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Application of a progressive-difference method to identify climatic factors causing variation in the rice yield in the Yangtze Delta, China

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Abstract Time series of rice yields consist of a technology-driven trend and variations caused by climate fluctuations. To explore the relationship between yields and climate, the trend and temporal variation often have to be separated. In this study, a progressive-difference method was applied to eliminate the trend in time series. By differentiating yields and climatic factors in 2 successive years, the relationship between variations in yield and climatic factors was determined with multiple-regression analysis. The number of hours of sunshine, the temperature and the precipitation were each defined for different intervals during the growing season and used as different regression variables. Rice yields and climate data for the Yangtze Delta of China from 1961 to 1990 were used as a case study. The number of hours of sunshine during the tillering stage and the heading to milk stage particularly affected the yield. In both periods radiation was low. In the first period, the vegetative organs of the rice crop were formed while in the second period solar radiation was important for grain filling. The average temperature during the tillering to jointing stage reached its maximum, which affected rice yields negatively. Precipitation was generally low during the jointing and booting stages, which had a positive correlation with yield, while high precipitation had a negative effect during the milk stage. The results indicate that the climatic factors should be expressed as 20- to 30-day averages in the Yangtze Delta; a shorter or longer period, e.g. 10 or 40 days, is less appropriate.

Keywords Rice · Yield · Climate variation · Yangtze Delta

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Introduction

Since crop yields are determined by environmental factors at different management levels, the concepts of potential and attainable yield have been proposed (Rabbinge 1993). For the potential yield, crop growth is determined solely by climatic factors (growth-defining factors) such as solar radiation or temperature. When soil resources, water or nutrients, are in suboptimal supply, these "growth-limiting factors" decrease potential production, resulting in an attainable yield. Finally, "growth-reducing factors", such as pests, diseases and weeds, determine the actual yield. The gap between the potential and attainable yield has a practical basis, as it is agronomically possible to increase the availability of growth-limiting factors by management, while the growth-defining factors are usually outside the control of farmers. Over the long term, climate can be considered as a random process and control of weeds, pests and diseases is a part of the crop management that has been improved greatly in the last few decades.

Thompson (1969) and Baier (1973) argued that time series of crop yields consist of two components. One is the tendancy of the yield to increase as a result of technological improvement, such as the application of high-yielding varieties and the increased use of chemical fertilizers and biocides, etc. The other is the variation in yield caused by a temporal variation in climate, which is referred to as the meteorological yield. To analyze the effect of climate on yields, the two components have to be separated. The technologically driven yield increase must be eliminated by removing the trend from yield series. There are some statistical approaches available for eliminating trends to analzye fluctuations in time series:

(1) curve fitting, a traditional method dealing with data that contain a trend; (2) filtering, often referred to as moving averages; and (3) differentiation, which is a special type of filtering (Chatfield 1996; Manly 1997). The curve-fitting and filtering methods are traditionally used in agroclimatological analyses to separate the meteorological yield from the technologically driven trend (Baier 1973; Monteith 1981; Mostek 1981; Parthasarathy et al. 1988; Wang 1989; Chmielewski and Potts 1995). The first two methods have limitations: different fitting and filtering methods may result in slightly different curves, or the trend may include meteorological factors, since these may have time coefficients of some years.

The application of the progressive-difference method has not been reported in this field. It creates a series of yield differences by progressively differentiating the yields of 2 successive years. The correlation between differences in yield and climatic variables is found by multiple-regression methods and then climatic variables contributing to yield variations can be identified. Separation of the meteorological yield from the technologically driven trend towards yield increase is not needed.

The Yangtze River is the longest river in China, and its delta is a highly developed economic zone with Shanghai at the center. Rice, sown in May and harvested in October, is the dominant crop in the delta. The delta has a subtroptical monsoon climate with monthly maximum temperatures of 26–30°C in July. The rainy season is from May to September. As the summer monsoon starts in spring, there are much greater variations in temperature, precipitation and solar radiation than at the same latitude (about 28.5°N) in the American continent and Europe (Domros and Peng 1988). Therefore, rice yields show marked inter-annual variations in the Yangtze Delta.

