disregarded usually in the study of the partition of solar energy. Eq. (16) is a fundamental relation in investigation of microclimate of rice crops and used to elucidate the interaction between plant climate and weather conditions.

The partition of solar energy above a rice field was studied by using Eq. (16) and observation data (RGE, 1967b). The results are presented in Figure 16. In this figure, the component B denotes the sum of B_w and B_s, and the sign of B is converted for the convenience of expression. Net radiation is characterized by a diurnal march with the maximum at about noon and the minimum at night time. Although the sensible heat flux was in phase with the diurnal march of net radiation, its amplitude was about one eighth as large as that of net radiation. The diurnal march of latent heat flux density was

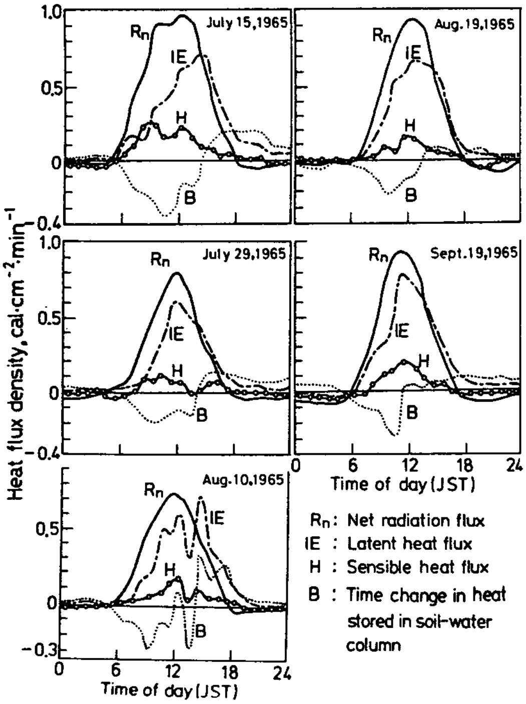


Fig. 16. Diurnal change in heat balance components of rice field at different growing stages (RGE, 1967 b).

found to be late to little extent in phase with compared with that of net radiation. It was found that large fraction of net radiation of rice crops under humid climate of Japan is used for evaporation of water. In a case that advectional heat flux gives strong effects on the heat balance, latent heat flux of crop lands should exceed the net radiation. Zhpabacbaev (1969) observed under semiarid conditions that latent heat flux from well irrigated rice fields exceeds net radiation flux.

One distinct feature in Figure 16 is that the heat for evaporation of water during the period after 1500 is supplied from soil-water column. With the development of rice crops, the heat stored in the soil-water column decreased gradually. This was mainly because of the interception of solar radiation flux by leaves.

As described above, the large part of net radiation of rice crops is used to evaporate water from leaves and the underlying water surface. This is an important characteristic of rice crops which is supplied enough water. The feature of the partition of solar energy is well characterized by Bowen ratio (β). Bowen ratio is defined by

$$\beta = \frac{H}{\ell E}$$

The magnitude of Bowen ration calculated on the basis of daily amounts of both quantities was found to be 0.2 to 0.4. Using the data obtained by heat balance analysis, the following relation was obtained (RGE, 1967 b).

$$lE = 0.82\ R_n \quad \text{.................................} \quad (17)$$

This is applicable to determine evapotranspiration of fully irrigated rice fields without the influence of advectional heat flux. Table 1 summarized the solar energy partition of rice crops during the whole growing period.

Table 1. Partition of solar energy at rice field for whole growing period (RGE, 1967 b).

	St	Rn	IE	H	β
kcal/cm^2	35.49	21.97	17.93	4.04	0.23
%	100.0	61.9	50.5	11.4	

(June 26 – October 5, 1965)

COUNTERMEASURES AGAINST UNFAVORABLE CONDITIONS

1. Water warming ponds

In the northern districts and the mountainous regions of Japan, the growth and yield of rice crops have been often limited by the application of so cold irrigation water as 15°C, resulting the reduction of the yield. It is reported that such cold water damages are increasing with the construction of large storage reservoirs for hydropower production and other purposes. This is mainly because of the large thermal inertia of the reservoirs. According to the statistical survey, the reduction of rice production due to the application of cold irrigation water into rice fields reaches about two to four percent of the total production in the northern district. The acreage of the rice fields suffering from the such cold irrigation water, however, is known to change year to year, depending upon the change in weather conditions. In cool summer with lower air temperature and solar radiation such as 1977 and 1980, the acreage of rice fields suffering from the cold irrigation water is reported to become two or three times as large as that under normal weather conditions.

