Development and Field Validation of a Brown Patch Warning Model for Perennial Ryegrass Turf

Michael A. Fidanza, Peter H. Dernoeden, and Arvydas P. Grybauskas

Graduate research assistant, professor of agronomy and associate professor of botany, respectively, University of Maryland, College Park 20742-5821.

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ABSTRACT

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Microclimate in perennial ryegrass (*Lolium perenne* 'Caravelle') was monitored for 3 years to identify environmental conditions associated with brown patch (*Rhizoctonia solani*) outbreaks and to develop a weather-based disease-warning model. The micrometeorological parameters measured were ambient air temperature, relative humidity, leaf wetness duration, precipitation, soil temperature, soil moisture, and solar radiation. Brown patch outbreaks were confirmed by the visual presence of foliar *R. solani* mycelium. An environmental favorability index (E) was developed to relate a combination of environmental conditions with brown patch outbreaks. The initial index (E_6) was based on relative humidity (RH $\geq$ 95% for $\geq$8 h; mean RH $\geq$ 75%), leaf wetness duration ($\geq$6 h) or precipitation ($\geq$12 mm), and minimum air ($\geq$16°C) and soil ($\geq$16°C) temperatures. Further analyses, however, revealed that an equally effective E was provided by a two-variable regression model (E_2). The E_2 model is $E = -21.5 + 0.15RH + 1.4T - 0.033T^2$, in which RH is the mean relative humidity and T is the minimum daily air temperature. For both E_6 and E_2 models, a threshold value (i.e., $E \geq 6$) constituted a brown patch warning. Brown patch outbreaks were predicted by both models with 85% accuracy over a 3-year period. All major infection events were predicted. In 1993, the warning model was used to field evaluate fungicide performance in perennial ryegrass and colonial bentgrass (*Agrostis tenuis* 'Bardot'). There were equivalent levels of blighting between the warning model and a 14-day calendar-based spray schedule, but the warning schedule provided a 29% reduction in fungicide applications.

Brown patch is caused by *Rhizoctonia solani* (Kühn) and is a major disease of turfgrasses worldwide (2,23). In cool-season turfgrasses, brown patch typically occurs during the summer and is associated with high temperatures and prolonged periods of high relative humidity and leaf wetness conditions (25).

Dickinson (8) conducted the earliest investigation on environmental conditions associated with brown patch. On golf-green turf (*Agrostis* spp.), Dickinson (8) observed that brown patch symptoms coincided with irrigation in the afternoon when maximum daytime air temperature ranged from 26 to 35°C then decreased to 15 to 21°C at night. The first reported brown patch warning model, however, was based solely on air temperature (6). Dahl (6) observed that brown patch occurred on 82% of days when the minimum air temperature was $\geq$21°C.

Rowley (19) monitored weather associated with development of brown patch of creeping bentgrass (*Agrostis palustris*) over a 2-year period, and used the environmental data to establish weather-based thresholds of disease risk. The thresholds were integrated into a model by Schumann et al. (22) that was assessed for accuracy on creeping bentgrass in Georgia, Massachusetts, and New Jersey. The authors concluded that fungicide applications could be reduced and acceptable brown patch control could be achieved by combining weather-based disease warnings with confirmation of pathogen presence through an enzyme-linked immunosorbent assay (22).

On high-value turf with low economic tolerance for disease injury, current brown patch management strategies involve the use of repeated, preventive fungicide applications (30). Urban environmental concerns and pest management costs have contributed to increased pressure to reduce or limit pesticide use (29). Strategically timed and targeted fungicide applications, as demonstrated by Hall (13) and Schumann et al. (22), may facilitate a reduction in fungicide use while maintaining acceptable disease control.

The objectives of this study were (i) to identify environmental conditions associated with brown patch outbreaks in 'Caravelle' perennial ryegrass (*Lolium perenne* L.) and (ii) to develop and field validate a brown patch warning model. The visual appearance of foliar mycelium was the basis for a disease outbreak for this model because golf-course superintendents invariably spray a fungicide on greens, tees, and usually fairways if mycelium of *R. solani* is present.

MATERIALS AND METHODS

Environmental monitoring. Micrometeorological conditions and occurrence of brown patch outbreaks were monitored and measured in a mature stand of perennial ryegrass turf from June 1991 through August 1993. Data from 1991 and 1992 were used to develop an environmental favorability index (E) for brown patch development that was field-tested in 1993. The study site was located at the University of Maryland Turfgrass Research Facility in Silver Spring. Soil was a Chillum silt loam (fine-silty, mixed mesic Typic Hapludult), pH 6.0, with 16 mg of organic matter per g of soil. The turfgrass plots included two mowing height treatments (17 and 45 mm); the plots were cut three times weekly from May through August and twice weekly during the spring and fall. Plots were 1.5 × 3.0 m and were arranged in a randomized complete block with four replications. The plots were distributed in a larger study area where fertility treatments were being assessed for their influence on brown patch. Turf clippings were removed, and turf was irrigated as needed to prevent drought stress. 'Caravelle' perennial ryegrass had been established and subsequently overseeded at the site for more than 3 years. Prior to renovating the site for

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Corresponding author: P. H. Dernoeden; E-mail address: pd9@umail.umd.edu

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this study, the study area had been blighted uniformly by naturally occurring populations of *R. solani* each summer. The site had received between 150 and 200 kg of nitrogen per ha annually since 1987.

