Relationship Between Strawberry Gray Mold Incidence, Environmental Variables, and Fungicide Applications During Different Periods of the Fruiting Season

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ABSTRACT

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Incidence of gray mold (caused by *Botrytis cinerea*) on harvested strawberry fruit was evaluated with respect to environmental influences and fungicide regimes over four consecutive years. Disease incidence at harvest was correlated with the average daily values of 13 environmental variables during four discrete periods (or combinations thereof); these periods occurred from bloom until harvest and were defined by the timing of fungicide applications in designated treatments. Correlation coefficients in sprayed plots were determined with a variable weighting factor that most accurately accounted for fungicide influence on individual environmental variable × spray period combinations. Two bloom sprays provided the same annual level of control as four to five sprays from bloom through harvest, whereas applications made only after bloom provided relatively little control. Similarly, disease incidence was correlated strongly with environmental variables measured during the bloom period, particularly the durations of relative humidity >80% and >90% and surface wetness at 15–25 C. Environmental factors after bloom were correlated much more weakly with disease incidence, with the exception of vapor pressure deficit (negative correlation) and rainfall during periods defined by the first postbloom spray. Optimum fungicide weighting factors (0.0 = full fungicide effect, complete negation of environmental influence; 1.0 = no fungicide effect, full influence of environmental variable) were 0.5–0.8 for those variables with the highest correlation coefficients during bloom but were 1.0 for the most influential variables during periods after bloom.

Additional keywords: dicarboximide, vinclozolin.

Gray mold, caused by *Botrytis cinerea* Pers.:Fr., is an important fruit rot of strawberry (*Fragaria* × *ananassa* Duchesne) wherever the crop is grown (14). In New York State, as in many other production regions, it is the disease against which most fungicide sprays are targeted.

Despite the importance of this disease, there have been relatively few attempts to use meteorological data to forecast the occurrence of gray mold epidemics in the field (10) or to relate the need for fungicide applications to host phenology and susceptibility. After analyzing data from a 6-yr study in an unsprayed strawberry plantation in Scotland, Jarvis (9) found high correlations between disease incidence at harvest and both cumulative rainfall and the number of hours with relative humidity (RH) greater than 80% during discrete time intervals up to 30 days before harvest. However, he suggested that these findings might prove more useful in forecasting the need for rapid harvesting procedures than for timing protective fungicide applications during the fruiting season. Gilles (6) in Belgium and Jordan (12) in England reported variable levels of control when fungicides were applied at different stages of crop development, but they provided little or no meteorological data with which to interpret their results. More recently, Bulger et al (4) used controlled environment studies to quantify the relationship between disease incidence on ripe fruit and the tem-

perature and duration of blossom wetness during the first 30 h after flowers were inoculated with *B. cinerea;* however, their results have not been related to control programs or disease development under field conditions.

Accordingly, the objective of this study was to improve the efficiency of gray mold control programs by relating disease incidence at harvest with environmental variables, fungicide application, and the interactions of these factors during discrete periods of strawberry development.

MATERIALS AND METHODS

Field plot treatments and disease assessment. Experiments were conducted from 1986 to 1989 in a single perennial strawberry planting at the New York State Agricultural Experiment Station near Geneva. Plants of the strawberry cultivar Catskill were obtained from a commercial nursery and planted in May 1985 in rows 1.2 m apart; a flat-bed, matted-row production system was used. The field was treated with the herbicide napropamide (Devrinol 50WP, ICI Americas, Wilmington, DE) shortly after planting and again in November, but no other pesticides were applied during the remainder of the year. Plants were fertilized with 72 kg each of N, P, and K per hectare in both June and September, deblossomed during the summer, and mulched with straw in early December. In subsequent years, mulch was removed from plants in the spring; the planting was fertilized with 72 kg each of N, P, and K per hectare both prior to bloom and again in midsummer. Standard herbicide and renovation practices were followed, and straw mulch was reapplied in December. No insecticides or acaricides were applied.

Fungicide treatments were initiated in the spring of 1986. All treatments employed a single rate of vinclozolin (Ronilan 50WP, BASF Corp., Research Triangle Park, NC), either 0.84 kg a.i./ha in 1986–1988 or 1.12 kg a.i./ha in 1989, applied in a volume of water equivalent to 936 L/ha. In 1986, sprays were applied with a hand-pumped knapsack sprayer with a flat spray nozzle (D. B. Smith Export Co., Utica, NY), operating at a pressure of 207 kPa. In all subsequent years, sprays were applied with a tractor-mounted boom sprayer operating at a pressure of 586 kPa; there were three TeeJet 8004 flat spray nozzles (Spraying Systems Co., Wheaton, IL) per row. Each year, sprays were initiated at approximately 10% bloom and continued at 6- to 13-day intervals (mean 9.7 days) to provide up to four application dates prior to the start of harvest; variations from an intended 10-day spray interval resulted from weather aberrations or from the need to adjust for periods of particularly rapid or slow crop maturation. An additional spray was applied after the first of two harvests in all years except 1989. Treatment variables consisted of the number and timing of fungicide applications; there were five, eight, eight, and four treatments in 1986–1989, respectively. Specific treatments, spray dates, and harvest dates are listed in Tables 1 and 2.