Therefore, the problems relating to the cold water damage have been very important in agrometeorology and agroengineering. Much efforts have been devoted into elucidating the cold water damage of rice crops and establishing the effective countermeasures. The reduction rate of rice production in rice fields due to the application of cold irrigation water is approximately evaluated by the following relation (Uchijima, 1964).

$$R = \frac{E_\Sigma}{-h\,(1+2a)} \ln \frac{T_m - T_c}{T_m - T_i} \quad \text{.....................(18)}$$

where R is the rate of rice yield reduction due to cold irrigation water,

E_Σ is the sum of evaporation, transpiration, and seapage and discharge from rice field ($cm^3/cm^2 s$),

$h = C_p \varphi D$ is the sensible heat transfer coefficient ($cal/cm^2 s\ ^\circ C$),

C_p and φ are respectively the specific heat at constant pressure and density of air ($cal/g^\circ C$, g/cm^3),

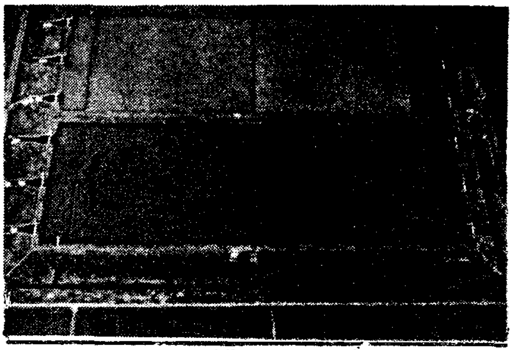
D is the conductance in the air layer above rice field (cm/s),

a is the gradient of the temperature vs. saturation water vapor at air temperature ($mmHg/^\circ C$),

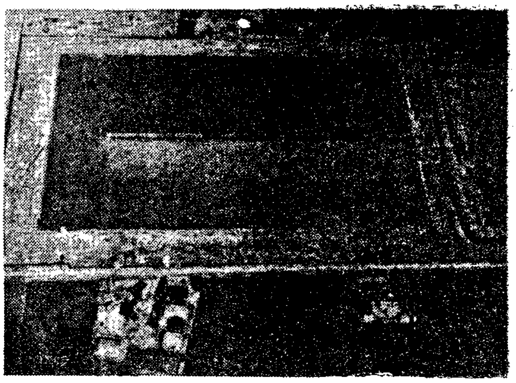
T_c is the critical water temperature of rice plants characterizing the water temperature response of rice yield ($^\circ C$),

T_i is the water temperature at the inlet of rice field ($^\circ C$),

T_m is the terminal water temperature to be determined by weather conditions ($^\circ C$).



ashikawa II pond



Higashiasahikawa Kami pond

Fig. 17. Photograph of warming ponds (Mihara et al., 1959).

Eq. (19) indicates clearly that there is three principal procedures for lightening the cold water damage of rice crops.

1: lowering the susceptibility of rice crops to cold water,

2: rising the water temperature at the inlet,

3: diminishing the water flow into rice field.

The first is the main target of rice breeding, the second is an practical application of knowledge of agrometeorology into agricultural practices, and third is the practical procedures in the field of agroengineering and agronomy.

Warming ponds or warming canals shown in Figure 17 are of large scale and semi-permanent procedures for warmining cold irrigation water, These ponds have been constructed mainly in the northern part of Japan. The numbers of warming ponds in these districts are reported to reach about

800 or over. The warming pond has the function of giving the radiant energy, sensible heat, and latent heat into cold irrigation water which passes in it.

Figure 18 shows the energy components affecting on the water warming pond and polyehylene tube as heat exchanger. The following heat balance equation is obtained among the each heat balance component.

$$C Q_W (T_e - Ti) = A_W (R_n + l E + H + B_s + B_W') \quad \text{..} (19)$$

where C is the volumetric heat capacity of water (cal/cm^3°C),

Q_W is the water flow into the pond (cm^3/s),

B_s is the heat flux density conducted into the bottom soil layer (cal/cm^{2}s),

B_W' is the time change in heat stored in water column (cal/cm^{2}s),

A_W is the surface area of the pond (cm^2).