The summer macroclimate at the study site consisted of warm temperatures and high atmospheric humidity, classified as temperate continental (27). The region is considered part of a transition zone between temperate and subtropical climates, which is suboptimal for temperate zone-adapted turfgrasses (27).

Except when otherwise noted, all sensors, probes, and measurement and control devices were obtained from Campbell Scientific (Logan, UT). Air temperature and relative humidity were measured with two sensors at a height of 300 mm above the plant canopy (model HMP35C). To ensure measurement accuracy, the instruments were housed in a 12-plate, louvered radiation shield and protected from direct sunlight and rain. Leaf wetness duration was estimated by two sensors (model 237) placed horizontally on the surface of the turf canopy in each mowing height treatment. A total of four sensors were used. The sensors were coated with flat white latex paint to improve their accuracy in detecting moisture (11). The sensors recorded periods of leaf wetness derived when the electrical resistance was less than 185 kΩ (15). Four temperature sensors (model 107) were placed in plots of each mowing height treatment. The sensors were buried to a depth of 25 ± 5 mm (9,18). Soil moisture was measured with gypsum blocks (model 227). Four blocks were placed in each mowing height treatment at a soil depth of 25 ± 5 mm to coincide with the depth of the temperature sensors. Precipitation was measured daily with a funnel-type gauge positioned 1.5 m above the soil surface. Solar radiation was measured with a pyranometer (model LI200S from LI-COR, Lincoln, NE). All environmental monitoring equipment was removed from the field and cleaned during October and calibrated prior to reinstallation during the following spring.

TABLE 1. Variables used to calculate the environmental favorability index (E) to provide a warning for brown patch outbreaks in perennial ryegrass grown near Silver Spring, MD

	Environmental variable[y]	Condition	Point value[z]
A:	Relative humidity >95%	≤4 h	0
		5–7 h	1
		≥8 h	2
B:	Mean relative humidity	<75%	0
		≥75%	1
C:	Leaf wetness duration or Precipitation in prior 48 h	≥6 h ≥12 mm	1
D:	Minimum air temperature	<16°C	−2
		≥16°C	1
E:	Minimum soil temperature	<16°C	−2
		≥16°C	1
F:	Precipitation in prior 48 h	≥40 mm	1

[y] Variables were measured in a 24-h period prior to 0600 h for all days during the evaluation period.

[z] Point values were determined for each category (i.e., A through F) and then were added to calculate E, where $E \geq 6$ equals high risk (environmental conditions potentially favorable for brown patch), and $E \geq 4$ equals low risk (environmental conditions not conducive for brown patch).

TABLE 2. Area under the disease progress curves (AUDPC) for brown patch epidemics on perennial ryegrass and colonial bentgrass that resulted from applications of the fungicide chlorothalonil, which was applied on a 14-day schedule, or after a disease warning model (E_2) indicated a need to spray

Fungicide scheduling method	Total no. of chlorothalonil applications	AUDPC[x] Perennial ryegrass	AUDPC[x] Colonial bentgrass
14-day interval[y]	7	621 b	12 b
Forecast[z]	5	641 b	14 b
Untreated	...	5,023 a	1,842 a

[x] AUDPC expressed as percent disease multiplied by day. Means followed by the same letter in a column are not significantly different according to Fisher's protected least significant difference test at $P \leq 0.05$.

[y] Chlorothalonil was applied on a 14-day interval beginning on 1 June and ending on 24 August 1993.

[z] Chlorothalonil was applied based when daily environmental favorability index values (E) ≥6, which resulted in applications on 8 June, 2 and 15 July, and 2 and 17 August 1993.

All monitoring instruments were connected to a CR10 measurement and control module with an AM-416 multiplexer encased in a weather-proof aluminum box and powered by a 12-V lantern battery. All instruments were programmed to measure environmental conditions at 5-min intervals and averaged data every 60 min.

The environmental conditions measured were summarized into 15 variables that were evaluated for their prediction of brown patch development. All variables summarized a 24-h interval beginning and ending at 0600 h. This interval was chosen because the mycelium of *R. solani* invariably develops in the turf canopy at night. The variables were mean relative humidity; hours of relative humidity ≥90 or ≥95%; hours of leaf wetness duration; total precipitation (millimeters) during the 24 or 48 h period prior to 0600 h; minimum, mean, and maximum air temperatures (degrees Celsius); minimum, mean, and maximum soil temperatures (degrees Celsius); mean soil water potential (megapascals); and mean and maximum solar radiation (watts per square meter).

