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A Biologically Oriented Threshold Decision Model for Control of Epidemics of *Septoria nodorum* in Wheat

For a long time, the only remedies available to control disease on wheat (*Triticum aestivum* L.) caused by *Septoria* species were protective fungicides such as captafol, which was effective against infection of heads and was usually applied after head emergence. Soon after the imidazoles and triazoles were introduced to control *S. nodorum* (Berk.) Berk. in Berk. & Broome, it became apparent that application before head emergence was more effective than use of protective fungicides. Routine prophylactic use of fungicides raised several problems, however. Low cereal prices demand the lowest possible production input, and this can be achieved only if epidemiological behavior of pathogens is predicted accurately on a regional scale. Treatment must be feasible at the most favorable growth stage, which coincides with the most vulnerable stages of the fungal population. Application of fungicides at this time should have tremendous economical and ecological benefit, particularly where disease caused by *Septoria* species does not occur regularly but fungicides are applied routinely as a protective measure. With increasing intensity of wheat cultivation (plant population density 550–600 heads per square meter, nitrogen 160–200 kg/ha, grain yield 6–10 t/ha), the leaf and head diseases are of economical importance. As a consequence, during the past 10 years, treatments have been applied regularly once to several times. Until 1986, especially protective fungicides, e.g., captafol, were used; currently, azole and morpholine products are more common.

In 1987, wheat was grown on about 220 million hectares, 7.6% of which were in Western Europe, 16.4% in North America, 25.6% in Eastern Europe, and 35.8% in Asia (Fig. 1A). That year the world wheat production was 507.4 million tonnes, 15.7% of which were produced in Western Europe, 16.4% in North America, 23.7% in Eastern Europe, and 34.3% in Asia (Fig. 1B). These figures reveal that Western Europe produces 15.7% of the world's yield on only 7.6% of the wheat crop area and that North America requires about twice the area to produce approximately the same amount. This illustrates, among other things, the differences in intensity of cultivation, i.e., in the use of production-promoting means for achieving and assuring optimum yields of high quality.

Control of fungus diseases has high priority for assuring yield, i.e., for avoiding yield losses. For this reason, the use of fungicides in the worldwide wheat hectarage is concentrated mainly in Western Europe, which uses 78% of the fungicides at an annual cost of $550 million in U.S. dollars (Fig. 2).

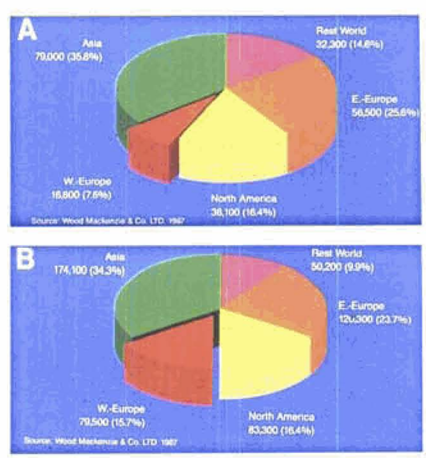

Fig. 1. Worldwide distribution of (A) the approximately 220,700,000 ha and (B) the approximately 507,400,000 t of wheat grown in 1987 (amounts shown × 1,000) (27).

In 1986, the wheat yield in the countries of Western Europe was 5.5–6.9 t/ha (av. 6.2 t), or about 2.7 times the yield in the United States and 3.2 times the yield in the Soviet Union (Fig. 3). The barley yield in Western Europe averaged 4.7–6.2 t/ha, or about twice that in the United States and three times that in the Soviet Union. These high yields in Western Europe are the result of intensified measures of arable farming and plant cultivation, including the use of plant protection products to minimize losses.

"Integrated plant protection" demands that pesticides be applied only when required by the state of the infection and that the pathogen be clearly identified. Scientific aids based on biological and meteorological parameters would be valuable in making the decision to apply fungicides. We developed and tested a model over a period of several years, in-

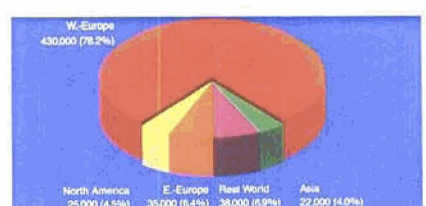

Fig. 2. Worldwide use of fungicides on wheat crops during 1987. Total cost in U.S. dollars was approximately $550 million (amounts shown × 1,000) (27).

cluding 4 years of intensive testing in 15 experimental locations in Bavaria. In 1988, after an enormous amount of biological data were evaluated, a decision model for control of *S. nodorum* based on threshold values was introduced. The number of pycnidia at consecutive growth stages of the wheat plant is measured to determine a threshold value at which spray action should be initiated. Sample leaves are gathered on predetermined days, and the qualitative and quantitative diagnosis of pycnidia is achieved by using either a stereoscope or the Bayer Cereal Diagnosis System (10).

We discuss here the concept, which is based on the essential facts of the biology of *S. nodorum* and its damaging effects. We describe the population dynamics of the pathogen during 1986–1988 and interpret them with reference to case studies at one location, Munich in Upper Bavaria. We discuss the effects of fungicide applications oriented to threshold levels at growth stages, and we provide background information about the use of the threshold concept.