One example showing the diurnal variation in energy components affecting on the warming pond is presented in Figure 19. The difference in temperature between the exit and the inlet was kept at a level of about 3.5°C, indicating that the temperature of cold water rose about 3.5°C by passing in it. The left hand side of Figure 19 shows clearly that air temperature is considerably higher compared with water temperature in the pond throughout the day, that water vapor pressure in the air is also higher than the saturation water vapor at the water temperature. This facts indicate that the sensible and latent heat fluxes are downward throughout the day. On clear and sunny days, the heat carried away from the unit water column in order to warm up cold irrigation water was found to vary 300 cal/cm^2 in the Hokkaido district to 700 cal/cm^2 in the central part of the Honshu district. The contribution of net radiation to warming cold irrigation water increased gradually with the movement from the southern part to the northern part, with the proportional decrease of the contribution of the sensible and latent heat fluxes. This was mainly due to that the temperature and water vapor pressure of the air goes down with movement from the southern part to northern part.

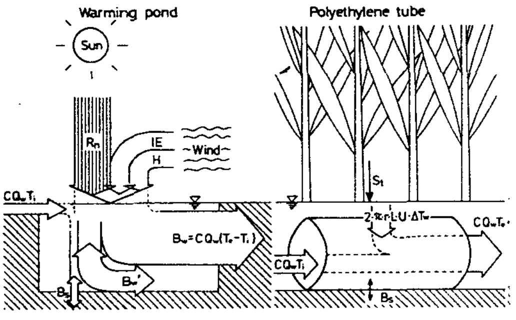


Fig. 18. Schematic representation of heat balance components affecting upon warming pond and polyethylene tube.

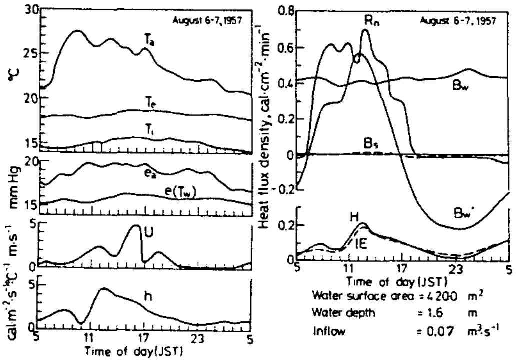


Fig. 19. Diurnal change in meteorological elements and heat balance components of water warming pond (Mihara et al., 1959).

The differential equation denoting the time change of temperature of water lump flowing in the warming pond yielded the following relation (Mihara et al., 1959).

$$A_W = \frac{C Q_W \ln (1 - \phi)}{-h (1 + 2a)} \quad \text{........................} (20)$$

where ϕ is the temperature rising coefficient and given by

$$\phi = \frac{T_e - T_i}{T_m - T_i} .$$

Eq. (20) is the basic relation for determining the surface area necessary to warm up cold water from T_i to T_e. The results obtained from Eq. (20) are

Table 2. Necessary surface area of warming pond to warm up cold water of 1 ton/s from T_i to T_e (Uchijima, 1972).

ϕ T_a	0.2	0.3	0.4	0.5	0.6	0.7	0.8
18	3.8	6.0	8.6	11.7	15.5	20.3	27.2
20	3.5	5.6	8.1	11.0	14.4	19.1	25.5
22	3.3	5.2	7.5	10.1	13.5	17.6	23.5
24	3.0	4.9	6.9	9.4	12.4	16.4	21.9
26	2.8	4.6	6.4	8.7	11.5	15.1	20.2
28	2.6	4.1	5.9	8.0	10.6	13.6	18.6
30	2.4	3.9	5.5	7.5	9.9	13.0	17.3

(unit is ha)

presented in Table 2.

As can be seen in this table, the necessary surface area of warming pond increases with lowering air temperature and increasing the temperature rising coefficient. Providing that the water flux into the pond (Q_W) differs from 1 ton/s, the necessary surface area of warming pond (A_W') is given by

$$A_W' = A_W \frac{Q_W}{1.0} \quad \text{..................................} (21)$$

where A_W is the necessary area of warming pond given in Table 2.

Usually, warming ponds are constructed in a part of rice producing area, resulting the decrease of the acreage of rice area. It therefore is very important to assess the benefit of the construction of warming pond from the standpoint of rice production. The following description is a simple assessment of the benefit of the construction of water warming pond. The change in the acreage of rice area, yield, and yield reduction rate before and after the construction of warming pond is given by

A_f , y , R_1 before the construction
$A_f - A_W$, y , R_2 after the construction

where A_f is the total acreage of rice producing area under consideration (ha),
y is the yield at rice field without the direct influence of cold irrigation water (t/ha),
R_1 and R_2 are mean reduction rate of rice production of total rice area before and after the construction of warming pond.