The objectives of this study are (1) to use the progressive-difference method to identify any relationship between crop yields and climatic variables, and (2) to identify the climatic factors causing the inter-annual variations in rice yield in the Yangtze Delta.

Materials and methods

Data

To apply the difference method and to identify which climatic factors determine rice yields in the Yangtze Delta, the following data were used:

1. Aggregate rice-yield data (1961–1990) in the Suzhou prefecture, an administrative sub-region of Jiangsu Province, from the Agricultural Bureau of Jiangsu Province, China.
2. Meteorological data and reccords of the crop development stage for the same period, from the Meteorological Bureau of the Jiangsu Province, China. The Suzhou Meteorological Station (20 m above sea level) is representative for the area, since topographical variation and regional differences of climatic variables are small. Solar radiation, temperature and precipitation are growth-defining factors in rice production. Therefore, the number of hours of sunshine, the average air temperature, and the precipitation over 10-day periods are considered as basic climate units. In the regression analysis these basic units have been aggregated into climatic variables over various periods, i.e. 20, 30 or 40 days.

Methods

The rice yields in the period 1961–1990 under study consist of a technologically driven trend component (Y_0), a variation component representing the variations in climatic factors (Y_w) and random errors (ε). If data are recorded in a standardized way, ε is supposed to be small and is considered negligible, and the crop yield for the jth year can be written as:

$$Y_j=Y_{wj}+Y_{0j} \tag{1}$$

for j=1, 2, ...n, in which n is the total number of years for which data are available. A time series of yield differences can be obtained with:

$$Y_j-Y_{j-1}=(Y_{wj}-Y_{wj-1})+(Y_{0j}-Y_{0j-1}) \tag{2}$$

for j=2, 3, ...n.

The following describes how the trend in the time series of yield differences (Y_j-Y_{j-1}) is eliminated.

Three types of trend in crop yields in different regions of China during 1949–1989 have been identified (Wang 1989): (1) no steady trend, (2) a linear increase and (3) a non-linear increase. Time series of yields with no steady trend can be directly used to analyze relationships between crop yield and climate, since there was no technological improvement. They will not be discussed further here.

The trend representing a linear increase in time can be described by:

$$Y_{0j}=a_0+a_1t \tag{3}$$

in which t is the number of years from the beginning of a series to the jth year and a_0 and a_1 are constants representing the initial level and the rate of increase in yield with time respectively.

The difference in yield between 2 successive years can be found from:

$$Y_{0j}-Y_{0j-1}=(a_0+a_1t)-[a_0+a_1(t-1)] \tag{4}$$

which can also be written as:

$$Y_{0j}-Y_{0j-1}=a_1 \tag{5}$$

On the basis of Eq. 1 and Eq. 5, the difference in yield between 2 successive years can be found from:

$$Y_j-Y_{j-1}=(Y_{wj}-Y_{wj-1})+a_1 \tag{6}$$

Yield differences between successive years are those due to the variation in climatic factors plus a constant. The difference in actual yields in Eq. 6 shows no relationship with time, i.e., no trend. It is caused by climatic factors only, whereas the trend in the yields increases linearly with time.

Yield variation as a function of climatic variables can be generally expressed as:

$$Y_w=f(x_1, x_2, ..., x_p) \tag{7}$$

in which x_1, x_2, ..., x_p are climatic variables, such as the number of hours of sunshine, temperature, precipitation, etc. Under many conditions, as a first-order approximation of the relationship, meteorological yield can be expressed as a function of these variables in the following form:

$$Y_w=a_1x_1+a_2x_2+...+a_px_p \tag{8}$$

Or, for a difference in yield between 2 successive years, Eq. 8 can be interpreted as:

$$Y_{wj}-Y_{wj-1}=a_1(x_{1j}-x_{1j-1})+a_2(x_{2j}-x_{2j-1})+...+a_p(x_{pj}-x_{pj-1}) \tag{9}$$

Equation 9 implies that variation in yield differences can be described by the differences in climatic variables in 2 successive years. Combining Eq. 6 with Eq. 9 gives a relationship between yield and climatic variables in terms of their respective differences, in 2 successive years:

$$Y_j – Y_{j–1} = a_1(x_{1j} – x_{1j–1}) + a_2(x_{2j} – x_{2j–1}) + ... + a_p(x_{pj} – x_{pj–1}) + a_0 \quad (10)$$

This function is referred to as the progressive-difference method for a yield/climate model.