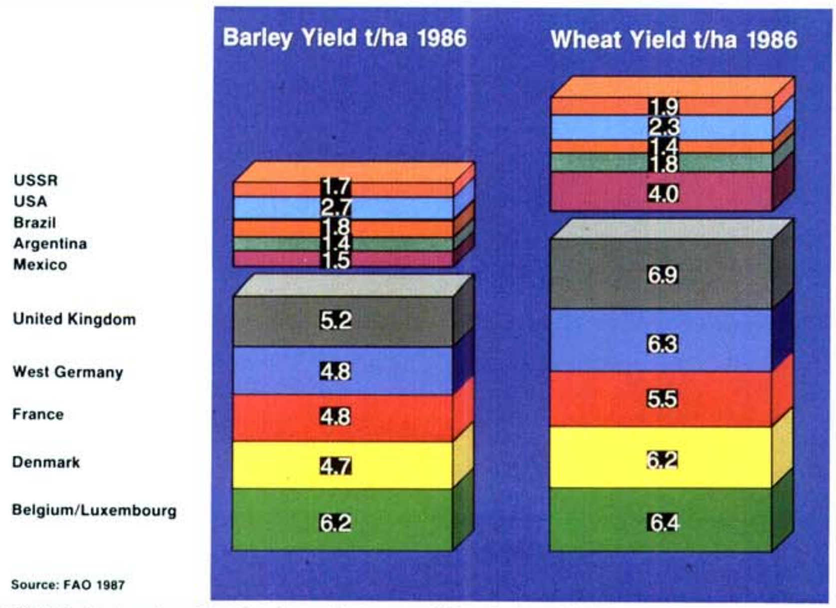

Fig. 3. Yield of wheat and barley in various countries during 1986 (1).

Table 1. Characteristics and enumerations of growth stages of wheat plants

Characteristics	Enumerations: EUCARPIA (EC) scale[a]	Enumerations: Feekes scale[b]
Stem elongation		
Pseudostem erection	30	...
First node detectable	31	5
Second node detectable	32	6
Third node detectable	33	7
Fourth node detectable	34	...
Flag leaf just visible	37	8
Flag leaf ligule just visible	39	9
Booting, inflorescence, emergence, and anthesis		
Boots just beginning to swell	43	...
Boots swollen	45	...
Flag leaf sheath opening	47	10
First spikelet of inflorescence just visible	51	10.1
Inflorescence half completed	55	10.3
Inflorescence completed	59	10.5
Beginning of anthesis	61	10.5.1
Anthesis half completed	65	10.5.2
Anthesis completed	69	10.5.3
Grain development and ripening		
Caryopsis (kernel) water ripe	71	10.5.4
Medium milk	75	11.1
Early dough	83	11.2
Hard dough	87	11.4
Caryopsis hard	91	11.4

[a] Zadoks et al (28).
[b] Feekes (8).

Biology of *S. nodorum*

S. nodorum survives on straw and stubble and in gramineous weeds and develops pycnidia and pseudothecia (*Leptosphaeria nodorum* Müller) in autumn and spring, respectively. Ascospores from pseudothecia are forcibly ejected from the fruit bodies and are responsible for primary infection of leaves of young wheat plants. The disease spreads chiefly by pycnidiospores carried by splashing raindrops. A rainfall of 0.7 mm per hour is sufficient for dissemination. After the pycnidiospores germinate, the pathogen either forms appressoria and penetrates the stomata or degrades the leaf tissue (cuticle) enzymatically by the mycelium, without forming appressoria. The fungus then penetrates the host tissue, simultaneously excreting metabolic products (toxins) (29). Spores germinate optimally at 20–25 C (range, 5–37 C) and 98–100% relative humidity (19,20). Germination is stimulated only when fluid, drop-forming water is present to dilute the amino acids in the spore slime, furthering the germination process (9,18). Parasitism continues and under optimal conditions (20 C, 90–100% RH) leads to necrosis, with the first pycnidia producing inoculum for secondary infection after 6–10 days.

Plants can be infected at all stages of development. The fungal population increases during the main growth period exclusively via the pycnidiospores formed in the pycnidia. Formation of pycnidia is favored by temperatures above 10 C (optimum, about 20 C) and a relative humidity of 95–100%. The time from infection to formation of pycnidia is about 6 days under optimum conditions. However, unfavorable conditions, such as a cool spring, can extend the period to up to 3 weeks. When temperatures rise, this period is reduced to 6–10 days.

The invasion of upper plant parts (head, flag leaf, and second leaf) depends on the degree of infestation at the lower to middle leaf levels. The pathogen does not necessarily move upward on the plant leaf by leaf. Given sufficient rainfall, the pathogen may spread simultaneously to various leaf levels.

Effects of Disease

The effect of Septoria leaf and glume blotch on yield of grain cannot be accurately determined from general fungicide experiments in which population development of the pathogen is unknown, especially when infection levels at different developmental phases of the plant are not defined. Thus, we devised a model of harmful effects of infections in different growth stages, characterized in two different systems (Table 1). Pot experiments (Mitscherlich vessels) were used to exclude disturbing external factors, and the probabilities of damage caused by infection limited to specific growth stages could be estimated according to spore densities (21,23–25). For instance, high inoculum densities (10^6 spores per milliliter) lead to yield losses as early as stage EC 32 (Fig. 4) and infections at stage EC 39 result in large yield losses. The latter appears to coincide with emergence of heads; this has been confirmed repeatedly. Experimental results further indicate that leaf infection at stage EC 59 or EC 69 leads to bigger losses than head infection.

