RECENT ADVANCES IN FORECASTING OF RICE BLAST EPIDEMICS USING COMPUTERS IN JAPAN

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ABSTRACT

Computer software for forecasting rice blast epidemics has undergone remarkable changes with the advances in computer hardware in the last decade in Japan. In the early stage of that decade, several predicting equations were proposed by either multiple regression or quantification analysis. A system for estimating favorable conditions for infection based on empirical criteria was developed. The weather data used in the system were retrieved from the Automated Meteorological Data Acquisition System by personal computer via telephone lines.

Several simulators incorporating ecological knowledge were subsequently developed. For example, the simulator of leaf blast epidemics, a deterministic model, was originally designed for a mainframe computer, and was later improved to be easily executed on a 16 bit personal computer. It can also estimate the effectiveness of some fungicides in the progression of the disease. Another simulator dealing with panicle blast epidemics, is a stochastic model using the Monte Carlo method which is able to simulate the disease progression within a panicle and to estimate the yield losses caused by panicle blast. However, temporary values are substituted for several processes which have not yet been verified experimentally.

Introduction

Rice is the most important and widely cultivated crop in Japan. Rice blast, caused by *Pyricularia oryzae* Cav., is one of the most destructive diseases to rice production. Therefore, it is important to control blast disease efficiently. Since the disease progression varies with the location or the year depending mainly on the weather conditions, forecasting of the disease epidemics is necessary for growers to prevent severe yield loss caused by the disease. Growers may want to know when the disease will start, how severe the epidemic will be, whether fungicides should be applied, or when fungicides should be applied. In forecasting such information, (1) Some predicting models of the disease epidemics should be constructed. (2) A large amount of data should be collected, i.e. past records of weather data and severity of the disease, and present conditions of rice susceptibility and inoculum potential. (3) The models should be then analysed using the data mentioned above. Each of these activities requires the use of computers.

In the last decade, computer hardware has made remarkable progress with time (almost day by day) in Japan. In the 1970s, the word, "computer" for scientific use referred only to mainframe computers. The users needed to describe the data on data sheets from their field notes, prepare punch cards, and then use the computer terminal in order to carry out the analysis. However, since 16 bit personal computers (PC) with disc drives for 1 mega byte diskets were released commercially in the early 1980s, most laboratories or researchers concerned about quantitative epidemiology have been using them. Nowadays, some of them possess lap-top type 16 or 32 bit PCs.

Statistical models

In the beginning of the last decade, when the PCs were not widely used, several phyto-pathologists tried to develop statistical models for forecasting using mainframe computers. Shimizu (1980), and his coworkers (Hashiguchi and Kato, 1983) in Nagano prefecture introduced a quantification analysis which included multiple regression analysis for forecasting. The forecasts

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predicted the percentage of the final acreage of the fields where blast occurred as of July 15 (the early stage of leaf blast epidemic). Some items were selected as independent variables, such as the date of initial incidence of leaf blast, plant height on July 15, the number of tillers per hill on July 15, cumulative number of spores trapped in the field from transplanting until July 15, and percentage of diseased plants on July 15. These items were classified in several categories which quantified these data. The predicting equations were composed using the past 22 years' data sets, and then verified using other data sets. Muramatu *et al.* (1977) in Shizuoka prefecture and Kono *et al.* (1977) in Hiroshima prefecture proposed separately multiple regression equations for predicting the blast epidemics. They used several items as independent variables, such as monthly mean temperature, monthly total precipitation, plant height in late June, minimum temperature or duration of sunshine in July and August. Then they estimated the initial occurrence of leaf blast, or percentage of acreage where leaf or panicle blast occurred based on the equations.

