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A quantitative model for prediction of Phomopsis seed decay of soybeans

Carmen Martorell Milla
Iowa State University

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Milla, Carmen Martorell, Ph.D.

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U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

A quantitative model for prediction of Phomopsis seed decay of soybeans

by

Carmen Martorell Milla

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GENERAL INTRODUCTION

The Diaporthe/Phomopsis Disease Complex of Soybeans

Species of Diaporthe and Phomopsis cause the diseases of soybeans (Glycine max (L.) Merr.) named pod and stem blight, stem canker and Phomopsis seed decay. The diseases are currently known as the Diaporthe/Phomopsis disease complex of soybean. The causal agents are endemic in nearly every area of soybean production in the world (Ploper, 1989). They cause major losses by reducing soybean stands, seed quality and yields by 50% or more (Kulik, 1983).

In recent years, stem canker caused by Diaporthe phaseolorum var. caulivora Athow & Caldwell (Dpc) has become a serious disease of soybeans in the southern soybean-growing areas in the United States (Sinclair, 1988). Typical symptoms include tip dieback and stem girdling that may kill the plant (Sinclair, 1982). Pod and stem blight, caused by P. longicolla Hobbs and Diaporthe phaseolorum (Cke. & Ell.) Sacc.var. sojae (Lehman) Wehm. & Sacc. (Dps) has little or no economic importance compared to stem canker (Schmitthenner and Kmetz, 1980). The main signs of pod and stem blight are small black fruiting bodies (pycnidia) which appear on stems, petioles, and pods after plants reach maturity (Sinclair, 1982).

The fungi Dpc, Dps and P. longicolla are all associated with the seed decay phase. It is the most important cause of seed deterioration in soybean fields (Ploper, 1989). This disease is of great concern to the seed industry. If conditions are favorable for the causal fungi, they can cause molding and fissuring of the seeds in the pods and in addition to reducing seed quality, they can lower germination (Peterson and Strelecki, 1965; McGee, 1986b; Gleason and Ferriss, 1984; Kulik and Schoen, 1981; Wilcox et al., 1985; Tekrony et al., 1984) and yield (Johnson and Berger, 1982). Phomopsis infected seeds have also been related to lower soybean flour and oil quality (Hepperly and Sinclair, 1978).

The taxonomic distinctions among these pathogens are controversial, primarily because of considerable variability in morphology, physiology and host relationships. Lehman (1922) originally named the causal organism of pod and stem blight disease Phomopsis sojae. He then identified the sexual stage and named it Diaporthe sojae (Lehman, 1923). Wehmeyer (1933) found no fundamental morphological differences between D. sojae (Lehman) and D. phaseolorum (Cke. and Ell.) (the cause of pod blight of lima bean) and reduced D. sojae to Diaporthe phaseolorum var. sojae (Dps). About twenty years after Lehman described D. sojae and typical pod and stem blight symptoms had been observed (Bretz, 1943), Athow and

Caldwell (1954) named the causal organism D. phaseolorum var. caulivora (Dpc).

Within the Dpc, two separate entities have been recognized (Hobbs and Phillips, 1985; McGee and Biddle, 1985; Keeling, 1988; Backman et al., 1985). One exists in the Upper Midwestern United States and the other in the Southeast. In a recent review of Morgan-Jones (1989) it is suggested, that based on accumulated evidence of differences between these two entities, D. phaseolorum that causes stem canker in the Southeastern United States should be referred to as D. phaseolorum forma specialis meridionalis and its anamorph as P. phaseoli f. sp. meridionalis.

In 1974, Kmetz et al. recovered a Phomopsis isolate from soybean that differed in morphology and pathogenicity from both Dpc and Dps. This organism was referred to as Phomopsis sp. Dps and Dpc have also been isolated from diseased seeds but are not as prevalent as this Phomopsis species in causing seed decay (Kmetz et al., 1978; McGee, 1982; Hobbs et al., 1985; Jeffers et al., 1982b). Because of the higher incidence of Phomopsis associated with the seed and considering that Phomopsis is the imperfect stage of both Dps and Dpc, Kmetz and co-workers (1978) suggested the name Phomopsis seed decay (PSD) to the disease caused by these fungi. The unknown Phomopsis species has been recently named P. longicolla by

Hobbs et al. (1985). It differs in cultural and morphological characteristics from P. phaseoli, the anamorph of D. phaseolorum var. sojae and is not known to have a teleomorphic stage.

Epidemiology of PSD

Infected soybean plant residue is the main source of inoculum from which the spores of the causal fungi are spread throughout the field (Garzonio and McGee, 1983). Sporulation has been observed in the spring on infested soybean debris (Athow and Caldwell, 1954; Backman et al., 1985). Infected seeds do not serve as a major source of inoculum and may serve only serve to introduce the pathogens into new areas (Garzonio and McGee, 1983). Phomopsis sp. was transmitted from inoculated soybean seeds to seedlings in the field (Garzonio and McGee, 1983). Although several weed species and/or cultivated plant species have been reported as sources of Dps, Dpc and P. longicolla, more information is needed to establish their role and potential impact on soybean diseases in the field (Roy and McLean, 1989). Short distance dispersal of the fungi is mainly by splashing rain (Rupe, 1989). It has been reported that seed infection by P. longicolla is highest in the lower third of the plant, with little infection

occurring in the upper third (Hepperly and Sinclair, 1980a; Kmetz et al., 1974).

P. longicolla may infect plants as early as two weeks after planting without showing symptoms. Infection may continue to occur through pod development (Rupe and Ferriss, 1987). McGee (1986a) showed that pods are not susceptible to infection after growth stage R7 (Fehr and Caviness, 1977) unless exposed to high relative humidity (86-97%) and temperatures above 19 C. However, these conditions during the maturation phase are unlikely to occur for long periods in Iowa because plants reach R7 in September when average daytime relative humidity is 60%. McGee (1986a) also showed that infection of pods after R6 is unlikely to cause seed infection, and that extensive seed infection does not occur before R7 growth stage.

The fungus can enter the seeds through natural openings in the seeds such as the micropyle and hilar region or through epidermal pores or pits on the surface of the seed coat (Singh and Sinclair, 1986; Vaughn et al., 1985). Phomopsis also has been found colonizing all the cell layers of the seed coat and embryonic tissues, causing tissue disintegration (Singh and Sinclair, 1986). It has been shown that because potassium is important in seed development, more fungal growth can occur in potassium deficient seeds (Jeffers et al., 1982a).

Symptoms of PSD are not seen before plants reach physiological maturity (R7) (Kmetz et al., 1978; McGee, 1986b). Pycnidia occasionally will develop on senescent pods (Sinclair, 1988), and seeds may show symptoms described above. It is possible that after physiological maturity, even though preexisting structural defense systems may be present, induced mechanisms may be less likely to occur (McGee, 1986b). This fungus, which is a well adapted saprophyte existing on crop residues or soil (Garzonio and McGee, 1983), will infect seeds only under favorable environmental conditions, which are usually weather related.