Brown patch warning model. Disease outbreaks were determined visually by noting the presence of *R. solani* mycelium on turfgrass foliage. Whenever mycelium was present, it was confirmed microscopically to ensure it was *R. solani.* Isolates were collected weekly from the test site, and most were AG 1-IA. From June 1991 through August 1993, the study site was monitored daily between 0700 and 0800 h for the presence of foliar mycelium. Disease outbreaks were recorded as either a 'yes' or 'no' based on the presence or absence of mycelium of *R. solani* in plots of each mowing height treatment. Relative amounts of foliar mycelium (i.e., low, moderate, and high) in each plot also were recorded. A reference to minor outbreaks indicates that only low or moderate amounts of foliar mycelium were observed, whereas the presence of a high amount of mycelium indicated a major outbreak. Carry-over of some hyphae likely occurred when mycelium was observed in large amounts for two or more consecutive days, but this kind of outbreak was relatively uncommon.

Environmental and disease outbreak data from 1991 and 1992 were subjected to correlation analysis to identify key environmental variables associated with disease development. Distributions of environmental variables were compared to better distinguish between specific conditions that occurred during brown patch outbreaks versus days when new mycelium of *R. solani* was not observed. Data were subjected to univariate analysis, a procedure that combines frequency distributions and descriptive statistics (5, 21). A Bonferroni correction factor was used to ensure that the environmental data on days with versus days without a brown patch outbreak were compared at the $P = 0.05$ significance level (20). Because there were 15 variables, the corrected probability level was calculated as $0.05/15 = 0.0033$.

An environmental favorability index (E) was developed from a combination of environmental variables associated with the occurrence of mycelium of *R. solani* during 1991 and 1992. At the conclusion of the 1992 season, the index was developed to summarize the relationship between several environmental variables and disease outbreaks and to represent that relationship as a single value, E. To calculate E, first arbitrary point values were assigned to correspond with specific conditions of the 15 environmental variables (10,16). Next, individual point values assigned to the specific environmental conditions were added, and this resulted in a daily cumulative index or E (Table 1). To evaluate the relationship between brown patch outbreaks and E, observed outbreaks were compared with calculated daily values of E. Six environmental variables (Table 1) were selected to calculate *E* because observed disease outbreaks during 1991 and 1992 repeatedly corresponded with the *E* determined from those variables. Chi-square analysis was used to test the null hypothesis that there was no relationship between the values of *E* as determined from the six environmental variables and brown patch outbreaks (17,31). Once an acceptable *E* was developed, the data were subjected to multiple regression analysis in an attempt to develop a simplified disease warning model (7,20).

Field validation. In 1993, the brown patch warning model, E_2, was evaluated on mature stands of 'Bardot' colonial bentgrass (*A. tenuis* Sibth.) and 'Caravelle' perennial ryegrass mowed to treatment heights of 13 and 22 mm, respectively. These test sites were near the 1991 and 1992 study area and had the same soil type. The plots were mowed twice weekly, and clippings were removed. The predominate *R. solani* biotypes were AG1-IA and AG2-2 IIIB on the perennial ryegrass and colonial bentgrass sites, respectively.

To test the reliability of *E* derived from the E_2 model, the fungicide chlorothalonil (2,4,5,6-tetrachloroisophthalonitrile) was applied when values of E_2 were ≥6. Fungicide was not reapplied within 14 days of a previous application regardless of the brown patch forecast. A comparative treatment of calendar sprays of chlorothalonil was applied on a 14-day schedule beginning on 1 June. Both treatments were compared to an untreated control. Treatments were arranged as a randomized complete block design with four replications; individual plots measured 1.5 × 1.5 m. Chlorothalonil was applied at a standard rate of 9.1 kg a.i. ha^{-1} on the dates noted in Table 2 with a CO_2, pressurized (262 kPa) sprayer equipped with an 8010 flan fan nozzle and calibrated to deliver 1,018 liters of water per ha.

Treatments were evaluated visually for brown patch by assessing the percentage of plot area blighted or discolored by the Horsfall-Barratt scale (14,23). Each Horsfall-Barratt value was converted to a percent according to the midpoint rule prior to statistical analysis (4). The plots were rated weekly for brown patch severity during the test period. Ratings greater than 2% were judged as unacceptable in commercially maintained "high quality" turf, and ratings greater than 5% were above the acceptable threshold for sites managed with integrated pest management practices.