Although emphasis was placed on the development of such statistical models for forecasting, these models have become recently unpopular for the following reasons: (1) Since they are not dynamic models, the prediction can not be extrapolated from the data sets other than those employed when the models were composed. When the cultivar, the cultivation period, or the cultivation systems used change, these predicting equations are no longer applicable. These equations can not be applied in other regions, either. (2) The coefficient of some independent variables did not often correspond to the expectation based on biological, due to the multi co-linearity of the regression. (3) More complex but sophisticated models have been developed, since recent epidemiological studies suggested that the relatively short term fluctuations of the weather conditions play a critical role in blast epidemics (discussed later). In the past, the ability to study rice blast was restricted by the unavailability of computing power. Presently, however, with the availability of high power PCs, the ability to run more complex models has increased remarkably.

Empirical model using criteria for infection conditions

The Meteorological Agency of Japan completed an Automated Meteorological Data Acquisition System (AMeDAS) in 1976. The system automatically acquires each factor relating to the precipitation, temperature, duration of sunshine, wind force and wind direction every hour at 840 points all over Japan. Users may retrieve these data via telephone Modems (Modulator-demodulator) to their PCs. In those days, several quantitative theories concerning the mechanism of blast epidemics had been proposed. Yoshino (1979) indicated the effect of the temperature and duration of the wet period on the probability of spore penetration into rice leaves. Kato and Sasaki (1978) clarified quantitatively the sporulation behavior of the fungus on the lesions. Suzuki (1969) showed the relation between the dispersion of the fungal spores and the weather conditions. Kobayashi (1984) observed general epidemics in the early stage of the leaf blast epidemic, where "solitary lesions" were randomly distributed in most fields in a district. He also proposed empirical criteria to determine whether the infection causing a general epidemic had occurred, based on either general climatic or micro-climatic conditions.

Under these circumstances, Koshimizu (1983) developed BLASTAM, a predicting system of favorable conditions for infection, using only weather data from AMeDAS. The criteria almost agreed with Kobayashi's rules (Kobayashi, 1984). At first, BLASTAM was composed for a mainframe computer, then Yokouchi *et al.* (1986) subsequently re-wrote the program for PCs. In the model, the wet period on rice leaves is assessed indirectly from only the data of precipitation, wind force, and duration of sunshine from AMeDAS, because wet periods are not observed by AMeDAS.

The criteria of BLASTAM are as follows: (1) Duration of rainfall from 6:00 to 15:00 is considered to be the wet period, provided that the duration of sunshine during 3 hr after rain is less than 0.1 hr and wind speed of each hour is less than 2 m/sec. (2) When it rains from 15:00 to 6:00 on the next day, the wet period is considered to start as soon as rainfall starts, and to continue until 9:00. However, if the following conditions are satisfied, the wet period is considered to end: a) If the duration of sunshine in the morning exceeds 0.1 hr. b) If the duration of sunshine after rain until sunset exceeds 0.2 hr. c) If the mean wind speed of any 3 hr exceeds 3 m/sec or wind speed of any hour exceeds 4 m/sec from 15:00 to 4:00 on the next day. d) If the wind speed exceeds 3 m/sec from 4:00 to 9:00. e) However, if the wind speed of any hour exceeds 4 m/sec, the end of the wet period is considered to be advanced by one hour from that time. (3) If there is a temporary rainfall after 15:00, and if another rainfall follows, later rains are not considered. (4) Rainfall with wind whose speed exceeds 4 m/sec is not considered to contribute to the wet period. (5) If it rains while the wind speed is 3 m/sec, the wind speed is considered to be 2 m/sec. If it rains with less than 0.1 hr sunshine, no sunshine is considered to be present. (6) If the precipitation exceeds 4 mm/hr, or exceeds 3 mm/hr for more than 2 hours, the wet periods from 9 hr before the rainfall to 9 hr after the rainfall are omitted. (7) When the duration of the wet period exceeds each critical value which depends on the mean temperature during the wet period (Tab. 1), the conditions are considered to be favorable for the infection. (8) The starting point of the wet period was found to occur after 16:00. If the starting point occurs after 7:00, the wet period is omitted. If the wet period continues until after 16:00, the wet period is broken off at 16:00. (9) If the average of the daily mean temperature for 5 days before the favorable conditions appear (including the day) is lower than 20°C or higher than 25°C, the wet period is omitted.

