

Comparison of Epidemics of Botrytis Fruit Rot and Powdery Mildew of Strawberry in Large Plastic Tunnel and Field Production Systems

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ABSTRACT

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Epidemics of Botrytis fruit rot (*Botrytis cinerea*) and powdery mildew (*Sphaerotheca macularis* f. sp. *fragariae*) in annual strawberry were compared in large plastic tunnel and field production systems during the 1998-99 and 1999-2000 seasons. Treatments were factorial combinations of two main plots (field and tunnel) and four subplots, including combinations of two cultivars (Camarosa and Sweet Charlie) and two captan schedules arranged in a split-plot design with three replications. The mean incidence of Botrytis fruit rot was 88 to 94% lower in tunnels than in the field. The incidence of Botrytis fruit rot for the untreated control in tunnels was less than 2%, which was 89% lower than that of the 7-day captan schedule in the field. This indicates that Botrytis fruit rot can be controlled effectively without fungicides in a tunnel cultural system. Powdery mildew was severe on susceptible cultivar Camarosa in tunnels. Early season yields of cultivar Sweet Charlie were significantly higher in tunnels than in the field. Shorter periods of leaf wetness and higher temperatures in tunnels may have contributed to a lower incidence of Botrytis fruit rot and a higher incidence of powdery mildew on fruit in tunnels compared with open field plots.

Additional keywords: cultural control, epidemiology, gray mold, protected culture

Florida is the major winter fresh strawberry supplier for the eastern United States and Canada, with 2,400 ha of fruit production fields primarily in west-central Florida and an annual farm gate revenue of \$160 million in 1997-98. In Florida, strawberry plants are grown as an annual crop in a hill plasticulture system (1), which includes preplant soil fumigation with a mixture of methyl bromide and chloropicrin, raised beds with black plastic mulch, and drip irrigation. Bare-root transplants are set during October. Fruit harvest begins in November and may continue until April.

Botrytis fruit rot caused by *Botrytis cinerea* is the major limiting factor in strawberry production in Florida, causing preharvest losses of up to 15% of the fruit on susceptible cultivars, even with weekly applications of fungicides (7). Botrytis fruit rot is controlled by a combination of cultural and chemical methods. Although differences in susceptibility to Botrytis

fruit rot were observed recently among several commercial cultivars, none were highly resistant (9). Cultural practices such as the removal of senescent foliage and diseased fruit (11), use of wider plant spacing (9), and use of drip irrigation instead of overhead sprinkler irrigation (1,18) have been used as supplemental measures to improve the control of Botrytis fruit rot. Because climatic conditions during the strawberry growing season in Florida are highly conducive to Botrytis fruit rot epidemics, control of the disease has been reliant largely on fungicides. Weekly application of captan has been a standard practice for the control of Botrytis fruit rot, and captan may be applied up to 24 times during a growing season.

Powdery mildew caused by *Sphaerotheca macularis* f. sp. *fragariae* occurs everywhere strawberries are grown. It mainly causes foliar damage, but also can infect fruit, especially on susceptible cultivars (6). Control of powdery mildew relies on the use of disease-free transplants in annual production systems and applications of protectant or systemic fungicides (8,10). Currently, commercial cultivars of strawberry have varying levels of resistance to powdery mildew (12). Among the two most popular cultivars grown in Florida, Camarosa is highly susceptible to powdery mildew, whereas Sweet Charlie is more resistant to powdery mildew.

Protected culture in greenhouses and plastic tunnels is used widely for strawberry production in other countries (3,15).

Plastic tunnels are the predominant strawberry production system used to force early fruit ripening and to protect fruit from unfavorable weather in France, Italy, and Spain (3). Reductions in the incidence of Botrytis have been observed on tomato and cucumber grown in the greenhouse (4). The effects of protected culture on Botrytis fruit rot development on strawberry, however, have not been studied extensively (6). Powdery mildew can be a problem under protected cultures (6,10). Jordan and Hunter (6) observed a significantly higher level of powdery mildew on strawberry leaves under colored films than under clear film or glass, although little information is available on powdery mildew development on strawberry fruit in protected culture systems.

Public concerns over pesticide residues on fresh-market commodities led to new restrictions on the use of fungicides on strawberries. Additional regulations may be imposed by the Environmental Protection Agency or other regulatory agencies in the future. Therefore, it is prudent to develop disease management programs that have less of a dependence on fungicides for disease control.

In west-central Florida, frequent rains and long periods of leaf wetness occur during the strawberry growing season (9). Such weather is highly conducive to Botrytis fruit rot epidemics. There usually are several nights with frost each season, and overhead sprinkler irrigation usually is used to protect plants from freeze damage (1). Plastic tunnels may provide an alternative means to control Botrytis fruit rot and to protect plants from frost, but this cultural system also may result in more powdery mildew on susceptible cultivars (6,10).

The objectives of this study were to compare epidemics of Botrytis fruit rot and powdery mildew on fruit between field and tunnel production systems, evaluate marketable yields of two major cultivars under these two production systems, and evaluate the potential of large plastic tunnels for control of Botrytis fruit rot. A preliminary report has been published (22).

