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A Model for Evaluating Climatic Productivity and Water Balance of Irrigated Rice and Its Application to Southeast Asia

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Abstract

A physiology-oriented dynamic model incorporating crop physiological data on IR36 rice was proposed for the evaluation of climatic productivity and water balance of irrigated rice. The model explained well the location-to-location variations of actual rice yield in Japan and the U.S.A.

The climatic productivity per crop at Bangkok (Thailand) and Los Baños (Philippines) was evaluated to be approximately 9.0 and 11.0 ton/ha for the wet- and dry-season crops, respectively. These values were significantly lower than the 19.3, 15.6 and 13.9 ton/ha evaluated for California, Milano and Niigata, respectively. The lower productivity in tropical Southeast Asia is mainly attributable to the too rapid development of the crop due to the higher temperature. Since three to four crops per year are possible in tropical monsoon regions, the annual climatic productivity in tropical monsoon Asia was estimated to be at least twice as high as in the most temperate regions. The climatic water balance at Bangkok and Los Baños was evaluated to be about −460 mm per dry-season crop, implying that at least this amount of irrigation water is necessary for the dry-season rice crop there.

I Introduction

The productivity of a crop is the result of interaction among its genetic attributes, the natural environment and cultivation technology. In the natural environment, pests, diseases and soils are, to some extent, technologically manageable, but climate on a wide scale cannot be controlled. Only adaptative measures can be applied to climate, e.g. selection of cultivars and adjustment of cropping season, in order efficiently to utilize climatic resources for crop production.

Although the enormous influence of climate and weather on crop performance and productivity is beyond doubt, our knowledge about climatic influences on crops is still far short of allowing quantitative evaluation. It will, therefore, be valuable to develop a rational crop-climate model which explains and predicts crop growth and yield from climatic conditions, not only for evaluation of climatic productivity but also for selection of suitable cultivars and determination of optimal cropping seasons, which constitute an essential part of what is needed for the establishment of more sustainable and efficient agricultural systems. It is the primary objective of this report to propose a model with which to evaluate the climatic productivity and water

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balance of rice cultivation at various locations in Southeast Asia and to identify suitable types of cultivar and the optimal cropping season for given climatic conditions.

Two types of models have hitherto been proposed for the evaluation and analysis of crop-climate or crop-weather relationships of rice culture. One consists of statistical regression models [Kudo 1975; Munakata 1976], the other of physiologically-based mechanistic models [Iwaki 1975; McMennamy and O'Toole 1983]. The former type is valid only under the limited environmental and technological conditions for which the model is developed and cannot be extrapolated beyond those conditions. The latter type is developed by integrating the physiological, ecological and physical processes of crop-weather interactions, thus offering a more general and meaningful approach to the evaluation and analysis of climatic influence on crop growth and yield. The model here proposed for the evaluation of climatic productivity of rice is of the latter type.

Although the existing rice growth simulation models [Iwaki 1975; McMennamy and O'Toole 1983] are comprehensive and meaningful from the viewpoint of crop physiology and microclimatology, they require that a multiplicity of experiments be conducted to evaluate their numerous parameters and to validate the models before they can be applied to a specific purpose. The model here represented has been developed by simplification of the individual physiological and physical processes of the crop growth and development so that it may be universally applicable. The basic idea of this model is essentially that of our previous model [Horie 1987], with small modifications to make it globally applicable.

This model gives climatic productivity and climatic water balance. The climatic productivity is here defined as the yield that may be expected under a given climate from the physiology of a given cultivar raised under an optimal cultivation technology. This implies that water, nutrients, pests, disease and weeds are optimally managed. Physiological data on IR36, which was carefully cultivated in our experimental field, was used for the evaluation, because this variety is cultivated in a wide variety of climatic regions, owing to its very early maturing. This paper describes the model and the results of its application to Southeast Asia and other major rice-producing areas in the world.

II The Model

The model for evaluating the climatic productivity of rice is constructed on the basis of the general principle that the grain yield Y_G forms a component of the total dry matter production W_t. Namely,

$$Y_G = hW_t, \qquad (1)$$

in which h is the harvest index.

It has been shown that crop dry matter production is proportional to the photosynthetically active radiation (PAR) or the shortwave radiation absorbed by a crop canopy [Gallagher and Biscoe 1978; Monteith 1977; Shibles and Weber 1966]. Horie and Sakuratani [1985] showed that this is also true for rice, and that the proportionality constant, the conversion efficiency from the radiation to biomass, is constant until the middle of the ripening stage, thereafter de-