Table 1 Relationship between the duration the wet period at various temperatures and the percentage of spore penetration

Temperature	Wet duration	Penetration
15°C	17 hr	4.5%
16	15	4.2
17	14	4.6
18	13	4.6
19	12	4.6
20	11	4.3
21	11	3.7
22	10	4.7
23	10	3.4
24	10	3.9
25	10	4.2

Source: Yoshino, 1979.

Based on these criteria, the model classifies the conditions of each day as: "favorable", "semi-favorable" and "unfavorable" for the infection. The "semi-favorable" conditions imply that a) while the wet duration exceeds 10 hr, the average of the daily mean temperature for the 5 previous days is lower than 20°C or higher than 25°C, or than the mean temperature during the wet period ranges between 15°C and 25°C, or b) while the mean temperature during a wet period ranges between 15°C and 21°C, the wet duration is less than the criterion of the model.

Based on those rules, it can be predicted that a general epidemic will start one week after the favorable conditions first appear. Then the leaf blast severity will rapidly increase 2 weeks after the starting time unless the weather becomes cool.

BLASTAM has been recently used in several prefectures in Japan, and its efficacy has been recognized. On the other hand, some defects have also been pointed out. Since the wet periods were assessed indirectly from AMeDAS which can not detect a precipitation of less than 1 mm/hr, BLASTAM tends to underestimate the wet duration. Therefore, favorable conditions for infection may be overlooked occasionally. Moreover since BLASTAM can predict only whether the conditions are favorable for rice blast, quantitative information on the disease progression can not be obtained.

In conclusion, BLASTAM is considered to be an effective tool for forecasting, as it enables to collect and process a large number of data in real time. Since the model can simultaneously predict favorable conditions for infection in many areas in a district, the underestimation of the wet duration is compensated to some extent, but also the model makes it possible to observe the trend of the epidemic in each district. However, its application is considered to be within the limits of predicting only the starting time of general epidemics and the rapid spreading period of rice-leaf blast.

Simulation models of leaf blast

With both the advances in the quantitative knowledge concerning the components of blast epidemics and advances in computer hardware and software technology, a systems analytical approach was introduced in forecasting in the early 1980s. While several simulation models were developed independently (Hashimoto *et al.*, 1984; Ohta *et al.*, 1982; and Takai *et al.*, 1985), the basic concepts of these models were similar. First, the whole relationship interlocking particular host, pathogen and environment was considered as a pathosystem. Then the ecological knowledge of previous blast epidemics was incorporated as numerical formulae into each model. Finally, these models were analysed in computers. For example, BLASTL, a simulation model of leaf blast epidemics, was written by Hashimoto *et al.* (1984) in Fukushima prefecture. The model, which was originally designed for a mainframe computer and written with FORTRAN, was later translated into BASIC to be easily analyzed on a 16 bit PC. In this model, one plant (hill) of rice is taken as a unit object for simulation. The relationships of each component are shown in Fig 1. The factors used include the temperature, precipitation, duration of sunshine and wind force derived from AMeDAS

