A STUDY ON THE LIMIT OF THE PADDY RICE CULTIVATION BY MEANS OF THE CLIMATIC PRODUCTIVITY INDEX

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Abstract There is a model of the climatic productivity of paddy rice which has been introduced by the author and Hanyu. The model has been named the "climatic productivity index of paddy rice", and it might be used as the index of climatic productivity which gives potential productivity of paddy rice under given climatic conditions. In this paper the limit value of the index expressing the climatic productivity at the limit of its cultivation was investigated. Judging from both sides of northern limit and height limit, it seemed that the limit value of its cultivation, Y_{po} = 500 was reasonable as far as the normal climate. In individual years, we could expect for more or less harvests (about 200kg/10a) at Y_{po} = 500, assuming good cultivation conditions. In the years of cool summer damage the distribution of the index and the unit yield were illustrated, and in the regions less than the limit value, a great deal of damage including completely ruined harvests are anticipated. Finally, the movement of the limit line in the case of climatic variations was investigated.

1. Introduction

The climatic productivity index of paddy rice

The maximum yield of the crop, which could be reached under certain climatic conditions and a certain technical level of cultivation, was named "climatic productivity" by Hanyu *et al.* (1966). They proposed a model for the ripening period of paddy rice, named the "climatic index on quantity of ripening".

The author and Hanyu (1980) proposed a new model named the "climatic productivity index", including meteorological data of nearly all growth stages, from the period of vegetative growth soon after rooting in paddy fields to the period of maturity, which expressed the climatic productivity of paddy rice. The model of the index was a kind of empirical equation derived from the routine crop experiment data by Statistics and Information Department of Ministry of Agriculture and Forestry. The data contained the meteorological data observed near the fields.

The meaning of the new index resolves itself into the following two points: (i) the optimum air temperature of the mean (θ_R) through the ripening period was 21.5°C, assuming that the ripening quantity was proportional to the natural logarithm of the total sunshine duration (S_R) during the period; (ii) when the mean air temperature (θ_V) during the period from the 50th to the 36th day prior to heading (the best time for the period of vegetative growth) and the mean value (θ_H) during the period from 25th to 1st day prior to heading, including the period of reduction division, get out of the respective optimum temperature ranges, the growth before heading causes a shortage, so that it acts on the ripening as a main factor of impediments.

There is a model of the climatic productivity during ripening period, which was introduced by Hanyu *et al.* (1966), and concerning point (i) above, the linearity of the model between S_R and the ripening quantity was modified to the relation of the natural logarithm between them. Referring to the method of the modeling, selecting from 1973 to 1977, the highest yield varieties among those of the 26 stations of the routine crop experiments, the values which were obtained when the yield divided by ln $(1+S_R/10)$ namely, the ripening quantity per corrected unit sunshine duration, were plotted against θ_R (Fig. 1). Because the curve combining the upper limit points was approximated to a parabora with its maximum at $\theta_R = 21.5°C$, the model was formalized as the following equation,

$$Y_R = \ln\left(1 + \frac{S_R}{10}\right) \cdot \left\{260 - 2.70 \cdot (\theta_R - \theta_O)^2\right\} \tag{1}$$

where the divisor of S_R 10 was used as the parameter showing non-linearity grade between the ripening quantity and S_R. The value of 10 was ascertained as the optimum order using the statistical data (Sugihara and Hanyu, 1980) and the experimental data (Munakata *et al.*, 1967).

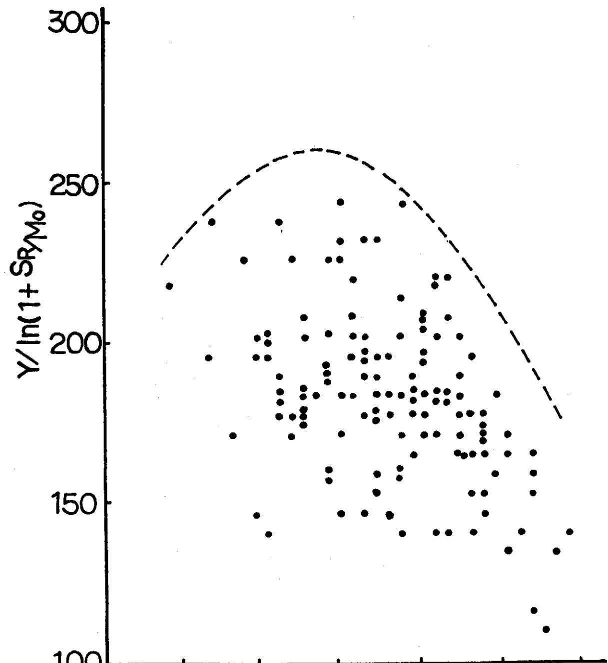

Fig. 1 Relationship between the mean temperature during the ripening period, θ_R, and $Y/\ln(1+S_R/M_o)$ at M_o=10. The broken line shows the potential quantity able to be ripened by given climatic conditions. Y is the unit yield, and M_o the optimum of the growth before heading (after Sugihara and Hanyu, 1980)

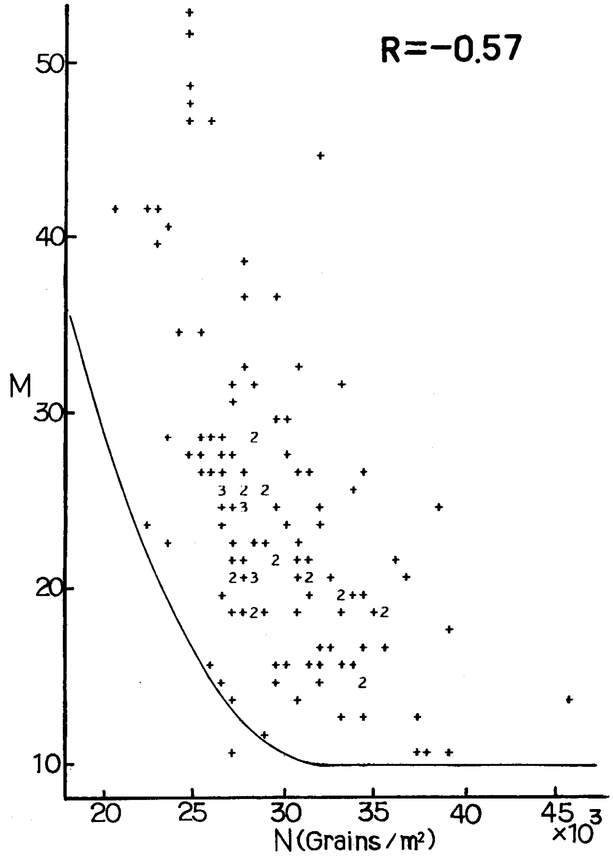

Fig. 2 Relationship between N(grain)-number and M-value (after Sugihara and Hanyu, 1980)