Infection following medium to low inoculum densities (10^3 spores per milliliter) caused only punctate necrosis in the area of 3% (not shown) but resulted in significant decreases in yield (Fig. 5). Because the chlorophyll-bearing organs exceed the punctate tissue damage, the slight necrosis cannot be responsible for this yield reduction in the sense of a loss of assimilative active tissue. The reduction has to be interpreted in the light of the pathogen's metabolites (toxins) interfering with the plant's physiology. For example, septorin, a phytotoxin synthesized by *S. nodorum*, leads to changes in the respiratory activity of wheat and consequently reduces assimilation rate (2–4,6,7). The results show that a negative effect on yield can be manifest as early as stage EC 32.

Epidemiology

Progression of an epidemic of *S. nodorum* in control plots. The development of an epidemic was monitored by sampling four replications of 20 plants from experimental plots on each test date (11,12,15–17,26). Samples were taken at weekly intervals from stem elongation (early May) to milky ripeness (end of July), for a total of 12 sampling dates. From these, infestation severity in the field (ISF = number of pycnidia), infestation frequency in the field (IFF = percentage of infected leaves), and degree of necrosis (NEC = percentage of necrotic leaf area) were ascertained for each separate leaf level. Triadimenol was used to control *Erysiphe graminis* DC. f. sp. *tritici* Ém. Marchal above the first control threshold of 60–70% infestation frequency (one or two pustules per plant) and the second threshold of 1–2% infestation severity (5,13); carbendazim was used to control *Pseudocercosporella herpotrichoides* (Fron) Deighton at stage EC 32.

Depending on temperature and rainfall, the time needed for development of sufficient inoculum for an epidemic varies widely from the early stages in the spring onward. As an example, we present disease development during 1986–1988 in a control plot at Munich at stages EC 30–32 to EC 75.

In 1986 (Fig. 6, left), the pathogen was present (ISF) on the lowest leaves (F-7, F-6) as early as stage EC 31. Because rainfall was frequent and weekly temperatures averaged 13–16 C, the pathogen quickly spread to middle and upper leaf levels. The first pycnidia formed on the flag leaf (F) just 1 week after the leaf was fully developed at stage EC 39 (26 May). When average weekly temperature rose to 20 C and rainfall became frequent, the epidemic virtually exploded onto the upper leaf organs. At stage EC 75, leaves F, F-1, and F-2 had 100% necrosis and the head had 41% necrosis.

In 1987 (Fig. 6, middle), the pathogen was present (ISF) on leaves F-7 and F-6 at stage EC 32. Even though rainfall conditions favored dissemination, weekly temperatures averaged only 9–10 C, or 5–6 C less than in 1986. These conditions delayed the formation of sufficient pycnidia on the lower to middle leaves to initiate a severe epidemic. Compared with 1986, the lower temperatures in spring lengthened the latent period, thus delaying disease progression on the middle (F-5 to F-3) and upper (F-2 to F) leaves.

In 1988 (Fig. 6, right), the pathogen was present (ISF) in small quantities on the lower leaves (F-7) of samples taken at stage EC 30 (2 May). Average weekly temperatures of 13–15 C favored formation of pycnidia, but lack of rainfall from mid-April to mid-May prevented infection of middle and upper leaves (F-5 to F-3). Stage EC 37 (16 May) marked the

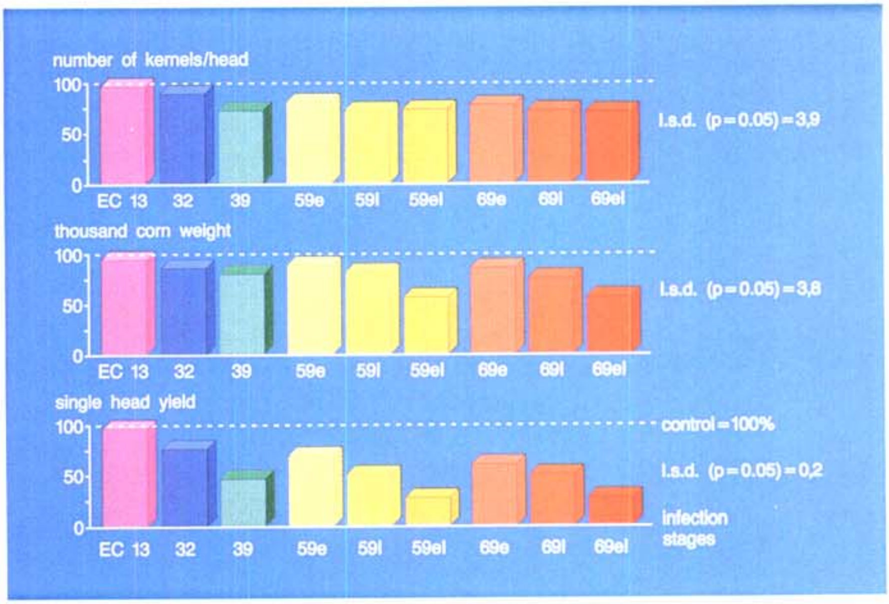

Fig. 4. Influence of *Septoria* infections (inoculum density 10^6 spores per milliliter) on yield of wheat plants inoculated at different growth stages in Mitscherlich pot experiments. Numbers = growth stage of plants when inoculated, e = head infections alone, l = leaf infections alone, el = whole plant infected; dotted lines = yield of control plants.