MATERIALS AND METHODS

Experiments were conducted at the University of Florida Gulf Coast Research and Education Center at Dover, FL, during the 1998-99 and 1999-2000 seasons. Prior to transplanting each season, a 6:2:8 (N-P-K) starter fertilizer was broadcast applied to

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the ground at 570 kg ha⁻¹, and beds were raised and fumigated with a mixture of methyl bromide and chloropicrin (98:2, vol:vol) at 400 kg ha⁻¹. The experimental design was split plot with three replications. Treatments included two main plots (open field and plastic tunnel) and four subplots, including factorial combinations of two cultivars (Camarosa and Sweet Charlie) and two captan application schedules. Captan schedules included 7- and 14-day intervals of 3.3 kg of active ingredient ha⁻¹ in 1998-99. Because very low levels of *Botrytis* fruit rot developed in tunnels in 1998-99, an untreated control was included in 1999-2000 and captan was tested only on the 7-day schedule. Each subplot was

12 m long and consisted of two rows on a single bed. Tunnels (15 × 5 × 3 m, each) were established to span four beds and covered with clear, plastic UV-absorbing film (Dura Green, Mount Dora, FL). Plastic side panels were opened and closed manually to facilitate air movement, temperature control, and pollinator access. Weather stations (Adcon Telemetry, Boca Raton, FL) were set up in the field and in one tunnel to monitor temperature, relative humidity, leaf wetness, and rainfall.

Plants of strawberry cultivars Sweet Charlie and Camarosa, from a Canadian nursery, were set on 16 October, 1998, and 15 October, 1999. Plants were overhead-sprinkler irrigated 10 h daily for 10 to 14

days for establishment and then drip irrigated and maintained according to recommendations for commercial production (1). Fruit were harvested twice weekly 30 November, 1998, to 29 March, 1999, in the first season, and 3 December, 1999, to 16 March, 2000, or 23 March, 2000, for Sweet Charlie or Camarosa, respectively, in the second season. The number of marketable fruit and culls, weight of marketable fruit, and numbers of *Botrytis*- and powdery mildew-diseased fruit were determined. The severity of powdery mildew on leaves was assessed on 12 March, 1999, and 27 January, 2000. Ten plants from each bed (subplot) were selected randomly for disease assessment. The severity of pow-