Individual plots were three rows wide and 8.0 m long (5.5 m in 1989) with a 1-m border between plots in a row, arranged in a randomized complete block design with four replicates. All fruit were harvested from the center 3 m of the center row of each plot (2.5 m in 1989), and symptomatic and asymptomatic berries were separated on the basis of characteristic gray mold lesions, which usually were sporulating (14). Harvested fruit were refrigerated immediately and then counted the following day to determine disease incidence. Data were analyzed with standard analysis of variance for randomized block design (17) and the Waller-Duncan k ratio least significant difference variable for mean separation. Prior to analysis, all data were subjected to arcsine transformation, which was chosen after several different variance-stabilizing transformations (none, arcsine, square root, and natural logarithm) were analyzed.

Spray period × environment × fungicide analysis. For purposes of analysis, the environmental period associated with each fungicide spray was defined as beginning 2 days before the application

TABLE 1. Time periods and fungicide application schedules used to define developmental and environmental periods

Year	Spray period[r]	Development stage[s]		Treatment[t]								Spray date			Start date[w]			Stop date[w]		
		Harvest 1	Harvest 2	1	2	3	4	5	6	7	8	Date	DOY[u]	DBH[v]	Date	DOY	DBH	Date	DOY	DBH
1986	1	EB		+	−	−	−	−	...	...	...	16 May	136	41/−[x]	14 May	134	43/−	24 May	144	33/−
	2	LB	EB	+	+	−	−	−	...	...	...	27 May	147	30/36	25 May	145	32/38	6 June	257	20/26
	3	GF	LB	+	+	+	−	−	...	...	...	9 June	160	17/23	7 June	158	19/25	16 June	167	10/16
	4.1[y]	PH		+	+	+	+	−	...	...	...	19 June	170	7/−	17 June	168	9/−	26 June	177	0/−
	4.2		GF	+	+	+	+	−	...	...	...	19 June	170	−/13	17 June	168	−/24	25 June	177	−/8
	5		PH	+	+	+	+	−	...	...	...	28 June	179	−/4	25 June	177	−/7	2 July	183	−/0
1987	1	EB		+	+	+	+	−	−	−	−	19 May	139	28/−	17 May	137	30/−	25 May	145	22/−
	2	LB	EB	+	−	+	+	+	−	−	−	28 May	148	19/27	26 May	146	21/29	2 June	153	14/22
	3	GF	LB	+	−	−	+	+	+	−	−	5 June	156	11/19	3 June	154	13/21	9 June	160	7/15
	4	PH	GF	+	−	−	−	+	+	+	−	12 June	163	4/12	10 June	161	6/14	16 June	167	0/8
	5		PH	+	−	−	−	+	+	+	−	19 June	170	−/5	17 June	168	−/7	24 June	175	−/0
1988	1	EB		+	+	+	+	−	−	−	−	17 May	138	41/−	15 May	136	43/−	24 May	145	34/−
	2	LB	EB	+	−	+	+	+	−	−	−	27 May	148	31/34	25 May	146	33/36	3 June	155	24/27
	3	GF	LB	+	−	−	+	+	+	−	−	6 June	158	21/24	4 June	156	23/26	13 June	165	14/17
	4.1	PH		+	−	−	−	+	+	+	−	16 June	168	11/−	14 June	166	13/−	27 June	179	0/−
	4.2		GF	+	−	−	−	+	+	+	−	16 June	168	−/14	14 June	166	−/16	24 June	179	−/6
	5		PH	+	−	−	−	+	+	+	−	27 June	179	−/3	25 June	177	−/5	30 June	182	−/0
1989[z]	1	EB	EB	+	+	−	−	...	...	...	...	25 May	145	29/33	23 May	143	31/35	2 June	153	21/25
	2	LB	LB	+	+	+	−	...	...	...	...	5 June	156	18/22	3 June	154	20/24	13 June	164	10/14
	3	GF	GF	+	−	−	−	...	...	...	...	16 June	167	7/11	14 June	165	9/13	19 June	170	4/8
	4.1	PH		+	−	−	−	...	...	...	...	22 June	173	1/−	20 June	171	3/−	23 June	174	0/−
	4.2		PH	+	−	−	−	...	...	...	...	22 June	173	−/5	20 June	171	−/7	27 June	178	−/0

[r] Period corresponding to the effective time of fungicidal activity for each application.
[s] Development stage prior to the harvest: EB = early bloom; LB = late bloom; GF = green fruit; PH = preharvest.
[t] Fungicide treatments applied at each spray date. + = Fungicide applied; − = no fungicide applied.
[u] Day of year; January 1 is day 1.
[v] Days before harvest. Harvest dates were 1986, 26 June (177), 2 July (183); 1987, 16 June (167), 24 June (175); 1988, 27 June (179), 30 June (182); 1989, 23 June (174), 27 June (178).
[w] Start and stop dates represent the beginning and ending date for each period under consideration.
[x] Values to the left of the slash are days before the first harvest; values to the right are for the second harvest.
[y] End dates of the fourth spray period differed slightly for each harvest in 1986, 1988, and 1989.
[z] Harvests in 1989 were only 4 days apart, and no fungicide was applied after the first harvest. Therefore, all but the last fungicide periods (and developmental stages) were considered identical for both harvests.