Alternatively, a non-linear trend of a yield series, such as a quadratic or exponential trend, can be expressed by a polynomial:

$$Y_{0j} = a_0 + a_1 t + \sum_{k=2}^{m} a_k t^k \quad (11)$$

The difference between 2 successive years is:

$$Y_{0j} - Y_{0j-1} = a_1 + \sum_{k=2}^{m} a_k [t^k - (t-1)^k] \quad (12)$$

The second item on the right is a nonlinear function of time. If the nonlinear item is not significant, then $Y_{0j}–Y_{0j–1}$ will be approximately constant and Eq. 10 can be used. The error caused by the omission depends on the magnitude of the nonlinear term. If the nonlinear term is large, the progressive-difference method is not appropriate. The suitability of the method can be determined by a correlation test between differences of yields and climatic factors. The basic unit of time for these variables is a period of 10 days, i.e., days 1–10, 11–20 and 21–30 (or 31) in a particular month. According to the characteristics of rice growth and development, climatic variables with different intervals are considered in the statistical model. For example, the 40-days period from 1 June to 10 July was divided into four periods of 10 or 11 days, i.e., 1–10, 11–20, 21–30 June and 1–10 July. The average values for two, three or four successive periods are then taken. Each climatic element therefore consits of ten individual variables with different time intervals: the intervals 1–10 June, 11–20 June, 21–30 June and 1–10 July contain 10 days each, 1–20 June, 11–30 June and 21 June–10 July contain 20 days, 1–30 June and 1 June–10 July contain 30 days and the entire period of 40 days.

Results

Inter-annual yield variations for rice were derived from time series of the yield and yield differences between years *i*–1 and *i* plotted against *i*. Figure 1 shows that differences in yields between successive years are randomly distributed, whereas rice yields have an apparent trend.

Climatic variables averages over different periods are individual elements in the regression model. On the basis of time series of yield differences and differences of climatic variables in successive years, significant factors were selected by a stepwise regression. This correlation can be expressed in the following way:

$$\begin{aligned} Y_j–Y_{j–1} = {} & 129.3+20.25(X_{1j}–X_{1j–1})+18.3(X_{2j}–X_{2j–1}) \\ & –216.3(X_{3j}–X_{3j–1})+7.50(X_{4j}–X_{4j–1}) \\ & –14.25(X_{5j}–X_{5j–1})\ (n=29,\ r^2=0.74) \end{aligned} \quad (13)$$

in which Y is rice yield (kg ha^{-1}); X_1 and X_2 are the amounts of sunshine (h/10 days) from 21 June to 10 July and from 11 September to 10 October respectively; X_3 is the average air temperature (°C) from 11 July to 10 August; X_4 and X_5 are the precipitation figures (mm) for 1–20 August and 11 September to 10 October respectively. A detailed list of these factors together with their corresponding developmental stages is shown in Table 1. Figure 2 is a comparison of estimated and measured rice yields. It shows that the simulated values correspond well with the measured ones. The linear relationship between simulated and measured values indicates that the estimate is quite reasonable.