The involvement of weather factors in seed infection caused by the Diaporthe/Phomopsis complex has been known for many years (Lehman, 1923; Kirkpatrick, 1957). Rainfall, relative humidity and air temperature have all been related to the development of the disease (Kmetz et al.,1979; Tekrony et al., 1983; Spilker et al., 1981). Several studies have related rainfall or irrigation during the growing season to severity of Phomopsis seed decay (Lehman, 1923; Kmetz et al., 1979; Shortt et al., 1981; Wilcox et al., 1974; Ross, 1975). In other studies, the effects of rainfall on seed infection has been related to growth stages at which it occurred. Lamka (1986) was able to correlate high levels of pod infection at R6 with periods of wet weather after the onset of flowering

(R1). Weather conditions prior to this growth stage had little effect on pod infection. Studies of pods at growth stages between R7 and R8 exposed to high relative humidities in growth chambers (Spilker et al., 1981; Hepperly and Sinclair, 1980b; Balducchi and McGee, 1987) showed the importance of moisture at physiological maturity. Rupe and Ferriss (1986) demonstrated the importance of water potential in the process of seed infection. They showed that Phomopsis sp. can grow and infect soybean seeds only when pods have a water content above 19%.

Reports about the importance of temperature in the development of the disease have not been consistent. However, most of the studies suggest that even though temperature might not be the most important weather factor influencing PSD (Tekrony et al., 1983), high moisture and high temperature during harvest maturity provide optimum conditions for the disease (Spilker et al., 1981; Kmetz et al., 1979; Balducchi and McGee, 1987).

In Iowa, Balducchi and McGee (1987) were able to define the temperature and humidity conditions favorable for seed infection to occur. Detached pods at growth stage R8 were exposed to different sequences of days at high (100%) and low (40 to 60%) relative humidity at different temperatures. High humidity conditions also were simulated in the field by

irrigating plants artificially and naturally inoculated with P. longicolla for 5-day periods during the R7 to R8 growth stages. The results of these studies showed that pods exposed to higher temperatures (25 C) required less time for seed infection to occur at 100% relative humidity than pods exposed to lower temperatures. At temperatures of 20 and 15 C, it took 4 and 5 days respectively, at 100% relative humidity to reach seed infection levels obtained with 3 days at 25 C. For high rates of seed infection to occur at least 3 continuous days of high humidity were necessary. A minimum critical temperature of 19 C was required for appreciable seed infection to occur.

The effect of cultivar maturity group, planting date, and timing of harvest are essentially related to weather conditions. Soybeans maturing under warm humid conditions have a higher probability of being infected with PSD if pods were infected at an earlier point in the growing season (Kmetz et al., 1975; Ross, 1975). Late maturing cultivars are usually less prone to Phomopsis seed decay, and has been suggested that environmental conditions in late fall, such as lower temperatures, are less favorable for the development of the disease. Planting early or planting early-maturing varieties, can therefore increase the probability of seed infection just because seeds are exposed to conditions that

enhance the development of the disease (Kmetz et al., 1975; Ross, 1975; Tekrony et al., 1984; Wilcox et al., 1974). On the other hand, delaying harvest has resulted in significant increase in seed infection with PSD (Wilcox et al., 1974; Dhingra and Sediyama, 1979).

Control of PSD

Several management options can be used to reduce the incidence of Phomopsis seed decay of soybeans. These measures include cultural practices, use of late maturing varieties, and chemical control. Seed infection by Phomopsis can be reduced and seed quality improved by practicing crop rotation. Garzonio and McGee (1983) demonstrated that seed infection with PSD is most severe in continuous soybeans and least following continuous corn. Jeffers et al. (1981) showed that with crop rotation the amount of initial inoculum of Phomopsis sp. is lowered.

Areas prone to fog or reduced wind movement such as river valleys, should be avoided because these conditions are more conducive to the disease due to the likelihood of long periods of high humidity. Early maturing varieties or early planted crops are more likely to develop the disease because seeds

would probably mature when environmental conditions are more favorable for seed infection (Tekrony et al., 1983).

There have been several reports on the possibility of detecting resistant or tolerant cultivars to PSD (Kulik, 1985; Sinclair, 1988). Resistance to seed infection has been associated with indeterminant and semideterminant growth habits (Thomison and Kenworthy, 1986), with pubescent lines (Hepperly and Sinclair, 1980b), and with hard seed coats (Abney and Ploper, 1988; Vaughn et al., 1985). Identification of sources of resistance have been limited because it has been difficult to separate environmental and host maturity effects from genotypic resistance. The lower levels of diseased seeds exhibited by late maturing cultivars have been misunderstood by some as resistant to Phomopsis but are, in fact, the result of disease escape (Thomison, 1985; Wilcox et al., 1985). Although no satisfactory resistance to Phomopsis is available in widely adapted cultivars (Pyndji and Sinclair, 1987), some genotypes consistently show a low incidence of infected seeds. Some cultivars that have been reported as showing resistance to PSD are `Morgan' (Kenworthy, 1988), PI417479 (Brown et al., 1987; Brown, 1987) and PI181550 (Vaughn et al., 1985). These differences suggest that there might be some mechanism of limiting fungal invasion of the seeds (Abney and Ploper, 1988).

Foliar fungicides to control Phomopsis seed decay have been used in most of the soybean growing areas of the USA (Kulik, 1983). The value of fungicide treatments has been mostly to improve seed quality with little effect on yield (Tekrony et al., 1985; Jeffers et al., 1982b; Sinclair, 1989).

Because fungicides must be applied before disease symptoms are visible and before it can be determined whether economically significant levels of seed infection will occur, their use has been somewhat limited (Ross, 1975; Tekrony et al., 1983). Fungicides are often applied either too early or too late in the growing season or are applied when there is insufficient disease pressure, and no improvement in either yield or seed quality is noted (McGee, 1986a). Benomyl, alone or in combination with other fungicides, has been reported as the most effective foliar fungicide in preventing infection by the Diaporthe/Phomopsis complex (Foor, 1978; Ellis and Sinclair, 1976; Vidic et al., 1986). It was found that a single application of a benzimidazole fungicide at R6 (full seed) was effective in controlling Phomopsis sp. (Tekrony et al., 1985).

Use of Predictive Methods in Disease Control

Knowledge of the epidemiology of some diseases has led to the formulation of predictive systems which can forecast the occurrence of infection or disease. Predictive models can be used to improve disease control. Their use is particularly important for low-value-per-acre crops grown on large acreages in which chemical control should be used only if it is cost-effective (Coakley, 1988a; Krause and Massie, 1975).

Developing models to predict diseases requires that the disease meet certain requirements: a) it causes economically significant decreases in the quality or quantity of the crop; b) that the disease varies between seasons; c) economic control measures are available; and d) sufficient information is available on the nature of the dependence of the disease on meteorological conditions (Bourke, 1970).

It is only been since the mid 1970s that mathematical models contributed to specific, practical forecasting efforts. Some of the forecasts developed during the last 50 years, have provided useful information to growers and disease managers. Even though these forecasts were developed without formal mathematical modelling, they were consistent with the epidemiological principles of forecasting (Fry and Fohner, 1985).

With the recognition that the climate has a great effect on disease epidemiology, many of the available predictive models require meteorological data (Coakley, 1988b). Stewart's bacterial wilt of corn is a classic example of a disease in which the predictive scheme used is based on climatic factors. The year-to-year fluctuation of this disease is associated with winter temperatures that affect overwintering populations of the corn flea beetle which transmits the bacteria (Castor et al., 1975).