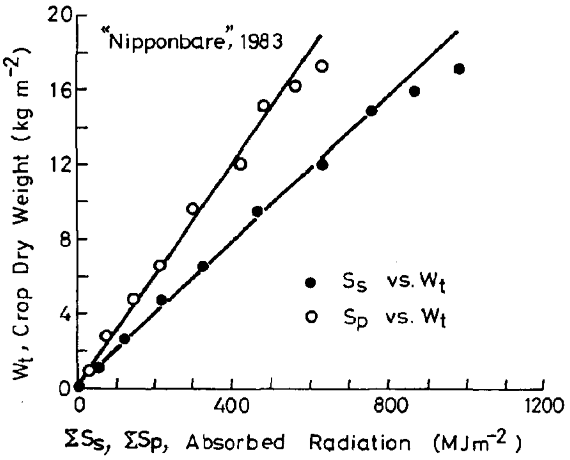

Fig. 1 Relationship between Total Crop Dry Weight (W_t) at Different Times of Growth and Absorbed Shortwave Radiation (S_s) or PAR (S_p) Cumulated over Time for Nipponbare Rice Grown at Tsukuba (Japan) [Horie and Sakuratani 1985]

creasing curvilinearly (see Fig. 1). They also showed by simulation and experiment that the conversion efficiency is practically unaffected by climatic conditions over a wide range of environments.

The model is based on the following general principle:

$$\varDelta W_t = c_s S_s, \qquad (2)$$

where $\varDelta W_t$ is the daily increment of the crop dry weight, c_s is the conversion efficiency of absorbed shortwave radiation to rice biomass (g/MJ), and S_s is the daily total absorbed radiation. Likewise, in the model, the growth in dry weight, leaf area or yield is computed day by day by inputting daily weather data.

The variables or the parameters h, c_s and S_s are functions of the environment, crop developmental stage and growth attributes. These functions and parameters have been determined by analysing the data of field experiments conducted for IR36 rice cultivars grown under widely different environmental conditions.

II. 1 *Crop Development*

The developmental processes of a rice crop, such as ear initiation, booting, heading, flowering and maturation, are strongly influenced both by the environment and by the crop genotype.

In this model, the developmental process of rice is represented by a continuous variable called developmental stage, DVS, in a similar way to that employed by de Wit *et al.* [1970]. DVS is defined in such a way that it is zero at the onset of the crop emergence, 1.0 at heading and 2.0 at maturation. Thus, the development at any moment in time is represented by a DVS value between 0 and 2.0.

The value of DVS at any moment of the crop development is given by integrating the developmental rate DVR with respect to time. That is,

$$\mathrm{DVS}\ (t) = \sum_{i=1}^{t} \mathrm{DVR}_i\,, \qquad (3)$$

where DVS(t) is the developmental stage at the tth day and DVR_i is the developmental rate at the ith day from the emergence. It is well known that day length and temperature are the main determinants of DVR. We found that the following equation predicts very well the crop developmental process until heading ($0 \leq \mathrm{DVS} \leq 1$) [Horie *et al.* 1986]:

$$\left.\begin{aligned}\mathrm{DVR} &= \frac{1}{G}\,\frac{1-\exp\{B(L_0-L_c)\}}{1+\exp\{-A(T-T_h)\}},\ \text{for } L_0 \leq L_c, \\ &= 0,\ \text{for } L_0 > L_c,\end{aligned}\right\} \qquad (4)$$

in which T and L_0 are daily mean temperature and day length; G is the minimum number of days for the heading of a given cultivar; L_c the critical day length for the development of a given cultivar; A, B and T_h are param-

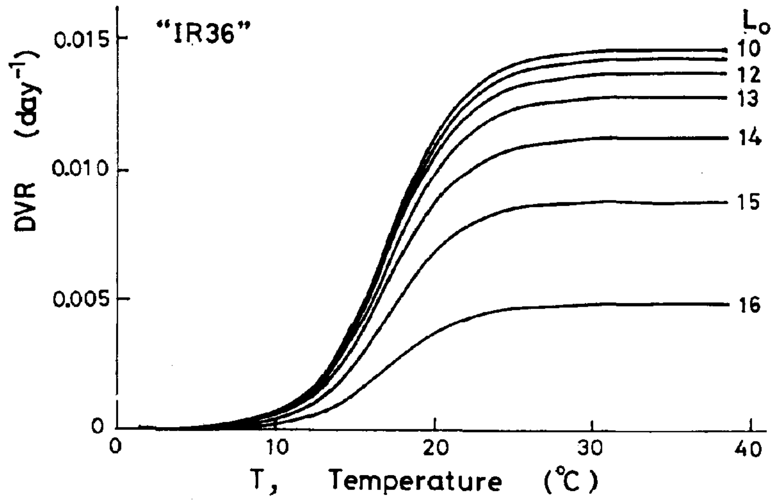

Fig. 2 Estimated Developmental Rate (DVR) of IR36 Rice as a Function of Daily Mean Temperature (T) and Day Length (L_0)