Thus, the total productions from the rice area before and after the construction of the warming pond are respectively as follows:

$$Y_1 = y\,(1 - R_1)\,A_f,$$
$$Y_2 = y\,(1 - R_2)\,(A_f - A_W) \quad \text{..................} (22)$$

where Y_1 and Y_2 are respectively the total rice productions of rice area before and after the construction(t).

By combining the two relations in Eq. (21), the following relation is obtained

$$\frac{Y_2}{Y_1} = (1 - \frac{A_W}{A_f})\,(1 + \frac{R_1 - R_2}{1 - R_1}) \quad \text{............} (23)$$

The results calculated from Eq. (23) for assessing the benefit of the construction of warming pond are plotted as a function of (A_W/A_f) and ($R_1 - R_2$) / ($1 - R_1$) in Figure 20. The shaded part in Figure 20 denotes the conditions in which the construction of warming pond brings about the reduction of total rice production of the rice area. Figure 20 seems to indicate that the construction of warming pond or warming canal in the rice producing area

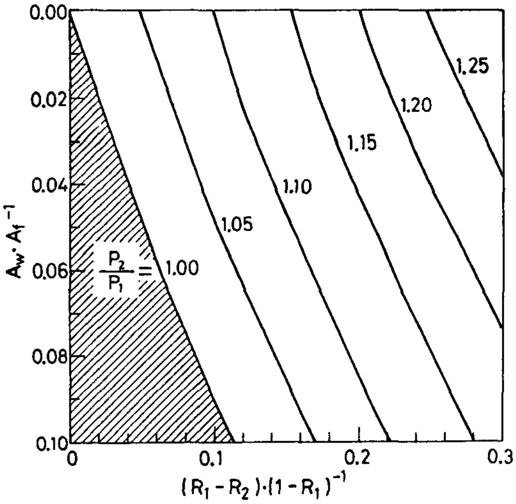


Fig. 20. Nomogram for assessing production benefit of construction of water warming pond in rice area (Uchijima, 1972).

brings hardly the increase of the total production. This is mainly because the construction of warming pond causes inevitable diminish of available field acreage for rice production and the reduction of rice acreage is hardly compensated by the decrease of rice yield reducing rate. It is therefore recommended that the warming pond is to construct not in rice field area but in waste lands (correspond to $A_w/A_f = 0.0$ on the Y-axis in Fig. 20).

2. Effects of polyethylene tube

As shown by observations of water temperature in rice fields, water temperature in a part of rice field far from the inlet of cold irrigation water is usually higher to large extent than that near the inlet. In such a part of rice field, net radiation on the water surface is mainly distributed into the canopy air layer as sensible and latent heat. A part of net radiation is conducted into the soil. As indicated in Figure 18, polyethylene tube functions as a heat exchanger between surrounding warm flooded water and cold irrigation water flowing in it. Namely, cold irrigation water flowing in it is warmed up by heat transferring from warm flooded water. The heat balance of polyethylene tube as a heat exchanger is expressed by

$$C\,Q_w\,(T_e - T_i) = 2\pi r \cdot L \cdot U \cdot \Delta T_w \ldots\ldots\ldots\ldots\ldots (24)$$

where r is the radius of polyethylene tube (cm, usually some 10 cm),

L is the length of polyethylene tube (cm),

U is the overall heat transfer coefficient between outer and inner fluids of polyethylene tube ($cal/cm^2\,s\,^\circ C$), ΔT_w is the logarithmic mean of temperature difference between flooded water and irrigation water flowing in it (°C) and given by

$$\Delta T_w = (T_e - T_i) / \ln\,[(T_w - T_i)/(T_w - T_e)]$$

Figure 21 shows one example indicating the effects of polyethylene tube as a heat exchanger upon the spatial distribution of the water temperature and of the heading time of rice crops. The percent area with water temperature below 20°C in the field with polyethylene tube is about one-third or one-fourth as large as that in the field in which cold irrigation water streams directly. This fact indicates evidently that the temperature condition of flooded water was improved by the application of polyethylene tube. The improvement of the temperature condition was clearly reflected on the spatial distribution of the heading time of rice crops. The percent area with the early heading time is larger for the field with polyethylene tube than for the field with direct application of cold irrigation water, resulting the increase of rice production of about 3.8 percent. It is reported that the percent