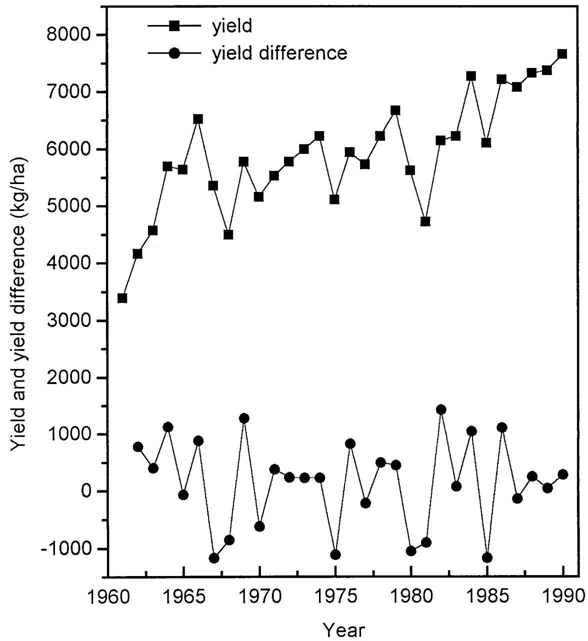

Fig. 1 Time series of rice yields and yield differences for successive years in the Yangtze Delta from 1961 to 1990

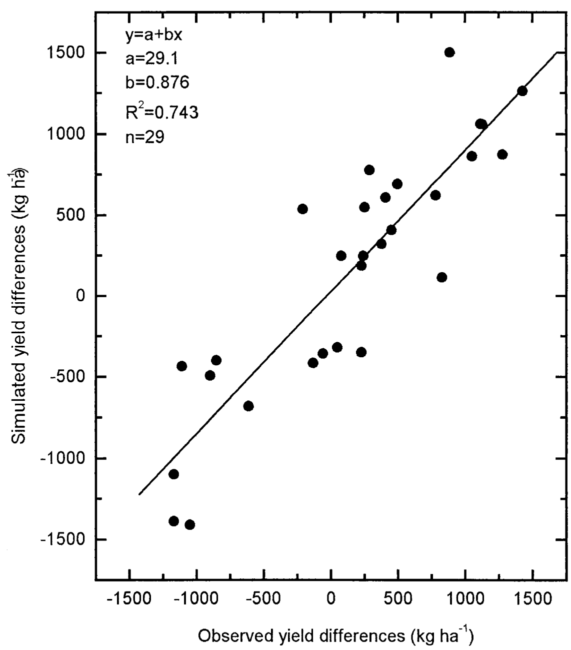

Fig. 2 Estimated and observed rice yield differences in the Yangtze Delta from 1961 to 1990

The results of computation using the model show a significant correlation between variances of the yield and differences in the indicated climatic variables. About 74% of the yield variation in rice yields in the Suzhou prefecture can be ascribed to the variations of climatic variables in the indicated key periods. The yield constant in Eq. 13 represents a technologically driven trend towards increasing yield of 129.3 kg ha^{-1} year^{-1}. Accord-

Table 1 The significant climatic variables influencing rice yield in the Yangtze Delta in China (1961–1990)

Variable	X_1	X_2	X_3	X_4	X_5
Measuring	Sunshine (h/10 days)	Sunshine (h/10 days)	Average air temperature (°C)	Precipitation (mm)	
Period	21 Jun–10 Jul	11 Sep–10 Oct	11 Jul–10 Aug	1 Aug–20 Aug	11 Sep–10 Oct
Sign of correlation	+	+	–	+	–
Significance (P)	<0.01	<0.01	<0.01	<0.01	<0.01
Developmental stage(s)	Tillering	Heading to milk	Tillering to jointing	Jointing to booting	Heading to milk