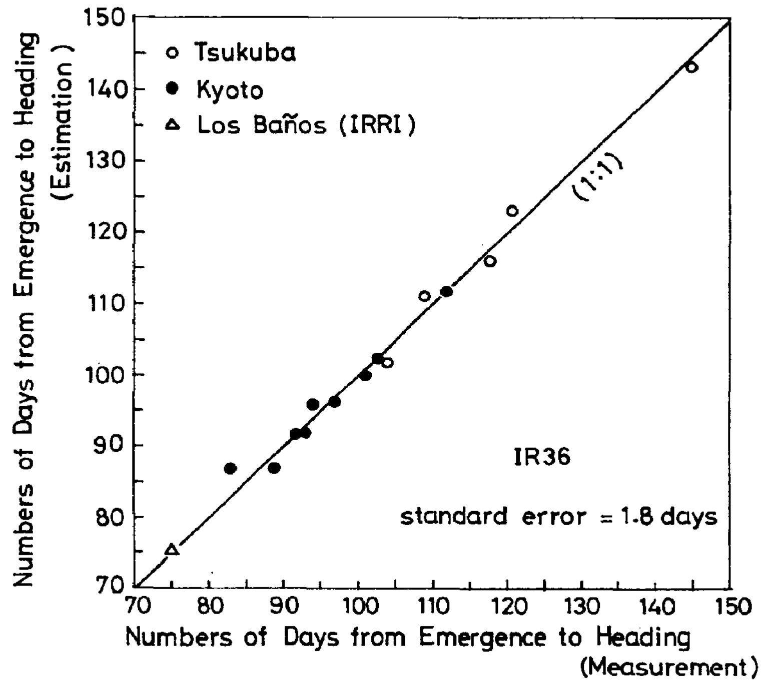

Fig. 3 Relationship between Estimations and Measurements of the Numbers of Days from the Emergence to the Heading of IR 36 Rice Grown in Different Seasons at Kyoto, Tsukuba (Japan) and Los Baños (Philippines)

eters. By using field experimental data on the heading of a given cultivar, the values of these crop parameters can be determined by the simplex method, a trial-and-error method for estimating the parameters of non-linear functions. The best estimates of these parameters for IR36 rice were $G=$ 65.6 days; $L_c=16.8$ hours; $T_h=17.3$°C; $A=0.421$; $B=0.479$. It should be noted that these values are strongly dependent upon the cultivar.

The DVR of IR36 is given in Fig. 2 as a function of temperature T and day length L_0. By using eqn (4) with these parameters, the day of heading of IR36 can be well estimated from climatic conditions (Fig. 3). As the figure shows, number of days required for the heading of IR36 varies from 75 days at IRRI (Philippines) to 145 days of one crop at Tsukuba (Japan), depending on the climatic conditions. The model predicts these heading days from the climate with a standard error of only 1.8 days.

By a similar equation to eqn (4), the crop developmental processes during the grain-filling stage ($1 \leq DVS \leq 2$) can be predicted as a function of temperature T alone.

II. 2 *Dry Matter Production*

To simulate the crop dry matter production by eqn (3), it is necessary to compute the absorbed radiation by the crop canopy S_t, which is a function of the incident solar radiation S, leaf area index (LAI; F) and the structure and optical properties of the canopy. Using the crop micrometeorological theory originating from Monsi and Saeki [1953], S_s is given by

$$S_s = S[1.0 - r - (1 - r_0)\exp\{-(1-m)k_* F\}], \quad (5)$$

where r and r_0 are the reflectances of the canopy and the bare soil, m the scattering coefficient and k_* the extinction coefficient of the canopy to daily shortwave radiation. The canopy reflectance r can be approximated well by the following equation [Research Group of Evapotranspiration 1967]:

$$r = r_f - (r_f - r_0)\exp(-0.5F), \quad (6)$$

in which r_f is the reflectance when the surface is completely covered by the vegetation. From Horie and Sakuratani [1985], the following values of these parameters were adopted for IR36 rice: $k_* = 0.57$, $m = 0.25$, $r_f = 0.22$ and $r_0 = 0.1$.

In most simulation models for crop growth so far developed, leaf area growth has been calculated from its weight growth by multiplying by a simple conversion factor, the specific leaf area. In this model, however, the leaf expansion growth of rice is modelled independently of the weight growth, for the reason already described in Horie *et al.* [1979].

Under the optimal cultivation conditions on which the model is based, it can be assumed that water and nutrients are not limiting factors to the expansion of the leaf area. Under this circumstance, LAI growth is mainly governed by the temperature. In this model the growth of LAI (F) until just before heading is given by the following function of daily mean temperature:

$$\left.\begin{aligned} \frac{1}{F}\frac{\mathrm{d}F}{\mathrm{d}t} &= R[1.0 - \exp\{-K_f(T - T_c)\}]\{1.0 \\ &\quad - (F/F_a)^{\eta}\}, \text{for } T \geq T_c, \\ &= 0, \text{ for } T < T_c, \end{aligned}\right\} \quad (7)$$

in which R is the maximum relative growth rate of LAI; T_c the minimum temperature for LAI growth; F_a the asymptotic value of LAI when temperature is non-limiting; and K_f and η are parameters. For these crop parameters, the following values were adopted on the basis of the field experimental data: $R = 0.247$ day^{-1}, $T_c = 11.5$°C, $K_f = 0.07$ and $\eta = 0.723$. The asymptotic LAI (F_a) when temperature is not limiting depends to a large extent on the amount of nitrogen application. Under the optimal cultivation conditions, however, nitrogen is applied in such a way as to control the maximum LAI within an optimal range. Since the optimal LAI is usually 5～6, we assumed F_a to be 5.5.