Another classic example is potato late blight, caused by Phytophthora infestans, which is particularly responsive to weather; for that reason its epidemiology has been studied extensively. It has long been known that major outbreaks of this disease are associated with weather conditions (Mackenzie, 1981). Systems used to predict disease occurrence have been developed during the past 20 years by various workers (Hyre, 1954; Wallin, 1962). Hyre (1954) developed a system based on records of daily rainfall and maximum and minimum temperatures. Another predictive scheme for potato late blight developed by Wallin and Waggoner (1950) is based on relative humidity and temperature. In the early 1970s, a computer program, known as Blitecast, was developed at the Pennsylvania State University (Krause and Massie, 1975). This is a combination of both systems mentioned above. It

schedules fungicide applications based on local weather conditions in each particular field. Other diseases for which weather factors are used as a basis for decisions in forecasting are leaf rust on winter wheat (Chester, 1946), Septoria nodorum on winter wheat (Tyldesley and Thompson, 1980), yellowing viruses on sugar beet crops (Watson et al., 1975), stripe rust on winter wheat, apple scab (Jones, 1980), Cercospora leaf spot of peanuts (Jensen and Boyle, 1966), fire blight of pear (Thomson, 1982), Botrytis leaf blight of onions (Vincelli and Lorbeer, 1989), and blue mold of tobacco (Nesmith, 1984).

In some cases predicted values for some diseases are based upon probability distribution. For these diseases, repeated simulations with identical input data have been able to determine the average development of the disease and the chance variation in development that might be expected. Some examples of simulator programs are: EPIDEM (Waggoner and Horsfall, 1969) that simulates tomato early blight; EPIMAY (Waggoner et al., 1972) for corn leaf blight; EPIVEN (Kranz et al., 1973) for apple scab; and a simulator for Ascochyta blight of chrysanthemum (McCoy, 1971).

A new forecasting technique called Model Output Enhancement (MOE) has been described recently (Royer et al., 1989). This system bases the prediction on mesoscale weather

forecasts. The authors used potato late blight as an example to generate this type of forecast.

Predictive Methods for Control of PSD

Different predictive systems have been developed in the USA since about 1976 to aid soybean seed producers in making fungicide application decisions. Bases for these predictive methods include yield potential, rainfall, dew, humidity, cultivar, cropping history, planting date, disease presence, seed production, temperature, tillage, seed quality at planting time, irrigation, yield history, and field location (Stuckey, 1989).

Initially the idea of using predictive methods for control of Phomopsis and Diaporthe spp. was to identify fields that would benefit from spraying by increasing their yields (McGee, 1988). The Illinois "point system" method was developed for this reason (Shurtleff et al., 1980). This system used ten criteria that were known to have an effect on the disease or the crop value. This method now is rarely used because foliar fungicides have not increased yields appreciably (McGee, 1988).

Fungicide use then was concentrated on seed crops, where there was more concern about the germinability of the seeds.

Tekrony et al. (1985) showed that one application of benomyl at growth stage R6 was effective in controlling Phomopsis seed decay; however, disease severity varies greatly from year to year and fungicides were not always needed. New predictive schemes were developed to assist seed producers in making decisions for fungicide use. In 1980, the Kentucky predictive system was developed (Stuckey et al., 1981). This point system was based on four criteria: cropping history, cultivar selection, planting date, and rainfall. All of these factors have been shown to increase severity of PSD (Garzonio and McGee, 1983; Tekrony et al., 1983; Spilker et al., 1981). Each criterion is assigned a point value and the decision is taken based on the total points obtained. Since 1984, a software program, "Points", has been available to enter data for each specific field. A limitation of the Kentucky system is the inability to accurately predict seed infection in fields with intermediate point totals in their scale (Stuckey, 1989).

A different type of predictive method was developed in Iowa (McGee, 1986a; McGee and Nyvall, 1984). This method is based on the knowledge that pods are a pathway for seed infection, that seed infection does not occur before R7 growth stage, and that inoculum reaching pods after R6 growth stage is unlikely to cause seed infection. This system uses

analysis of pod infection by Phomopsis spp. at R6 to predict the need for fungicide application. Determining the level of pod inoculum is a direct means of identifying the potential for seed infection. The pod infection test is performed on R6 maturity pods sampled from seed production fields. Pods are treated with a surface sterilant, immersed in the herbicide Basagran, and incubated in a moist chamber for seven days. Pods are then examined for the presence of fruiting bodies of the pathogen and the number of infected pods are recorded. When using the Iowa pod test predictive method the grower is advised to apply a foliar fungicide to the growing crop if more than 50% of the pods during R6 growth stage are infected. If less than 25% of the pods are infected, a fungicide application is not considered to be necessary, and if pod infection levels are between 25 and 50%, other factors (weather, cultivar maturity, planting date, etc.) should be considered in deciding if a fungicide application would be beneficial.

The advantages and disadvantages of the Kentucky and the Iowa methods have been discussed in recent reviews by McGee (1988) and Stuckey (1989). Several companies in different states are using the Iowa method and have expressed savings in spraying costs by the use of the system (McGee, 1988). A definite weakness in both methods is that they cannot account

for the effect of weather between R7 and harvest (McGee, 1988). To be effective, the fungicides currently registered require that applications be made before seed infection occurs.

As previously discussed, several studies have related weather conditions between R7 and harvest maturity to seed infection by the Diaporthe/Phomopsis complex (Tekrony et al., 1983; Balducchi and McGee, 1987; Rupe and Ferriss, 1987). Short term weather forecasts (1 to 5 days) which now are fairly accurate (Coakley, 1988a) may therefore prove very useful in improving the predictability of seed infection by harvest maturity.

Rationale and Objectives

Epidemiological studies of soybean seed infection by Phomopsis longicolla (the main cause of Phomopsis seed decay) have indicated that pods are a pathway for infection of seeds. These studies also indicated that extensive seed infection can only be expected after R7 growth stage (beginning maturity) (McGee, 1986a), and then only if certain conditions of temperature and humidity occur (Balducchi and McGee, 1987). Benzimidazole fungicides can successfully control the disease if applied to the growing seed crop prior to seed infection.

However, in Iowa, as in other soybean producing states, the application of a foliar fungicide to control this disease might not always be necessary. Low inoculum levels on the pods or fall weather which is unfavorable for the development of the disease result in seed infection levels which are too low to justify a fungicide spray.

Disease prediction methods have been developed in Iowa and Kentucky that allow decisions to be made on the need for a fungicide application during the growing season. The Iowa pod test predictive method has been used successfully to identify soybean fields that might benefit from a fungicide application to control Phomopsis seed decay. However, both the Kentucky and Iowa predictive methods have a significant limitation. They do not account for the effect of weather after the predictive measurement has been made. The data that relate the effects of temperature and humidity to the movement of P. longicolla from pods to seeds (Balducchi and McGee, 1987), indicated that the Iowa pod test predictive method could be improved by the incorporation of short term weather forecasts. The purpose of this study was to develop a mathematical model for the prediction of Phomopsis seed decay in soybeans by using information about the inoculum level at R6 growth stage and weather conditions from R6 onward as predicted with short term (1 to 5 days) weather forecasts.