and continuing until 2 days prior to the next fungicide application (or for the last spray before harvest, until 7 days after the application or until berries were harvested, whichever came first). Assumption of a 2-day period of fungicide influence prior to application was based on the demonstrated curative activity of vinclozolin against infection of lowbush blueberry blossoms by *B. cinerea* (13) and of sour cherry blossoms by *Monilinia fructicola* (G. Wint.) Honey (18). The defined environmental periods largely corresponded to phenological stages of crop development and were designated as the early bloom (EB), late bloom (LB), green fruit (GF), and preharvest (PH) periods.

Weather data were recorded at the Climatological Reference Station (no. 3031840) at Geneva, New York, located about 1.5 km from the strawberry plots. Surface wetness duration was measured at a height of 1.5 m with a DeWitt recorder (Valley Stream Farm, Orono, Ontario, Canada) located in an apple orchard 1 km from the plots. The following weather variables were summarized for each period and expressed as daily averages: temperature, expressed as growing degree days with base temperatures of 0, 10, and 15 C (GDD_0, GDD_{10}, and GDD_{15}, respectively) (GDD per day); cumulative hours when temperature was 15–25 C (hours per day); hours when temperature was 15–25 C during periods of surface wetness (hours per day); accumulated absolute deviation of the mean daily temperature from the range of 15–25 C (°C per day); total hours of surface wetness (hours per day); total accumulated rainfall (centimeters per day); total hours during which the RH was >80% and >90% (hours per day); accumulated pan evaporation (millimeters per day); accumulated solar radiation (megajoules per square meter per day); and total vapor pressure deficit (pascals per day). A summary of these data for each fungicide period is provided in Table 3.

A fungicide weighting factor was derived for each treatment × spray period × environmental variable combination. Initially, a value of 1.0 was assigned when no fungicide was applied, and 0.0 was assigned when a fungicide was applied. We rationalized that when a fungicide was applied to a treatment plot, the influence of the environmental variable would be nil for that spray period. Thus, when a fungicide was applied and its associated weighting factor (0.0) was multiplied by the environmental variable, the result was a value of 0.0. Conversely, when no fungicide was applied, a weighting factor of 1.0 was used to multiply the environmental variable, allowing the full influence of the variable to remain. The products of environmental variables and fungicide weighting factors for each spray period were correlated with the percentage of diseased fruit or with an appropriate transformation (none, square root, natural logarithm, and inverse) of this variate. Subsequently, we recognized that fungicide influence might be quantified more accurately in less absolute terms, so correlation analyses for each environmental variable were conducted with weighting factors of 0.0–1.0 at 0.1-unit intervals. In this case, each ascending value conferred incrementally less influence of the fungicide application, culminating in a value of 1.0 to indicate no fungicide influence on the environmental variable. The final selected (optimum) weighting factor for each environmental variable × spray period combination was that which yielded the highest correlation coefficient with transformed disease incidences.

TABLE 2. Effect of different fungicide regimes on the incidence of strawberry gray mold over four consecutive seasons

Year	Fungicide application number[w]					Gray mold incidence (%)[x]			
						Harvest			Control[z]
Treatment[v]	1(EB/–)	2(LB/EB)	3(GF/LB)	4(PH/GF)	5(–/PH)	1	2	Total[y]	(%)
1986	5/16	5/27	6/9	6/19	6/28	6/26	7/2		
1	+	+	+	+	+	16.2 c	42.0 ab	27.5 c	48
2	–	+	+	+	+	22.7 b	36.5 b	28.9 c	46
3	–	–	+	+	+	34.3 ab	45.2 a	38.3 c	28
4	–	–	–	+	+	38.3 a	36.3 b	38.6 b	28
5	–	–	–	–	–	44.5 a	56.8 a	53.3 a	...
1987	5/19	5/28	6/5	6/12	6/19	6/16	6/24		
1	+	+	+	+	+	9.2 d	4.5 b	6.5 d	76
2	+	–	–	–	–	19.3 c	9.3 a	13.4 cd	51
3	+	+	–	–	–	9.5 d	7.0 ab	7.9 d	71
4	+	+	+	–	–	8.3 d	8.0 ab	8.0 d	70
5	–	+	+	+	+	17.7 c	6.0 ab	11.2 cd	59
6	–	–	+	+	+	33.2 b	4.9 ab	17.1 bc	37
7	–	–	–	+	+	39.2 ab	7.8 ab	22.7 ab	16
8	–	–	–	–	–	45.6 a	13.6 a	27.1 a	...
1988	5/17	5/27	6/6	6/16	6/27	6/27	6/30		
1	+	+	+	+	+	0.3 ns	0.2 ns	0.3 ns	...
2	+	–	–	–	–	0.4	0.2	0.3	...
3	+	+	–	–	–	0.0	0.0	0.0	...
4	+	+	+	–	–	0.0	0.0	0.0	...
5	–	+	+	+	+	0.2	0.1	0.1	...
6	–	–	+	+	+	0.1	0.2	0.1	...
7	–	–	–	+	+	0.1	0.0	0.1	...
8	–	–	–	–	–	0.3	0.2	0.2	...
1989	5/25	6/5	6/16	6/22		6/23	6/27		
1	+	+	+	+	–	5.3 c	2.1 b	3.1 c	85
2	+	+	–	–	–	2.8 c	3.1 b	2.9 c	86
3	–	+	–	–	–	15.7 b	12.1 a	13.6 b	36
4	–	–	–	–	–	31.8 a	14.5 a	21.1 a	...