In rice, it is commonly observed that LAI attains a maximum at about the heading stage and declines gradually during the maturing stage. However, the physiology and the environmental response of the leaves during this maturation process are obscure. For this reason, the change in LAI from the time just before the heading to the maturation of the crop is represented by a unique function of only the crop developmental stage DVS.

By use of the above equations, the crop absorbed radiation S_s in each day can be obtained, and the dry matter production can be simulated by eqn (3). As Fig. 1 showed, the conversion factor c_s is constant until the middle of the grain filling stage, and is approximately 2.0 g/MJ for IR36 rice [Horie and Sakuratani 1985], and thereafter it decreases gradually to zero. These features of the change of c_s may be represented by

$$\left.\begin{aligned} c_s &= 2.0 \text{ g/MJ, for } 0 \leq \text{DVS} \leq 1, \\ &= 2.0\frac{1+C}{1 + C\exp\{(\text{DVS}-1)/\tau\}}, \\ &\quad \text{for } 1 < \text{DVS} \leq 2, \end{aligned}\right\} \quad (8)$$

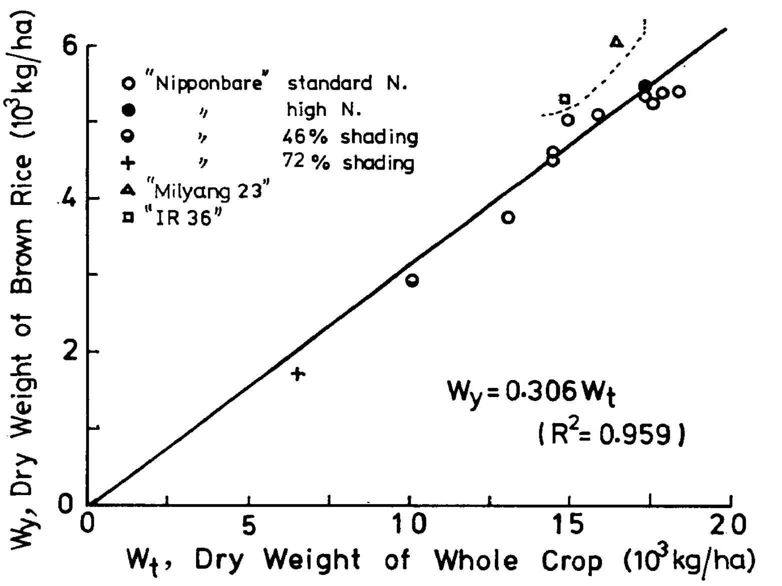

Fig. 4 Relationship between the Dry Weight of Brown Rice and That of Whole Crop for Nipponbare, IR36 and Milyang 23 Rices Grown under Different Environmental Conditions [Horie 1987]

in which C and τ are parameters, the best estimates of which were $\tau=0.1$ and $C=0.001$.

II. 3 *Harvest Index*

Fig. 4 shows that the relationship between the dry weight of brown rice (W_y) and that of the whole crop (W_t) is linear over a wide range of W_t, indicating that the proportionality constant, the harvest index h, is constant. However, this is not always so. The harvest index decreases if the percentage of sterile spikelets increases, or if the crop ceases growth before completing its development due to environmental adversity. If water conditions are not limiting, cool temperature is the largest environmental factor that affects the sterility percentage and hence the harvest index h. The increased number of sterile grains brought about by cool temperature at the booting and flowering stages is called cool-summer damage due to floral impotency, and the premature cessation of growth due to autumn coolness is called cool-summer damage due to delayed growth.

In this model, the harvest index h is represented as a function of the percentage sterility of rice spikelets γ and the crop developmental stage DVS, in oder to take account of both types of the cool-summer damage, as follows:

$$h=h_m(100-\gamma)[1.0-\exp\{-K_h(\mathrm{DVS}-1.22)\}], \quad \text{for DVS} \geq 1.22, \quad (9)$$

where h_m is the potential harvest index of a given cultivar and K_h a parameter. For these parameters, the following values were adopted for IR36: $h_m=0.37$ and $K_h=5.57$. Eqn (9) implies that the harvest index decreases as γ increases due to cool temperature at the booting and flowering stages, or as the cessation of the growth is earlier than the full maturation (DVS=2.0) due to cool autumn temperature.