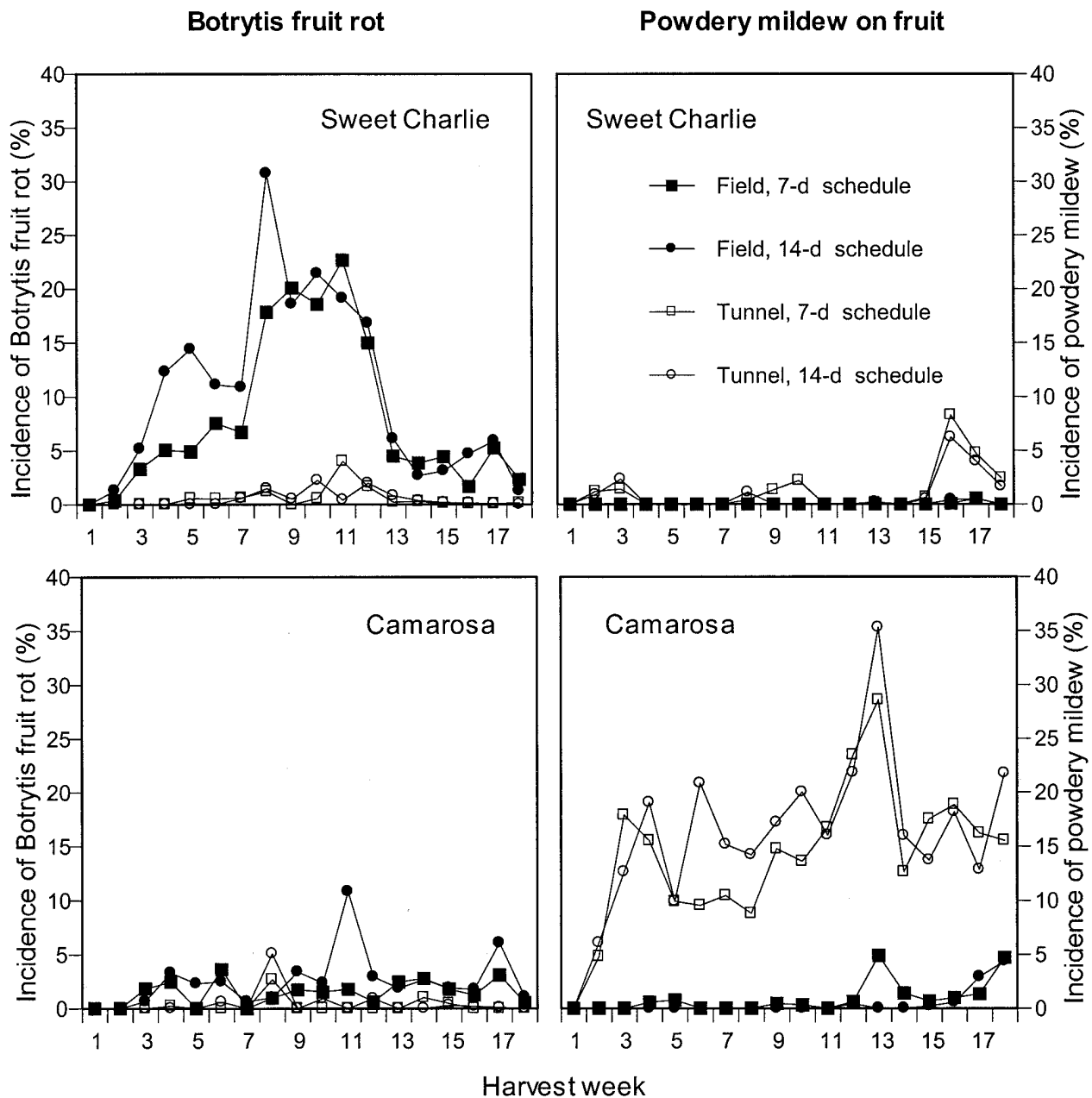


Fig. 1. Weekly incidence of *Botrytis* fruit rot and powdery mildew on fruit of strawberry cultivars Camarosa and Sweet Charlie grown in the field and in large plastic tunnels in the 1998-99 season. Two captan spray programs, with 7- and 14-day schedules at the rate of 3.3 kg of active ingredient ha⁻¹, were included.

dery mildew was determined with the use of a 0 to 5 rating scale in which 0 = no visible symptoms, 1 = less than 10% foliage diseased, 2 = 10 to 25% foliage diseased, 3 = 25 to 50% foliage diseased, 4 = 50 to 75% foliage diseased, and 5 = more than 75% foliage diseased.

Statistical analysis was performed with SAS, release 6.12 (SAS Institute, Cary, NC). Analysis of variance was performed for the cumulative incidence of Botrytis fruit rot and powdery mildew on fruit and marketable yield for the early-period (harvests from the first 8 weeks), late-period (all harvests after the first 8 weeks), and whole-season data. The incidence of Botrytis fruit rot and powdery mildew on fruit

were calculated as the percentage of diseased fruit in the total number of fruit harvested during a period. Incidence data were arcsine-square root transformed prior to analysis. Marketable yield was cumulative from all harvests during each period. Where the interactions of main plot and subplot were significant, analysis of variance also was performed separately for each main plot (field and tunnel). Mean comparisons were made with Fisher's protected least significant difference test ($P \leq 0.05$). The incidence of Botrytis fruit and powdery mildew fruit were calculated from two harvests each week. Weekly disease incidence was plotted against time (harvest week) to compare disease progress curves

between treatments. Analysis of variance also was performed on the foliar severity of powdery mildew.

RESULTS

Botrytis fruit rot. Botrytis fruit rot epidemics were severe in the field but not in tunnels during both seasons (Figs. 1 and 2). Cultural systems significantly affected the development of Botrytis fruit rot during early-, late-, and whole-season periods in 1998-99 and 1999-2000 (Table 1). In the field, the incidence of Botrytis fruit rot during all three periods ranged from 1.5 to 2.6% on Camarosa and 5.9 to 9.2% on Sweet Charlie in 1998-99, and 2.7 to 4.3% on Camarosa and 16.5 to 18.8% on Sweet

