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A Methodology in Predicting the Influence of Climatic Variables on Crop Yield

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Herminia C. Tanguilig

For additional information, please contact:

Author's name	:	Herminia C. Tanguilig
Designation	:	Associate Professor
Affiliation	:	Don Mariano Marcos Memorial State University
Address	:	Bacnotan, La Union
Tel. no.	:	(072) 242-5641; (072) 888-5352
E-mail	:	hermtang@yahoo.com

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ABSTRACT

Weather interacts with components of agricultural production system. An understanding of these interactions is essential in formulating crop production strategies.

On one hand, it is difficult to establish quantitatively this complex interaction with some reasonable degree of reliability. The most feasible approach is to conduct long-term experiments involving continuous cropping and subject to analysis to generate rational or statistical relations.

On the other hand, crops react differently to climatic parameters at various stages of development and these responses are usually manifested in the final yield of the crop, hence not only reliable climatological data for the whole season is needed but it is also essential to know the temporal distribution of a climatological variable at each growth stage.

In the context of studying the influence of a single weather parameter over a given period, effect on yield was determined by dividing the growth period into seven-day periods. Such analysis based on weekly weather data determined the effect of seasonal variation of weather factors more accurately than monthly weather data using a prediction equation.

I. INTRODUCTION

Climate is a function of crop yields. It affects the soil and plant processes, and the occurrence of pests and diseases which ultimately influence growth characteristics, the ocular predictors of crop yield. Rainfall, air temperature, and wind are the most critical factors for pest occurrence (Haufe, 1975; IRRI, 1977; Kato, 1976; McQuigg, 1974; Schrodter, 1975; and Soria and Quebral, 1973).

Agronomic studies are also concerned with the relationships between environmental and developmental processes of plants since growth and development of crops are also a function of past and present environmental conditions. Hence, it is often of interest to know the extent to which individual parameter influences crop development.

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** Associate Professor V, Don Mariano Marcos Memorial State University (DMMMSU), Bacnotan, La Union

It is difficult to establish quantitatively the complex interaction between plants, soil, and climatic variables with some reasonable degree of reliability. The most feasible approach to evaluate their interrelationships is to conduct long-term experiments involving continuous cropping and subject the results to analysis to generate rational or statistical relations.

Correlation techniques are important tools for investigating relationships between crop growth and environment (Kuehl, K.O. et al, 1975). Correlation studies, however, have not been successful due to the following reasons: reliable meteorological data and related yield are not available in series for a sufficiently many number of years; meteorological data used in these studies may not be representative of the area where the crop yield was taken from; and, the variations in crop yield that may attributed to plant variety, soil conditions and, management inputs are extremely difficult to evaluate.

Since crops react differently to climatic parameters at various stages of development, it is also essential to understand the temporal distribution of a climatological variable at each growth stage. It is in this context that the study was conceived with the following objectives:

1. To develop prediction equations for predicting rice yield with climatic variables as predictors; and
2. To determine the reliability of the prediction equations.

II. REVIEW OF LITERATURE

Review of Application of Crop-Weather Models

One of the earlier applications of statistical correlation used in weather-crops analysis is that of Hooker (1907), who correlated yields with precipitation and separately with temperature, using overlapping calendar periods during the crop cycle. According to Stanhill (1973), simple correlations can have useful predictive value in a situation where a single factor exerts a dominating influence on crop performance. For more than one climatic parameter having an important effect on crop performance, various forms of multivariate analysis representing a further development of simple correlation-regression approach can be used (Baier, 1973). However, monthly or seasonal values could not explain well the variation in yield compared to two-day, five-day, eight-day period (Screenivasan et al, 1973; Huda et al, 1975; Basak, 1957). This is due to the fact that a change in an inch of rainfall may not change suddenly from month to month, but gradually from short period of time or week during the growing season.

Davis and Pallesen (1940) analyzed a five-day rainfall data in relation to corn yield and concluded that although the total rainfall for the season is not significantly correlated with yield, the distribution of seasonal rainfall is correlated with yield.

Hendricks and Scroll (1943) considered the joint effects of rainfall and temperature on crop yields in three states and concluded that high temperatures have beneficial effect on final yield when sufficient moisture is available and detrimental effect when moisture supply is deficient. The same result was obtained by Stacy et al (1957) using a second degree orthogonal polynomial on 38 years data on corn yield with climatic variables, rainfall and temperature, in Georgia.