By use of the cooling degree-day concept of Uchijima [1976], the relation between daily mean temperature T and the percentage sterility may be approximated by the following equation:

$$\gamma=\gamma_0+K_q Q_T^a, \quad (10)$$

where γ_0, K_q and a are empirical constants, and Q_T is the cooling degree-days given by

$$Q_T=\sum_i(22.0-T_i), \quad T_i \leq 22.0. \quad (11)$$

From the experimental data of Shibata *et al.* [1970], we estimated the values of these parameters as: $\gamma_0=4.6$, $K_q=0.054$ and $a=1.56$.

By taking into account the sensitivity of the rice panicle to cool temperatures, eqn (11) is summed over the sensitive period $0.75 \leq$ DVS

≤ 1.2 in the developmental stage.

In this model the potential growing season of the rice crop is defined as the period in which daily mean temperature is above 13.0°C, which value was set by referring to Yoshida [1981: 269]. Hence, the terminal condition of the simulation occurs either when DVS reaches 2.0 (full maturation), or when the air temperature reaches this critical value. The latter means premature cessation of the growth.

II. 4 *Climatic Water Balance*

The model also evaluates the water balance in an irrigated rice field during growth. In the water balance, the inflows are precipitation and irrigation, while the outflows are evapotranspiration, seepage, percolation and surface run-off. Of these elements, seepage, percolation and surface run-off depend not only on climate but also on topography and soil properties. Since it is beyond the scope of this study to evaluate the actual water balance by taking into account these non-climatic factors, only climatic water balance is evaluated here. The climatic water balance is defined as the difference between precipitation P and evapotranspiration ET. If the climatic water balance (P–ET) is negative, it means that at least this amount of irrigation water is necessary to sustain the climatic rice productivity which the model evaluates.

The climatic water balance was calculated on a monthly basis. The following equation of Makkink [1957] was used to evaluate the evapotranspiration ET, since this equation was found to apply well to irrigated rice fields irrespective of the growth stage [Sakuratani and Horie 1985]:

$$ET=a\frac{\Delta}{\Delta+\varepsilon}\frac{S}{l}, \qquad (12)$$

in which Δ is the slope of saturation vapour pressure curve at air temperature (mb/°C); ε is the psychrometric constant (=0.66 mb/°C); l is the latent heat of vaporization (=2454 J); a is an empirical constant (=0.93).

III Climatic Data

The climatic data were quoted from Müller [1982: 306]. Since data on solar radiation S are available from very few weather stations, they were estimated from sunshine hours L, by using the following equation of Doorenbos and Pruitt [1977: 179]:

$$S=0.25+0.50\left(\frac{L}{L_0}\right)S_0, \qquad (13)$$

where L_0 and S_0 are potential sunshine hours and solar radiation outside the atmosphere. These variables were obtained by applying astronomical formulae as a function of calendar date and latitude.

The daily climatic data, which the present model requires, are not available from usual climatic data tables of the world. Hence the model was designed so that annual courses of daily radiation and temperature could be estimated from monthly data by using Fourier series for each location.

IV Results and Discussion

IV. 1 *Model Validation*

Fig. 5 shows the simulated growth and developmental process of IR36 rice under normal climatic conditions in main (wet) rice crop season at Bangkok, Thailand. Since Bangkok has a typical tropical monsoon climate, the variations in daily mean temperature T, solar

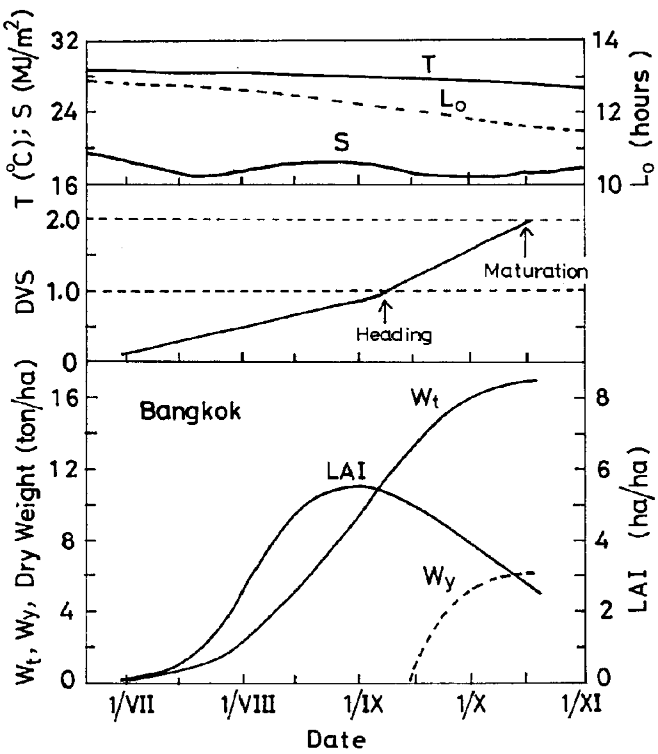

Fig. 5 Simulated Dynamics in Crop Developmental Stage (DVS), Leaf Area Index (LAI) and Dry Weights of Brown Rice (W_y) and Whole Crop (W_t), Together with the Daily Mean Temperature (T), Day Length (L_0) and Radiation (S) Conditions during the Growth Period of Wet-Season Rice Crop at Bangkok, Thailand