Next, the modeling for the growth before heading was the second point of the model. A new variable based on it was introduced. The variable named M has a minimum value (M_O) of 10, which is the divisor of S_R in Eq. (1). In the case of optimum growth, $M = M_O$, the ripening quantity could be expected to become Y_R. If there is a shortage of growth and the M-value increases, the quantity shows a decrease to the actual yield, Y. The definition of M was given as the following equation,

$$M = S_R / [\exp [Y / \{260 - 2.70 \cdot (\theta_R - \theta_O)^2\}] - 1] \qquad (2)$$

Regarding the number of grains (N) as an index of growth before heading, the negative relationship between N-number and M-value was found out to be $r = -0.57$ (Fig. 2). At that time, using actual unit yield (Y), the index of ripening (Y_R) shown by Eq. (1), variable M, and M_O in the case of optimum growth, the following equation was obtained,

$$M = S_R / \{(1 + S_R / M_O) \cdot \exp (Y / Y_R) - 1\} \qquad (3)$$

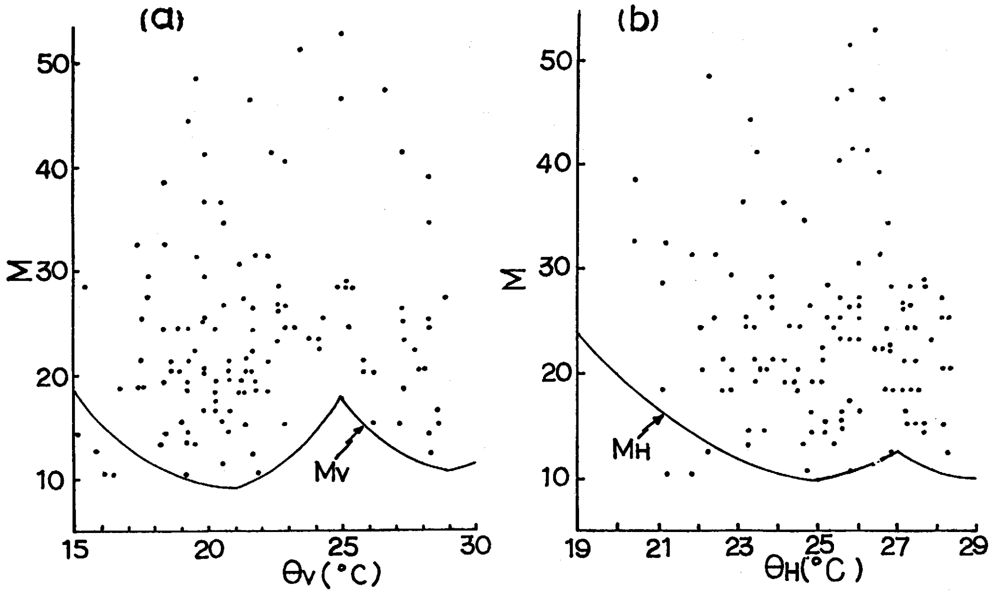

Fig. 3 Relationship between θ_v and M-value (a), and between θ_H and M-value (b). The lower limit curves show dependence of the growth indices, M_V and M_H, upon θ_V and θ_H, respectively (after Sugihara and Hanyu, 1980)

The above equation expresses how much the ripening quantity decreases when the shortage of the growth is indicated by M-value.

The second meaning of the Y_p model was obtained by plotting the individual M-value from Eq. (2) against the mean air temperatures before heading, θ_V and θ_H, respectively (Fig. 3). The curve combining the lower limit points of the M-value on θ_V, was denoted by M_V, and similarly those on θ_H by M_H. Considering the common characteristic of the curves M_V and M_H, the values increase on the lower sides of them because of the shortage of the growth due to lower temperature. Then M_V shows the optimum growth at θ_V = 21.0°C, as does M_H at θ_H = 25.0°C. On the higher sides, the growth indicated by the M-value shows the tendency of a shortage of growth at approximately θ_V = 25.0°C and θ_H = 27.0°C. Finally, on the highest side of θ_V and θ_H, it seems that the growth increases again. The larger value between M_V and M_H, selected as M_G, was named the "climatic index of growth" and was substituted with the following equations,

$$
\begin{aligned}
&\text{If } M_H \geqq M_V,\ M_G = M_H \\
&\quad M_H < M_V,\ M_G = M_V \\
&M_H = 0.400\,(\theta_H - 25.0)^2 + 10.0, \quad \theta_H \leqq 25.0 \\
&\quad = 0.625\,(\theta_H - 25.0)^2 + 10.0, \quad 25.0 < \theta_H \leqq 27.0 \\
&\quad = 0.625\,(\theta_H - 29.0)^2 + 10.0, \quad 27.0 < \theta_H \\
&M_V = 0.278\,(\theta_V - 21.0)^2 + 9.0, \quad \theta_V \leqq 21.0 \\
&\quad = 0.625\,(\theta_V - 21.0)^2 + 9.0, \quad 21.0 < \theta_V \leqq 25.0 \\
&\quad = 0.500\,(\theta_V - 29.0)^2 + 11.0, \quad \theta_V > 25.0
\end{aligned}
\qquad (4)
$$

Then, introducing M_G-index, the model on the climatic productivity of paddy rice, named the "climatic productivity index", was defined as the following equation,

$$Y_p = \ln (1 + S_R/M_G) \cdot \{260 - 2.70 \cdot (\theta_R - \theta_O)^2\} \quad (5)$$

where M_G was laready obtained in Eq. (4), and S_R denotes the sunshine duration, θ_R the mean temperature during ripening period, and $\theta_O = 21.5°C$.