Explanation of Thesis Format

This thesis is composed of a general introduction, a paper entitled, "A quantitative model for prediction of Phomopsis seed decay of soybeans", a general summary, additional literature cited, acknowledgements, and appendix. The paper will be submitted for publication to a professional journal. The Ph.D. candidate, C. M. Milla will be the senior author, with Dr. D. C. McGee and Dr. S. E. Taylor as coauthors.

A QUANTITATIVE MODEL FOR PREDICTION OF PHOMOPSIS SEED DECAY OF SOYBEANS

ABSTRACT

The Iowa pod test predictive method has been used since 1984 to predict seed infection levels of Phomopsis seed decay (PSD) and thus aid seed growers in making decisions for fungicide use. However, the method has a limitation in that it cannot account for effects of weather conditions on seed infection after pod infection has been assayed. The moisture and temperature conditions during the period from growth stage R7 to R8 that affect seed infection are well defined. This study was undertaken to incorporate short-term weather forecasts with that pod test predictive method.

Weather and disease data were collected in Iowa during the growing season of 1987 and 1988. A mathematical model was developed for prediction of PSD by incorporating into a regression equation pod inoculum levels at R6 growth stage (full pod), a coded number for consecutive days with rain during growth stages R7 to R8 (physiological maturity), and daily maximum and minimum temperatures for this rainy period. The weather data to be used with this model are obtained through short term (1 to 5 days) weather forecasts as reported by weather stations for the area. Results from this study clearly indicate that the predictive ability of the Iowa pod

test is greatly improved when weather data are incorporated into the predictive scheme.

INTRODUCTION

Phomopsis seed decay (PSD) of soybeans (Glycine max (L.) Merr.) is of great concern to the soybean seed industry in the Midwest of the United States because it reduces seed quality and germination (McGee, 1986; Wilcox et al., 1985; Gleason and Ferriss, 1984), and yield (Johnson and Berger, 1982). The disease is caused by a complex of fungi including Diaporthe phaseolorum (Cke. & Ell.) Sacc. var. sojae (Lehman) Wehm. & Sacc., D. phaselorum var. caulivora Athow and Caldwell, and Phomopsis longicolla Hobbs. Epidemiological studies have shown that pods can become infected from flowering (R1) onward (Rupe and Ferriss, 1987). However, extensive seed infection however does not occur before R7 (McGee, 1986), and only under certain weather conditions. Balducchi and McGee (1987) showed that high relative humidity (100%) was essential for disease development, and at least 3 continuous days of 100% relative humidity were necessary for development of high rates of seed infection from pods incubated at 25 C. A minimal critical temperature of 19 C was required for significant seed infection to occur.

Chemical control of this disease can be achieved if a foliar fungicide is applied to the growing crop at R6 growth stage, when seeds have not been infected (McGee and Brandt,

1979). Various methods have been developed to predict the level of seed infection and thereby assist seed producers in making decisions for fungicide use (Stuckey et al., 1981; McGee, 1986). The Iowa pod test predictive method, (McGee and Nyvall, 1984; McGee, 1986) has been used successfully by seed producers in the Midwest since 1984. The system is based on measuring the inoculum level of Diaporthe/Phomopsis on the pods, which then is used to predict seed infection. A limitation of this system is that it cannot account for the effect on seed infection of weather after R6 growth stage, when the pod test is completed.

Because climatic conditions favoring the development of seed infection have been well defined (Balducchi and McGee, 1987), the Iowa predictive method could be greatly improved if used in combination with short term weather forecasts. The purpose of this study is to develop a predictive system for PSD by incorporating in a mathematical model pod inoculum levels at R6 and weather conditions during growth stages R7 and R8.

MATERIALS AND METHODS

Sampling Sites

Samples of soybean pods were obtained from thirty-six and thirty-two soybean seed production fields throughout Iowa during 1987 and 1988, respectively. The fields comprised a range of different soybean cultivars. Fields were selected based on their proximity to a weather station in which daily rainfall and temperature were continuously recorded. In most cases a station was located within 10 miles of the field. Fields comprised a range of different cultivars.

A specific area within each field was arbitrarily selected for the collection of samples at R6 growth stage (full pod) and again at harvest maturity. At R6 growth stage 100 pods were sampled from the middle part of the plant. They were still green, full length and completed filled out (McGee and Nyvall, 1984). They were kept in a cooler for up to 2 days until processing in the laboratory. The same procedure was followed at harvest, with samples taken from the same part of the field. For each field, information on the cultivar grown, planting dates, and dates at which the different growth stages occurred was provided by the field managers.

Disease Data

The disease data used for development of the predictive model were as follows:

1. Pod infection at R6 growth stage.

Pod infection levels caused by Phomopsis longicolla was determined by the Iowa pod test procedure described by McGee and Nyvall (1984). Green pods that were fully extended and expanded were immersed in a 1.3% sodium hypochlorite solution for one minute, drained, and immersed in a 1:10 Basagran (sodium salt of bentazon (3-(1-methylethyl)-1H-2, 1, 3-benzothiadiazin-4 (3H)-one 2, 2-dioxide)) water solution for ten seconds. They were then incubated in 20x30 cm plastic boxes on damp blotters at room temperature (approximately 21 C) for seven days under continuous light. After seven days the number of pods on which Phomopsis pycnidia were detected was counted.

2. Seed infection at harvest maturity.

Two hundred seeds, removed from the sampled pods from each field, were surface-sterilized using 0.5% sodium hypochlorite solution for 1 minute, rinsed in sterile water and plated on acidified potato dextrose agar (APDA). They

were incubated in the dark at room temperature for 14 days. The number of seeds for which colonies of the Diaporthe/Phomopsis complex developed were counted.

Meteorological Variables

Weather data used in this study were obtained from "Climatological Data", a publication issued monthly by the U. S. Department of Commerce for each state. It lists each station by location and tabulates daily meteorological data as recorded at each station. For each field, climatic data were taken from the weather station nearest the field (Station 1) and a station located on the opposite side of the field (Station 2). Precipitation records from both stations were used in a weighted average to estimate the real conditions at the field site. For example, if Station 1 were closer to the field than Station 2, records from Station 1 were given correspondingly a greater weight. If a field was within 3 miles of a station, data were taken from that station only. Only Station 1 was used for temperature values.

This study utilized weather data that occurred from growth stages R7 (beginning maturity) to R8 (full maturity), and from R7 to harvest maturity. A field was considered to be at the R7 growth stage when one normal pod on the main stem

was brown or tan and at the R8 growth stage when 95% of the pods had reached the mature, brown color (Fehr and Caviness, 1977). Seven to ten days of good drying weather were required after R8 before soybeans were ready to be harvested. The dates at which the plants reached these growth stages were estimated based on the information provided by the "Iowa Soybean Yield Test Report", a publication by the Extension Service of Iowa State University that reports the approximate dates on which different soybean varieties reached maturity (R8) when grown in the northern, central and southern districts of Iowa.