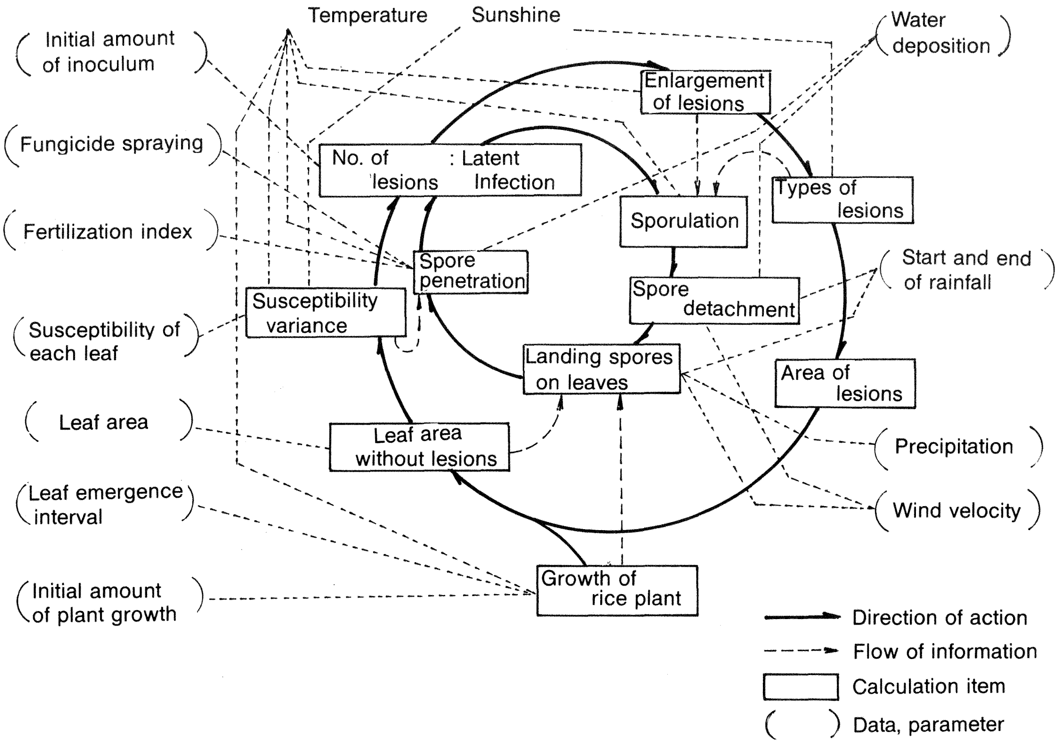

Fig. 1 Relationship of each component of BLASTL.
Source: Hashimoto *et al.*, 1984.

every hour and duration of the wet period estimated by the dew balance which Hashimoto *et al.* developed (Hokutow Scale Co. Ltd. Fukushima, Japan), respectively. The level of fertilization, susceptibility and leaf area of each leaf in relation to the position and intervals of leaf emergence are determined as parameters, according to hypothetical conditions. The model calculates the development of leaf blast, which is indicated by the temporal changes of the number of leaf lesions, the susceptibility of the host or the probability of spore penetration, etc. The weather data of the present year, up to the forecasting time, followed by data of several previous years are used, for the practical purpose of forecasting leaf blast epidemics.

BLASTL has been used in several prefectures in Japan. Especially in Fukushima, BLASTL has been used for forecasting leaf blast epidemics for several years. Although it was practical for forecasting, it was found that the host plants were less susceptible during cool weather conditions than during the warm conditions which followed the cool conditions. BLASTL was then improved to reflect these phenomena (Hashimoto *et al.*, 1984).

BLASTL contains a sub-model for fungicide application, although presently the changes in the amount of fungicides deposited on leaves with time are available only for Fthalide, a popular protectant fungicide used in Japan (Ishiguro *et al.*, 1988). Since the efficiency of the fungicide in controlling the disease progression can be simulated based on the knowledge relating to the fungicides, BLASTL may become a useful tool for determining the timing of fungicide application.

Simulation models of panicle blast epidemics

It has been considered that panicle blast is directly responsible for the yield loss of rice, while leaf blast plays an indirect role in yield loss as inoculum supplier to panicles. Although both types of blast play important roles in the yield loss, the development of simulation models of leaf blast epidemics preceded that of panicle blast. The difficulty in the development of panicle blast models may be ascribed to the small amount of information collected in each component of the pathosystem, and to the fact that the structure of the panicles is too complex to enable the construction of models unless special methods are used. Takasaki (1982) first attempted to develop a simulation model of panicle blast epidemics in terms of probabilities. He treated the spore deposition processes and penetration processes as stochastic processes, respectively. In the model, each panicle was divided into small sites as units, where the probability of infection was calculated according to a particular probability function, and then the affected panicles were classified into several types. Although this model dealt with stochastic phenomena, the model was deterministic. Consequently, the model was not able to take account of the secondary infection originating in panicles, while Kato *et al.* (1978) emphasized the importance of the second infection in panicle blast epidemics.