The validity of the Y_p-index as a climatic productivity model

The validity of the Y_p-index has been examined by Hanyu and the author (1981). Using *the climatic table of Japan part 4, pentad normals,* by the Japan Meteorological Agency,

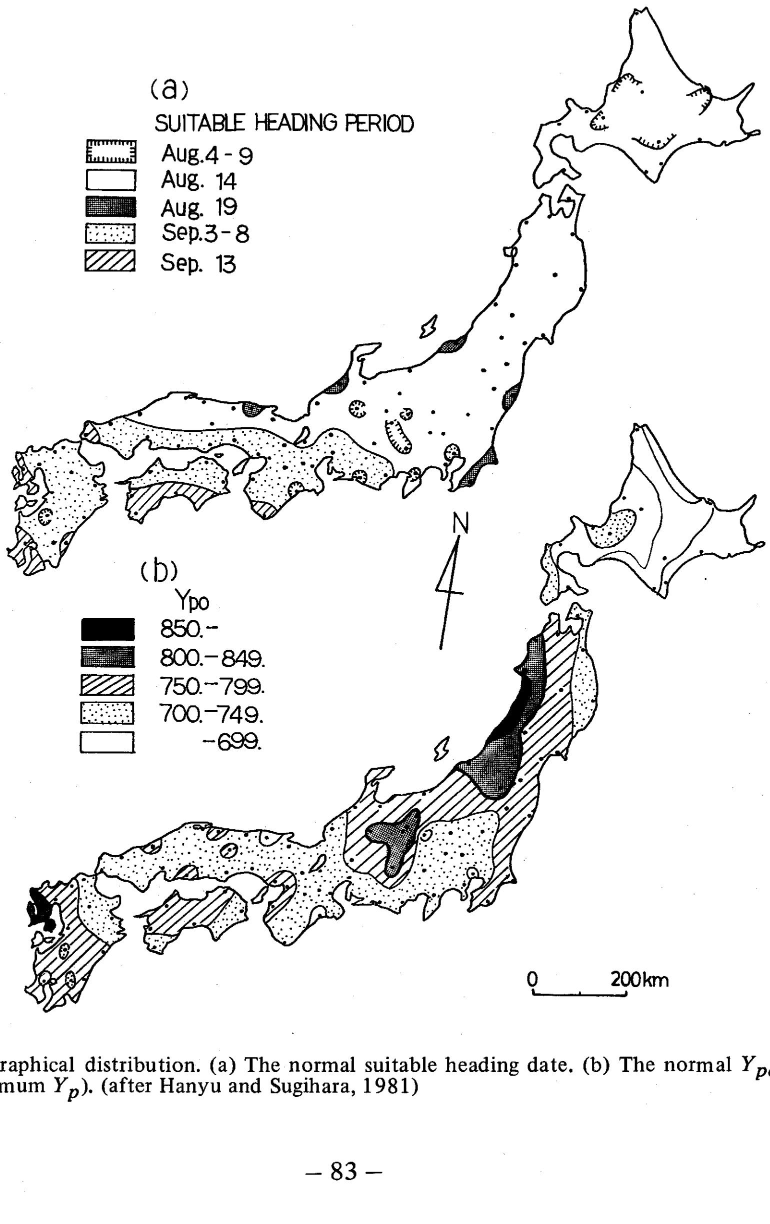

Fig. 4 Geographical distribution. (a) The normal suitable heading date. (b) The normal Y_{po} (the maximum Y_p). (after Hanyu and Sugihara, 1981)

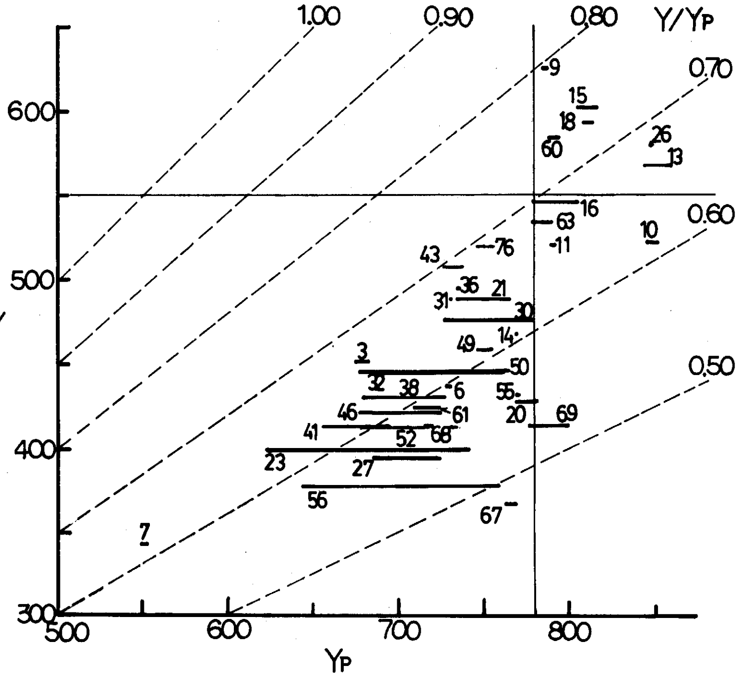

Fig. 5 Relation between the mean regional yield (Y, kg/10a) in 1965–1975 and the normal Y_{po}. The right and left ends of each horizontal line denote the maximum Y_p value (Y_{po}) and the Y_p value at the mean heading date (Y_{pm}), respectively. The correlation coefficient between Y_{pm} and Y is 0.752. Numerals in the figure denote the main productive regions. 3:Kamikawa Basin, 6:Ishikari Plain, 7:Tokachi P., 9:Tsugaru P., 10:Akita P., 11:Kitakami B., 13:Shonai P., 14:Sendai P., 15:Yamagata B., 16:Niigata P., 18:Aizu B., 20:Hamadori Coast, 21:Toyama P., 23:North Kanto P., 26:Matsumoto B., 30:Kujukuri C., 31:Izumo P., 32:Yonago P. 36:Ohmi B., 38:Nohbi P., 41:Enshu nada C., 43:Okayama P., 46:Ise P., 49:Sanuki P., 50:Wakayama P., 52:Tokushima P., 55:Fukuoka P., 56:Kochi P., 60:Tsukushi P., 61:Ohita P., 63:Kumamoto P., 67:Miyazaki P., 68:Miyakonojo B., 69:Kagoshima Bay C., 76:Sanbongihara Plateau (after Hanyu and Sugihara, 1981)