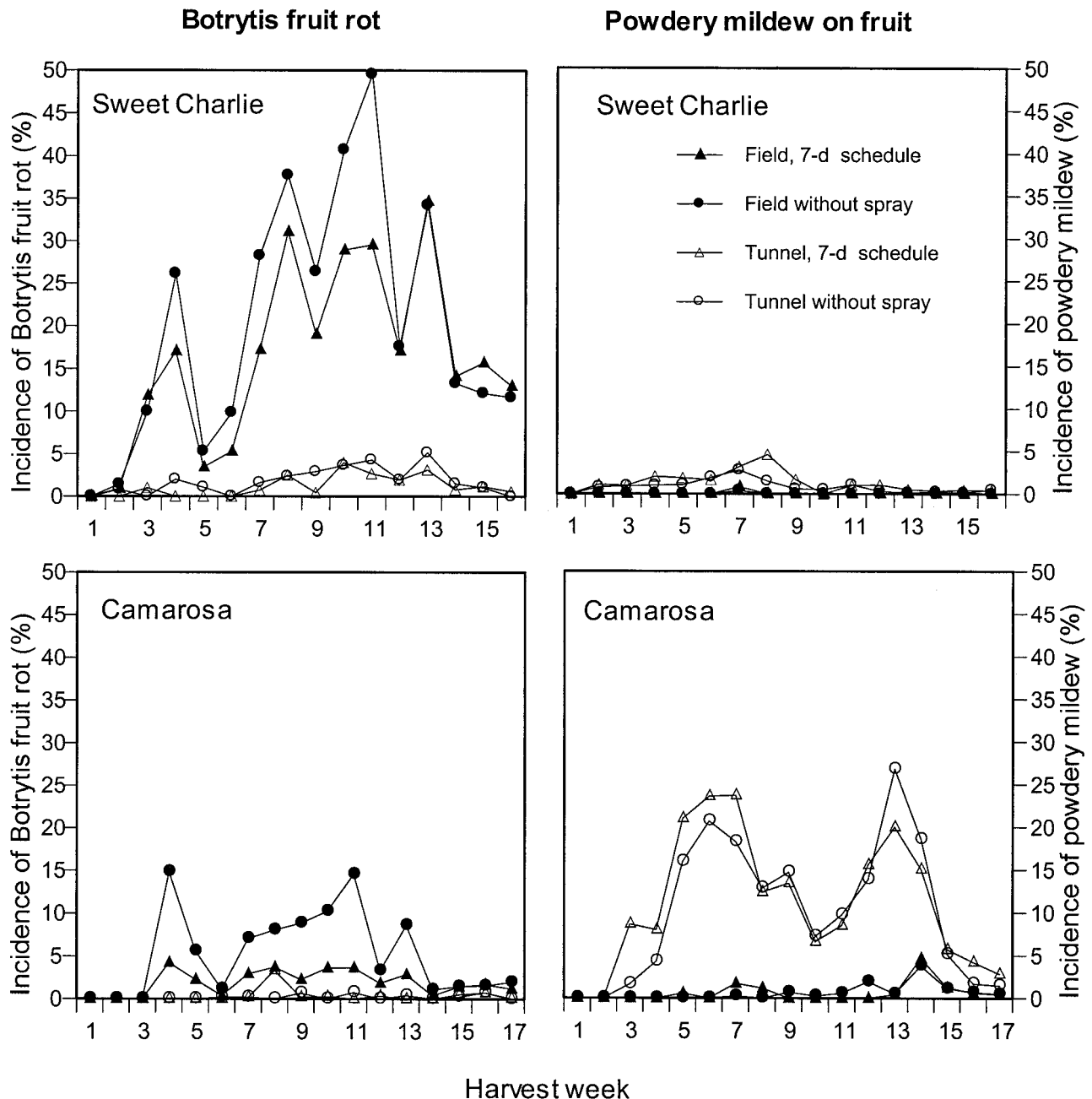


Fig. 2. Weekly incidence of Botrytis fruit rot and powdery mildew on fruit of strawberry cultivars Camarosa and Sweet Charlie grown in the field and in large plastic tunnels in the 1999-2000 season. Two captan spray programs, with a 7-day schedule at the rate of 3.3 kg of active ingredient ha⁻¹, and an untreated control were included.

Table 1. Analysis of variance describing effects of culture (field and plastic tunnel), cultivar (Camarosa and Sweet Charlie), and captan on cumulative incidence of Botrytis fruit rot and powdery mildew on fruit and marketable yield for three different periods during 1998-99 and 1999-2000