Recently, Ishiguro and Hashimoto (1988) proposed a stochastic model using the Monte Carlo method. They combined each component of the pathosystem based on ecological information (Fig. 2)., In their model, each panicle was divided into small sites as calculating units (Fig. 3), as in the Takasaki's model. In the model, some temporary values and functions are substituted for some processes which have not been determined experimentally or quantitatively. They recognized that spore deposition processes and penetration processes were stochastic processes, respectively: hypothetically, the probability distribution of the number of spores deposited on each unit, which was not proved experimentally, followed a Poisson distribution, and the probability of spore penetration into each unit site was determined by Yoshino's equations (Yoshino, 1979) whose variables included the wet duration and temperature during the wet period. The Monte Carlo method was applied in these processes, in which the former used Poisson random numbers and the latter used uniform random numbers generated by computer, respectively. For example, when the wet duration and the temperature during the wet period reach particular values, the probability that a spore will penetrate into the host (P) is estimated by Yoshino's equations. Then, the probability that a spore will not penetrate (q) is:

$$q=1-P \qquad (1)$$

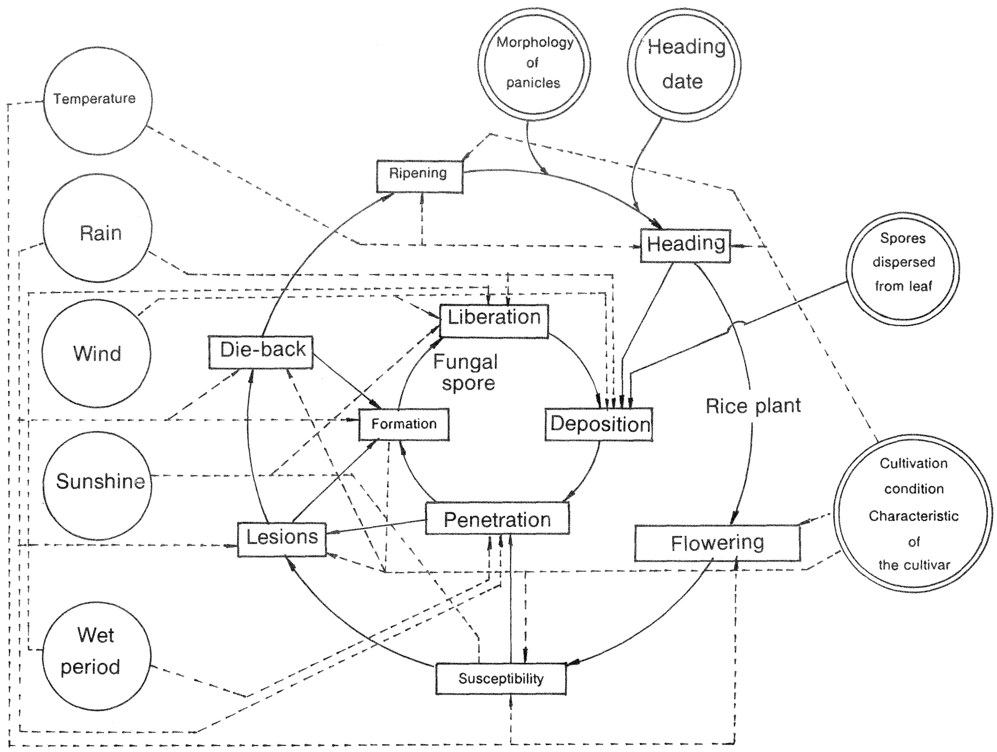

Fig. 2 Relationship of each component of the simulator of panicle blast epidemics. Single circles and double circles indicate weather data and parameters, respectively. Squares indicate the components of the model. Broad lines indicate the order of calculation. Both thin and dotted lines indicate the flow of information. Source: Ishiguro and Hashimoto, 1988.