Brown patch severity over time was summarized as the area under the disease progress curve (AUDPC) (units were percent disease × day) (28) with the formula $\Sigma[(y_i + y_{i+1})/2][t_{i+1} - t_i]$, where y_i is the amount of disease, t_i is the time of the *i*th rating, and $i = 1,2,3\ldots n - 1$ (1,24). The AUDPC data were subjected to analysis of variance by SAS (20). Mean separations were based on Fisher's protected least significant difference test at $P = 0.05$ (12,26).

RESULTS

Environmental favorability index. Among environmental variables, soil temperature, soil moisture, and leaf wetness duration data were statistically similar in mowing height treatments, and therefore, data were averaged over mowing height (data not shown). Environmental data were pooled from 1991 and 1992 ($n = 174$ evaluation days) and subjected to statistical analyses. Correlation coefficients among the 15 environmental variables ranged from

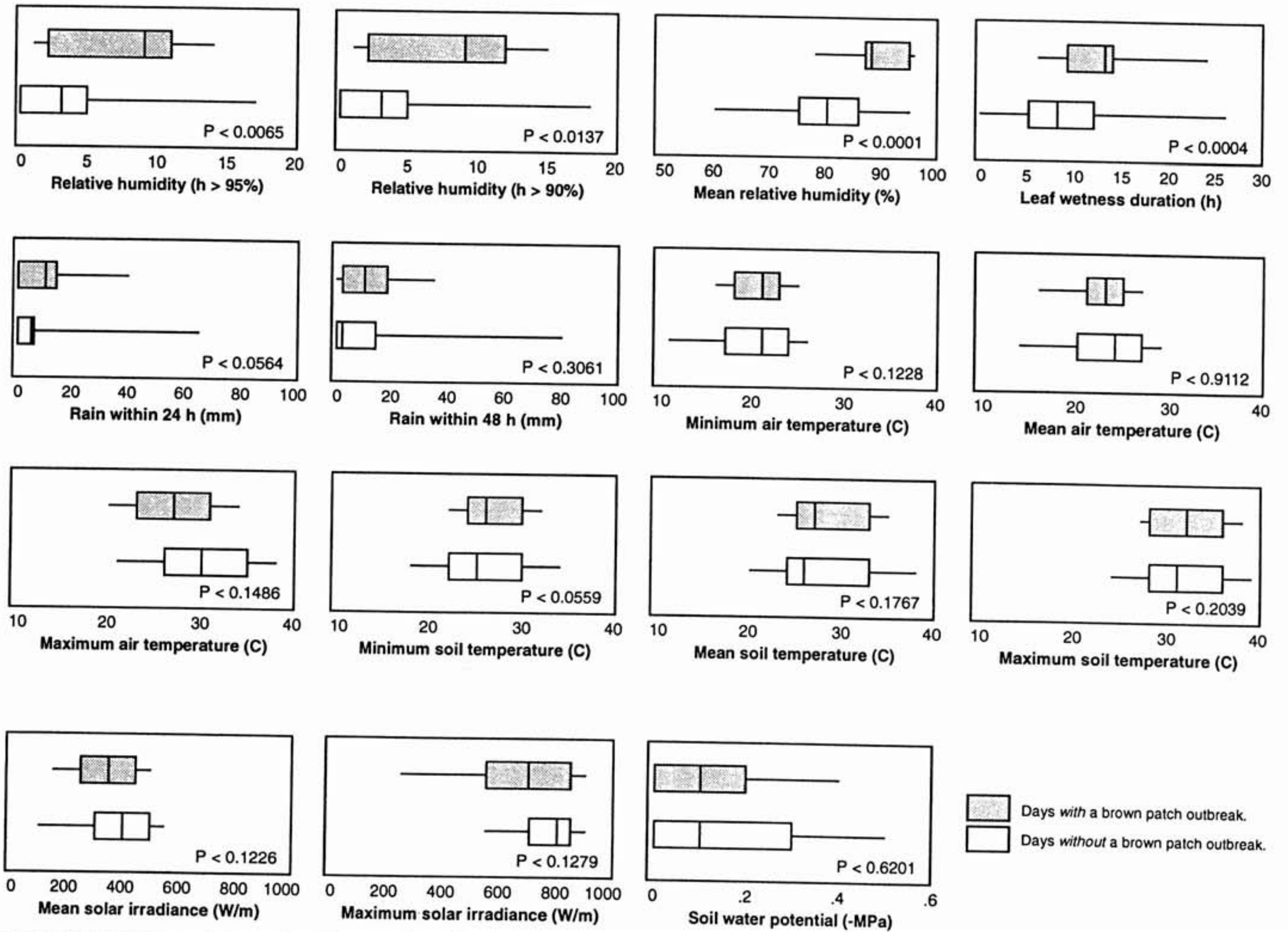

Fig. 1. The distributions of observed environmental variables during days when brown patch outbreaks occurred versus days when brown patch outbreaks did not occur. Data represent 25% (left side of box), 50% (center line of box), and 75% (right side of box) of the observations recorded in 1991 and 1992 ($n = 174$). Horizontal lines extending away from the boxes for days with and without outbreaks indicate extreme measurements observed. The data distributions were significantly different at the 5% level, where $P < 0.0033$ ($0.05/15 = 0.0033$).