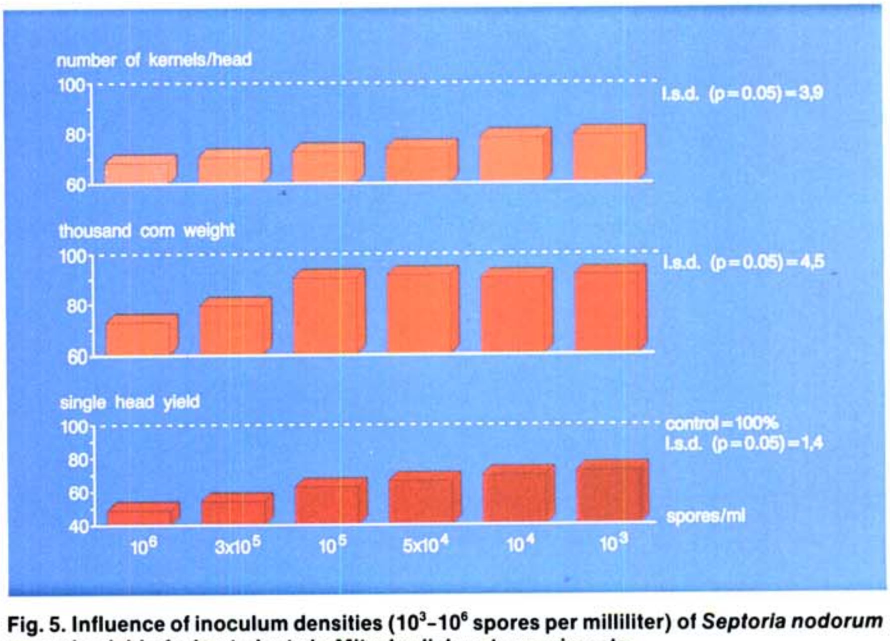

Fig. 5. Influence of inoculum densities (10^3–10^6 spores per milliliter) of *Septoria nodorum* on grain yield of wheat plants in Mitscherlich pot experiments.

beginning of a rainy period, and thereafter the pycnidia values rose slightly on F-4. However, without formation in the spring of a vigorous population on lower and middle leaves, the pathogen failed to reach the upper leaves (F-3 to F), and disease severity was low.

Influence of threshold and stage-oriented control measures on infection by *S. nodorum*. An epidemiological threshold was chosen on the basis of the temperature-moisture relationship and the number of pycnidia at certain leaf positions. Because the number of pycnidia can increase rapidly when weather conditions are favorable, we chose an experimental threshold value of five pycnidia as an average on test leaves. The effectiveness of decisions based on this threshold value is shown here relative to development of the pathogen in control plots and to coordination of growth stage with the use of the fungicide prochloraz.

The progress of infection was monitored in 1986 at the Ingolstadt site on the wheat cultivar Basalt (Fig. 7, red line). Weather conditions stimulated continuously increasing numbers of pycnidia from stage EC 33 onward on lower leaves and from stages EC 39–43 on middle leaves.

The threshold of five pycnidia as an average on leaf samples was reached on F-5 between stages EC 33 and EC 37, and prochloraz was applied immediately (stage EC 37, 19 May) (Fig. 7, violet line). This single application resulted in low numbers of pycnidia on leaves F-4 to F-2 up to stage EC 59 and was effective over a period of 4 weeks. The threshold value was reached again at stage EC 59, on leaves F-3 and F-2, and prochloraz was applied a second time (stage EC 69, 20 June). This application held the pathogen population in check until stage EC 75. The difference in yield compared with that of a control area was 0.8 t/ha, or an 11% increase.

Because epidemic situations vary from year to year, depending on the biological requirements of the pathogen and conducive meteorological conditions, treatment that is related to the growth stages of the plant will affect the pathogen only if the disease is present at the time of application or if the sprays accidentally interfere with the epidemic. From an epidemiological point of view, these stage-oriented treatments are randomly timed and randomly successful.

The usual practice in Europe is to apply only one treatment (so-called ear treatment) against *S. nodorum*, at stages EC 59–61. This routine measure was compared with the epidemic-based applications. Comparison of the yellow (stage EC 59) and red (control) lines in Figure 7 shows that pathogen development was reduced significantly on leaves F and F-1. Because population growth on lower and middle leaves was undisturbed, the resultant high inoculum level overtaxed the effectiveness of the fungicide. The difference in yield compared with that of a control area was 0.4 t/ha, or a 6% increase.

For wheat crops infested by *P. herpotrichoides*, applications of prochloraz + carbendazim should be timed from stage EC 30 to stage EC 37. Sometimes these applications coincide with the beginning of a *S. nodorum* population. Such a situation existed at the Ingolstadt site in 1986, since the threshold was first reached at stage EC 37. This routine application of fungicide at stage EC 37 did not control the disease until plant maturity (Fig. 7, green line). Infection of leaves F-2 to F increased from stage EC 71 onward. The difference in yield compared with that of a control area was 0.3 t/ha, or a 4% increase.