[v] Treatment designations correspond to those in Table 1.

[w] All fungicide applictions consisted of vinclozolin at either 0.84 kg (1986–1988) or 1.12 kg (1989) per hectare. Application numbers correspond to the fungicide periods listed in Table 1; the first application was at early bloom, and the fifth application followed completion of the first harvest. EB = early bloom; LB = late bloom; GF = green fruit; PH = preharvest.

[x] Percentage of berries with symptoms of gray mold at harvest. Values given are mean incidences for all berries in either 6.5-m (1989) or 8.0-m (1986–1988) row per plot, four replicate plots per treatment. For each individual year, means within a column not followed by a common letter are significantly different ($P = 0.05$) according to the Waller-Duncan exact Bayesian k ratio least significant difference rule (analysis performed on arcsine-transformed values). ns = no significant difference among means.

[y] Cumulative incidence for all berries from both harvest periods.

[z] Cumulative control (%) = (incidence unsprayed − incidence treatment)/incidence unsprayed × 100.

Data from two harvests were analyzed separately each year by correlating disease incidence with the parameters for the four spray periods prior to each harvest. For example, disease measurements from the first harvest in 1986 (day-of-year 177) were correlated with parameters derived from periods beginning on days 134, 145, 158, and 168, whereas data from the second harvest (day-of-year 183) were correlated with parameters derived from periods beginning on days 145, 158, 168, and 177 (Table 1). Stepwise regression (Minitab, release 7.2) was performed to determine the best set of environmental variables to predict disease incidence at harvest; in all cases, each value for the environmental variables used in analyses was multiplied by its optimal fungicide weighting factor prior to regression. Various transformations of the dependent variable (none, arcsine, square root, and natural logarithm) were evaluated to maximize predictability of the regression equations. Data were also analyzed separately for the unsprayed treatments to determine the best set of environmental variables to predict disease levels at harvest independent of any

TABLE 3. Average daily accumulated values of environmental variables associated with each fungicide application period for 1986–1989

Year	Spray period[x]	Days in period	Wetness (h)	Rain (cm)	RH > 80 (h)	RH > 90 (h)	Growing degree days Base 0 C	Base 10 C	Base 15 C	Temp. dev.[y] (C)	Temp. 15–25 C (h)	Temp. 15–25 C + wet (h)	Pan evaporation (mm)	VPD[z] (pascals)	Solar radiation (MJ/m^2)
1986	1	11	9.5	0.50	15.7	11.2	17.0	7.0	2.0	1.9	12.1	3.3	3.7	373	12.9
	2	13	6.9	0.17	9.2	7.2	19.3	9.3	4.3	1.9	12.2	2.5	6.0	706	20.7
	3	10	9.1	0.91	11.5	7.8	19.6	9.6	4.6	0.7	17.0	6.9	5.7	467	17.7
	4.1	10	4.6	0.27	5.7	3.2	17.2	7.2	2.2	1.4	14.8	3.3	5.8	640	22.3
	4.2	9	4.8	0.30	6.3	3.6	16.9	6.9	2.0	1.2	13.9	3.3	6.5	613	22.1
	5	7	7.7	0.61	9.9	7.1	18.9	8.9	3.9	1.1	16.3	3.9	5.4	693	20.2
1987	1	9	8.3	0.09	16.8	14.0	16.4	6.4	1.4	3.4	8.2	2.3	4.4	387	14.2
	2	8	6.5	0.28	11.6	9.1	24.9	14.9	9.9	1.4	14.4	5.9	5.7	746	17.1
	3	7	8.7	0.46	12.7	9.1	17.1	7.1	2.1	1.6	14.3	5.1	3.5	360	13.2
	4	7	1.6	0.20	6.7	5.0	21.4	11.4	6.4	0.9	14.9	1.3	7.2	693	22.5
	5	8	7.5	0.58	13.4	11.0	22.5	12.5	7.5	1.0	16.1	6.8	5.6	573	19.4
1988	1	10	14.7	0.40	15.3	13.5	15.1	5.1	1.0	2.5	7.9	2.2	3.6	400	13.3
	2	10	6.4	0.10	2.4	0.4	17.6	7.6	2.6	1.9	9.0	1.1	6.3	826	21.5
	3	10	4.4	0.02	1.6	0.1	17.2	7.2	2.2	1.9	10.9	0.4	7.9	973	22.6
	4.1	14	5.6	0.09	2.4	0.6	21.0	11.0	6.0	1.2	12.0	2.7	8.3	1,093	23.0
	4.2	11	5.9	0.12	2.1	0.7	21.6	11.6	6.6	1.3	11.7	3.2	8.6	1,173	24.0
	5	6	8.3	0.1	4.8	1.2	16.2	6.2	1.2	2.1	9.7	0.7	6.1	680	17.3
1989	1	11	7.1	0.42	10.6	8.6	18.4	8.4	3.4	1.2	15.1	4.0	4.2	507	17.8
	2	11	5.8	0.46	12.4	9.8	18.2	8.2	3.2	1.0	16.3	2.6	4.7	573	19.5
	3	6	10.3	0.42	13.0	11.2	18.3	8.3	3.3	0.3	16.2	4.8	3.3	426	15.0
	4.1	4	10.0	0.45	17.0	8.8	22.0	12.0	7.0	0.2	20.2	10.0	3.5	426	15.0
	4.2	8	8.8	0.46	15.2	12.4	23.0	13.0	8.0	0.5	17.0	8.6	4.9	573	18.1