0.001 to 0.888; coefficient values ≥ 0.665 were statistically significant ($P = 0.05$). Correlations among environmental variables and disease outbreaks were not significant, however, with the highest correlations associated with hours of relative humidity >95% ($r = 0.420$) and mean relative humidity ($r = 0.419$).

Because the correlation analyses did not provide evidence of strong associations between the environmental variables and brown patch outbreaks, the data distributions of the 15 variables and brown patch were compared (21) (Fig. 1). Among most of the 15 variables evaluated, there was no distinct separation between days with or without brown patch outbreaks. Best separation was noted with mean relative humidity and hours of leaf wetness duration. The degree of overlap among the distributions of these variables was significant at $P < 0.0033$.

The point values used to calculate E were those that resulted in the highest chi-square value, thereby indicating the strongest association with *R. solani* infection events. The combination of six variables with the highest chi-square values ($\chi^2 = 53.27$; $P < 0.001$) were hours of relative humidity >95%, mean relative humidity, hours of leaf wetness duration and precipitation during the 48 h prior to 0600 h, minimum air temperature, and minimum soil temperature (Table 1).

The six variables were the basis of the initial model (E_6). The second favorability index (E_2) was constructed by multiple regression analysis. Stepwise multiple regression analysis was used to identify the most significant of the 15 environmental conditions that predicted observed values of E (3,20). Several environmental variables were identified as potential model parameters; however, minimum air temperature and mean relative humidity data provided the simplest and best-fit model (Fig. 2A and B). The second-order regression model calculated a value of E_2 based on minimum air temperature and relative humidity: $E_2 = -21.5 + 0.15RH + 1.4T - 0.033T^2$, in which E_2 was the environmental favorability index, T was the minimum daily air temperature (degrees Celsius), and RH was the mean daily relative humidity (percent) for a 24-h period beginning and ending at 0600 h daily. All estimated coefficients were significant at $P = 0.0001$, and the adjusted coefficient of determination for the model was 0.70. Examination of the residuals (i.e., the difference between the original data and the data predicted by the regression equation) supported the assumption that errors were independent and normally distributed, had a mean of zero, and had a constant variance.

We arbitrarily set values of $E \geq 6$ to indicate that the environment was highly favorable for a disease outbreak. $E = 5$ was considered equivalent to moderate disease risk, and $E \leq 4$ indicated that conditions were nonconducive. Thus, predicted values of E in Figure 2B indicated that a minimum air temperature of ≥16°C and a mean relative humidity ≥95% were required to produce conditions highly favorable for a disease outbreak.

The index (E) derived from the regression model (E_2) and the additive six-variable model (E_6) were compared to dates when foliar mycelium was observed, and both models predicted 6 of 6 brown patch outbreaks during 1991 and 9 of 12 disease outbreaks during 1992. Therefore, E developed from the regression model provided comparable disease warnings but utilized fewer environmental inputs.

Environmental favorability index assessment, 1991. An early brown patch outbreak occurred on 3 June prior to the initiation of data collection. Chlorothalonil was applied (6.3 kg a.i. ha^{-1}) to slow the disease, and, therefore, may have prevented outbreaks on 17 and 18 June when E values of ≥6 were observed (Fig. 3). These early warnings, however, were disregarded because of the application of chlorothalonil. During July and August, all six brown patch outbreaks coincided with $E \geq 6$ (Fig. 3). A major disease outbreak (i.e., high amounts of foliar mycelium) occurred on 2 July, when $E = 6$ (Fig. 3). The 24-h period prior to 2 July was associated with prolonged periods of mean relative humidity of 97% and a minimum night air temperature of ≥23°C. Environmental conditions favorable for brown patch persisted through 10 July. Two subsequent outbreaks were observed on 7 and 10 July and were associated with high disease outbreak favorability ($E \geq 6$). From 11 to 26 July, prolonged periods of high humidity were not observed. Rainfall events from 22 through 25 July preceded high humidity (95%) conditions, and $E \geq 6$ was observed on 26 July (Fig. 3). A major disease outbreak was observed 48 h afterward on 28 July. Favorable environmental conditions for a disease outbreak were not observed again until 9 August ($E \geq 6$), and trace amounts of foliar mycelium were observed on 11 August (Fig. 3). A high-risk warning on 14 and 15 August preceded a minor outbreak on 18 August. A brown patch warning was given on 27 August ($E \geq 6$), but no foliar mycelium was observed within 72 h, and this forecast was considered false. In summary, all six brown patch outbreaks coincided with or were preceded by an E value of ≥6. Two predicted outbreaks were ignored because chlorothalonil had been applied within the previous 14 days. On one date (27 August), however, there was a brown patch warning, but no foliar *R. solani* mycelium or subsequent increase in blighting were observed.