Other experiences with threshold-oriented control of *S. nodorum*. During 1986–1989, infection of the wheat cultivar Basalt was studied at 15 locations distributed throughout Bavaria. Epidemics of *S. nodorum* developed similarly when presummer weather patterns were the same over a large area but also were affected by local storms in June and July.

In 1988, dry weather and high temperatures during April and May delayed development of disease at all experimen-

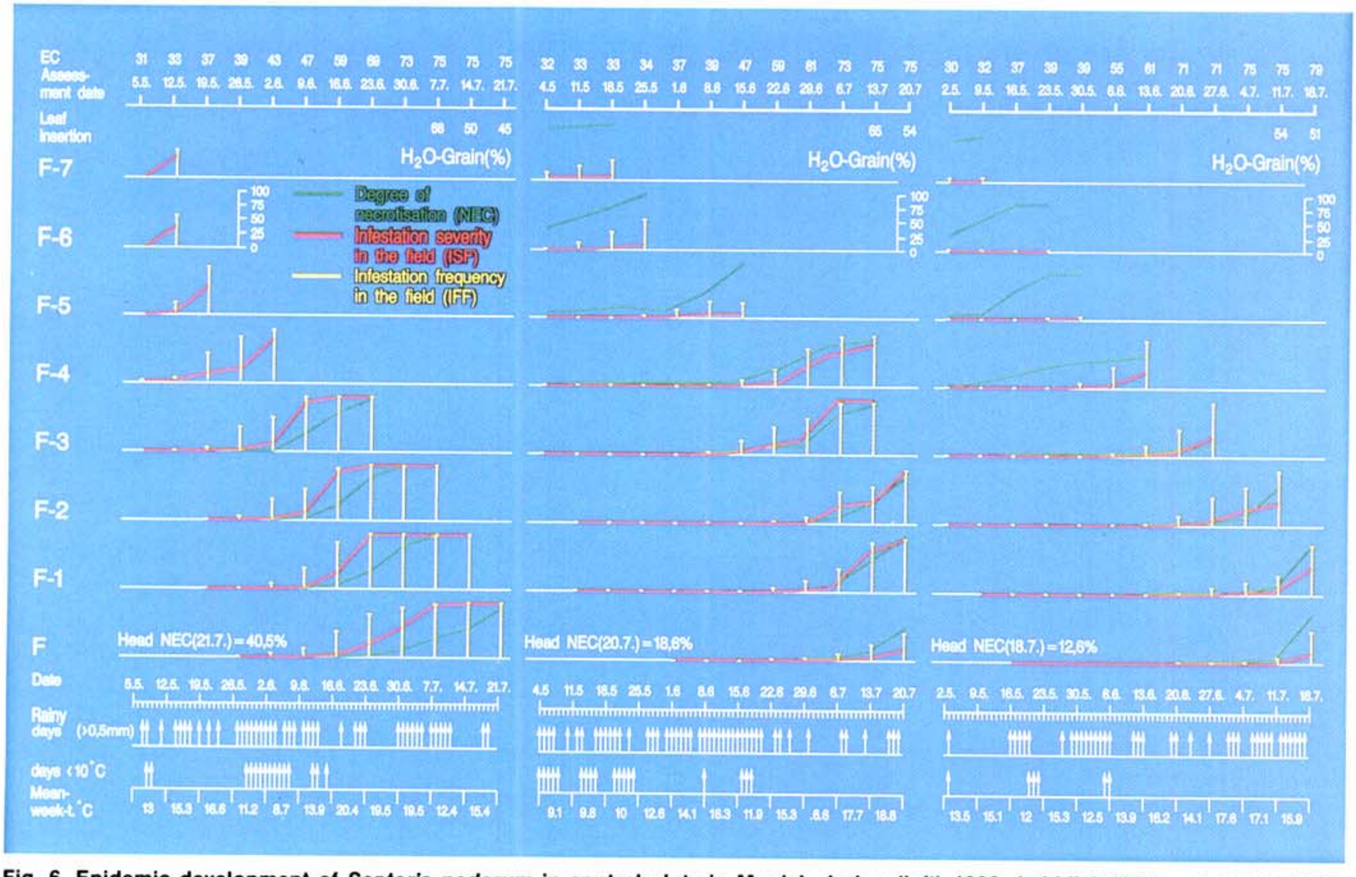

Fig. 6. Epidemic development of *Septoria nodorum* in control plots in Munich during (left) 1986, (middle) 1987, and (right) 1988. F = flag leaf, F-1 = second upper leaf, F-7 = eighth upper leaf; infestation parameters = ISF, IFF, and NEC; assessment dates and morphological development stages (EC = EUCARPIA scale); days with more than 0.5 mm of rainfall; days with temperatures less than 10 C; average weekly temperatures; degree of head necrosis.

tal sites. The model indicated that the threshold was reached in only 30% of the locations; in the remaining 70%, the stage-oriented treatments would have been economically ineffective.

The onsets of epidemics of *S. nodorum* in Bavarian wheat crops from 1980 to 1989 are shown in Figure 8. Customary fungicide applications related to the growth stages of the plant and thus timed at random, e.g., stage EC 37 or stages EC 59–61, are economically effective only in years when the pathogen is present at the date of application or if the sprays accidentally interfere with the epidemic. In many years, however, the criteria for an epidemic do not coincide with such randomly timed, stage-oriented treatments, and such treatments are not justifiable economically and ecologically. From an epidemiological point of view, such use of fungicides has little or no influence—an effect the farmer cannot ascertain. Even so, 80% of Bavarian farmers apply a treatment at stages EC 59–61. Sometimes when an epidemic begins early, these treatments are partly successful.