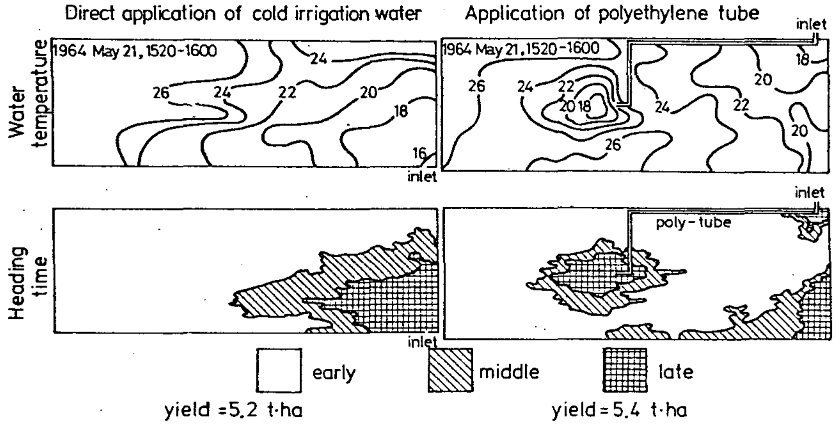


Fig. 21. Effects of application of polyethylene tube on growth and yield of rice crops (Kanegawa and Tomiyama, 1965).

increase of rice production by the application of polyethylene tube varies somewhat largely year to year, depending upon weather conditions (Kanegawa and Tomiyama, 1965).

Since polyethylene tube absorbs much heat from the surrounding warm flooded water through its film, the temperature of flooded water near by the tube is usually retained at tolerably lower level to rice crops. It therefore is recommended that the placement of polyethylene tube in the rice fields alters at an interval of about 5-6 days. The necessary length of oplyethylene tube to warm up cold irrigation water from T_i to T_e can be evaluated from the following relation which is obtained from Eq. (24).

$$L = \frac{Crv}{2U} \ln \left[\frac{T_m - T_i}{T_m - T_i - \overline{\Delta T_w}} \right] \qquad (25)$$

Hanyu (1963) reported that the values of total heat transfer coefficient (U) changes in the range between $2.5 \cdot 10^{-3}$ and $10 \cdot 10^{-3}$ cal/cm²s°C, depending upon flow velocity of water in the tube. Using the

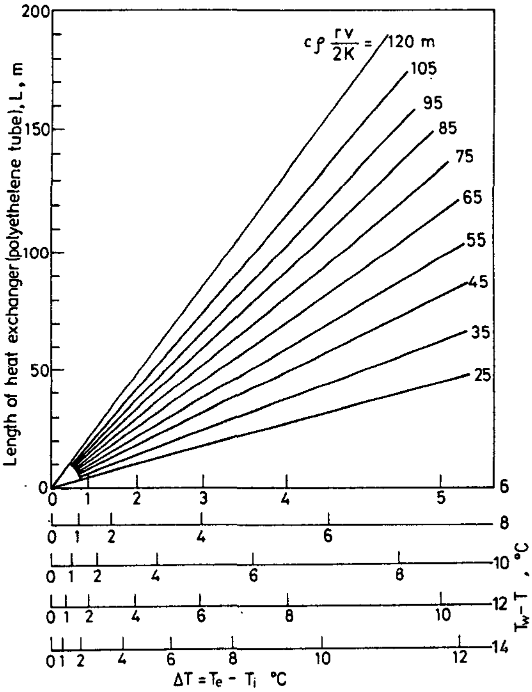


Fig. 22. Nomogram for determining necessary length of polyethylene tube to warm up cold water from T_i to T_e (Uchijima, 1972).

values of U reported by Hanyu (1963), the necessary length of the tube to warm up cold water from T_i to T_e were calculated from Eq. (25). Figure 22 shows the necessary length of polyethylene tube as a function of $(T_w - T_i)$ and $(C\,r\,v)/2U$. The necessary tube length increases with the increment of $(C\,r\,v)/2U$, namely, the amount of water flowing in it and with the decrease of $(T_w - T_i)$. Because $(T_w - T_i)$ decreases in cool summer conditions, the necessary length of the tube should increase. This nomogram makes it possible to determine the necessary tube length and to evaluate rise of water temperature in the tube under given conditions of the length and weather.

3. Windbreak net

As described in the preceding chapter, mesophyll resistance controlling the flux density of carbon dioxide into crop leaves has a close connection with leaf temperature. Increase of wind velocity causes the lowering leaf temperature, because high wind enhances heat transfer between the air and leaves. Under cloudy and windy conditions, leaf temperature is known to be somewhat lower than the air temperature, while under sunny and calm conditions, leaf temperature is usually higher than the air temperature. In a case that the air temperature is so low as that observed in cool summer years, leaf temperature of rice crops should be lower than that at which the mesophyll resistance of leaves increases considerably (see Figure 12).