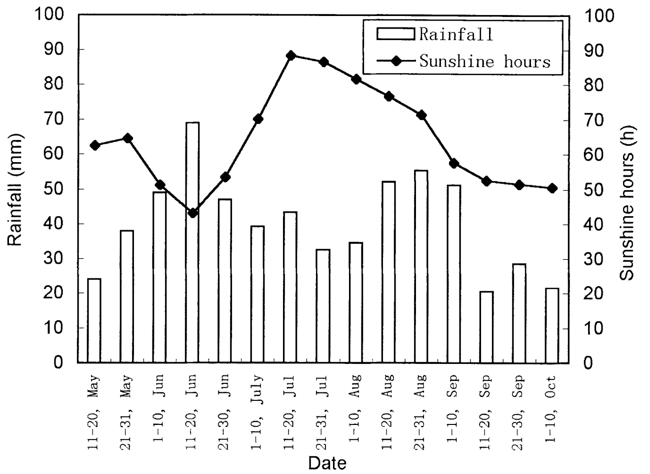

Fig. 3 Average rainfall and number of sunshine hours in the Yangtze Delta from 1961 to 1990

ing to Eq. 13, rice yields increase by 3879.0 kg ha^{-1} in 30 years, which corresponds well with the actual yield increase during the period 1961–1990 (Fig. 1). In the following we discuss in detail the contribution of the individual climatic variables to the yield.

Solar radiation

Solar radiation provides the energy needed for photosynthesis and thus influences yield. In the area under study, the long-term average radiation is higher than that of the inland basin (Cheng 1993), but its inter-annual variation is also very high because of abundant precipitation in the summer and cloudiness during large parts of the growing season. One such period is the tillering stage from 21 June to 10 July. This period falls in the rainy season, referred to as Mei-Yu which in Chinese means “rain during the maturation of the plum”. The average amount of sunshine in this wet period is half that in the period 21–31 July (Fig. 3). Li (1990) reported that the number of tillers is positively correlated with the number of hours of sunshine in the 30 days after transplantation, which corresponds well with the period 21 June–10 July. This is called shading stress.

Another critical period for solar radiation is from panicle initiation to about 10 days before maturity during which solar radiation is relative low and the amount of photosynthesis greatly influences yield. Low solar radiation during the grain-filling and ripening stages reduces the percentage of filled spikelets (Murty and Sahu 1987; Petr et al. 1988).

Inter-annual variation of rice yields caused by the variations these variables with solar radiation is calculated from the minimum and maximum values of the climatic variables by using Eq. 13. Changes in the hours of sunshine in these key periods caused yields to vary between –569.0 kg ha^{-1} and 706.7 kg ha^{-1} at the tillering stage, and between –232.4 kg ha^{-1} and 1231.6 kg ha^{-1} from the heading to the milk stage compared to the multi-annual average (Table 2).

Temperature

Results of the statistical analysis suggest that high temperature has adverse effects on yield from the tillering stage to the booting stage, the time in which the annual maximum temperature occurs. In this period the daily maximal temperatures exceed 35°C, which may induce heat injury to rice plants (Sharma and Singh 1999).

Variations of temperature between the maximum and minimum values in the tillering to jointing stage induce deviations of –237.9 kg ha^{-1} to 237.9 kg ha^{-1} from the long-term average (Table 2).

Precipitation

Two key periods of rice growth can be identified in which precipitation has significant effects on yield. The first period is 1–20 August, when rice is at the jointing and booting stage. The generally low precipitation, controlled by the subtropical anti-cyclone in the period after the rainy season Mei-Yu, reduces rice yields (Fig. 3). Water stress during the vegetative stage reduces plant height, tiller number and leaf area (Sharma and Singh 1999).

The second period is from 11 September to 10 October, when rice is at the heading and milk stages and excessively high precipitation is disadvantageous to grain-filling and maturity. High precipitation is generally associated with high relative humidity, which favors the incidence of diseases, particularly blast.

Compared to the multi-annual average, minimum and maximum precipitation at the jointing and booting stages causes yields to deviate from the average by between

Table 2 Estimation of deviations of rice yield compared to the multi-annual average climate in the Yangtze Delta in China (1961–1990)

Value	X_1 (h/10 days)	X_2 (h/10 days)	X_3 (°C)	X_4 (mm)	X_5 (mm)
Mean	49.1	52.7	27.1	33.2	33.3
Maximum	84	120	28.2	95	60
Minimum	21	40	26.0	0	2
Variation rate of yields	20.25 (kg h^{-1})	18.3 (kg h^{-1})	–216.3 (kg °C^{-1})	7.5 (kg mm^{-1})	–14.25 (kg mm^{-1})
Variation of yields (kg ha^{-1})	–569.0 to 706.7	–232.4 to 1231.6	–237.9 to 237.9	–249.0 to 463.5	446.0 to –380.5

–249.0 kg ha^{-1} and 463.5 kg ha^{-1}, and between 446.0 kg ha^{-1} and –380.5 kg ha^{-1} respectively (Table 2).