The effects on yield (average of six locations) of threshold- and stage-oriented applications of fungicide and of four treatments to achieve maximum control were compared (Fig. 9). The threshold-based treatment reduced losses more than the application at stages EC 59–61 but not as much as the four sprays. The threshold-based application achieved the same or higher net profit as the four sprays. The threshold-oriented treatment is especially attractive from an ecological viewpoint, because fewer fungicide treatments result in similar net profits.

Threshold-oriented Decision Model

The decision model we devised (Table 2) requires both a qualitative and a quantitative diagnosis of the pathogen and a reliable description of the growth stages of wheat. The model applies regardless of cultural practices, previous crop, cultivar, sowing time, or soil preparation and may help decision making in the case of pathogens other than *S. nodorum*. The Bayer Cereal Diagnosis System (Fig. 10) facilitates diagnosis and manages a large number of samples effectively. For implementation of the model, the wheat crop should be monitored at designated time intervals from stage EC 31 to stage EC 71. According to the results of Kolbe (14) and of our 4-year experiments, wheat develops in the time schedule shown in Table 3. Differences in crop development sites have been insignificant.

When the decision model is used to determine initiation of sprays based on test leaves (leaves to be observed) and pycnidia, severity of infection can serve as a guide to treatment of later infections by *S. nodorum*. From stage EC 34 onward, decisions are based on an average observation of more than one pycnidium per test leaf. At this level of infection, a fungicide spray should be recommended because most of the inoculum for higher leaves and heads is formed on the lower, i.e., test, leaves. Fungicide applied at this time would retard development of the pathogen and reduce the inoculum potential for higher leaves. As plants grow taller, higher indicator leaves are examined. The critical decision phase generally lies between stages EC 34–37 and EC 71–73; if the threshold level is exceeded within this period, an azole fungicide with systemic properties (22) should be used. After stages EC 71–73, the preharvest interval limits the use of fungicides.

When the threshold is exceeded for the first time at stages EC 47–51, usually only one application of fungicide is needed. The first treatment can be effective for 3–4 weeks. After this time, new inoculum can be expected to develop and a second application may be needed if infection on the test leaves reaches the threshold value. A chronology between the first and second treatments (Table 4) has been established on the basis of experience to date. After an application at stages EC 34–37, a second could become necessary from stage EC 51 onward, whereas a first treatment at stage EC 39 or EC 43 might