Such a lower leaf temperature should affects the photosynthetic activity of leaves of rice crops.

On the other hand, the temperature of rice leaves protected from high and cold wind becomes usually higher than the air temperature. The facts described above have the implication that the protection of rice crops from cold and strong wind by windbreak forest or windbreak net should brings about good effects on the growth of rice plants. In 1980 where severe cool summer hit rice crops over the whole area of Japan, beneficial effects of windbreak net were observed clearly in the Ishikari plain of the Hokkaido where cold northeast wind prevailed in

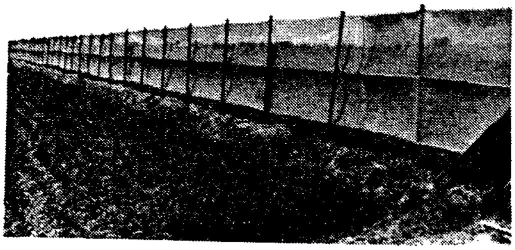


Fig. 23. Windbreak nets stretched on rice fields (after Hokkaido Nat'l. Agr. Expt. Stan., 1980).

the early stage of rice growth. Figure 23 shows windbreak net stretched on rice fields. Windbreak net consists of chemical fiber and has the porosity of about 50 percent. Unit windbreak net is 2m height and 10m long. In rice fields, windbreak nets are continuously set in lengths of 100 to 200m at a right angle to the prevailing wind.

Many researchers have conducted experiments for making clear the beneficial effects of windbreak nets on rice crops (e.g. Uchijima, Odaka, and Fujita, 1977 : Tomari, Fujiwara, and Ishiguro, 1978). They revealed that windbreak nets improve substantially temperature conditions of flooded water, and bring about the increase of rice yield. Maki (1979) showed experimentally the increase of water temperature behind windbreak nets. The rise in water temperature of flooded water was found to decrease gradually with the distance from the windbreak nets. It is concluded that the increase of water temperature behind the nets is mainly due to lowering the intensity of air mixing by the nets.

Since windbreak forest or windbreak net absorbs strongly the momentum of wind, weak wind region is formed behind it. With the increment of the distance from the windbreak net, wind increases again, because of vigorous mixing of air in the surface air layer. Figure 24 indicates experimental results about the influence of windshelter on wind regime and turbulent transfer coefficient. The relationship shown in this figure can be approximated by

$$\frac{K_{in}}{K_{out}} = 0.26 + 0.86\frac{U_{in}}{U_{out}} \quad \text{.......................} (26)$$

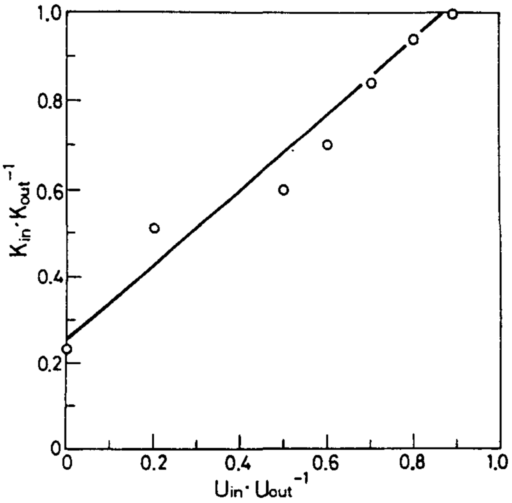


Fig. 24. Influence of windshelter on turbulent transfer coefficient in the surface air layer (Konstantinov and Struzer, 1974).

where K and U are respectively turbulent transfer coefficient and wind velocity in the surface air layer (cm^2/s, cm/s),
subscripts in and out denote the quantities behind windshelter and open field, respectively.

Heat transfer coefficient h controlling heat exchange between flooded water and the surface air layer, consequently water temperature, is expressed as follows:

$$h = C_p\rho \,[1/\int_0^z \frac{dZ'}{K(Z')}] \quad \text{..........................} (27)$$

where K(z') is the profile of turbulent transfer coefficient in the surface air layer.

From Eqs. (26) and (27), we can conclude that the value of h is lower behind windbreak nets than in open fields.