Discussion

Simulation models to quantify the relationship between crop growth and environmental factors have advantages over empirical methods because they are based on the underlying processes governing crop production, but they also contain many empirical relationships. Models of crop growth are plot-specific and they must be calibrated for different ecological regions (Goudriaan 1999). The general applicability of simulation models is, therefore, greatly limited. The role of empirical models has been re-evaluated recently, and hybrid models of regression and simulation proposed (Landau et al. 2000). Regression models are useful tools for exploring key elements that determine the formation of yields.

A general limitation of regression models is that only the apparent relationships between yield and climatic factors are identified. Such relationships are not always causal. Variables in a regression model must have mechanistic meaning as climatic factors correlate with each other. For example, high precipitation is usually accompanied by low radiation and temperature in the Yangtze Delta; hence it is difficult to distinguish between effects of growth-defining (radiation and temperature) and growth-limiting factors (rainfall). Results obtained by regression analysis must be cautiously analyzed and compared with results from field trials to identify climatic factors relevant in yield formation.

In the present study, a progressive-difference method has been applied to identify a relationship between variations in yield and climatic variables during different crop stages. The method presented is simple and does not require yield trends due to technological improvement to be eliminated. From a historical point of view, the rate of yield increase may vary with time as different technologies are adopted. Here we assume that technical improvement changes gradually, so the technologically driven yield increase is taken as a constant. Kulkarni and Narahari Pandit (1988) used a discrete step to introduce separate time trends to account for the technological "shifts". How far the difference method may be applied depends on the characteristics of the yield time series. The absolute yield variance increases with increasing yield levels. Hence, yields of such time series should be normalized to achieve better agreement between yields and climatic variables.

Crop yields fluctuate from year to year as a consequence of multiple interactions between physiological processes and physical constraints imposed by the environment (Monteith and Ingram 1998). Under the subtropical monsoon climate in the Yangtze Delta, the number of hours of sunshine, temperature and precipitation in particular periods of the growing season are specifically important for the yield of rice. Some key variables in identified periods may influence inter-annual variation of rice yields, which may be due to a large variation of the variables in the period under consideration. Some variables that have been found to be insignificant may potentially have an important effect on the yield, but did contribute to the variation of yield in the period under consideration, because they remained relatively constant.

The results of this work show that the best time scale for describing relevant climatic variables is approximately 20–30 days. Shorter or longer periods, such as 10 or 40 days, do not result in any significant climatic variable. The results suggest that shorter periods do not well represent climatic characteristics in a growth stage, and longer time scales smooth out climate fluctutations. The level of significance of regression variables depends on climatic characteristics and the sensitive period of rice growth. Landau et al. (2000) summarized the effects of climatic factors over physiologically meaningful periods rather than over daily changes in climate. The crop growth was split into five phases: a vegetative and an early-reproductive phase, anthesis, grain-filling and a remaining pre-harvest phase (Landau et al. 2000). We also adopted this method to define climatic factors for different intervals, i.e. 10, 20, 30 and 40 days. The time scale on which climatic factors are considered is important, because a smaller unit of time such as 1 or 5 days creates a larger number of variables, which will increase the computation time.

Identification of beneficial and unfavorable factors that determine the variation of rice yields is helpful to farmers and managers of food production (Rabbinge et al. 1994). Farmers take into account temporal variation in their operational decisions. Blending experience and intuition, they know when to prepare the land, sow, control pests and diseases, and harvest. Identification of the periods that most affect yield, as presented in this paper, allows farmers to manage such operations better.

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