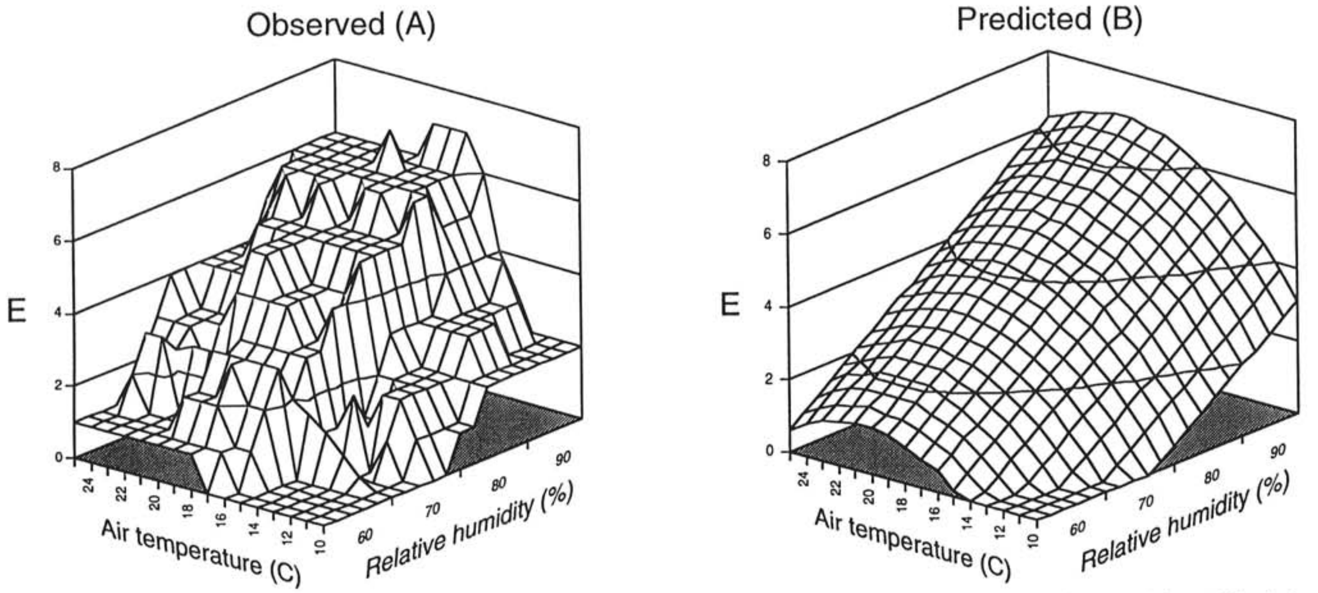

Fig. 2. Relationship of minimum daily air temperature (degrees Celsius) and mean daily relative humidity (percent) to the environmental favorability index (E) for brown patch outbreaks. **A,** Six-variable index (E_6) calculated from field observations. **B,** Two-variable index (E_2) predicted from the regression equation.

Environmental favorability index assessment, 1992. Brown patch was first predicted on 5 and 6 June when E was ≥6 (Fig. 3). At those times, the relative humidity was ≥94%, and minimum air temperature was 17°C. Because no foliar mycelium of *R. solani* was observed within 72 h, these warnings were considered false. The minimum air temperature, however, was ≤13°C on four consecutive days prior to 5 June, and the E value was ≤2 on 1 to 4 June.

From 10 to 14 June, minimum air temperature again decreased to ≤16°C, and the E value ranged from 1 to 5 on those days (Fig. 3). High relative humidity (90%) was observed on 26 June; however, minimum air temperature was 15°C on that date. An outbreak was not observed on 26 June, but the E value for that date predicted a moderate disease risk. Additionally, minimum air temperatures ranged from 9 to 18°C on six consecutive days prior to 26 June.

The major outbreak events observed on 1 and 2 July coincided with an $E \geq 6$ (Fig. 3). A minor brown patch outbreak on 8 July was preceded by an $E \geq 6$ on 4 July. Trace amounts of *R. solani* mycelium were observed on 14 and 15 July. The relative humidity conditions necessary for foliar mycelium development did not occur at that time, and therefore, the E value did not predict those minor outbreaks. Trace amounts of foliar mycelium again were observed on 22 July, and this minor outbreak also was not predicted. Brown patch outbreaks on 24, 28, and 29 July coincided with or were preceded by high-risk warnings ($E \geq 6$) on 24 and 25 July. Extended periods of high relative humidity ≥93% and minimum air temperatures of ≥20°C during late July were most conducive to brown patch.