In order to assess effects of windbreak nets on the temperature of flooded water, heat balance equation of flooded water was numerically solved, expressing the saturation water vapor pressure corresponding to water temperature by

$$e\,(T_w) = 4.75 + 0.265T_w + 0.0094T_w^2 + 0.0000402T_w^3 \text{.......................................} (28)$$

The results so obtained are presented in Figure 25. As can be seen in this figure, water temperature is higher than the air temperature (horizontal dotted line) in a range of h lower than about $4\text{-}5{\cdot}10^{-4}$ cal/cm^{2}s°C, while in a h-range higher than about $4\text{-}5{\cdot}10^{-4}$ cal/cm^{2}s°C water temperature is lower than the air temperature. Critical value of h, at which the water temperature becomes lower or higher compared with the air temperature, increased with increasing net radiation. Under usual weather conditions, it is known experimentally that heat transfer coefficient in daylight hours is between $1.5{\cdot}10^{-4}$ and $4.5{\cdot}10^{-4}$ cal/cm^{2}s°C (see Fig. 19).

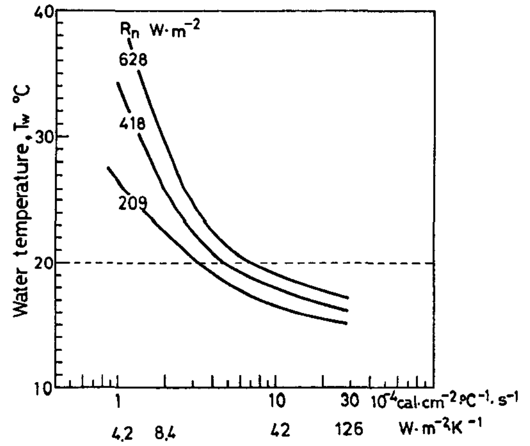


Fig. 25. Change in temperature of flooded water with increasing heat transfer coefficient (Uchijima, 1977).

It is possible to conclude from the discussions mentioned above that the reduction of wind velocity and heat transfer coefficient by stretching windbreak nets gives beneficial effects on temperature conditions of rice leaves and of flooded water, consequently on the growth and yield of rice crops. However, further studies are needed to establish quantitative relationships between the reduction of wind by windbreak nets and rice yield.

CONCLUSIONS

It is apparent from the above description on the relationships between rice crops and climatic conditions that the growth and yield of rice plants are strongly influenced by weather fluctuations. In the middle latitude, the thermal resources have been most important environmental constrain. The accumulation of dry matter by standing rice crops can be expected by the data of daily mean of air temperature and daily solar radiation over the growing period with acceptable error. Yield index of rice crops shows clear decrease in a temperature range below a critical temperature. Critical temperature has changed among rice producing areas, depending upon the difference of the susceptibility to low temperature among rice cultivars raised in these areas. The thermal resources for the cultivation of rice crops have fluctuated distinctly over the past century.

Theoretical and experimental results indicate evidently that an erect leaved canopy is superior to a horizontal leaved canopy in the dry matter production. This is because the erect leaved canopy makes possible deeper penetration and even distribution of radiation energy in canopies. By comparing the magnitude of r_a, r_s, and r_M, it is concluded that the photosynthetic absorption of carbon dioxide is mainly controlled by r_M and that the influence of r_a on canopy photosynthesis can be disregarded in general. The magnitude of r_M responds distinctly to leaf temperature in a range below 20°C. This means that the cold and high wind as observed in cool summer years should cause the lowering leaf temperature, consequently the photosynthetic activity of rice leaves. r_s decreases firstly very rapidly with increasing PAR-flux density, and approximates to minimum in a PAR range above 0.3 cal/cm^2 min. The aerodynamical and optical properties of rice crops have changed with the development of rice plants. The such change in turn have given somewhat large effects on the reflectivity of solar radiation of the canopy and on the air mixing in the surface air layer.

The introduction of physical research procedures such as the aerodynamical method and the heat balance method has helped to elucidate effects of countermeasures against unfavorable weather conditions. The heat balance method has enabled the assessment of the benefit of water warming pond and polyethylene tube as a kind of heat exchanger. Nomograms for determining the necessary length of polyethylene tube to warm up cold irrigation water are illustrated using results obtained by heat balance analysis. Windbreak nets consisting of chemical fibers are effective to protect rice crops from cold and strong wind. In order to assess the influence of windbreak nets on plant climate, the change in the temperature of flooded water with the increment of heat transfer coefficient, cosequently of wind is calculated from the heat balance equation of flooded water.

As can be understood from the above results, the rice-micrometeorology has made many contributions to solving practical problems in rice cultivation. However, increasing climate fluctuation is giving adverse effects on the growth and yield of rice crops in many rice producing countries. Our present knowledge of the rice-micrometeorology is still not enough and too fragmentary to solve complicated and urgent problems relating to rice production under fluctuating weather conditions. The following problems remain to be investigated.