Season-variation source	Early period ^x			Late period			Whole season		
	df	MS ^y	P > F	df	MS	P > F	df	MS	P > F
1998-99-Botrytis fruit rot incidence									
Block	2	0.0025	0.3938	2	0.0050	0.0041	2	0.0038	0.0115
Culture	1	0.1575	0.0162	1	0.1501	0.0010	1	0.1407	0.0017
Block × culture (error _a)	2	0.0026		2	0.0002		2	0.0002	
Cultivar	1	0.0465	0.0010	1	0.0203	0.0001	1	0.0207	0.0001
Culture × cultivar	1	0.0509	0.0007	1	0.0046	0.0140	1	0.0119	0.0006
Captan ^z	1	0.0048	0.1924	1	0.0017	0.1011	1	0.0029	0.0435
Culture × captan	1	0.0011	0.5136	1	0.0009	0.2127	1	0.0005	0.3690
Cultivar × captan	1	0.0011	0.5129	1	0.0014	0.1350	1	0.0012	0.1751
Culture × cultivar × captan	1	0.0036	0.2537	1	0.0007	0.2966	1	0.0000	0.9004
Error _b	12	0.0025		12	0.0012		12	0.0005	
Powdery mildew incidence on fruit									
Block	2	0.0006	0.7612	2	0.0093	0.0146	2	0.0073	0.0237
Culture	1	0.2664	0.0111	1	0.2517	0.0022	1	0.2425	0.0005
Block × culture (error _a)	2	0.0030		2	0.0005		2	0.0001	
Cultivar	1	0.1351	0.0001	1	0.2170	0.0001	1	0.1995	0.0001
Culture × cultivar	1	0.1129	0.0001	1	0.0470	0.0001	1	0.0505	0.0001
Captan	1	0.0001	0.8060	1	0.0000	0.9645	1	0.0000	0.9598
Culture × captan	1	0.0018	0.3777	1	0.0004	0.6210	1	0.0001	0.7680
Cultivar × captan	1	0.0000	0.9557	1	0.0000	0.9335	1	0.0000	0.9180
Culture × cultivar × captan	1	0.0012	0.4844	1	0.0007	0.4918	1	0.0009	0.4342
Error _b	12	0.0022		12	0.0015		12	0.0014	
Marketable yield									
Block	2	2.19E + 06	0.0166	2	1.04E + 07	0.1062	2	2.20E + 07	0.0476
Culture	1	3.50E + 05	0.0315	1	3.61E + 07	0.1104	1	2.94E + 07	0.1407
Block × culture (error _a)	2	1.15E + 04		2	4.76E + 06		2	5.20E + 06	
Cultivar	1	4.32E + 05	0.3027	1	2.84E + 07	0.0182	1	3.59E + 07	0.0258
Culture × cultivar	1	3.71E + 06	0.0083	1	1.09E + 08	0.0002	1	1.53E + 08	0.0002
Captan	1	9.65E + 04	0.6199	1	2.44E + 05	0.8043	1	6.48E + 05	0.7385
Culture × captan	1	2.45E + 04	0.8017	1	3.62E + 05	0.7633	1	5.75E + 05	0.7532
Cultivar × captan	1	2.14E + 06	0.0336	1	1.38E + 06	0.5577	1	6.97E + 06	0.2845
Culture × cultivar × captan	1	9.67E + 05	0.1329	1	9.67E + 05	0.8728	1	4.41E + 05	0.7828
Error _b	12	3.72E + 05		12	1.02E + 05		12	5.55E + 06	
1999-2000-Botrytis fruit rot incidence									
Block	2	0.0047	0.0976	2	0.0036	0.0782	2	0.0039	0.0512
Culture	1	0.3374	0.0049	1	0.2629	0.0023	1	0.2768	0.0014
Block × culture (error _a)	2	0.0017		2	0.0006		2	0.0004	
Cultivar	1	0.0933	0.0001	1	0.2022	0.0001	1	0.1718	0.0001
Culture × cultivar	1	0.0474	0.0002	1	0.0614	0.0001	1	0.0594	0.0001
Captan	1	0.0075	0.0544	1	0.0019	0.2118	1	0.0027	0.1316
Culture × captan	1	0.0157	0.0095	1	0.0001	0.7311	1	0.0014	0.2598
Cultivar × captan	1	0.0009	0.4524	1	0.0010	0.3625	1	0.0004	0.5611
Culture × cultivar × captan	1	0.0040	0.1447	1	0.0036	0.1010	1	0.0039	0.0743
Error _b	12	0.0016		12	0.0011		12	0.0010	
Powdery mildew incidence on fruit									
Block	2	0.0015	0.1679	2	0.0002	0.2656	2	0.0002	0.3293
Culture	1	0.3549	0.0007	1	0.0708	0.0086	1	0.1293	0.0017
Block × culture (error _a)	2	0.0003	0.7181	2	0.0006		2	0.0002	0.3627
Cultivar	1	0.1530	0.0001	1	0.1137	0.0001	1	0.1300	0.0001
Culture × cultivar	1	0.0975	0.0001	1	0.0151	0.0001	1	0.0297	0.0001
Captan	1	0.0086	0.0051	1	0.0001	0.3848	1	0.0011	0.0356
Culture × captan	1	0.0000	0.9919	1	0.0007	0.0457	1	0.0008	0.0580
Cultivar × captan	1	0.0019	0.1276	1	0.0000	0.6421	1	0.0000	0.7224
Culture × cultivar × captan	1	0.0011	0.2339	1	0.0000	0.6111	1	0.0000	0.9477
Error _b	12	0.0007		12	0.0002		12	0.0002	
Marketable yield									
Block	2	5.36E + 06	0.0005	2	1.39E + 07	0.0206	2	2.22E + 07	0.0102
Culture	1	8.62E + 04	0.8658	1	2.71E + 07	0.0993	1	2.41E + 07	0.2119
Block × culture (error _a)	2	2.35E + 06		2	3.15E + 06		2	7.35E + 06	
Cultivar	1	5.24E + 07	0.0001	1	2.16E + 08	0.0001	1	4.81E + 08	0.0001
Culture × cultivar	1	5.76E + 06	0.0015	1	1.29E + 08	0.0001	1	1.89E + 08	0.0001
Captan	1	1.31E + 06	0.0748	1	1.69E + 06	0.4311	1	2.43E + 04	0.9324
Culture × captan	1	4.94E + 05	0.2543	1	1.48E + 07	0.0328	1	2.07E + 07	0.0263
Cultivar × captan	1	3.07E + 04	0.7705	1	1.33E + 05	0.8231	1	2.92E + 05	0.7690
Culture × cultivar × captan	1	1.01E + 03	0.9576	1	1.37E + 01	0.9982	1	7.91E + 02	0.9878
Error _b	12	3.44E + 05		12	2.55E + 06		12	3.23E + 06	

^x Early period is the first 8 weeks of harvests and the late period is for all harvests after the first 8 weeks of each season. Whole-season period includes all harvests for each season. Analysis of variance was performed on arcsine-square root-transformed data.

^y Mean square.

^z Captan treatment included two spray programs, with 7- and 14-day schedules at 3.3 kg per active ingredient ha⁻¹ in the 1998-99 season. In the 1999-2000 season, captan treatments were changed to include the 7-day schedule and an untreated control.