If there are some spores deposited- on a unit and there is no interaction among the spores, the probability that any spore on a unit will not penetrate (q') is:

$$q'=q^n \quad (2)$$

where n is the number of spores deposited on a unit. Then, the probability that at least one spore will penetrate (P') is as follows:

$$P'=1-q' \quad (3)$$

Then, let $\xi[0,1]$ be uniform random numbers which are generated by computer and range from 0 to 1.0. In the case of:

$$0\leqq P'\leqq \xi[0,1] \quad (4)$$

the penetration is considered to occur on the unit. On the other hand, in the case of:

$$\xi[0,1]\leqq P' \quad (5)$$

the penetration is considered not to occur.

The simulation is executed using the meteorological data as in the case of BLASTL, and the rice growth habit, the cultivation methods employed, and the number of spores liberated from the leaf lesions for an inoculum as parameters, respectively. The growth of each grain, the susceptibility of each site of the panicles to blast, and the appearance and enlargement of the lesions were calculated every day, whereas the production, liberation, deposition, and penetration of the spores were

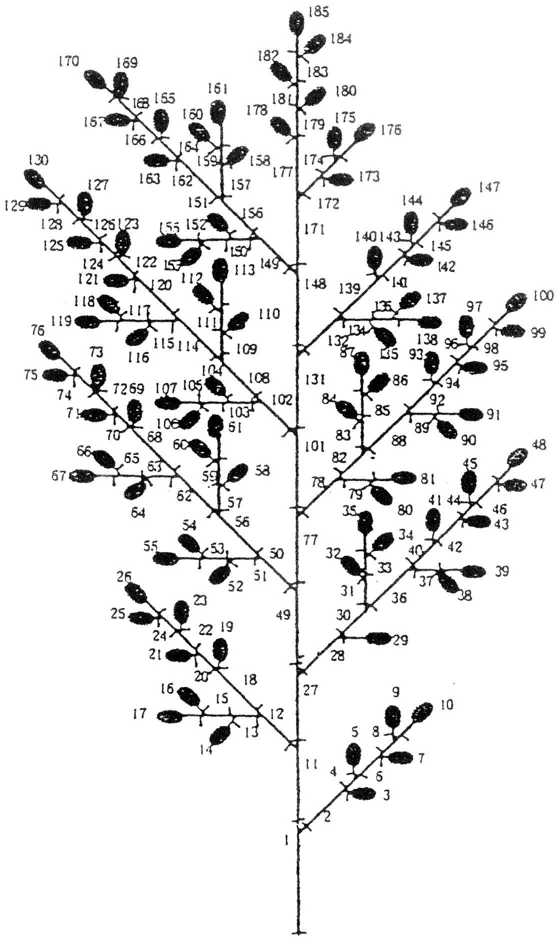

Fig. 3 A panicle divided into small sites as calculating units. Each number indicates the order of calculation. Source: Ishiguro and Hashimoto, 1988.

calculated every three hours. The yield losses caused by panicle blast were estimated every day.

Because the Monte Carlo method is a method which calculates one of the possible values of some probability functions from certain random numbers repeatedly, the results of the simulation vary with the trials run. However, using the Central limit theorem, the estimate of the population mean and its confidential interval are determined as follows:

$$\hat{\mu}=\mu\pm\kappa s/\ n \qquad (6)$$

where $\hat{\mu}$ is the estimate of the population mean, $\hat{\mu}$ is the sampling mean, s is the estimate of the population standard deviation, n is the number of trials, and κ is a constant (when the confidence coefficient is 95%, κ = 1.96), respectively. Fig. 4 shows an example of the simulation.