To determine the growth period over which data should be taken for the development of the best model, correlations with seed infection at harvest maturity were made for weather data between growth stages R7 to R8 and between R7 and harvest maturity. The predictive value of the resulting full models was compared for those same growth periods. The growth stage from R7 to R8 was found to work better for the development of the full model; therefore, this growth period was used for further analyses. The period from R7 to R8 for all the fields tested ranged from 8 to 16 days in 1987 and from 8 to 14 days in 1988. Corresponding periods from R7 to harvest maturity were 17 to 25 in 1987 and 17 to 23 in 1988.

The weather variables considered in the study were as follows:

- Average daily maximum temperature (TMAX)
- Average daily minimum temperature (TMIN)
- Temperature difference (TDIFF) between average daily minimum and average daily maximum temperatures.
- Precipitation (MOIST)

Average maximum (TMAX) and average minimum temperatures (TMIN) were computed from daily temperatures observed on consecutive days with precipitation during the period from R7 to R8. Temperature differences (TDIFF) represented the difference between the average daily maximum and the average daily minimum temperature during those same days.

For each field, moisture values were determined from periods of continuous rain between growth stages R7 and R8, and temperature conditions during this period. This value was refered to as "MOIST" in equations subsequently developed. To define periods of rain at a particular site, a value of 1.0 was assigned for each day measurable rain was recorded at both Stations 1 and 2. If rain was recorded at Station 1 only, 0.5 was assigned. If recorded at Station 2 only, 0.25 was assigned. Values for consecutive days of rain then were determined as illustrated on Table 1. The hypothetical

example indicates a rain days value of 2. In this case only one prolonged period of rain occurred between growth stages R7 and R8. When two or more periods occurred the one considered most favorable for seed infection to occur was selected for use in the model. These would be periods which were longer and/or experienced higher temperatures.

Table 1. Examples of estimation of number of days with rain for different fields

	Aug						Sept						
	R7												R8
	29	30	31	1	2	3	4	5	6	7	8	9	10
Station 1	-	-	-	-	*	-	*	-	-	-	-	-	-
Station 2	-	-	-	*	*	*	-	-	-	-	-	-	-
Rain values				.25	1	.25	.5						
Number of days with rain	= .25 + 1 + .25 + .5 = 2												

- = no rain * = rain

Moisture values were then determined for selected rain day values using a 0 to 5 scale (Table 2) derived from the work of Balducchi and McGee (1987). In this work it was shown that the period of continuous high moisture necessary for significant seed infection to occur was dependent on

temperature during the wet period. They showed, for example, that at temperatures of 20 and 15 C, it took 4 and 5 days, respectively, at 100% relative humidity to reach the level of seed infection attained within 3 days at 25 C. In the present study, temperature conditions during rain periods were defined at two levels. The first was based on the average maximum temperatures (TMAX) of $\geq$23 C, 16-22 C and, $\leq$15 C. A second level, with two divisions was made within the $\geq$23 C and 16-22 C classes, and was based on the differences (TDIFF) between the average daily maximum and average daily minimum temperatures. Small differences ($\leq$8 C) indicated that humidity was high, while large differences (>8 C) indicated lower humidity. The temperature classes thus ranged from most favorable for seed infection at TMAX of $\geq$23 C and a TDIFF $\leq$8 C, to least favorable at a TMAX $\leq$15 C. Table 2 also indicated rain day values ranging from most favorable at 6 to least favorable at 0. A 0 to 5 scale then was applied to define the least to most favorable conditions for seed infection using the combined data for rain value days and temperature.

An arbitrary value of 3.00 (Table 2) was assigned to represent weather conditions that were conducive to the same level of Phomopsis seed infection (3, 4 and 5 days at 25, 20 and 15 C, respectively). This information is based on the work of Balducchi and McGee (1987). The other values in the

same table were extrapolated from this value as follows: for conditions optimal for seed infection (TMAX $\geq$23 C, and TDIFF $\leq$8 C), the same number was assigned as the rain day value, ranging from 0 to 5.00, which has been considered the maximum MOIST value possible. For the same maximum temperature, but with a higher TDIFF value, a corresponding MOIST value was assigned that was one unit less than the MOIST value for a low TDIFF. To have MOIST values corresponding to the fractioned number of rain day values, whole numbers were subdivided in intervals of 0.25. The same procedure was followed to assigned MOIST values when TMAX is 16-22 C, and when TMAX is $\leq$15 C, except that for this low TMAX value the TDIFF was not considered, and therefore, has only one column.

Model Development

Regression analyses were used to generate models. Seed infection was used as the dependent variable for data from 1987 and 1988 separately, and for the two years combined. The analyses were made using SAS (Statistical Analysis System) procedure. A full model included linear and quadratic terms of the independent variables POD, TMAX, TDIFF and MOIST, and the two variable linear interactions between them giving 14 total combination factors. Temperature differences were

obtained from the same dates indicated for AVG TMAX. The analyses were made using degrees F, which is the legal unit used in U. S. government publications. The actual values for each of these variables used in the development of the models are shown in Tables 3 and 4.

Each full model was reduced by deleting the least significant independent variables. The final parameter selection for the reduced models was based on having the least number of terms, without much reduction in the coefficient of determination R^2, and that the total number of correct predictions was the same as for the full model.

Model Testing

Researchers at Kentucky and Iowa agree that a desirable goal is to limit seed infection by the Diaporthe/Phomopsis complex to 15% (Stuckey, 1989). Significant loss in germination potential occurs when seed infection levels are greater than 15%. Models were tested on the basis of their ability to predict final seed infection levels above or below this value.

Table 2. Moisture point values (MOIST) that represent conditions for Phomopsis seed infection resulting from different number of days with rain at different temperature[1]

Rain day Value	Average maximum temperatures (TMAX) ≥23 C (73 F) Temperature differences (TDIFF) ≤8 C (≤15 F)	>8 C (>15 F)	16-22 C (61-72) ≤8 C (≤15 F)	>8 C (>15 F)	≤15 C (59)
6.00	5.00	4.00	5.00	4.00	4.00
5.75	5.00	4.00	4.75	3.75	3.75
5.50	5.00	4.00	4.50	3.50	3.50
5.25	5.00	4.00	4.25	3.25	3.25
5.00	5.00	4.00	4.00	3.00	3.00[c]
4.75	4.75	3.75	3.75	2.75	2.75
4.50	4.50	3.50	3.50	2.50	2.50
4.25	4.25	3.25	3.25	2.25	2.25
4.00	4.00	3.00	3.00[b]	2.00	2.00
3.75	3.75	2.75	2.75	1.75	1.75
3.50	3.50	2.50	2.50	1.50	1.50
3.25	3.25	2.25	2.25	1.25	1.25
3.00	3.00[a]	2.00	2.00	1.00	1.00
2.75	2.75	1.75	1.75	0.75	0.75
2.50	2.50	1.50	1.50	0.50	0.50
2.25	2.25	1.25	1.25	0.25	0.25
2.00	2.00	1.00	1.00	0.00	0.00
1.75	1.75	0.75	0.75	0.00	0.00
1.50	1.50	0.50	0.50	0.00	0.00
1.25	1.25	0.25	0.25	0.00	0.00
1.00	1.00	0.00	0.00	0.00	0.00
0.75	0.75	0.00	0.00	0.00	0.00
0.50	0.50	0.00	0.00	0.00	0.00
0.25	0.25	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00

[1]Conditions for which the same level of seed infection was obtained: a=3 days at 25 C, b=4 days at 20 C, c=5 days at 15 C (Balducchi and McGee, 1987).