Charlie in 1999-2000 (Table 2). In tunnels, the incidence of Botrytis fruit rot was less than 1 and 2% in 1998-99 and 1999-2000, respectively.

Cultivars and the interaction of cultural systems and cultivars significantly affected the incidence of Botrytis fruit rot during early-, late-, and whole-season periods in both seasons, indicating that cultivar effects on Botrytis fruit rot depend on the cultural system (Tables 1 and 2). The incidence of Botrytis fruit rot in the field was significantly higher on Sweet Charlie than on Camarosa during all three periods in both seasons. In contrast, the incidence of the disease in tunnels was not significantly

different between cultivars, except during the late- and whole-season periods in 1999-2000. The incidence of Botrytis fruit rot on Sweet Charlie in tunnels was reduced by 97, 93, and 94% in 1998-99, and 95, 90, and 91% in 1999-2000 compared with those in the field for the early-, late-, and whole-season periods, respectively. The incidence of Botrytis fruit rot on Camarosa in tunnels also was reduced by 57 to 90% compared with those in the field during all three periods (Table 2).

There were no significant differences in the incidence of Botrytis fruit rot between the 7- and 14-day captan schedules during the early-, late-, and whole-season periods

in the field and tunnels in 1998-99 (Table 2). In 1999-2000, the incidence of Botrytis fruit rot was significantly lower in the 7-day captan schedule than in the untreated control during the early period in the field and during the late- and whole-season periods in tunnels. The incidence of Botrytis fruit rot in the untreated control in tunnels was reduced by 89% compared with the 7-day captan schedule in the field.

Powdery mildew. Severe epidemics of powdery mildew developed only in tunnels during both seasons (Figs. 1 and 2). The cultural system, cultivar, and cultural system-cultivar interaction significantly affected the incidence of powdery mildew on

Table 2. Cumulative Botrytis fruit rot incidence and marketable yield for different cultural systems (field and tunnel), cultivars (Camarosa and Sweet Charlie), or captan treatments (7- or 14-day schedule or no captan) from three periods during 1998-99 and 1999-2000

Culture-cultivar or captan	1998-99 Season			1999-2000 Season		
	Early period ^a	Late period	Whole season	Early period	Late period	Whole season
Botrytis fruit rot incidence (%)^v						
Field-Camarosa	1.49 b ^w	2.56 b	2.33 b	4.28 b	2.72 b	3.05 b
Field-Sweet Charlie	9.15 a	5.86 a	6.39 a	16.51 a	18.75 a	18.27 a
Tunnel-Camarosa	0.64 a	0.11 a	0.24 a	0.47 a	0.31 b	0.35 b
Tunnel-Sweet Charlie	0.29 a	0.39 a	0.37 a	0.85 a	1.93 a	1.66 a
Powdery mildew on fruit (%)^x						
Field-Camarosa	0.09 a	1.83 a	1.48 a	0.40 a	0.84 a	0.74 a
Field-Sweet Charlie	0.00 a	0.12 b	0.10 b	0.08 a	0.01 b	0.02 b
Tunnel-Camarosa	12.81 a	16.73 a	15.75 a	16.63 a	6.15 a	8.91 a
Tunnel-Sweet Charlie	0.61 b	2.34 b	2.04 b	1.84 b	0.39 b	0.75 b
Marketable yield (kg/ha)						
Field-Camarosa	3,479 a	17,168 a	20,647 a	8,594 a	23,627 a	32,221 b
Field-Sweet Charlie	2,961 a	15,074 a	18,035 a	4,660 b	12,996 b	17,656 a
Tunnel-Camarosa	2,934 b	10,442 b	13,376 b	7,734 a	16,873 a	24,607 a
Tunnel-Sweet Charlie	3,989 a	16,892 a	20,881 a	5,759 b	15,503 a	21,262 b
Botrytis fruit rot incidence (%)						
Field-No captan ^y	ND ^z	ND	ND	12.59 a	10.91 a	11.26 a
Field-7-day schedule	4.15 a	3.72 a	3.79 a	8.19 b	10.57 a	10.06 a
Field-14-day schedule	6.49 a	4.71 a	4.92 a	ND	ND	ND
Tunnel-No captan	ND	ND	ND	0.58 a	1.33 a	1.14 a
Tunnel-7-day schedule	0.39 a	0.21 a	0.25 a	0.74 a	0.91 b	0.87 b
Tunnel-14-day schedule	0.55 a	0.29 a	0.37 a	ND	ND	ND
Powdery mildew on fruit (%)						
Field-No captan	ND	ND	ND	0.43 a	0.39 a	0.39 a
Field-7-d schedule	0.09 a	0.93 a	0.77 a	0.06 b	0.46 a	0.37 a
Field-14-d schedule	0.00 a	1.02 a	0.81 a	ND	ND	ND
Tunnel-No captan	ND	ND	ND	10.23 a	3.47 a	5.33 a
Tunnel-7-day schedule	6.08 a	9.70 a	8.90 a	8.24 a	3.07 a	4.33 b
Tunnel-14-d schedule	7.34 a	9.37 a	8.89 a	ND	ND	ND
Marketable yield (kg/ha)						
Field-No captan	ND	ND	ND	7,004 a	18,832 a	25,836 a
Field-7-day schedule	3,125 a	15,897 a	19,022 a	6,249 a	17,792 a	24,041 a
Field-14-day schedule	3,316 a	16,345 a	19,661 a	ND	ND	ND
Tunnel-No captan	ND	ND	ND	6,837 a	15,137 b	21,974 b
Tunnel-7-day schedule	3,431 a	13,689 a	17,120 a	6,656 a	17,239 a	23,895 a
Tunnel-14-day schedule	3,494 a	13,645 a	17,139 a	ND	ND	ND

^a Early period is the first 8 weeks of harvests, late period is for all harvests after the first 8 weeks of each season, and whole season includes all harvests of that season.