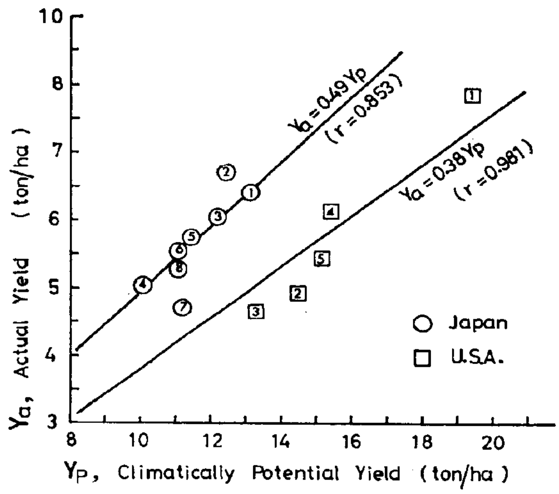

Fig. 6 Relationship between the Evaluated Climatic Productivity and the Actual Rice Yield for Climatically Different Loctions in Japan and the U.S.A. The numerals on the figure are: 1, Niigata; 2, Nagano; 3, Toyama; 4, Saitama; 5, Okayama; 6, Aichi; 7, Kohchi; and 8, Kagoshima in Japan; and 1, California; 2, Missisipi; 3, Louisiana; 4, Arkansas; and 5, Texas in the U.S.A.

radiation S and day length L_0 in the wet season are very small. The results shown in Fig. 5 illustrate well how the model evaluates the climatic productivites of irrigated rice under given climatic conditions.

As has already been described, the model evaluates climatic productivities in grain yield of rice, but not the actual yield. The climatic productivity of a given cultivar was defined as the yield that may be expected under a given climate from its physiology. To examine the validity of the model evaluation, the evaluated yields were compared with the actual yields over climatically different areas of rice production in Japan and the U.S.A. These countries were selected because rice production technologies are fairly uniform there and hence the location-to-location yield variation can be considered to be due to climatic variation. The actual and the evaluated yields are compared in Fig. 6. In the Japanese results, the productivities at the south of Niigata are represented, because Niigata was found to be the northern limit for the cultivation of IR36 rice, the standard cultivar used for the evaluations.

As in Fig. 6 shown, linear relationships are obtained between the evaluated yield and the actual yield for both Japan and the U.S.A. This indicates that the location-to-location yield variations in Japan and the U.S.A. are mainly caused by climatic variations, and that the model evaluates well the climatic productivity of rice. The relation between the evaluated climatic yield Y_p and the actual yield Y_a can be represented by the following equation with a high correlation coefficient (r=0.981 for the U.S.A. and r=0.853 for Japan):

$$Y_a = KY_p, \qquad (14)$$

in which K is the proportionality factor.

The proportionality factor K in eqn (14) is an index of the overall technology level for rice production, which includes soil improvement, irrigation systems, managements of the crop, water, nutritions, pests, diseases and weeds, and selection of cultivars. The values of K are 0.49 in Japan and 0.38 in the U.S.A., suggesting that the prevailing overall technology level for rice production is more than 20% higher in Japan than in the U.S.A. In this way, the model is also applicable to the evaluation of technology, by excluding the climatic effects.

In conclusion, the model here proposed can successfully be applied for the evaluation of climatic productivity and overall cultivation technologies in rice production in different locations of the world.