Table 3. Average climatological data from R7 to R8 for each soybean field sampled in Iowa during 1987

Field Number	Average TMAX (F)	Average TDIFF (F)	Moisture Point Value
1	73.75	13.50	4.00
2	83.00	24.50	1.00
3	76.80	18.00	4.00
4	69.60	19.50	4.00
5	76.50	23.50	1.00
6	79.75	21.50	1.75
7	71.00	22.00	0.00
8	76.00	31.50	0.00
9	76.00	18.00	0.00
10	64.00	12.00	0.00
11	78.70	21.70	1.25
12	78.00	21.25	2.25
13	71.70	14.70	2.00
14	74.30	16.60	2.00
15	82.50	17.50	0.50
16	78.00	24.00	0.00
17	70.00	9.50	1.00
18	80.50	17.30	3.00
19	71.50	18.50	0.00
20	78.50	14.50	2.00
21	76.00	26.50	1.00
22	72.00	18.25	2.50
23	75.00	22.70	1.00
24	74.25	20.75	2.50
25	76.20	21.20	4.00
26	74.00	18.50	1.00
27	71.70	13.70	2.00
28	74.00	26.50	1.00
29	78.00	13.70	2.50
30	72.20	18.70	4.00
31	81.00	25.00	0.00
32	78.30	14.60	3.00
33	80.50	25.00	3.00
34	81.00	22.30	1.00
35	82.00	24.50	1.00
36	68.00	17.30	3.00

Table 4. Average climatological data from R7 to R8 for each soybean field sampled in Iowa during 1988

Field Number	Average TMAX (F)	Average TDIFF (F)	Moisture Point Value
1	76.70	19.40	1.00
2	72.00	16.00	0.00
3	80.00	23.50	0.50
4	81.50	23.00	3.00
5	82.30	25.60	0.25
6	77.70	23.00	2.00
7	80.00	20.00	1.00
8	74.00	25.50	0.25
9	73.50	15.00	2.00
10	80.00	23.00	2.00
11	76.00	16.50	1.00
12	74.00	20.50	1.00
13	77.50	21.50	1.00
14	77.00	18.50	1.00
15	72.00	12.70	1.00
16	76.00	21.00	0.00
17	70.00	13.00	0.00
18	76.20	20.80	1.00
19	77.30	17.30	1.00
20	74.50	27.00	0.25
21	80.70	24.70	1.50
22	82.00	26.00	1.00
23	78.00	22.50	1.25
24	70.00	19.00	1.00
25	70.50	20.00	0.00
26	78.50	24.70	0.00
27	74.50	21.50	0.00
28	84.00	26.50	1.00
29	80.00	25.00	1.00
30	77.00	15.50	1.00
31	78.30	26.00	0.50
32	75.60	17.60	0.50

RESULTS

Pod infection levels by P. longicolla varied greatly during 1987 and 1988 (Tables 5 and 6). In 1987, they ranged from 0 to 93% with most infection levels above 10%. In 1988, they were high in a few fields, but most of the fields either were not infected or only lightly infected. These low infection values in the second year were expected due to the drought conditions during that year that were unfavorable for the dispersal and establishment of the pathogen on the pods. According to a weather summary (Hillaker, 1988), Iowa precipitation was 10.45 inches (265.4mm) below normal during 1988, and temperatures during the soybean growing season were significantly warmer than normal.

Levels of Phomopsis seed decay were also quite different in the harvested seeds during 1987 and 1988 (Tables 5 and 6). While seed infection levels in 1987 ranged from 0 to 23%, in 1988 the highest level of infection found was 8%. Because of the importance of moisture, low seed infection levels were expected in that year. The range in pod and seed infection levels for both years sampled provided a wide variation in disease occurrence that could be used for the development of the model.

Table 5. *Phomopsis* pod and seed infection (%) from soybean production fields sampled in Iowa during 1987

Field Number	% pods infected with *Phomopsis* spp. at R6 growth stage	% seeds infected with *Phomopsis* spp. at harvest
1	18	1.0
2	11	4.5
3	61	20.0
4	56	10.5
5	54	0.0
6	2	15.5
7	14	8.0
8	10	1.0
9	92	0.0
10	47	15.0
11	25	0.5
12	0	3.5
13	4	3.5
14	92	20.5
15	23	4.5
16	5	6.5
17	93	23.5
18	11	6.0
19	4	0.0
20	1	9.5
21	12	2.5
22	1	12.5
23	11	12.5
24	6	3.0
25	5	1.2
26	18	19.5
27	2	8.5
28	8	2.5
29	23	6.0
30	10	11.0
31	16	18.5
32	58	21.5
33	6	4.5
34	13	1.5
35	8	0.5
36	38	5.0

Table 6. *Phomopsis* pod and seed infection (%) from soybean production fields sampled in Iowa during 1988

Field Number	% pods infected with *Phomopsis* spp. at R6 growth stage	% seeds infected with *Phomopsis* spp. at harvest
1	0	0.0
2	0	0.0
3	1	0.0
4	0	1.5
5	3	0.0
6	7	0.5
7	0	0.0
8	0	0.5
9	3	0.0
10	0	0.5
11	0	0.0
12	0	0.0
13	2	0.5
14	1	0.0
15	91	7.5
16	1	0.5
17	1	3.5
18	4	1.0
19	44	8.0
20	6	0.0
21	0	0.0
22	0	0.0
23	1	0.0
24	26	0.0
25	0	6.0
26	0	0.5
27	0	0.0
28	1	0.5
29	1	0.5
30	0	0.0
31	3	0.0
32	0	0.0

The regression analysis program generated different regression equations when various independent variables were related to seed infection. The full model (Table 7) included 14 terms as independent variables (three weather variables occurring from R7 to R8, percent of infected pods at R6, and their respective quadratic terms and linear interactions). Reduced models using 11, 7, 4, and 3 terms also were considered. All of these models were fitted using data from 1987, 1988, and the combination of both years.

The purpose of reducing the models was to generate a simple equation with a minimal number of terms, capable of the same prediction as the complete model. As the number of terms in the models was reduced, their respective coefficients of determination declined, as expected. The R^2 corresponding to 1987 data was greatly reduced when a model with two terms was fitted, but was comparable to the more complicated model when three terms (POD, POD*TDIFF, and POD*MOIST) were used (Table 7). The values of R^2s corresponding to the combination of both years were also lowered after deleting some terms, but the reduced model with the same three terms (POD, POD*TDIFF, and POD*MOIST) gave R^2 values similar to that of the full model. This suggested that the terms removed were not critical to the model. It was determined that the best selection of terms for the model should be POD, POD*TDIFF, and POD*MOIST.