from July 15 through the heading, Y_p was calculated every 5 days according to Eq. (4) and Eq. (5). The maximum value through the period was distinguished from the others and denoted by Y_{po}. The heading period of Y_{po} was named the "suitable heading period". The geographical distribution of the normal suitable heading period and the normal Y_{po} which are obtained using the normal data have already been illustrated (Fig. 4). The high value regions of the index and the high level regions of the mean yield nearly correspond with each other, and the distribution of the heading, except for the regions where early delivery rice is cultivated, seemed to almost fit the actual mean heading dates of the prefectures. Further, in regard to main productive regions on the plain or on the basin scale, of the 36 points all over the country, the mean Y_p, which was calculated using the data of the meteorological stations at the regions, on the actual heading date in the prefecture level, was denoted by Y_{pm}, and the mean regional yield, which was averaged from 1965 to 1974 using the data of several smallest administration units in the regions, denoted by Y. Between Y_{pm} and Y, a certain correlation (r = 0.752) was found (Fig. 5). It is clear from Fig. 5 that the Y_{po}-values in the high production regions, more than 550 kg/10a, are always greater than 780. From these results, it was thought that the Y_p-index may be used as the index of climatic productivity of paddy rice under given climatic conditions.

The above mentioned results refer to the regional variations in the Y_p-index. Next, the annual variations should be studied. The author and Hanyu (1981) have carried out research on the annual variations, both Y_{pm} and Y from 1965 to 1978 in the main productive regions shown in Fig. 5, 8 points of which showed certain correlations ($r \geq 0.6$) between them. Because within these regions it seems that cold district varieties and common or late varieties of the regular cultivation are mainly planted, it was assumed that the Y_p-index was useful for cold resistant and high yield varieties in regard to an annual fluctuation of the climatic productivity. However, in the areas of the early delivery rice where early ripening varieties are planted, there is no correlation between Y_{pm} and Y. But a correlation between them can be found, assuming that θ_O, the optimum temperature of θ_R, is a parameter which changes in the various regions one by one. Then, it was examined how useful the Y_p-index was as a prediction equation of the yield. The following results were obtained: assuming (i) the above-mentioned parametarization of θ_O and (ii) the introduction of the technical term with the stagnation models of the technical advance, the prediction equations are valid for 25 points out of 36 points.

The examination on the limit of the paddy rice cultivation by the Y_p-index

Because the Y_p-index seemed to be useful for the cold resistant and high yield varieties as the climatic productivity model, in this paper the limit value of the Y_p-index expressing the climatic productivity at the limit of the paddy rice cultivation was investigated.

About the climatic limit of the paddy rice cultivation, the mean air temperature on the warmest month, 20°C, is used as one of the limit indices, and accumulated temperatures used as another. There is room for improvement in these limit indices, because of the failure to consider the condition of the sunshine which is an important factor of existence. On this point, it seems that the Y_p-index including nearly all stages of the mean air temperatures (θ_V, θ_H, θ_R) and the total sunshine duration (S_R) has a new meaning as the limit index of the paddy rice cultivation.

When the limit value is decided, the moving of the limit line will be estimated in the various cases.

2. Method and Data

The normal Y_{po} distribution in Hokkaido, the northern limitation of paddy rice in Japan, is overlapped on the distribution of paddy fields. Then the minimum value of Y_{po} within the overlapped region is taken as an index of the limit of the paddy rice cultivation.

Next it is applied to the height distribution of the normal Y_{po} and the height limit of the paddy rice cultivation is inferred and an attempt is made to compare it with the actual limit of the upland cultivation.

Moreover, for 14 years from 1965 to 1978, the correspondence of the regional yield to Y_{po} is examined about 3 regions in Hokkaido in relation to the limit value.

After the limit value of cultivation is determined, the Y_{po} distribution around the limit value in the recent years, 1976, 80 of the cool summer damages, is illustrated, and compared with the unit yield of the smallest administration units in Hokkaido.

Finally, the movement of the limit line is supposed in the various climatic states which the normal climate would change. In this case, the mean air temperatures, θ_V, θ_H, θ_R and the sunshine duration, rise and fall mechanically, and Y_{po} is calculated using the new $\theta_V, \theta_H, \theta_R$, and S_R, in each case.

The original data which was used in order to calculate Y_p is *the climatic table of Japan part 4* for the normal, *the Meteorological Agency annual report* from 1965 to 1978 for the individual years, and *the Meteorological Agency monthly report* from April to October for 1980.

At the time of calculating Y_{po}, first of all Y_p is calculated by sliding the heading period every 5 days from July 15 according to Eq. (4) and Eq. (5). Then we regard the maximum Y_p as Y_{po}. The meteorological data used are the mean temperature and the total sunshine duration of 5 days; however, that in 1980 is the value of 10 days so value of 5 days is interpolated. Although the points of calculation extend all over the meteorological stations,