^v Botrytis fruit rot incidence values are expressed as the percentage of fruit harvested with Botrytis rot in the total fruit harvested during the period.

^w Means followed by the same letter within a column in each section are not significantly different as determined by Fishers protected least significant difference test ($P \leq 0.05$).

^x Powdery mildew incidence values are expressed as the percentage of fruit harvested with powdery mildew in the total fruit harvested during the period.

^y Captan treatment included two spray programs, with 7- and 14-day schedules at 3.3 kg of active ingredient ha⁻¹ in the 1998-99 season. In the 1999-2000 season, the captan treatments were changed to include the 7-day schedule and an untreated control.

^z ND = not determined.

fruit during the early-, late-, and whole-season periods in both seasons (Table 1). Tunnel culture was conducive to the development of powdery mildew on fruit. The incidence of powdery mildew on Camarosa fruit was 12.8 to 16.7% in 1998-99 and 6.2 to 16.6% in 1999-2000 in tunnels during all three periods. Additionally, it was 141-, 8-, and 10-fold higher in tunnels than in the field in 1998-99 and 41-, 6-, and 11-fold higher in tunnels than in the field in 1999-2000 for the early-, late-, and whole-season periods, respectively (Table 2). Sweet Charlie had a consistently lower incidence of powdery mildew (0 to 2.3%) than Camarosa in the field and tunnels in both seasons, except during the early period in the field (Table 2). Captan schedules did not affect the incidence of powdery mildew on fruit, except during the early period in the field, and in the whole-season period in tunnels in 1999-2000, when the incidence of powdery mildew on fruit was significantly higher with the 7-day captan schedule than in the untreated control (Table 2).

The foliar severity of powdery mildew was assessed for both seasons. Analysis of variance indicated that the foliar severity of powdery mildew differed between the field and tunnels in 1998-99 ($P = 0.0538$) and 1999-2000 ($P = 0.0891$) and that the cultivar and cultural system-cultivar interaction significantly affected the foliar severity (Table 3). The foliar severity of powdery mildew was significantly higher on Camarosa than on Sweet Charlie in both seasons, except there was no significant difference in foliar severity of powdery mildew between the two cultivars in tunnels in 1999-2000.

Marketable yield. Significant differences in marketable yield between strawberries treated on the field or tunnels ($P = 0.0315$) occurred during the early period in 1998-99 (Table 1). Yield differences also were evident ($P = 0.0993$) between cultural systems during the late period in 1999-2000. Marketable yields were significantly different between cultivars during early-, late-, and whole-season periods in both seasons, except during the early period in 1998-99 (Tables 1 and 2). Significant cultural system-cultivar interactions occurred during all three periods in both seasons,

indicating that yield differences resulting from disease depend upon cultural systems. The yield of Sweet Charlie in tunnels during the early period increased 35 and 24% compared with the field in 1998-99 and 1999-2000, respectively. The yield of Camarosa in tunnels during the early period, however, decreased 19 and 11% compared with the field in 1998-99 and 1999-2000, respectively (Table 2).

Marketable yield differences between the 7- and 14-day captan schedules were not significant in the field and tunnels in 1998-99. In 1999-2000, the yields of fungicide-treated plants in the late- and whole-season periods were significantly higher than those of the untreated plants. The early-season yield of plants in tunnels, however, was not affected significantly by fungicide treatment. Additionally, the yield from plants grown in the open field was not affected by fungicide treatment, regardless of the harvest period (Table 2).

Microclimate. Temperature, relative humidity, leaf-wetness duration, and precipitation in the field and tunnel from the 1998-99 season are illustrated in Figures 3 and 4. Because of equipment failure, leaf-wetness duration data in tunnels were not available for the second season. Shorter leaf-wetness periods and higher temperatures were associated with the tunnel compared with the field. In 1998-99, during the early period (weather data recorded 5 November, 1998, to 22 January, 1999), there were 77 days, with an average of 12.9 h of dew in the field. In contrast, there were only 30 days, with an average of 4.5 h of dew in the tunnel. The average temperatures were 19.3 and 20.4°C, and the average relative humidities were 85.8 and 78.9% in the field and tunnel, respectively. During the late period (weather data recorded 23 January, 1999, to 29 March, 1999), there were 67 days with an average of 11.7 h of dew in the field compared with 26 days with an average of 5.2 h of dew in the tunnel. The average temperatures were 18.2 and 19.7°C, and the average relative humidities were 78.5 and 70.8% in the field and tunnel, respectively. In the field, there was 16.3 and 14.2 cm of rainfall during the early and late periods, respectively. In 1999-2000, the weather differences between the tunnel and field were

similar to those in 1998-99 (data not shown).