Table 7. Independent terms included in the fitted models and their respective coefficients of determination (R^2). Data obtained in Iowa during 1987 and 1988

Terms in the model	Coefficient of Determination 1987	1988	1987-88
POD, TMAX, TDIFF, MOIST, POD*POD, TMAX*TMAX, TDIFF*TDIFF, MOIST*MOIST, POD*TMAX, POD*TDIFF, POD*MOIST, TMAX*TDIFF, TMAX*MOIST, TDIFF*MOIST	.50	.91	.48
POD, TMAX, TDIFF, MOIST, POD*POD, TMAX*TMAX, POD*TMAX, POD*TDIFF, POD*MOIST, TMAX*TDIFF, TMAX*MOIST	.48	.91	.47
POD, TDIFF, MOIST, POD*TMAX, POD*TDIFF, POD*MOIST, TMAX*TDIFF	.47	.73	.43
POD, TDIFF, POD*TDIFF, POD*MOIST	.42	.55	.42
POD, POD*TDIFF, POD*MOIST	.42	.52	.42
POD*TDIFF, POD*MOIST	.23	.52	.33
POD, POD*MOIST	.25	.52	.37
POD, POD*TDIFF	.32	.52	.33

Table 8. Coefficients of determination of full models fitted for data that included weather conditions from R7 to R8 and from R7 to harvest collected in Iowa in 1987 and 1988.

Growth Period	Coefficients of determination 1987	1988	1987+1988
R7 to R8	0.50	0.91	0.48
R7 to Harvest	0.40	0.93	0.44

When corresponding R^2 values were generated over the period R7 to harvest maturity, the coefficient of determination of the resulting full model was lower than those obtained for the period from R7 to R8 was used (Table 8).

The capabilities of the various models in predicting actual seed infection values were compared with those of the pod test alone (Table 9). Seed lots with levels of Phomopsis seed decay greater than 15% were considered to be significantly infected and therefore would have benefit from chemical spray before seed maturation. Seed infection values of 15% or less were considered low, and these seed lots would not have benefited from spraying. A correct prediction resulted when the models or pod test suggested the same decision concerning a fungicide application as the actual seed infection value. The predictive ability was given by the total number of correct predictions divided by the total number of observations. A comparison of the predictive

abilities of the full models developed with data from R7 to R8 and from R7 to harvest maturity is given in Table 10.

Table 9. Comparison of the predictive ability of the Iowa pod test with the full and reduced models fitted for data from 1987, 1988, and the combination of both years

Predictive Scheme	Predictive Ability[a] (%) 1987	1988	1987+1988
Model with 14 terms	92	100	94
Model with 11 terms	92	100	94
Model with 7 terms	92	100	94
Model with 4 terms	92	100	94
Model with 3 terms	92	100	94
Model with 2 terms (POD, POD*MOIST)	83	100	91
Model with 2 terms (POD, POD*TDIFF)	83	100	89
Model with 2 terms (POD*TDIFF, POD*MOIST)	81	100	91
Iowa Pod Test	78	91	84

[a]Predictive Ability is the number of fields for which both the predicted and the actual seed infection values suggested the same decision concerning a fungicide application.

Table 10. Predictive ability of full models fitted for data that included weather conditions from R7 to R8 and from R7 to harvest collected in Iowa in 1987 and 1988

Growth Period	Predictive Ability 1987	1988	1987+1988
R7 to R8	92%	100%	94%
R7 to Harvest	86%	100%	88%

The selected model includes the variables POD, POD*TDIFF, and POD*MOIST and has been named CYPOD. The results of a regression analysis relating these variables to seed infection at harvest maturity are given in Table 11. The final equation that resulted from fitting the model with the combined data from 1987 and 1988, and is as follows:

$$\% \text{ seed infection} = 2.806 + 0.267*POD - 0.013*POD*TDIFF + 0.051*POD*MOIST$$

Table 11. Regression model (CYPOD) relating pod inoculum levels at R6 and weather variables to Phomopsis seed infection at harvest maturity

Parameter	Coefficient	Pr > /T/
Intercept	2.806	0.0003
POD	0.267	0.0030
POD*TDIFF	-0.013	0.0055
POD*MOIST	0.051	0.0031

The results from comparing the predictive abilities of the CYPOD and the Iowa pod test method are shown in Table 12.

Table 12. Comparison of the predictive abilities (%) of the Iowa pod test and the CYPOD for data from 1987, 1988 and the combination of both years

Method	1987	1988	1987+1988
Iowa Pod Test	78	91	84
CYPOD	92	97	94

The actual seed infection values for 1987 and 1988 and the predicted values resulting when using the final model are given in Tables A1 and A2 in the Appendix.

DISCUSSION

Results from this study confirmed that moisture and temperature during maturation of the soybean crop, as well as pod-borne inoculum greatly influenced the severity of Phomopsis seed decay. Pod infection appeared to be the most important variable associated with this disease, as suggested by a highly significant regression coefficient for this variable (Table 11). The other 2 variables in the model were interactions with pod infection (POD*TDIFF and POD*MOIST), which substantiates the importance of this variable.

Moisture, as measured by the number of consecutive days with rain, together with maximum temperature and the difference between maximum and minimum temperatures for the wet period was the most significant weather variables influencing seed infection. These results were not surprising because as described earlier, temperature differences indicate conditions of relative humidity, and relative humidity and/or precipitation have been reported as the most important weather related factors affecting PSD (Kmetz et al., 1979; Tekrony et al., 1983; Lamka, 1986; Balducchi and McGee, 1987; Spilker et al., 1981).

Estimations of the number of consecutive days with rain

were better related to seed infection than was the total amount of rain for the same period. Similar results were obtained by Balducchi and McGee (1987) who suggested that the duration rather than the amount of precipitation was more important for the development of the disease. Tekrony et al. (1983) were able to correlate incidence of seed infection, with minimum air temperature and minimum relative humidity occurring from R5 to harvest maturity but not with total precipitation or precipitation per day. Their results have been attributed to the long period of time for which precipitation was considered, ignoring variation in the distribution and number of precipitation events.

When data from growth periods R7 to R8 and from R7 to harvest maturity were compared, it was found that weather conditions from R7 to R8 gave the better correlation with seed infection (Tables 8 and 10). Therefore, climate data from this period were used in the development of the model. These results agree with the work of Balducchi and McGee (1987), who compared seed infection levels in pods collected at R7 and R8, and found that despite having similar temperatures in R7 and R8, R8 plots did not develop high levels of seed infection as compared to plots from R7. It has been suggested that at R8 more time is needed for pod tissues to reach high moisture and allow the movement of the fungus. R7 pod tissues contain

considerably more moisture and require a shorter period of high humidity for seed infection to occur. Tekrony et al. (1983) found significant correlations of minimum relative humidity with seed infection for the growth periods of seed filling to physiological maturity and physiological maturity to harvest maturity, but correlation coefficients were higher during the the period from R5 to physiological maturity.

The Iowa pod test which has been in use for several years, has proven to be useful to the seed industry in identifying fields that should be sprayed with fungicides. However, a limitation of this test is that when pod infection levels range from 25 to 50%, this method fails to give a clear recommendation. It is necessary to consider other factors such as weather, cultivar maturity, and planting date and make a personal judgement about the prediction. Another limitation of the test is that it does not account for weather conditions that occur after R6 growth stage, when the test is performed. A high level of infection on the pods does not always result in high levels of infection in the seeds. Weather factors occurring after R7 are essential for the development of the disease.