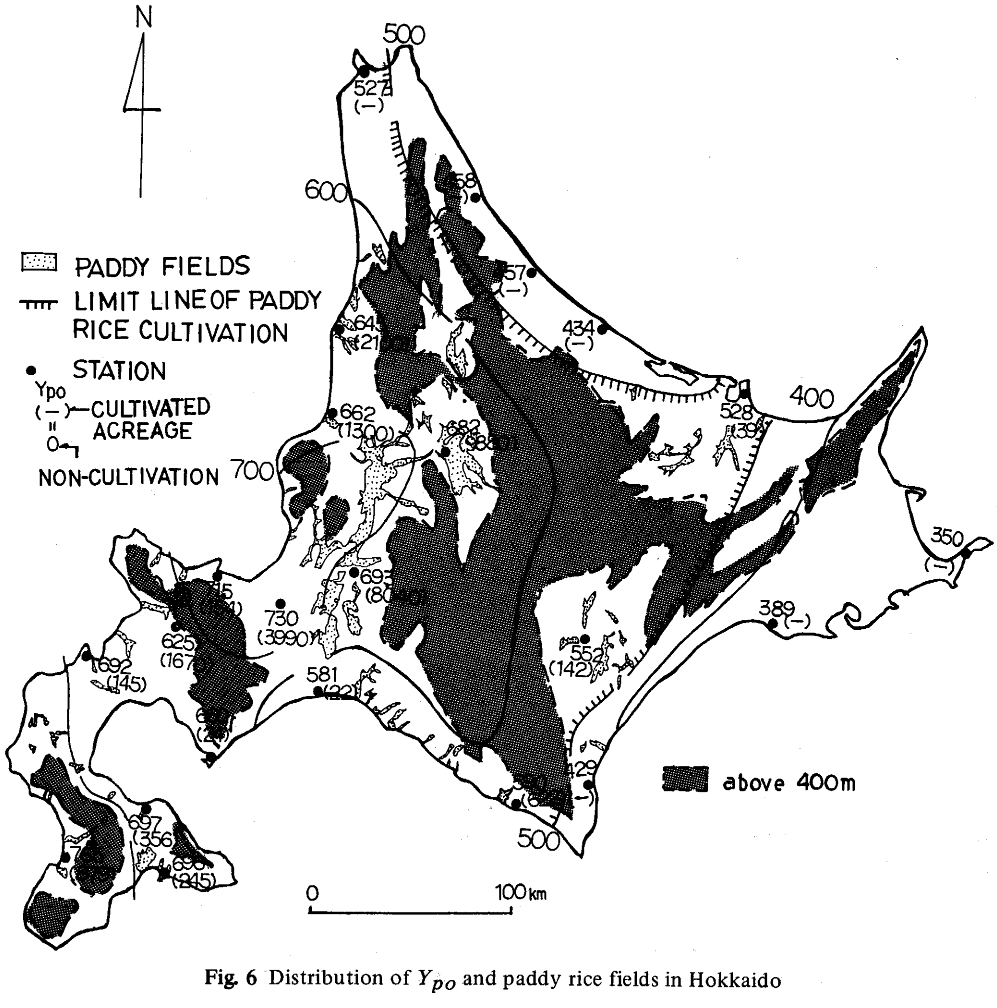

Fig. 6 Distribution of Y_{po} and paddy rice fields in Hokkaido

only Y_{po} of North Japan and of high points above the sea are mainly used in this paper.

The acreage data of the paddy rice cultivation and unit yield of the smallest administration units (cities, towns, and villages) is obtained from *the Statistics of Crops* by Ministry of Agriculture and Forestry. The regional yields in the scale of a plain or basin were calculated from the data of acreages and harvests of several smallest administration units.

Moreover, the year of 1969 corresponds to one of the maximum acreage years. It was pointed out by Okamoto (1965) that the other was the period of 1930 when the marginal region had been the smallest; however the rice field acreages decreased in the years after the cool summer damages in 1931, 1932, 1934 and 1935. Then, the author uses 1969 data which shows the stable region of the paddy rice cultivation.

3. Results and Consideration

The distribution of Y_{po} and paddy fields in Hokkaido

The normal Y_{po} values were calculated for the 23 meteorological stations where the normal data were available in Hokkaido. The results are shown in Fig. 6, where isoplethes of Y_{po} are drawn at intervals of 100, and the paddy field acreage for each station is noted in brackets. When the region (the level of the minimum unit of administration) was non-cultivation, a bar was used instead of zero. The paddy field positions according to the land use map in Hokkaido (*Large Japan Atlas*, Teikoku Shoin, 1957) are shown by shadings.

Judging from Fig. 6, the isopleth of Y_{po} = 500, separating the cultivated regions from the non-cultivated, and including the paddy fields, seems to be adequate. It is shown on the figure by hatched lines which are distinguished from the others.

Height distribution of Y_{po}

In order to obtain the height distribution of Y_{po} high meteorological stations were selected from all over the country. In Fig. 7, Y_{po} and height of the each station were plotted against the x coordinate axis and y coordinate axis, respectively. The plotted points can be divided into the following regions: (A) the middle of Japan and further west, (B) the northeastern section of Japan, (C) Hokkaido.

The value of Y_{po} = 500, which is estimated as the limit of cultivation, is substituted into each nearly linear relation between Y_{po} and the height. In Fig. 7, it is possible to read the height limit of cultivation by interpolation with (A), and by extrapolation with (B) and (C). As a result, it is about 1300m to 1400m in the middle of Japan and further west, about 800m to 900m in the northeastern section of Japan, and under 400m in Hokkaido.

About the height limit of paddy rice in Japan, it is known that, Bandokoro, the eastern foot of Mt. Norikura, 1200m to 1400m, Sugadaira, 1200m, and Ooshika village, 1000m to 1400m are the highland cultivation limit. In the northeastern section of Japan, Wasezawa, the northern foot of Mt. Bandai, 840m is generally regarded as the height limit.

The height limits estimated by Y_{po} = 500 and those of the above common description agree precisely. Judging from both sides of northern limit and height limit, it seemed that the limiting value of the paddy rice cultivation by means of the Y_p-index, Y_{po} = 500 was reasonable assuming a normal climate.

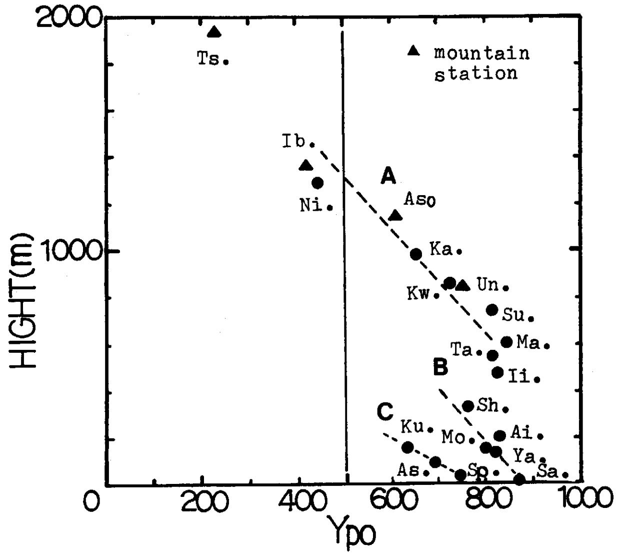

Fig. 7 Relation between Y_{po} and height.
(a) Middle and Southwest Japan
(b) Northeastern District of Japan
(c) Hokkaido
Ts. Mt. Tsurugi, Ib. Mt. Ibuki, Ni. Nikko, Aso Mt. Aso, Kw. Kawaguchiko, Ka. Karuisawa, Un. Mt. Unzenkade, Su. Suwa, Ma. Matsumoto, Ta. Takayama, Ii. Iida, Sh. Shirakawa, Ai. Aizuwakamatsu, Mo. Morioka, Ya. Yamagata, Sa. Sakata, Ku. Kuchan, As. Asahikawa, Sp. Sapporo