1) making clear the behavior of soil-rice-air systems under fluctuating weather conditions,
2) determining the meteorological criteria of rice crops, taking into consideration climate fluctuation,
3) establishing methods for assessing agroclimatic resources,
4) forecasting the change in agroclimatic resources in relation to climatic change in future,
5) establishing techniques of forecasting rice production not only statistically, but also by dynamic models, or by remote sensing,
6) establishing ways of avoiding surpluses or shortages of agroclimatic resources in respective regions.

Synthesizing the fragments of knowledge to be obtained through investigations of the problems mentioned above would greatly contribute to increase and stabilize the rice production. Exchange of information, data and techniques between relevant disciplines of science is urgently needed to solve successfully the above problems.

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DISCUSSION

Question (Dr. Sang-Youl Je, Kyungbuk National University)

You convinced me that erect canopies give greater productivity than non-erect one. Is there any effect of temperature, in addition to distribution of radiation, on the advantages of erect-leaved?

Answer (Dr Z. Uchijima)

Leaf structure is known to give significant effects on leaf temperature, for example, the leaf temperature of an erect-leaved canopy is lower than that of a horizantal-leaved conopy under high solar elevation conditions. On the other hand, under the conditions of low solar elevation, leaf temperature of an erect-leaved canopy becomes higher than that of a horizontal-leaved canopy. This is mainly due to that the incident angle of sun beam on the leaf blade changes in relation to the solar elevation. The change in leaf temperature between two plant structures should give effects on the respiration activity and photosynthetic activity.

Question (Dr. Sang-Youl Je)

Is there any specific chemical change in cellular level when rice plant is exposed to the continuous low temperature?

Answer (Dr. Z. Uchijima)

I am not sure about this problem, because I am not plant-physiologist but agrometeorologist. Many meteorological data show evidently that the low air temperature usually associates with cloudy or rainy days. According to the actinometric observation data, the solar radiation on cloudy or rainy days is rich in red-radiation and infrared rediation camparing with that on clear and sunny days. Physiological researches indicate clearly that the activity of amino-acid and protein bio-synthesis in plants is proportionally correlated to the fractional intensity of blue-radiation and ultraviolet radiation in the solar radiation. The facts mentioned above seem to indicate that continuous low air temperature with low radiation should give adverse effects on the contents of nitrogen containing compounds in cereals. It is known that the protein content in wheat raised in regions with clear and dry weather is higher than that of wheat raised in regions with quite opposite weather conditions.

Question (Dr. Ho-Jin Lee, Seoul National University)

You indicated that standing dry matter of rice has very close relationship with sum of daily air temperature. 1) Would you explain these relationship in both regions of rich and poor temperature resources? 2) We can imagine two cases with same total of daily temperature but different time length, such as low temperature with long growth period and high temperature with short growth period. Can we expect the same dry matter production? 3) I think these values, sum of temperature and radiation, can be used for introducting a variety to a certain area. Would you tell us your opinions for practical application of this concept?

Answer (Dr. Z. Uchijima)

1) Because, the relationships between ΣTa or ΣSt and W were obtained by using data in four years at five places over the whole area of Japan, the relationships can be applied to both rich temperature region like the Kyushu district and poor temperature region like the Tohoku and Hokkaido districts. 2) Excluding extreme weather conditions like the unusual year of 1980, dependence of the accumulation of dry matter on weather conditions should be held with acceptable errors. 3) In order to apply this concept for determining the distribution of crop varieties in a region, it is necessary to study in more detail the requirement of crop varieties to temperature resources and water resources. If the such information was well provided, we can use this weather index for introducing a crop variety suitable to weather conditions in a region. Other index, that is, ΣT_{10} has been successfully used to evaluate the distribution of crop species in more wide area in relation to weather condition.

Question (Dr. Ho-Jin Lee)

We experienced very poor rice yield in 1980 because of cool summer. Some people are talking about we are now in cooling trend and others are not. Could you predict how often this kind of disaster can happen in near future?

Answer (Dr. Z. Uchijima)

Although we can explain very well various meteorological phenomena experienced in the past, it is very difficult to predict or expect coming meteorological events with the accuracy necessary for agricultural production. This is mainly because the physical basis of climatic fluctuation is still very far from the necessary achievement and the nature of meteorological phenomena is stocastic to large extent. Therefore, we can say that meteorological phenomena may be undeterministic or intransitive in physical sence. This means that we cannot say whether climate is becoming cooler and cooler or not. However, observation results seem to indicate that climate is becoming more variable, affecting food production.