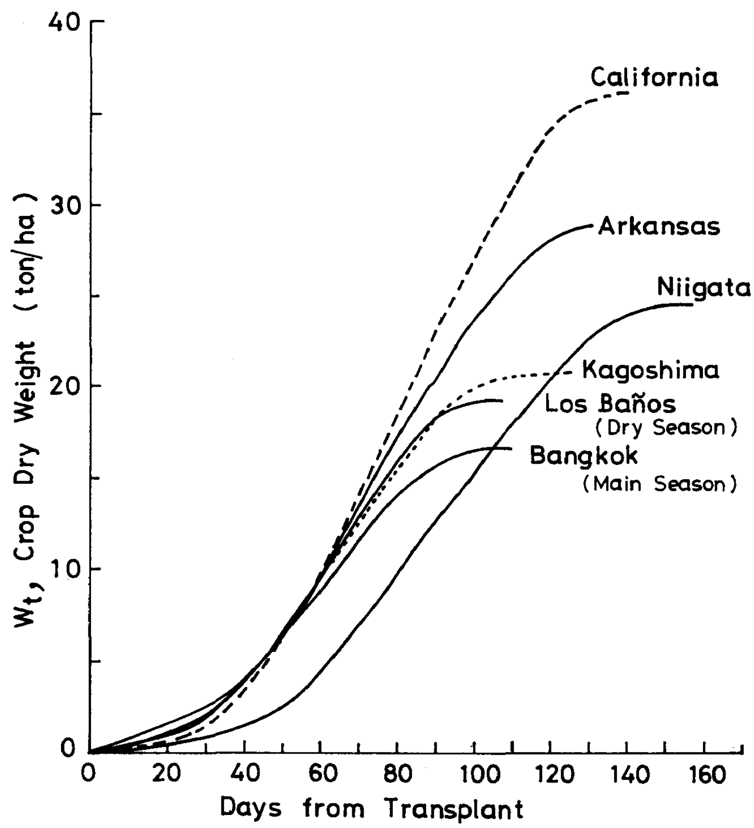

Fig. 7 Climatically Evaluated Growth Curves in Whole Dry Weight of Irrigated Rice Crops at Different Locations in the World

IV. 2 *Climatic Productivity and Water Balance of Southeast Asia in Comparison with the Rest of the World*

Fig. 7 represents the evaluated growth curves in whole crop dry weight W_t for some major rice-producing areas in the world.

It can be seen that the evaluated crop dry weights at Los Baños (Philippines) and Bangkok (Thailand) are lower than those at temperate regions. The climatic productivity in terms of dry weight in California is outstanding, followed by those in Arkansas and Niigata. The lower productivity in tropical Southeast Asia is attributable to a shorter growth period, since the growth rate during the grand growth period is comparable to that in California. This means that, under the high temperature and the short day conditions in tropical monsoon regions, IR36 rice develops too rapidly and reaches maturity with insufficient growth.

The higher dry matter production in California is attributable to both the rapid growth rate and the fairly long growth period, which result from the extremely high radiation (about 30 MJ/m^2/day) and the moderate temperature conditions. The high productivity in Niigata is mainly attributable to the longer growth pe-

Table 1 Evaluated Climatic Productivity, Actual Yield and Climatic Water Balance in the Rice Production at Climatically Different Locations in the World

Place (Country)	Cropping Condition	Climatic Productivity (ton/ha)	Expected Yield under Japanese Technology Level (ton/ha)	Actual Yield (ton/ha)	Climatic Water Balance (mm)
Bangkok (Thailand)	Wet (main)-Season Crop	9.0	4.4	2.1[1)]	+ 227
	Dry-Season Crop	11.6	5.4	—	− 458
	3 Crops Total	28.8	14.1	—	− 598
Los Baños (Philippines)	Wet-Season Crop	9.0	4.4	2.3[2)]	+ 359
	Dry-Season Crop	10.2	5.0		− 452
	3 Crops Total	26.2	12.8	—	+ 154
Niigata (Japan)	Current Cropping	13.9	6.8	6.4[3)]	− 69
Kagoshima (Japan)	Current Cropping	11.1	5.4	5.3[3)]	+ 418
California (U.S.A.)	Current Cropping	19.3	9.5	7.9[4)]	−1, 121
Arkansas (U.S.A.)	Current Cropping	15.4	7.5	6.1[4)]	− 524
Milano (Italy)	Current Cropping	15.6	7.6	5.2[5)]	− 418

Source
1) Thailand, Ministry of Agriculture [1978: 19]
2) FAO [1983: 111]
3) Japan, Ministry of Agriculture, Forestry and Fishery [1986: 288]
4) USDA [1984: 35]
5) Japan, Ministry of Agriculture, Forestry and Fishery [1984: 395]

riod (about 155 days), which reflects the lower temperature during the grand period of rice growth.

Table 1 summarizes the evaluated climatic productivity and water balance for the major rice-producing areas of the world, together with the actual yields. The climatic productivity and the actual yield both are represented by the weight of unhulled grain with 14% moisture.

The climatic productivities per crop in tropical Southeast Asia are approximately 9.0 and 11.0 ton/ha in the wet and dry seasons, respectively. These values are signifiacntly lower than those of 19.3 ton/ha in California, 15.6 ton/ha in Milano and 13.9 ton/ha in Niigata. The evaluated climatic productivity of 11.0 ton/ha in the dry season of tropical Southeast

Asia equals the highest yield recorded at the International Rice Research Institute (IRRI) in the Philippines, while the 13.9 ton/ha in Niigata is comparable to the highest rice yield recorded in Japan. Thus, the climatic productivity evaluated by this model coincides approximately with the highest rice yields recorded in the respective climatic regions.

Although the climatic rice productivity of California is exceptionally high, the model estimates that at least 1,100mm of irrigation water is necessary to sustain this productivity. The climatic water balance of the dry-season crop in tropical Southeast Asia, on the other hand, is significantly smaller, approximately −460mm. Rice production in an arid climate like that of California is possible only where water resources are available. Such places are exceptional among the world's rice producing areas.