The relation between Y_{po} and the regional yields at 3 regions in Hokkaido

The regional yields from 1965 to 1978 were calculated for Kamikawa B., Ishikari Pl. and Tokachi Pl. which are the main paddy regions in Hokkaido. During the same period, the meteorological stations, Asahikawa, Sapporo, and Obihiro in these respective regions, were selected in order to calculate Y_{po}. The values Y_{po} and Y which are the value of 3 regions over 14 years (hence 42 points) were plotted in Fig. 8, the x coordinate axis of which is Y_{po} and y coordinate axis Y.

Regarding Fig. 8, firstly, a clear relationship (r = 0.549) between them is found, and, secondly, the bending of the upper limit line against Y_{po} at Y_{po} = 500 is revealed. The bending line shows the maximum yields which are cropped under the best one of various conditions. The bending at Y_{po} = 500 means that Y_{po} = 500 acts as a critical value of the climatic productivity, under which the yields decrease so rapidly as to become zero at about Y_{po} = 400. Because the value of Y_{po} = 400, where the regional yield become zero, is the situation under the best cultivation conditions, it seems that Y_{po} = 450 is satisfactory for the limit value under the mean technical level of cultivation. Although the limit value of the above-mentioned Y_{po} = 450 is for individual years, it is assumed that as the normal value Y_{po} = 500 is adequate for the limit value of the paddy rice cultivation. In individual years, we could expect for a certain amount of harvest (about 200kg/10a), assuming good conditions.

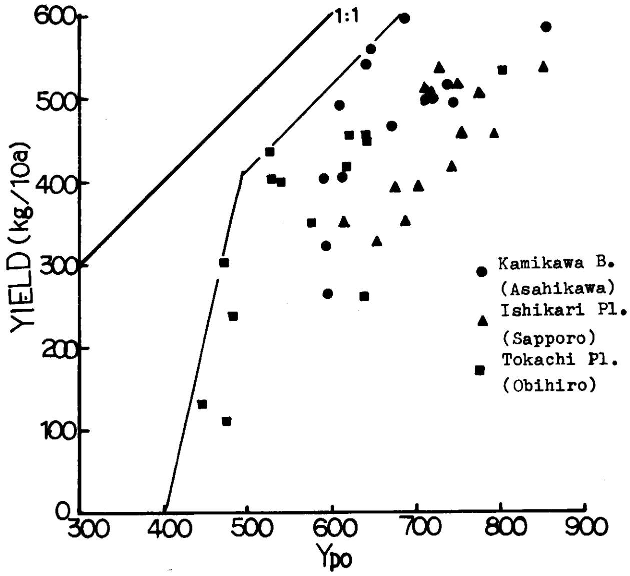

Fig. 8 Relationship between Y_{po} and Regional Yield in Hokkaido from 1965 to 1978

The distributions of the Y_{po} and the yields in the years of cool summer damage

Choosing the recent years of cool summer damage, the isoplethes of Y_{po} = 500, 400, and 600, were illustrated in Fig. 9, where (a) is that in 1976 and (b) in 1980. The yield distribution of the smallest administration unit in Hokkaido was overlapped in 1976 with the Y_{po} distribution (c). Looking at the relationship between the isoplethes of Y_p and the levels of yield, it can be pointed the following points. Firstly, the region of less than Y_{po} = 400 is restricted to that of Nemuro, Kushiro and a part of Abashiri, which is the most eastern part of Hokkaido, where non cultivated areas or cultivated areas of the yields are less than 100kg/10a. Secondly, the limit line separating eastern part of Hokkaido from the western, runs from Wakkanai, the most northern city in Hokkaido, to Hidaka. Between this line and the isopleth of Y_{po} = 400, the area mainly belongs to the level of the yield less than 300kg/10a. Thirdly, the isopleth of Y_{po} = 600 covers the core regions of the paddy rice cultivation, where the level of the yield mainly belongs to the class of 300 to 399 kg/10a; however the level of the yield more than 400kg/10a is also conspicuous. The level of Y_{po} = 500 corresponds to the level of 200 to 299kg/10a mostly, and to the yields less than 400kg/10a.

In order to ascertain the relationship between the level of the Y_{po} and the class of the yield, a table showing the relationship between them was drawn up. This is Table 1 and the above mentioned was ascertained.

When we compare the two years, 1976 and 1980 of cool summer damage, in 1980 the limit line of Y_{po} = 500 extends from Shimokita Peninsula through Sanriku Coast which shows the severity of the cool summer. In the regions less than the limit value a great deal of damage might have been done including some completely ruined harvest.