A fourth degree multiple correlation equation was used to explain the variation of corn yield (Runge and Odell, 1968). Using the same methodology, they found out that the maximum daily temperature and rainfall have a large effect on corn yield from 25 days before to 15 days after anthesis. The maximum temperature beneficial to corn yield was between 32.2°C and 37.8°C as long as moisture is not limited.

Huda et al (1975) reported that the average weekly climatic variables are beneficial during nursery period, while adverse effect are noted on the vegetative stage of rice yield. The ripening stage was found most susceptible to excessive climatic variables. The climatic variables related to rice yields are rainfall, maximum temperature, minimum temperature, and relative humidity.

III. MATERIALS AND METHODS

Sources of Data

Secondary data came from the continuous cropping rice yield experiments conducted in the same field during the period 1962 – 1979 at the International Rice Research Institute (IRRI), Los Banos, Laguna, Philippines. Cultural practices which have become standard in agronomy experiments at the Institute were used.

Yield of IR 8 rice variety was chosen from the experiment since IR 8 was continuously planted for 14 years (1968 to 1982). Climatic data such as rainfall, relative humidity, maximum temperature and solar radiation were gathered from IRRI and from the College Weather Station, UPLB for corresponding series years with crop yield.

Mathematical Yield-Model Development

Understanding the response of the crop on the weather especially during the growing season is of utmost significance. In the context of studying the influence of single weather parameter over a given time period, effect on yield was determined by dividing the period into n subdivisions. Thus, the linear regression model of the yield of the IR 8 rice variety (Z) in tons per hectare on the climatological factor may be expressed as:

$$Z = A_o + a_o x_1 + a_1 x_2 + ... + a_n x_n + x \quad \ldots\ldots\ (1)$$

where A_o is the regression constant: $x_1, x_2, ..., x_n$ are magnitude of a particular climatological variable in various time intervals t, t = 1, 2, …, n; $a_o, a_1, ..., a_n$ are the partial regression coefficients; x is the random error effect. Hence, if infinitely small subdivisions of time were taken, the linear regression function may be replaced by a regression integral of the form

$$Z = A_o + \frac{1}{T}\int_0^T axdt + x \quad \ldots\ldots\ldots\ldots\ (2)$$

where x is the dimatological factor experienced by the crop in the element of time dt; the integral being derived over the entire period of the growing season, i.e., from planting to maturity; T is the entire period of the growing season; a is a function of time t.

From equation 2, it follows that a is actually a continuous function of time t and indicates the average increase in yield for a unit increase in the climatological factor.

The whole growing season of IR 8 was divided into n = 18 seven-day periods for the first and second cropping and n = 17 seven-day periods for the third cropping season.

Based on physiological considerations, it is assumed that a coefficient of regression of crop on the climatic variables in one seven-day period would not differ significantly from one in adjacent seven-day periods. In this context, it is conceivable to think that there exists a relationship between yield and increased climatological influences that change slowly from one short period of time to another (Fisher, 1924).

Response of crops to any climatic variable is quadratic in nature on time. This is because the effect of a particular climatological variable on the crop at its early growth stage is less than the effect at later growth stage. The accumulated effect of a particular climatological variable at a certain period is dependent on the previous amount of that particular climatological variable at each time period (Chang and Vergara, 1971). Hence, a second degree moment was taken from the start of the growing season to maturity. The second degree multiple regression equation which explains the relationship between the rice yield and amount and distribution of a particular climatic variable during the growing season of the rice crop may be written as

$$Z = A_o + a_o \sum_{i=1}^{n} t_i^o y_i + a_1 \sum_{ii=1}^{n} t_i^1 y_i + a_2 \sum_{i=1}^{n} t_i^2 y_i + V \quad \ldots\ldots\ldots\ldots \quad (3)$$

where $a_o, a_1,$ and a_2 are partial regression coefficients; A_o is a constant; y_i is any climatic variable within any given i^{th} (i = 1, 2, .. , 18 or 17) seven-day period during the growing season; $t_1 = 1$ represents the first week of the growing season and $t_{18} = 18$ or $t_{17} = 17$ represents the end of the growing season to identify the specific period the climatological data is taken after planting or before harvest. The term t_i accounts for the accumulated effect of the climatic variable over time.