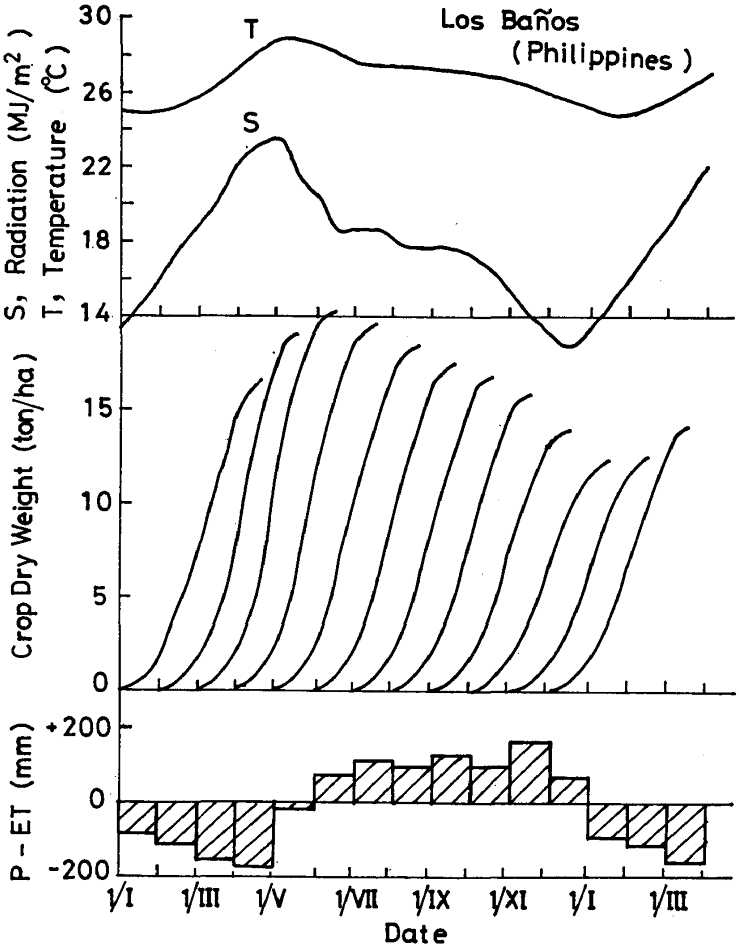

Fig. 8 Simulated Growth Curves of IR36 Rice, Successively Transplanted on the 1st Day of Each Month, Together with the Climatic Water Balance (P—ET), Daily Mean Temperature (T) and Radiation (S) Conditions at Los Baños, Philippines

Although the climatic productivity per one crop is low in tropical Southeast Asia, up to four crops could be raised each year provided that early maturing cultivars like IR36 were transplanted continuously. This is mentioned, of course, only for the purpose of discussing climatic potential, and such a cropping system is not recommended in practice, because of pests, diseases and weed problems. The total climatic productivity of three crops per year in tropical Southeast Asia is evaluated to be approximately two times as high as in the majority of the temperate regions (Table).

Table also shows for each region the yield that could be expected if the present Japanese level of rice production technology were applied. This yield is derived by multiplying the evaluated climatic productivity at each location by the factor K (=0.49), according to eqn (14). Under this assumption, the rice yield per crop in tropical Southeast Asia would double. If three crops per year were raised under these conditions, the total production would be about six times the present level. The climatically potential productivity of rice in tropical monsoon Asia, evaluated by this model, is a further two times this expected yield under the assumption of Japanese technology.

From the above analyses and discussions, it may be concluded that the climatic potential for rice production in Southeast Asia is enormous, and only a part of the potential is at present realized. To utilize the climatic resources more efficiently and to establish a more stable rice production system in Southeast Asia, technological investments are necessary in irrigation and drainage systems, soil improvement and management of water, nutrients, pests, diseases and weeds, as well as in varietal improvements.

IV. 3 *Cropping Season Analysis*

The model can also be applied to predict the optimal cropping season and/or a most suitable genotype under given climatic conditions.

Fig. 8 is the result of cropping season analysis by applying the model to the climatic conditions of Los Baños. It shows the evaluated growth curves of successively transplanted rice crops on the first day of each month, together with the annual courses of temperature, radiation and the climatic water balance. The model predicts that, under the climatic conditions of Los Baños, the yields of crops harvested in May and June are highest (10.2∼10.8 ton/ha), while those of crops harvested in December and January are lowest (6.6∼7.4 ton/ha). Similar results were also obtained in the cropping season analysis for Bangkok. The results shown in Fig. 8 agree well with the experimental data of IRRI [1974: 49] at Los Baños.

Although the potential productivity of the dry-season crop is significantly higher than that of wet-season crop, irrigation is indispensable for the dry-season crop (Fig. 8). Even with early maturing rice cultivars like IR36, at least 460 mm of irrigation water is necessary for the dry-season crop at Los Baños or at Bangkok (Table 1). Here again the importance of devising an irrigation and drainage system can be pointed out.

To apply the present model to the prediction of the most suitable genotype of rice to a given climatic condition, further experimental work is necessary to evaluate the crop parameters of the model for various cultivars.

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