[x] Period corresponding to the effective time of fungicidal activity for each application.
[y] Accumulated absolute deviation of the mean daily temperature from the range of 15–25 C.
[z] Vapor pressure deficit.

TABLE 4. Highest correlation of square root of percent diseased fruit with average daily environmental variable values weighted for optimal effect of fungicide during that spray period

Variable	Fungicide spray period[w,x,y] EB	LB	GF	PH	EB+LB	LB+GF	GF+PH	EB+LB+GF+PH
Hours wet	0.372**(0.3)	0.557**(0.9)	0.277**(0.9)	−0.279**(1.0)	0.546**(0.8)	0.645**(0.9)	0.030 (0.7)	0.331**(0.6)
Hours RH > 80%	0.698**(0.6)	0.727**(0.7)	0.611**(1.0)	0.290**(1.0)	0.776**(0.6)	0.702**(0.7)	0.508**(1.0)	0.673**(0.6)
Hours RH > 90%	0.664**(0.5)	0.735**(0.6)	0.530**(1.0)	0.351**(1.0)	0.775**(0.5)	0.653**(0.6)	0.487**(1.0)	0.661**(0.5)
Growing degree days								
Base 0 C	0.400**(0.4)	0.539**(0.9)	−0.344**(1.0)	0.056 (1.0)	0.505**(0.6)	0.300**(1.0)	−0.208**(1.0)	0.376**(0.8)
Base 10 C	0.390**(0.3)	0.545**(0.8)	−0.344**(1.0)	0.056 (1.0)	0.600**(0.7)	0.337**(0.9)	−0.208**(1.0)	0.398**(0.8)
Base 15 C	0.332**(0.2)	0.553**(0.6)	−0.344**(1.0)	0.056 (1.0)	0.662**(0.6)	0.356**(0.7)	−0.208**(1.0)	0.371**(0.6)
Absolute temperature deviation | 15–25 C |[z]	0.458**(0.4)	−0.562**(1.0)	−0.278**(1.0)	−0.390**(0.8)	0.336**(0.1)	−0.477**(1.0)	−0.386**(0.9)	0.172* (0.0)
Hours temperature 15–25 C	0.417**(0.3)	0.704**(0.8)	0.548**(1.0)	0.563**(1.0)	0.511**(0.5)	0.698**(0.9)	0.599**(1.0)	0.504**(0.8)
Hours temperature 15–25 C and wet	0.451**(0.3)	0.735**(0.7)	0.560**(0.9)	0.140* (1.0)	0.698**(0.6)	0.851**(0.8)	0.428**(1.0)	0.591**(0.7)
Pan evaporation	0.310**(0.0)	−0.323**(1.0)	−0.515**(1.0)	−0.332**(0.9)	0.263**(0.0)	−0.517**(1.0)	−0.529**(0.9)	−0.333**(1.0)
Rain	0.359**(0.0)	0.649**(0.7)	0.655**(0.8)	0.495**(1.0)	0.575**(0.5)	0.851**(0.8)	0.746**(1.0)	0.674**(0.7)
Vapor pressure deficit	0.233**(0.0)	−0.456**(1.0)	−0.706**(1.0)	−0.398**(1.0)	0.194**(0.0)	−0.690**(1.0)	−0.669**(0.9)	−0.542**(1.0)
Solar radiation	0.308**(0.0)	−0.392**(1.0)	−0.459**(1.0)	0.184**(1.0)	0.281**(0.0)	−0.561**(1.0)	−0.320**(0.9)	0.138* (0.0)

[w] One period interval included 2 days before application of fungicide to 2 days before application of the next fungicide and corresponded to the developmental stages: EB = early bloom; LB = late bloom; GF = green fruit; PH = Preharvest.
[x] Significance levels ($n = 200$); *, $P = 0.05$ for $r \geq 0.138$; **, $P = 0.01$ for $r \geq 0.181$.
[y] Numbers in parentheses are fungicide weighting factors associated with greatest correlations. Weighting factors were multiplied by the environmental variable for the period when a fungicide was applied. The factor ranged from 0.0 (fungicide completely negated the influence of the environmental variable) to 1.0 (fungicide had no effect on the influence of the environmental variable).
[z] Accumulated absolute deviation of the mean daily temperature from the range of 15–25 C.

fungicide effect. Selection of equations was based on parsimony, coefficients of determination, significance of parameters, and randomness of residual plots.