On 12 and 14 August, high relative humidity (≥95%) and minimum air temperature (≥19°C) conditions corresponded to high-risk forecasts (Fig. 3). The high disease risk warnings on 12 and 14 August, however, were considered false because foliar mycelium of *R. solani* did not appear within 72 h. An $E = 6$ also was recorded from 16 to 19 August, and foliar mycelium was observed on 18 and 19 August. A minor infection event on 26 August was preceded by a high-risk forecast 1 day earlier.

In summary, 9 of 12 brown patch outbreaks were associated with an $E \geq 6$, and 3 of 12 outbreaks were considered minor and occurred without an E-based warning. All major brown patch infection events were predicted during 1992. Four of the high-risk warnings issued during 1992 were false; however, two of these false warnings occurred during early June and were preceded by low temperatures (≤15°C) 24 h prior to the forecast.

Disease warning model validation, 1993. The potential for $E \geq 6$ to predict disease outbreaks was validated on perennial ryegrass and colonial bentgrass in 1993. From June through August 1993, a combined total of 22 outbreaks was observed on both test sites (Fig. 4). Both models (E_2 and E_6) provided an E value of ≥6 for 19 of the 22 brown patch outbreaks during 1993, however, the E_2 model was used to validate disease warnings during 1993.

The E_2 model provided warnings for the most severe brown patch outbreaks in perennial ryegrass (3 and 4 July) and colonial bentgrass (9 June and 3 and 4 July) (Fig. 4). Subsequent brown patch outbreaks on 14 and 19 July and on 2 through 17 August also were predicted. Environmental conditions did not warrant a warning from 8 to 13 July, yet trace amounts of active *R. solani* mycelium were observed on 8 and 11 July. At both 1993 test sites, an $E_2 \geq 6$ was associated with all major ($n = 4$) disease outbreaks.

Fungicide-treated perennial ryegrass plots were disease free until 16 July; however, unacceptable blight (≥5%) levels were observed with both fungicide treatments from 21 July through 24 August (data not shown). When comparing all treatments over time on perennial ryegrass, significantly greater AUDPC values were observed in non–fungicide-treated plots (Table 2). The AUDPC values showed that blight levels were similar between spray treatments; however, use of the E_2 model resulted in two less fungicide applications.

For colonial bentgrass, mycelium of *R. solani* was first observed on the site on 9 June, but only in non–fungicide-treated check plots. Unacceptable injury was first observed on 21 June in non–fungicide-treated plots, whereas all fungicide-treated plots had acceptable injury (≤1% blight) for high-value turf throughout the evaluation period (data not shown). When comparing all treatments on colonial bentgrass over time, significantly greater AUDPC values were observed in non–fungicide-treated plots, whereas no differences in blight severity were observed among all fungicide-treated plots (Table 2). Use of the disease warning model (E_2 model) resulted in two less fungicide applications when compared to the 14-day calendar spray schedule.

DISCUSSION

Analyses of environmental conditions monitored during 1991 and 1992 revealed that a combination of 6 of 15 environmental

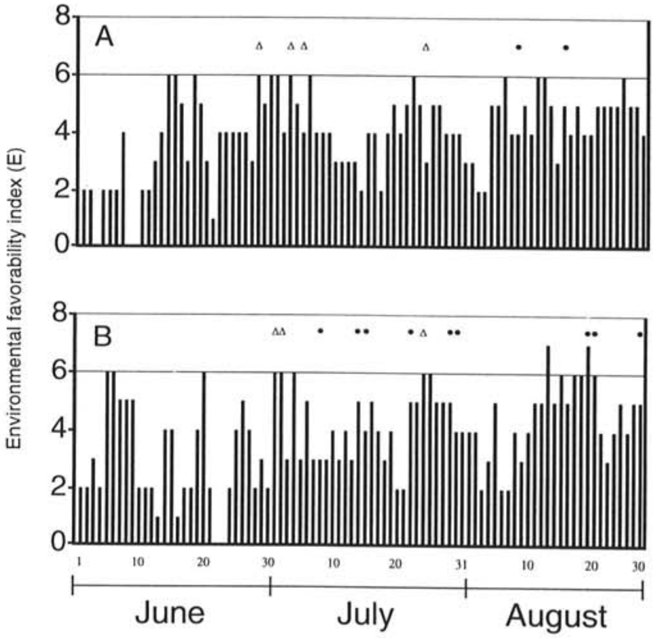

Fig. 3. Predicted values of the two-variable environmental favorability index (E_2) plotted with observed major (△) and minor (●) brown patch outbreaks in perennial ryegrass 'Caravelle' grown near Silver Spring, MD, during **A,** 1991 and **B,** 1992. Brown patch was predicted to occur if the environmental favorability index (E) was ≥6.