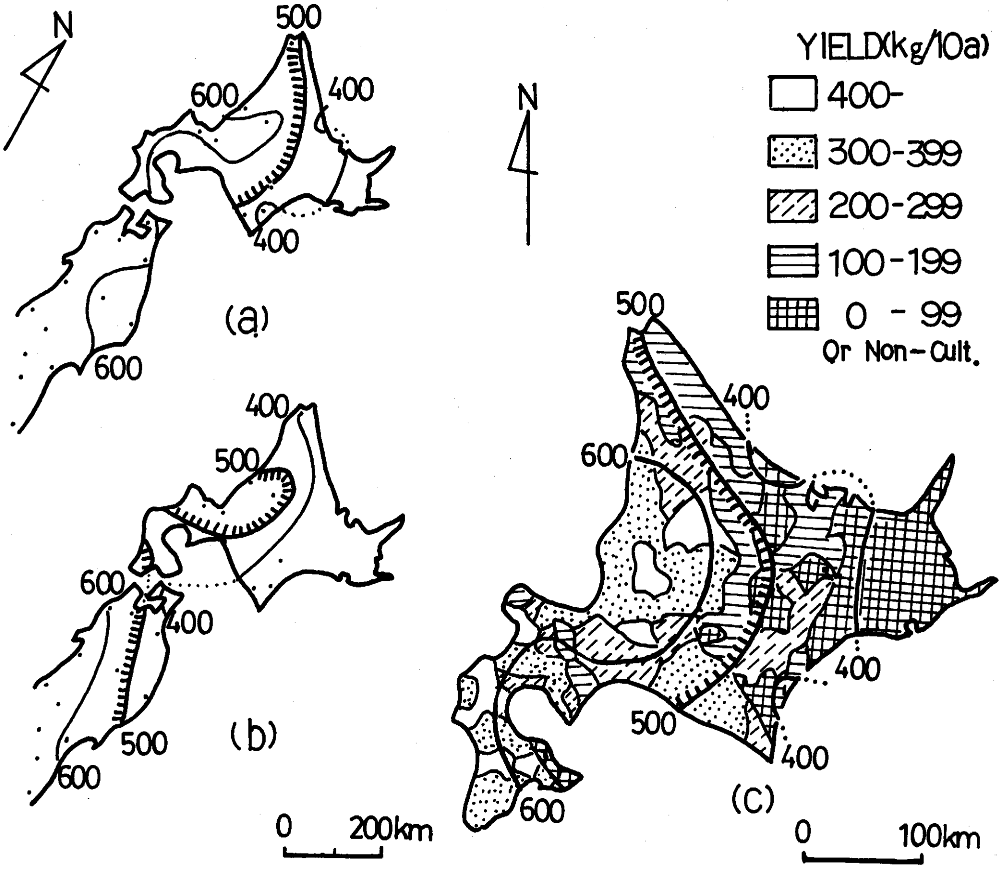

Fig. 9 Distribution of Y_{po} in cool summer damages years, (a) 1976, (b) 1980 and (c) distribution of unit yields of the smallest administration units of Hokkaido in 1976

Table 1 Correlation table in cool summer damage year (1976) between Y_{po} and unit yield of the smallest administration unit to which the meteorological stations belong

		Levels of Y_{po}				Total
		−399	400−499	500−599	600−	
Ranges of Yield (kg/10a)	Non-cultivation	4	2	1		7
	0−99		1			1
	100−199					0
	200−299		2	1	1	4
	300−399			3	4	7
	400−				2	2
Total		4	5	5	7	21

The movement of the limit line in the case of climatic variations

The moving of the limit line of the paddy rice cultivation can be considered by means of the Y_p-index, assuming changes of climatic factors from normal state.

Firstly, in Fig. 10 considering the various temperature departures such as (a) +2°C, (b) +1°C, (c) −1°C, (d) −2°C, and (e) −3°C, we can obtain the moving of the limit line and both of the isoplethes Y_{po} = 400 and 600. It is seen from Fig. 10 that if the mean air temperature rises by 2°C, the marginal region shrinks within the tip of Nemuro Peninsula, so that all the land in Hokkaido would be cultivatable for paddy rice according to climatic environment. Conversely, if the mean air temperature falls by 3°C, the region of Y_{po} above 500 shrinks within the tip of Matsumae Peninsula, so that it can be assumed that the whole of Hokkaido becomes marginal.

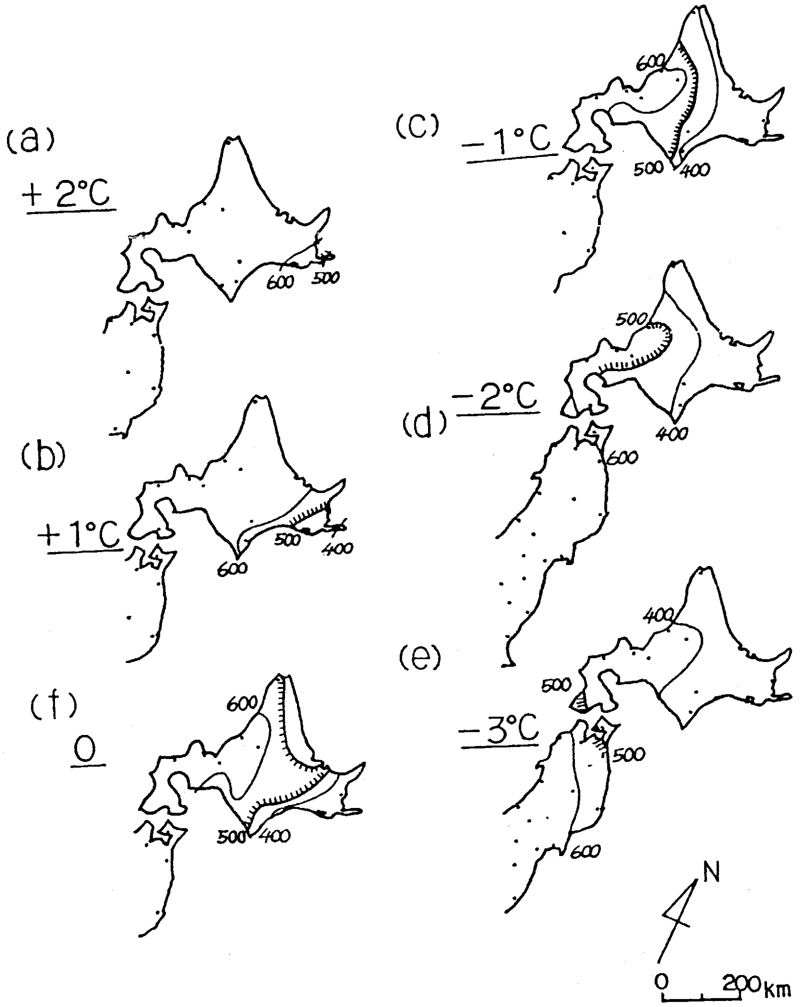

Fig. 10 The movement of the limit line of the paddy rice cultivation (Y_{po}=500) in the case of the following departures from mean temperatures: (a)+2°C (b)+1°C, (c)−1°C, (d)−2°C, (e)−3°C and (f)the normal state

Secondly, the effect of sunshine duration on the moving of the limit line is considered. Considering the S_R departures such as (a) +40 hours, and (b) –40 hours, the movement of the three lines by calculating Y_{po} is obtained in Fig. 11. The effect of sunshine duration by 1 hour per day seems to be less than the effect of mean air temperature by 1°C on the movement of the limit line. But the possibility of the shifts of the mean temperatures by 1°C and the mean sunshine duration by 1 hour per day must be compared statistically. Including the secular change of Y_{po} the properties of the changeable ones will be investigated on a future occasion.