RESULTS

Effect of fungicide regimes. Mean disease incidence varied widely among years; incidences in unsprayed plots were 53, 27, <1, and 21% in 1986–1989, respectively (Table 2). Nevertheless, the influence of the first two fungicide applications (i.e., during the bloom period) was pronounced in all years except 1988, when virtually no disease developed in any treatment. For instance, in both 1987 and 1989, these two applications alone provided the same level of control as did the complete program entailing regular sprays from early bloom until just before fruit were harvested (Table 2). Relatedly, omission of the first two sprays resulted in a significantly ($P = 0.05$) higher incidence of gray mold than was obtained with the complete program. For instance, omission of these applications from the complete program reduced control (relative to unsprayed plots) from 76 to 37% in 1987 and from 48 to 28% in 1986 (Table 2). Omitting just the first spray from the complete program had no discernible effect in 1986 and little effect in 1987; however, in 1989, control was reduced from 86% in the treatment receiving early and late bloom sprays to 36% when only the late bloom spray was applied (Table 2).

In contrast with the bloom sprays, those applied in the immediate preharvest period had relatively little effect on disease incidence. For example, in the treatment receiving just two preharvest applications, control was only half that of the full program in 1986 and was statistically insignificant ($P = 0.05$) in 1987 (Table 2).

Spray period × environment × fungicide interactions. Of all transformations tested, square root-transformed disease incidence data consistently produced the highest correlations with environmental variables. When such data were correlated with fungicide-weighted environmental variables, the resulting correlation (r) values were highly significant ($P = 0.01$) for 97 of the 104 environmental variable × spray period combinations analyzed (Table 4). Consistent with the effects of various fungicide regimes on gray mold incidence, the highest correlations generally involved weather variables measured either during the LB period or during a combination of this period and that immediately before or after it. The maximum correlation coefficient obtained ($r = 0.85$) applied to measurements of two different variables (total rainfall and hours of surface wetness at 15–25 C) during the combined LB plus GF spray periods. The next higher values were those for hours with RH > 80% and RH > 90% during the combined EB plus LB periods ($r = 0.78$ and 0.76, respectively), slightly exceeding those for hours during the LB period with RH > 90%, surface wetness at 15–25 C, and RH > 80% ($r = 0.74$, 0.74, and 0.73, respectively) (Table 4). In contrast, correlations between transformed disease incidence and environmental measurements during the PH period were consistently among the weakest; e.g., r values for the latter three variables were 0.35, 0.14, and 0.29, respectively, during this period (Table 4).

Two high correlations that did not include the LB period involved vapor pressure deficit during the GF period ($r = -0.71$) and rainfall during the GF plus PH period ($r = 0.75$) (Table 4). Comparison of two sets of related variables associated with generally high correlation coefficients reveals 1) a consistent and substantially higher correlation between transformed disease incidence and hours of surface wetness at 15–25 C versus hours of wetness at all temperatures and 2) slightly greater correlations involving hours with RH > 80% versus hours with RH > 90% during most spray periods or combinations (Table 4).

Optimal fungicide weighting factors were 0.5–1.0 for the 11 environmental variable × spray period combinations most highly correlated with transformed disease incidence (i.e., absolute value of $r > 0.7$) (Table 4), reflecting the incomplete control provided by even the most effective fungicide treatments in various years (Table 2). Of these combinations, the lowest weighting factor (i.e., the greatest fungicide effect) was applied to the correlation between disease incidence and the number of hours with RH > 90% during the successive EB plus LB periods; weighting factors were either 0.6 or 0.7 for five of the other six such combinations involving high RH or surface wetness during periods including LB. Conversely, the two combinations in this group with weighting factors of 1.0 (no fungicide effect) were vapor pressure deficit during the GF period and rainfall during the cumulative GF plus PH periods (Table 4). The general ineffectiveness or redundancy of fungicide applications during the GF and PH periods indicated in Table 2 is also reflected by the fungicide weighting factor of 1.0 for 21 of the 26 combinations analyzed for these two discrete periods (Table 4). In contrast, fungicide weighting factors were 0.0–0.3 for nine of the 13 variables during the EB period, although the correlations between these variables and disease incidence were limited ($r = 0.23$–0.45) (Table 4).