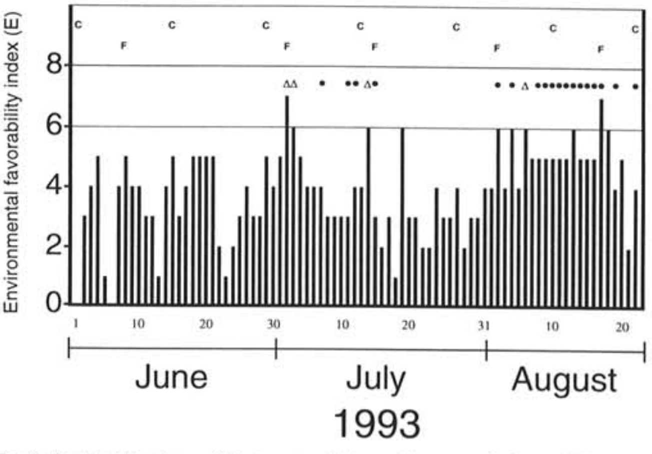

Fig. 4. Predicted values of the two-variable environmental favorability index (E_2) plotted with observed major (△) and minor (●) brown patch outbreaks in 1993. Brown patch was predicted to occur if the environmental favorability index (E) was ≥6; this index was based on minimum daily air temperature >16°C and mean daily relative humidity >95%. Outbreaks observed on 9 and 20 June and 19 July occurred only on colonial bentgrass 'Bardot,' and the 4 August outbreaks occurred only in perennial ryegrass 'Caravelle'; all other brown patch outbreaks occurred on both species of grass. Dates on which fungicides were applied at 14-day intervals are denoted by C, and those applied according to the brown patch warning model are denoted by F.

variables most influenced the occurrence of *R. solani* infection events in perennial ryegrass. Multiple regression analyses of the 15 variables, however, showed that E as derived from the E_2 model was most related to minimum daily air temperature and mean relative humidity, with 70% of the variability explained by the model. The six- (E_6) and two-variable (E_2) models were compared, and both predicted 85% (34 of 40) of all infection events from 1991 to 1993. The six missed predictions were associated with minor infection events. Five of the six missed predictions, however, were preceded by major infection events, and all major infection events were successfully predicted by both models. Hence, the two-variable model (E_2) provided the best combination of accuracy and simplicity. A separate six-variable model developed by Schumann et al. (22) employed disease-risk thresholds based on brown patch severity, not on the appearance of foliar mycelium. Because most of their (22) severity variables were similar to E_6, it is likely that both models would provide similar warnings. Hence, both warning models could be used effectively in temperate as well as transition-zone regions of turfgrass adaptation.

Leaf wetness duration and precipitation were important elements in brown patch outbreaks. Leaf wetness duration (minimum ≥6 h or ≥8 to 10 h for severe disease outbreaks) was an important factor leading to the development of foliar mycelium. Precipitation events provided longer periods of high humidity and leaf wetness conditions (at least ≥6 h), and severe disease outbreaks generally coincided with ≥12 mm of rainfall. The influence of soil moisture on brown patch occurrence was inconclusive, because periods of high humidity, precipitation events, and normal irrigation practices often resulted in soil moisture levels near field capacity.

On seven occasions during 1991 and 1992, but on none during 1993, $E \geq 6$ was observed with no visible evidence of foliar *R. solani* mycelium within 72 h. Two of these warnings in 1991 were disregarded because chlorothalonil was applied within the previous 14 days, and two false forecasts in 1992 possibly may be discounted because of low (≤13°C) air temperatures in the days immediately preceding the warning period. The model developed by Schumann et al. (22), however, initially had greater false forecasts (average >6 missed predictions per year per site), which was attributed to a decrease in air temperature below 15°C immediately after the warning. Model accuracy was improved by canceling a disease warning if air temperature fell below 15°C within 24 h of a warning (22).

Although two false forecasts during early June 1992 were accompanied by an $E = 6$ (minimum air temperature ≥ 16°C), no disease may have developed because it was early summer and there may have been insufficient inoculum. Further research is needed to fully characterize the influence of soil temperature-based degree days on the development of *R. solani* foliar mycelium.

The E field validation in 1993 by the E_2 model in both perennial ryegrass and colonial bentgrass employed seven calendar-based fungicide sprays compared to five model-based applications. Calendar- and model-based fungicide applications provided equivalent levels of brown patch control. Hence, there was a 29% reduction in fungicide application frequency at both sites when the E_2 model warning-based spray schedule was used. The unacceptable blighting in fungicide-treated perennial ryegrass during late July and August was not due to a failure of the index. Instead, it was attributed to the inability of chlorothalonil to provide effective control for 14 days during a prolonged period when the environment was extremely favorable for brown patch development. Commercially acceptable brown patch control may be achieved if chlorothalonil is applied at 10-day intervals during prolonged periods of highly favorable conditions for brown patch development.

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