Although the model has not yet been fully verified, several results of the simulation have supplied interesting information. For example, it was indicated that the number of spores discharged from the leaf lesions, as well as the weather conditions after heading, played a critical role in the disease progression. It was also suggested that die-back, a phenomenon in which the lesions on the

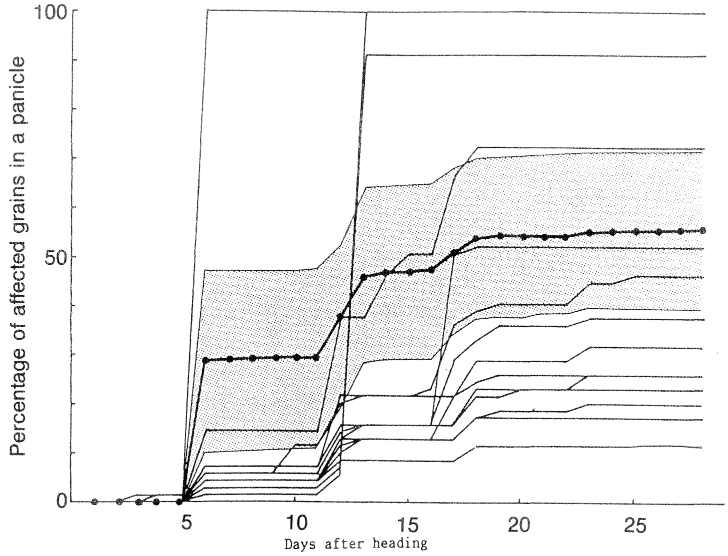

Fig. 4 Simulation of panicle blast epidemics. Simulation was repeated 20 times. Thin lines indicate the results of the simulation. Broad line indicates the estimated mean, and the shaded area indicates the confidential limit, where the confidential coefficient is 95%. Source: Ishiguro *et al.*, 1988.

spikelet or rachis branch extend gradually toward the proximal direction (Hirano *et al.*, 1963), would cause the increase of damage at the late stage of ripening. Although it is concluded that the model will be a useful tool for the epidemiological study of rice panicle blast epidemics, or the forecasting or decision-making of fungicide application, the model takes too much time to be analysed with even the present level of ability of a mainframe computer. There is the dilemma of determining whether the biological reality of the model should be sacrificed by reducing its size or maintained as a relatively inaccessible tool, as Teng and Rouse (1984) emphasized. We intend to attempt to improve the model based on two different strategies. One is to reduce the size of the model, provided that the sensitivity of the model does not decrease too much. Sensitive -analysis, which detects the components which do not affect relatively the results of the model, is considered to be an effective method for that purpose. The other strategy is to keep up with the advances in computer hardware and software technology, then to further improve the model.

Conclusion

It is considered that the forecasting of disease epidemics using computers may be, one of the most attractive areas in plant disease epidemiology. In Japan, computer software for forecasting rice blast epidemics has undergone remarkable changes with the advances in computer hardware in the last decade, as mentioned above. Since the computer technology continues to progress, it is assumed that some forecasting models which are not practical under the present conditions of technology will be available in the near future. However, some problems must be solved. First, it is necessary to acquire the weather data used in real time. Although only the data from AMeDAS are available in almost real time, the direct measurement of the wet period by electronic devices is essential especially for predicting the conditions favorable for the infection of the blast fungus. It is therefore necessary to develop automated delivery systems of data, including electronic sensors for the wetness on the surface of the rice plants, analog-digital (A/D) converters, and data loggers. Second, as the accuracy of weather forecasting is not adequate presently, it will be necessary to develop new strategies for disease control based on incomplete information. Finally, the results of the models must be compared with the actual disease progression. Until the validity of the models is confirmed, the components of the pathosystem should be analyzed more accurately in order to improve the models.

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Discussion

Zadoks, J.C. (The Netherlands): I was very much impressed by the rice blast simulation models presented. I would like to know whether these models have been validated in the field, if yes whether they are applied for forecasting and lastly whether the farmers follow the models' recommendations.

Answer: The simulation model of leaf blast epidemics is used practically for forecasting in Fukushima prefecture. Although the estimated values do not always coincide with the observed values, the trend of an epidemic can be forecast. The panicle blast model has not yet been validated.

Kajiwara T. (Japan): Such a forecasting system is used in many prefectures in Japan to determine the time and schedule of application of fungicides. Also this system is very useful to determine whether fungicides should be applied as often a minor occurrence of the disease does not require the application of fungicides.