When transformed disease incidence data from only the unsprayed plots were analyzed, the relative correlations among environmental variable × spray period combinations were very

TABLE 5. Correlations of square root of percent diseased fruit in unsprayed (control) treatments with average daily environmental variable values for each spray period

Variable	Fungicide spray period[x,y]							
	EB	LB	GF	PH	EB+LB	LB+GF	GF+PH	EB+LB+GF+PH
Hours wet	0.297	0.498**	0.346*	−0.260	0.514**	0.695**	0.097	0.342*
Hours RH > 80%	0.700**	0.731**	0.673**	0.312	0.774**	0.741**	0.541**	0.697**
Hours RH > 90%	0.662**	0.734**	0.573**	0.334*	0.743**	0.675**	0.499**	0.671**
Growing degree days								
Base 0 C	0.333*	0.584**	−0.409*	0.050	0.459**	0.324	−0.242	0.394*
Base 10 C	0.321	0.584**	−0.409*	0.050	0.569**	0.324	−0.242	0.407*
Base 15 C	0.254	0.584**	−0.409*	0.050	0.658**	0.324	−0.242	0.352*
Absolute temperature deviation | 15–25 C |[z]	0.427**	−0.559**	−0.299	−0.415	0.177	−0.490**	−0.404*	−0.131
Hours temperature 15–25 C	0.343*	0.667**	0.654**	0.617**	0.433**	0.730**	0.672**	0.526**
Hours temperature 15–25 C and wet	0.379*	0.721**	0.624**	0.167	0.680**	0.918**	0.452**	0.620**
Pan evaporation	0.204	−0.341*	−0.575**	−0.373*	0.069	−0.560**	−0.568**	−0.326*
Rain	0.247	0.595**	0.671**	0.503**	0.517**	0.866**	0.782**	0.689**
Vapor pressure deficit	0.069	−0.474**	−0.788**	−0.453**	−0.130	−0.754**	−0.742**	−0.562**
Solar radiation	0.199	−0.399*	−0.531**	0.112	0.108	−0.638**	−0.368*	−0.030

[x] Spray periods: EB = early bloom; LB = late bloom; GF = green fruit; PH = preharvest.
[y] Significance levels ($n = 36$): *, $P = 0.05$ for $r \geq 0.325$; **, $P = 0.01$ for $r \geq 0.418$.
[z] Accumulated absolute deviation of the mean daily temperature from the range of 15–25 C.

similar to those obtained when all data were analyzed. For example, the maximum correlation ($r = 0.92$) again was obtained for hours of surface wetness at 15–25 C during the combined LB plus GF periods (Table 5). Other correlation coefficients with absolute values ≥0.7 were those for RH > 80% and RH > 90% during the EB and/or LB periods ($r = 0.70$–0.77); hours of surface wetness at 15–25 C during the LB period ($r = 0.72$); vapor pressure deficit during the GF, LB plus GF, and GF plus PH periods ($r = -0.79$, -0.75, and -0.74, respectively); and rainfall during the LB plus GF and GF plus PH periods ($r = 0.87$ and 0.78, respectively) (Table 5).

When stepwise regression was performed on all weighted data to predict disease incidence at harvest, the best equation was

$$\text{SQRT}(\textit{Incidence}) = 1.025 + 0.6293\ TW_{LB} - 0.2235\ GDD_{15\ GF+PH} + 2.440\ R_{GF+PH} + 0.01411\ W_{EB+LB+GF+PH}$$

where TW_{LB} is the daily hours the temperature was 15–25 C with surface wetness during the LB period; $GDD_{15\ GF+PH}$ is the average degree growing days (base 15 C) for the GF and PH periods; R_{GF+PH} is the sum of the average daily accumulated rainfall during the GF and PH periods; and $W_{EB+LB+GF+PH}$ is the sum of the average daily hours of wetness in all periods. In this equation, $n = 200$, and the intercept was not significant; with the intercept, $R^2 = 83.8\%$. When data from only unsprayed treatments were similarly analyzed, the best equation was

$$\text{SQRT}(\textit{Incidence}) = 1.028 + 0.09978\ RH_{80LB} - 0.1317\ TW_{EB} - 0.02228\ TW_{GF}$$

where RH_{80LB} is the hours of RH > 80% during the LB period, and TW_{EB} and TW_{GF} are the hours of surface wetness at temperatures of 15–25 C during the EB and GF periods, respectively. In this equation, $n = 24$, and $R^2 = 94.3\%$.

DISCUSSION

Regression analyses of data from sprayed and unsprayed plots showed a strong association between gray mold incidence at harvest and environmental variables during the bloom period, particularly the durations of RH > 80%, RH > 90%, and surface wetness at temperatures of 15–25 C. After bloom, environmental factors showed considerably less association with disease incidence, with the exception of vapor pressure deficit and rainfall during periods including those defined by the first postbloom ("green fruit") spray. Similarly, levels of gray mold control provided by seasonal fungicide treatments appeared to result almost entirely from the effect of sprays applied during the early and late bloom periods. On the basis of the moderate fungicide weighting factors associated with the greatest correlation coefficients, the ability of fungicide applications to negate environmental influences was limited for those variables most affecting disease development. However, the apparent magnitude of such limitations was influenced by the relatively poor control provided by all treatments in 1986, the only year in which sprays were applied with a low-pressure knapsack sprayer. Variable application procedures can significantly affect fungicide deposits and gray mold control in strawberry plantings (5), but the degree to which this factor itself may have influenced our results cannot be determined.

Fungicide weighting factors represented an attempt to address the combined influence of environment and fungicide application on disease development. If fungicide effects had been handled as an additional independent variable, there would have been no combined effect except as crossed variables. In contrast, the present method allowed each environmental variable to be weighted independently according to the magnitude of the fungicide effect by assuming that a fungicide application could reduce or negate whatever effect the environmental variable had on disease incidence (whether positively or negatively correlated). We believe this method provides a novel approach to the analytical dilemma of accounting for the combined effects of environment and fungicides in disease management systems.