Analysis of the Data

Fifty-two seven-day periods of the climatological data for each cropping year are computed, i.e. mean weekly for minimum temperature, maximum temperature, relative humidity, solar radiation and weekly total for rainfall. These fifty-two seven-day data are then divided into eighteen seven-day period for the first and second cropping seasons and seventeen seven-day period for the third cropping season. The climatological data in each of the eighteen or seventeen seven-day periods of each growing season designated by y_i ($y_i = y_1, y_2, ..., y_{18}$ or y_{17}) and t_i^S $((t_i = 1,2,3,...,18 or 17)$ where S is the power of t (S = 0, 1, 2), the climatological distribution constants as variables of the model were calculated as follows:

$\sum_{i=1}^{n} t_i^o y_i = \sum_{i}^{n} y_i =$ total amount of a climatological data for the cropping season

$\sum_{i=1}^{n} t_i^1 y_i = \sum_{i=1}^{n} t_i y_i =$ sum of the cross-product of the time interval t_i and amount of climatological data at period t_i over the entire cropping season

$\sum_{i=1}^{n} t_i^2 y_i =$ sum of the cross products of t_i^2 and y_i over the entire cropping season

For this particular analysis, a second degree distribution for the entire cropping season of the climatological factors was assumed to sufficiently express the relationship.

Before fitting the amount and the distribution of climatological factors on rice crop yield, the rice yield was examined for the presence of trend. It was noted that the downward trend was present and hence, the trend (T = 1 for the first year and T = 12 for the last year of the cropping season) was incorporated in the model to correct decreasing yield in the time series. Hence, by incorporating the trend (T), the second degree multiple regression equation model between rice yield and climatological variables can be expressed as:

$$Z_T = A_o + a_o \sum_{i=1}^{18 or 17} t_i^o y_{iT} + a_1 \sum_{i=1}^{18 or 17} t_i^1 y_{iT} + a_2 \sum_{i=1}^{18 or 17} t_i^2 y_{iT} + a_3 T + x_T \quad \ldots\ldots (4)$$

where: $Z_T =$ crop yield per hectare at year T; $A_o =$ regression constant; $a_o, a_1, a_2, a_3 -$ partial regression coefficients; y_{iT} - value of climatic variable for the ith seven-day period at year T, i = 1, 2,..18 or 17; $t_i -$ the number of each of the seven-day periods (it is 1 for the first seven-day period of the growing season and 18 or 17 at the end of the growing season); T - the year number (beginning with one (T =1) in 1968 and ending with 12 in 1979) which will be included to correct the long term upward or downward trend in crop yield; $x_T -$ random error effect at year T. The joint effect of climatic variables on IR 8 rice crop were not analyzed using the method developed by Runge (1968), Runge and Odell (1958) and Stacy et al 1957), inasmuch as the series of twelve years of IR 8 rice crop yield data is not sufficient to treat the joint effects of climatic variables on the crop.

Test on the Reliability of the Regression Equation

After fitting the second degree multiple regression model to the given body of data, an assessment was made of the adequacy of fit. The model has a good fit if R^2 is not too far from unity. The larger R^2 is, the better the model explains the variation in the data.

Thus R^2 is a measure of how well the climatological data explains the variation in yield.

IV. RESULTS AND DISCUSSION

Reliability of the Model

Results reveal that the prediction equation, as shown below, estimates the crop yield on average weekly climatological data.

$$Z_T = A_o + a_o \sum_{i=1}^{18 or 17} t_i^o y_{iT} + a_1 \sum_{i=1}^{18 or 17} t_i^1 y_{iT} + a_2 \sum_{i=1}^{18 or 17} t_i^2 y_{iT} + a_3 T + x_T$$

Analysis of the statistical results (Table 1) reveals that except for minimum temperature during the first cropping season and maximum temperature during the first and third cropping season, weekly total rainfall, weekly average relative humidity and weekly average solar radiation did not significantly affect rice yield. It is interesting to note that rainfall was expected as a significant factor but the finding reveals otherwise because the crop was irrigated throughout the growing season. These findings conform with Uchijima's (1980) which reveals that rice plants are most sensitive to water supply and temperature throughout the growing season.

Influence of Rainfall on Crop Yield

The data did not show evidence that rainfall significantly affects rice yield as specified in the model using a = 5% (Table 1). The non-significance of rainfall as a predictor of rice yield is due to the fact that the crop was irrigated.