Comparing (a) and (b) in Fig. 11, the decrease of the sunshine duration by 80 hours (2 hours/day) causes a decrease in Y_{po} by about 100. Similarly, it is seen from Fig. 10 that the same decrease of the Y_{po} by 100 corresponds to the decrease of about 1°C in the mean air temperatures.

Finally, the situation when the temperatures falls by 2°C and the sunshine duration decreases by 40 hours is considered. The three isoplethes of the Y_{po} are obtained in Fig. 11 (c). This case was assumed to be one of climatic productivity in a year of cool summer damage. Then comparing the limit line of this case with that in Hokkaido in 1980 similar results were found. But, applying the same conditions to the northeastern section of Japan, the climatic productivity in 1980 is less by about 1°C.

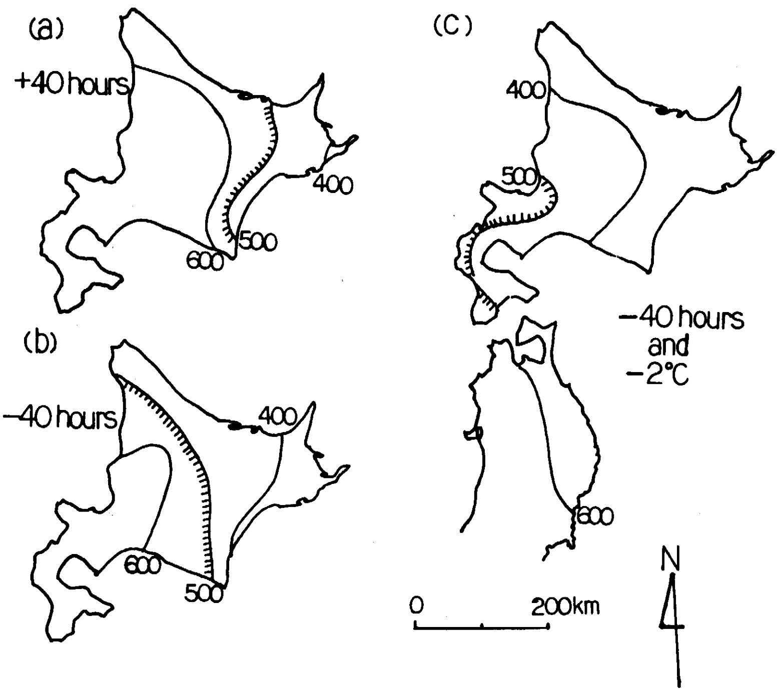

Fig. 11 The movement of the limit line of the paddy rice cultivation (Y_{po}=500) in the case of the following variations in sunshine duration: (a)+40 hours,(b)–40 hours, and (c) a 40 hours decrease in sunshine duration and 2°C decrease in temperature

4. Conclusion

The climatic productivity index of paddy rice (called the Y_p-index for short) shows how much product per 10a can be expected climatically at the present level of cultivation techniques (the routine crop test from 1973 to 1977), assuming a constant climate and removing from consideration the main factors which normally impede production. It is defined as Eq. (4) and Eq. (5).

The geographical distribution of the Y_p-index was, by way of mean state, regarded as suitable to express the distribution of the climatic productivity of paddy rice. Applying the model to the cold-resistant and high-yield varieties, an attempt was made to predict the value of the cultivation limit of paddy rice.

In Hokkaido, the distribution of non-cultivated region of paddy rice nearly corresponded to the region where the maximum Y_p value (Y_{po}) according to the normal was 500 or less.

When this value was applied to the height distribution (Fig. 7) Y_{po} was calculated for meteorological stations in various parts of Japan. The values of the height limit for the middle of Japan and further west, the northeastern section of Japan, and Hokkaido were assumed to be approximately 1400m, 900m, and 400m, respectively. This value was appropriate to the limit height of each place. So far as we took the values for normal years, Y_{po} = 500 seemed to be a suitable limit value given the northern limitation and height limit of the paddy rice cultivation.

About the 3 regions in Hokkaido Y_{po} against the regional yield on the plain or on the basin scale was examined for the past 14 years (Fig. 8) and it found that the regional yield decreased rapidly as a critical value of Y_{po} = 500. It can be assumed that if the yield was zero Y_{po} would be around 400 given suitable cultivation conditions, but on the average it would probably be around 450.

In the year of cool summer damages (1976), judging from distribution of Y_{po} and the yield of the smallest administration units, the place where Y_{po} was 500 or less corresponded to the place where the yield was less than 300kg/10a. In addition the limit line of Y_{po} = 500 was regarded to be valid when comparing of years of cool summer damages.

In the event that the mean air temperature changed, the movement of the limit line of the paddy rice cultivation was illustrated (Fig. 10). As a result it became clear that in Hokkaido if mean temperature decreased by 3°C, almost all of Hokkaido would be out of the limit of the paddy rice cultivation; conversely if it increased by 2°C, almost all of Hokkaido would be within the limit.

Next in the event that the total sunshine duration (S_R) during the ripening period increased or decreased by 40 hours, the movement of the limit line was shown (Fig. 11). The movement was smaller than that of mean temperature and the change from +40 hours to –40 hours corresponded to a Y_{po} value of 100. This change also corresponded to a change of 1°C in mean temperatures. Judging from the above, it can be inferred that the condition of sunshine duration has an important effect on the climatic limit of the paddy rice cultivation as does the temperature condition. Furthermore quantitatively speaking, the change of the mean sunshine duration by 2 hours per day corresponds to a change in mean temperature of 1°C, so that they produce almost the same range of the movement of the limit line.

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