Our results are generally consistent with those of other workers who have investigated various aspects of the epidemiology and control of strawberry gray mold. For instance, Powelson (15) noted that the vast majority of gray mold infections appear to originate at the stem end of strawberry fruit and demonstrated that these infections result from the expansion of latent infections of the floral parts into the receptacle. Gilles (6) and Jordan (12), in phenologically timed spray experiments similar to ours, showed that applications during bloom were most important for providing fungicidal control of the disease under Belgian and English environmental conditions, respectively; however, the former author also obtained significant benefit from subsequent sprays and concluded the "importance" of regular fungicide applications from bloom until the beginning of harvest (6). Bulger et al (4) predicted significantly higher incidences of fruit rot when blossom wetness periods occurred at temperatures of 15–25 C than when such periods occurred at 10 or 30 C; this prediction is supported by the substantially higher correlations we obtained using hours of surface wetness at 15–25 C relative to hours of wetness at all temperatures during bloom periods.

In Scotland, Jarvis (9) found a very high correlation between disease incidence at harvest and total rainfall during the period 11–30 days prior to first picking. Although no phenological data were provided, such preharvest intervals correspond roughly to the early bloom through green fruit periods in our experiments, depending on which of the two harvest periods is considered (Table 1). Rainfall during the combined late bloom plus green fruit periods was one of the two environmental variable × spray period combinations with the highest correlation coefficients in our study (Tables 4 and 5). As did we, Jarvis (9) found a high correlation between duration of RH > 80% in the prepicking periods and gray mold incidence at harvest; however, he found the greatest correlation when this variable was considered over the entire period 6–30 days before first picking, whereas we obtained the greatest correlation when only the early plus late bloom periods were considered (Tables 4 and 5). Temperature and duration of surface wetness throughout various periods were not considered in this previous study (9).

We are mindful that high correlations between environmental variables and disease incidence do not denote a cause-and-effect relationship and acknowledge other limitations of our analytical system. For instance, the employed designations of discrete periods of crop development may be conceptually useful but are necessarily approximations of a continuous ontogenic process and must be considered as such. Also, durations of RH > 80%, RH > 90%, and surface wetness at 15–25 C, three of the variables most highly correlated with gray mold incidence, are likely to have been different within plant canopies than they were external to the canopies where measured. Nevertheless, these data provide potential insight and invite further inquiry into the role of environmental factors on different stages of disease development, e.g., production of inoculum, establishment of quiescent infections, and the subsequent stimulation and expansion thereof (10).

For example, since most infections seen at harvest originate on open or senescing flower parts (6–11,15), to what extent do the strong correlations between disease incidence and durations of high moisture during bloom result from the effects of these variables on the initial infection process? Alternatively, given that most inoculum for floral infections is produced from previously infected strawberry leaves as they die or senesce (1,2), to what extent might extended periods of high RH or surface moisture influence the intensity of sporulation from such leaves during this critical period of disease establishment? Is the strong negative correlation between disease incidence and vapor pressure deficit during the green fruit stage due to an inhibitory effect of this variable (or a covariate) on the expansion of initial infections of stamens or styles into the receptacle (3)? Jarvis (9) suggested that water relations of fruit nearing ripeness might influence development of latent mycelium and that wet weather may exert a stimulatory effect by promoting increased uptake of water into the fruit. In our regression analysis, rainfall during the green fruit plus preharvest periods was one of the most important vari-

ables for predicting gray mold incidence at harvest when data from all plots were considered. Similarly, rainfall during the same combined spray periods was strongly correlated with disease incidence, yet fungicide applications had no influence on this association (Tables 4 and 5). Such results would be consistent with a hypothesized stimulation of latent mycelium within the fruit under high rainfall conditions. However, they also would be consistent with an alternative hypothesis, i.e., stimulation of lush canopy growth after bloom under high rainfall conditions resulting in 1) poor penetration of fungicide sprays and 2) longer periods of high RH and surface moisture within such canopy microclimates than were detected externally and used for analysis. Clearly, the relationship between environmental variables and gray mold development is complex and incompletely understood.

The results of our spray timing trials and those of others cited above have led to recommendations in New York State that fungicide sprays for gray mold be targeted during the early and late bloom periods and that dicarboximide fungicides not be used after this time (16). Restricting dicarboximide usage to two applications during their period of maximum effectiveness rather than season-long usage limits both fungicide costs and the pressure for selecting isolates of *B. cinerea* resistant to these materials. Cessation of fungicide sprays after bloom allows production of fruit with minimal fungicide residues for those who so desire; or alternatively, substituting dicarboximides with more broad-spectrum materials during the postbloom period allows targeting of other diseases that may be of greater importance at this time. Gray mold control programs can be further refined by more precisely identifying the environmental conditions under which blossom sprays are likely to be beneficial, perhaps by considering the durations of high RH conditions and/or surface wetness at various temperatures (4) during this period.

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