Comparing the total amount of rainfall for the whole growing season to the optimum requirement for plant growth (Table 2), rainfall should have been a significant factor. According to Yoshida (1977), the amount of rainfall needed during the vegetative and reproductive stage are 200 mm/month and 300 mm/month, respectively; and the growth and yield of crops are affected by weather fluctuations that deviate from the optimum; and that rice plants are most sensitive to water supply and temperature throughout the growing season (Uchijima, 1980). Furthermore, Moomaw and Vergara (1964) pointed out that 2,000 mm rainfall is adequate for one rice cropping season provided that distribution of rainfall is reasonably uniform.

Influence of Minimum Temperature on Crop Yield

Table 1 also shows that minimum temperature significantly affects rice yield at 5% level of significance. The minimum temperature range of 20.48ºC – 21.30ºC during the vegetative phase may have significantly affected the rice crop since the range is within the optimum range of 19°C to 23°C. According to Vamadevan (1974), high minimum temperature at vegetative is found to have a significant negative role in determining yield.

It is also interesting to note that at reproductive stage, the minimum weekly temperature varied between 20.49°C and 21.63°C, considered moderately low temperature range, which favors high spikelet number. According to Tanaka (1962), blooming (at 11th week of the crop growth period) is adequate when the minimum temperature range is from 19°C to 23°C. Ueki (1966) also claimed that spikelets become sterile if critical low temperature hits the critical growth stage and this type of damage cannot be compensated for even if weather conditions are favorable afterward.

The temperature range of 22.15°C to 23.30°C (Table 2) which is within the optimum may have significantly effected the grain filling. According to Munakata et al (1967), the optimum temperature range for ripening is of the range 20°C to 23oC.

Influence of Maximum Temperature on Crop Yield

During the first cropping season, data showed evidence that maximum temperature significantly affects rice yield at 10% level of significance (Table 1). This may attributable to the favorable maximum temperature during the vegetative and reproductive stages. Maximum temperature contributed about 60 % variation in yield (R^2 = 65.88%). The temperature range 29.11°C to 30.68°C was favorable to tillering during the vegetative stage. The temperature range 30.90°C to 32.34°C during the reproductive stage was favorable for blooming as well.

V. SUMMARY AND CONCLUSION

The second degree multiple regression equation appears to be sufficiently reliable for practical purposes, giving objective information far better than subjective guesses.

Rainfall does not significantly affect rice yield when the crop is irrigated. The favorable amount and distribution of minimum temperature during the crop growth significantly affects rice yield. The favorable amount of maximum temperature during the vegetative and reproductive stage significantly affects rice yield.

Table 1. Coefficient of Determination (R^2) of Climatic Variables

	R^2 value (Coefficient of Determination)		
Climatic Variable	1st Cropping	2nd Cropping	3rd Cropping
Rainfall	55.87 ^{ns}	28.08 ^{ns}	51.94 ^{ns}
Minimum Temperature	86.09 *	57.13 ^{ns}	40.16 ^{ns}
Maximum Temperature	65.88 *	31.73 ^{ns}	62.98 *
Relative Humidity	57.05 ^{ns}	39.86 ^{ns}	56.85 ^{ns}
Solar Radiation	52.69 ^{ns}	52.57 ^{ns}	42.77 ^{ns}

* - significant @ 10% level of significance; ns – not significant

Table 2. Comparison of Amount of Climatic Variable and Optimum Requirement at Various Growing Period

Climatic Variable/Cropping Period	**Growth Period**			**Optimum Requirement**
	Vegetative	Reproductive	Ripening	
Rainfall:1st ropping	(whole growing	Period) = 136.89 mm		2,000 mm (whole growing season
2nd cropping	(whole growing	Period) =136.89 mm		
3rd cropping	221.71 mm (whole growing	262.04 mm Period)= 942.61 mm		200 mm/month (vegetative stage); 300 mm/month (reproductive stage)
Minimum Temperature				
1st Cropping	20.48°C to 21.30°C	20.49°C to 21.63°C	22.15°C to 23.30°C	Veg.-15°C to 18°C; Rep.-22.2 °C Rip.-20°C-23°C
2nd Cropping	(whole growing	Period) - 22.85oC to 23.59oC		
3rd Cropping	22.86°C to 3.37°C	22.03°C to 22.9°C	21.63°C to 22.03°C	
Maximum Temperature				
1st Cropping	29.11°C to 30.68°C	30.90°C to 32 °C	32.92°C to 34.24°C	
2nd Cropping	32.85°C-33.95°C	31.43°C-32.43°C	31.52°C-31.61°C	
3rd Cropping	30.33°C-31.81°C	29.6°C-30.65°C	29.18°C-29.53°C	

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