Results obtained with this work clearly indicate that CYPOD has improved the Iowa pod test as a predictive method by incorporating short term weather parameters in the system

(Table 10). During 1987, a year with an average rainfall and temperature, CYPOD was able to correctly predict 14% more of the seed infection values than did the Iowa pod test. In a dry year such as 1988, the difference in the predictive abilities of these two methods was not as large, probably because weather conditions did not favor the development of the disease and pod and seed infection were low. However, for that year, CYPOD only failed for 3%, while the Iowa pod test failed in 9% of the cases. This suggests that CYPOD more accurately detected unfavorable weather conditions for development of seed infection than did the pod test.

For practical application of CYPOD, data for pod-borne inoculum at R6 growth stage would be required and information about weather conditions occurring between growth stages R7 and R8, which could be obtained from radio or television forecasts of the area. A moisture point value (MOIST) can be obtained from Table 2 and the predictive value for seed infection at harvest maturity then calculated by applying the CYPOD equation. The calculation of the predicted values can be repeated every 3 to 5 days when a new weather forecast is given for the area, until plants reach R8 or when application of a fungicide is no longer possible or convenient.

In addition to predicting Phomopsis seed infection for control purposes, the model may also be of value to seed

companies which could use the system in a particular year to indicate seed quality problems at harvest time. Prediction of seed infection risk may be helpful for planning the utilization of the seed crop. However, even though this method is fairly simple, easy to follow and appears to have good predictive ability, it has some limitations. The model has been based on observations and expresses the risk of seed infection under known weather conditions. In practice the accuracy will be limited by the uncertainties associated with forecast conditions. Weather forecasting is fairly reliable for 3 to 5 days. Long term weather forecasts such as 10 or 20-day, have a greater margin of error. Besides, long term weather forecasts are not always accessible to the public. The full implementation of this model will require that the risks and uncertainties associated with the method and with forecasts be evaluated from an economic perspective. A method such as that described by Mason (1982) should be used to evaluate the accuracy of the model.

Without validation, the model cannot be considered complete. One way to proceed is to split the data obtained in two sets and estimate the coefficients and measure the accuracy of the model as explained by Draper and Smith (1981). This procedure can be done when more data is collected either from direct observations or from historical data, including

pod and seed infection records, that may be furnished by seed companies.

This model was developed with data from 1987 and 1988 which are considered an average and dry year respectively. Even though there was a wide variation in weather conditions during those two years, the model may not be extrapolated to work well under extremely wet conditions or extremes of temperature. Temperature, not just daily temperature range, is known to influence disease development. The model selected (Table 7) does not include the actual maximum temperature (TMAX), but during seasons with greater temperature range then 1987 and 1988, it may well become a major consideration. Therefore, it is necessary to test and adjust the model during several years under different weather conditions before its final adoption. It should be tested with forecast as well as observational data.

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Table A.1. Entries used in the development of the CYPOD and the predicted values obtained for 1987 data

Seed[a]	POD[b]	TMAX[c]	TDIFF[d]	MOIST[e]	Predicted[f]
1.0	18	73.75	13.50	4.00	8.08
4.5	11	83.00	24.50	1.00	2.72
20.0	61	76.80	18.00	4.00	17.05
10.5	56	69.60	19.50	4.00	14.76
0.00	54	76.50	23.50	1.00	3.13
15.5	2	79.75	21.50	1.75	2.95
8.00	14	71.00	22.00	0.00	2.45
1.00	10	76.00	31.50	0.00	1.29
0.00	92	76.00	18.00	0.00	5.35
15.0	47	64.00	12.00	0.00	7.85
0.5	25	78.70	21.70	1.25	3.87
3.5	0	78.00	21.25	2.25	2.80
3.5	4	71.70	14.70	2.00	3.50
20.5	92	74.30	16.60	2.00	16.52
4.5	23	82.50	17.50	0.50	4.18
6.5	5	78.00	24.00	0.00	2.54
23.5	93	70.00	9.50	1.00	20.66
6.00	11	80.50	17.30	3.00	4.91
0.00	4	71.50	18.50	0.00	2.89
9.50	1	78.50	14.50	2.00	2.98
2.5	12	76.00	26.50	1.00	2.40
12.5	1	72.00	18.25	2.50	2.96
12.5	11	75.00	22.70	1.00	2.99
3.0	6	74.25	20.75	2.5	3.52
1.2	5	76.20	21.20	4.00	3.46
19.5	18	74.00	18.50	1.00	4.11
8.5	2	71.70	13.70	2.00	3.18
2.5	8	74.00	26.50	1.00	2.53
6.0	23	78.00	13.70	2.50	7.71
11.0	10	72.20	18.70	4.00	5.05
18.50	16	81.00	25.00	0.00	1.76
21.5	58	78.30	14.60	3.00	15.98
4.5	6	80.50	25.00	3.00	3.34
1.5	13	81.00	22.30	1.00	3.09
0.5	8	82.00	24.50	1.00	2.75
5.00	38	68.00	17.30	3.00	10.07

[a]Actual seed infection values.
[b]Levels of pod infections obtained at R6.
[c]Average maximum temperature during consecutive wet days from R7 to R8.
[d]Average temperature differences during consecutive wet days from R7 to R8.
[e]Moisture point value.
[f]Predicted seed infection values.

Table A.2. Entries used in the development of the CYPOD and the predicted values obtained for 1988 data

Seed[a]	POD[b]	TMAX[c]	TDIFF[d]	MOIST[e]	Predicted[f]
0.0	0	76.70	19.40	1.00	2.80
0.0	0	72.0	16.0	0.00	2.85
0.00	1	80.00	23.50	0.50	2.77
1.5	0	80.50	23.00	3.00	2.80
0.00	3	82.30	25.60	0.25	2.62
0.5	7	77.70	23.00	2.00	3.25
0.00	0	80.00	20.00	1.00	2.80
0.5	0	74.00	25.50	0.25	2.80
0.00	3	73.50	15.00	2.00	3.32
0.5	0	80.00	23.00	2.00	2.80
0.0	0	76.00	16.50	1.00	2.80
0.0	0	74.00	20.50	1.00	2.80
0.5	2	77.50	21.50	1.00	2.87
0.00	1	77.0	18.50	1.00	2.87
7.5	91	72.00	12.70	1.00	16.41
0.5	1	76.00	21.00	0.00	2.79
3.5	1	70.00	13.00	0.00	2.90
1.0	4	76.20	20.80	1.00	2.97
8.0	44	77.30	17.30	1.00	6.69
0.0	6	74.50	27.00	0.25	2.33
0.0	0	80.70	24.70	1.50	2.80
0.0	0	82.00	26.00	1.00	2.80
0.0	1	78.00	22.50	1.25	2.84
0.0	26	70.00	19.00	1.00	4.52
6.0	0	70.50	20.00	0.00	2.80
0.5	0	78.50	24.70	0.00	2.30
0.0	0	74.50	21.50	0.00	2.80
0.5	1	84.00	26.50	1.00	2.77
0.5	1	80.00	25.00	1.00	2.79
0.0	0	77.00	15.50	1.00	2.80
0.0	3	78.30	26.00	0.50	2.64
0.0	0	75.60	17.60	0.50	2.80

[a]Actual seed infection values.
[b]Levels of pod infections obtained at R6.
[c]Average maximum temperature during consecutive wet days from R7 to R8.
[d]Average temperature differences during consecutive wet days from R7 to R8.
[e]Moisture point value.
[f]Predicted seed infection values.