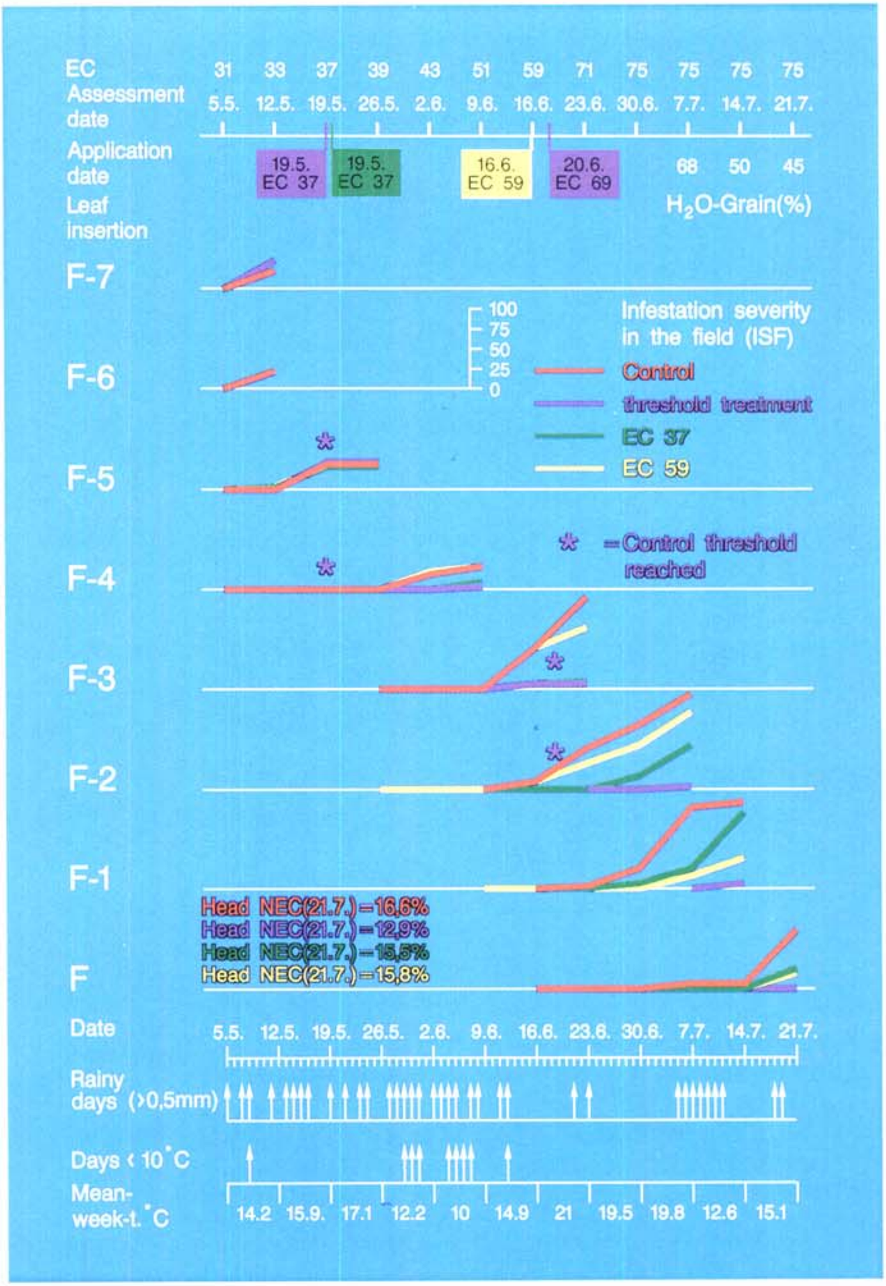

Fig. 7. Progress of infestation by *Septoria nodorum* at Ingolstadt site in 1986. Epidemic development of *Septoria nodorum* in control plots (red lines); threshold-oriented fungicide measures with prochloraz (violet lines); growth stage-oriented fungicide treatment at stages EC 59-61 (yellow lines); growth stage-oriented fungicide treatment at stage EC 37 (green lines).

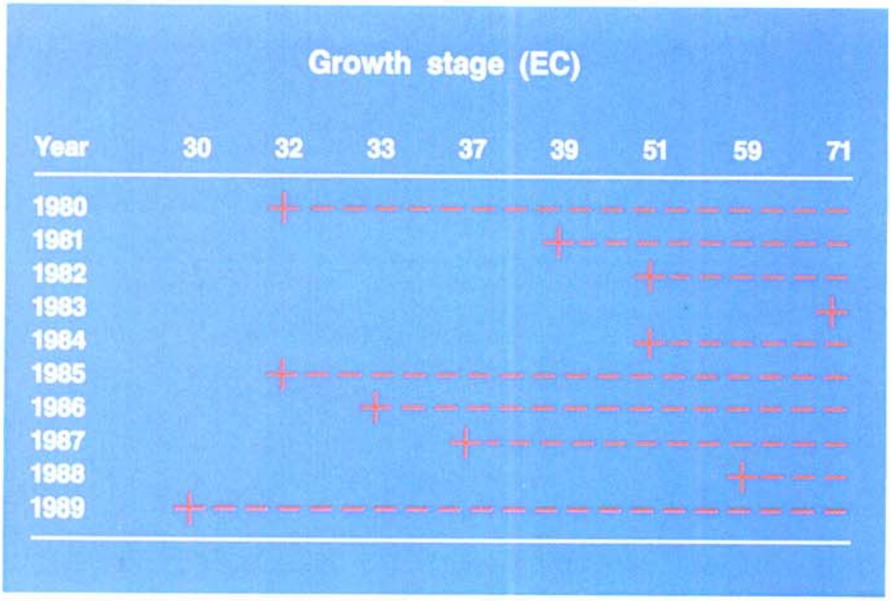

Fig. 8. Growth stages at onset of epidemics of *Septoria nodorum* in Bavarian wheat crops during 1980–1989.

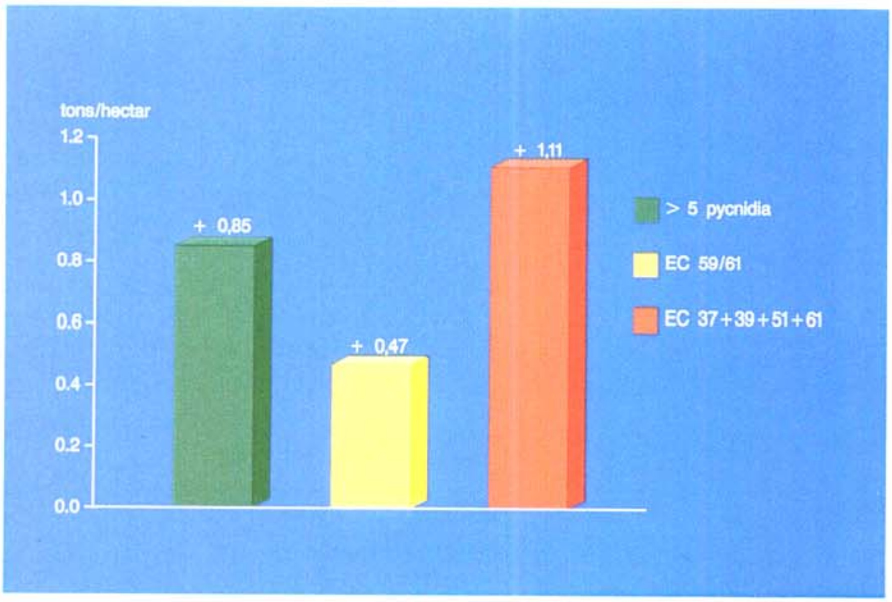

Fig. 9. Average grain yield from experiments with threshold- and stage-oriented control of *Septoria nodorum*. Yield is shown in response to (left) sprays (av. 1.6) at a threshold of more than five pycnidia per leaf, (middle) fungicide treatments at stages EC 59–61 only, and (right) fungicide treatments at stages EC 37, EC 39, EC 51, and EC 61.

Table 2. Threshold decision model for biologically oriented control of *Septoria nodorum* on wheat

EC scale growth stage	Indicator leaves	Decision
31	F-6/F-5	Observation period for quantification of primary infections
32	F-6/F-5	
33	F-6/F-5	
34	F-5	Transitory phase
37	F-5/F-4	Decision period for first and second threshold-oriented use of fungicide; average: more than one pycnidium per indicator leaf
39	F-5/F-4	
43	F-4/F-3	
47	F-4/F-3	
51	F-3/F-2	
61	F-3/F-2	
65	F-3/F-2	
69	F-3/F-2	
71/73	F-2/F-1	

be followed by a second at stage EC 59 or EC 65, respectively. Either systemic or contact fungicides can be used for the second treatment. If the threshold is never exceeded on the indicator leaves during the designated decision period (stages EC 34–37 to EC 71–73), no spray is needed.

To assess the extent of infestation by *S. nodorum*, 30–40 plants should be examined for pycnidia. Necrotic tissue is especially important because pycnidia generally form in dead leaf tissue.

Discussion

Appraisal of Septoria leaf and head disease can be a problem if the onset and progress of infection are not properly described. Systems based only on evaluation of unspecified leaf lesions or meteorological data are inadequate. The decision model we have described is based on pycnidia formation and change in inoculum dynamics and is being tested in various regions. Because the system uses pathogen-specific parameters, it can be used for all wheat-growing situations.

This model could have been developed only in a region where the disease is almost certain to occur and to reduce crop yield considerably, but it could also be applied in areas with only an occasional epidemic and resulting yield losses. Our study was restricted to *S. nodorum* for reasons of local occurrence. *S. tritici* Roberge in Desmaz. becomes virulent on some early sowings, and since the same biological parameters apply to both species, the model should be largely transferable. Necessary changes will have to be discovered through experience, since *S. tritici* is primarily a leaf pathogen.

Disease caused by *S. nodorum* will be the only single cause of damage in exceptional years, under certain crop conditions, or when cultivars resistant to other pathogens, such as fungi causing powdery mildew, are planted. Development of the model necessitated exclusion of

Fig. 10. The Bayer Cereal Diagnosis System for identifying fungal structures (e.g., pycnidia, conidia) in nonspecific necroses consists of two transparent sheets of plastic connected with hinges and guide strips for monocular lens systems (30- to 100-fold), between which wetted leaves with lesions can be placed on graduated scales. Either natural (field) or artificial (laboratory) light can be used, and work can be performed at a constant level, without focusing.

other biological agents, including *P. herpotrichoides, E. g.* f. sp. *tritici, Puccinia recondita* Roberge ex Desmaz, *Puccinia striiformis* Westend., and *Drechslera tritici-repentis* (Died.) Shoemaker. However, the model can be integrated into a practical or experimental situation without difficulty if the first application of fungicide is determined by the prevailing state of infestation. This and subsequent applications of suitable fungicides can exert a stronger or weaker influence on the development of *S. nodorum*, as determined by appropriate diagnoses. At present, the effects on different pathogens are insufficiently quantified to allow reliable conclusions to be drawn.

Occurrence and harmful effects of *Septoria* species have been underestimated. Control measures more often address easily visible diseases (e.g., powdery mildew), or applications of fungicide have been planned and carried out routinely. The use of the model enables greater precision, and fungicides can be chosen more intelligently. Fungicides cannot eliminate *Septoria* species from field crops, but epidemic-based control measures hold the pathogen in check to minimize yield loss.

For fungicide tests, it is advisable to include a treatment with sufficient sprays to suppress the pathogen completely so that losses prevented by the biologically oriented control can be quantified and the reliability of the model can be tested. In practice, it is better for ecological reasons to integrate chemical measures with other cultural practices.

Table 3. Chronological sequence of growth stages of winter wheat in Bavaria and North-Rhine-Westphalia (NRW)

EC scale growth stage	Date: Bavaria	Date: NRW	Standard deviation (± days)[a]	Time interval (days): Bavaria	Time interval (days): NRW
31	4 May	8 May	5.3	...	...
32	9 May	15 May	5.2	5	7
33	12 May	...	...	3	...
34	16 May	...	...	4	...
37	18 May	24 May	4.7	2	9
39	24 May	31 May	5.0	6	7
43	5 June	6 June	5.2	1	6
47	8 June	...	...	3	...
51	10 June	9 June	5.0	2	3
55	13 June	...	...	3	...
59	16 June	12 June	5.0	3	3
61	18 June	14 June	4.7	2	2
69	23 June	18 June	4.7	2	4
71	25 June	23 June	4.7	2	5

[a]Based on data from NRW (14).

Table 4. Chronology between the first and second threshold-based fungicide treatments to control *Septoria nodorum* on wheat

EC scale growth stage at which fungicide use indicated: First threshold	Second threshold	Indicator leaves
37	51/59*[a]	F-3/F-2
	59/65**	
39	59/65*	F-3/F-2
	59/73**	
43	65**	F-3/F-2
	73**	F-2/F-1
Second use from 47/51 to 71/73	No second use	

[a]Mean time between first and second thresholds: * = 3 weeks, ** = 4 weeks.

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