DISCUSSION

In this study, we observed much less Botrytis fruit rot in the tunnels than in the field, especially on Sweet Charlie, a highly susceptible cultivar. The early-season yield was higher in tunnels than in the field only for Sweet Charlie.

This study is part of our efforts to develop alternative production systems or modify cultural practices for Botrytis fruit rot control. Wider within-row plant spacing has been shown to reduce Botrytis fruit rot by 26 to 42% compared with narrower spacings (9), and the removal of senescent foliage slightly reduced Botrytis fruit rot (11). These methods can supplement chemical control but are ineffective to replace fungicides to control Botrytis fruit rot. The present study documents the successful control of Botrytis fruit rot with large plastic tunnels as an alternative production system. Tunnel culture provides better control of Botrytis fruit rot than the conventional production system, i.e., an open field with standard fungicide applications. Thus, it has the potential to serve as a nonchemical alternative for the control of Botrytis fruit rot.

The dramatic reduction of Botrytis fruit rot in tunnels can be attributed to a few possible mechanisms. Shorter periods of leaf wetness were associated consistently with the tunnel compared with the field. The frequency of days with leaf wetness was over 60% less in the tunnel than in the field in 1998-99. The infection of flower and fruit by *B. cinerea* and subsequent sporulation are favored by extended periods of leaf wetness (2,17,19,20,21). The incidence of infection by conidia of *B. cinerea* at 15 to 25°C increases from near zero to 90% as the leaf-wetness duration increases from 6 to 24 h (19). Therefore, shorter periods of leaf wetness inside tunnels would reduce fruit infection by *B. cinerea*.

Conidia of *B. cinerea* are dispersed mainly by splashing rain and wind (19). Precipitation plays an important role in spore production and the dispersal of many pathogens, including *B. cinerea*. Frequent rains during the strawberry fruiting season would increase the splash dispersal of inoculum, resulting in more infections on fruit in the field than in the tunnel (19). Inside tunnels, plants were protected from rain and splash dispersal of inoculum.

Reduced light intensity in tunnels also might affect *B. cinerea* infection and spore production. Films absorbing near-UV radiation reduce spore production in vitro for *B. cinerea* and other pathogens (13) and provide a reduction in the incidence of Botrytis on tomato and cucumber grown in the greenhouse (4). The film used in the present study was a clear UV-absorbing film. Thus, it is possible that the infection

Table 3. Foliar severity of powdery mildew in 1998-99 and 1999-2000

Cultural system	Cultivar	Foliar severity of powdery mildew ^y	
		1998-99	1999-2000
Field	Camarosa	2.02 a ^z	1.75 a
	Sweet Charlie	0.65 b	1.20 b
Tunnel	Camarosa	3.12 a	1.18 a
	Sweet Charlie	0.63 b	1.00 a

^y Foliar severity of powdery mildew was determined by a 0-5 rating scale in which 0 = no visible symptom, 1 = less than 10% foliage diseased, 2 = 10 to 25% foliage diseased, 3 = 25-50% foliage diseased, 4 = 50-75% foliage diseased, and 5 = more than 75% foliage diseased.

^z Means followed by the same letter within a column in each section are not significantly different as determined by Fishers protected least significant difference test ($P \leq 0.05$).

and sporulation of *B. cinerea* was inhibited in tunnels.

In 1998-99, the 7-day captan schedule did not provide additional control of Botrytis fruit rot compared with the 14-day captan schedule in the field or tunnels. This might be the result of the relatively low disease pressure in the field in 1998-99. When disease pressure is low, small treatment effects are more difficult to separate. Because very low levels of Botrytis fruit rot developed inside the tunnels in 1998-99, only the 7-day captan schedule and an untreated control were evaluated in 1999-2000. Even though the 7-day captan schedule significantly reduced the incidence of

Botrytis in tunnels, the disease level was less than 2% in the untreated control. Thus, there seems to be no need to use fungicide to control Botrytis in tunnel systems. In 1999-2000, the 7-day captan schedule provided control of Botrytis during the early period in the field and the late period in tunnels but not the early period in tunnels and the late period in the field. The lack of differences in the incidence of Botrytis fruit rot observed between the 7-day captan schedule and the untreated control during the early period in the tunnels might be the result of very low levels of disease. The cause for the failure of disease control during the late period in the field is uncer-

tain. One possible explanation is that increased rainfall during that period in the field may have reduced fungicide residues.

The development of powdery mildew is favored by low light intensity, moderate to high relative humidity without free moisture, and temperatures of approximately 15 to 27°C (5,10,12,14). In both seasons, environmental conditions in tunnels favored powdery mildew development, except at the end of the season (March) when temperatures apparently became too high. Surprisingly, the difference in the foliar severity of powdery mildew between the field and tunnels was not significant. In contrast, the incidence of powdery mildew

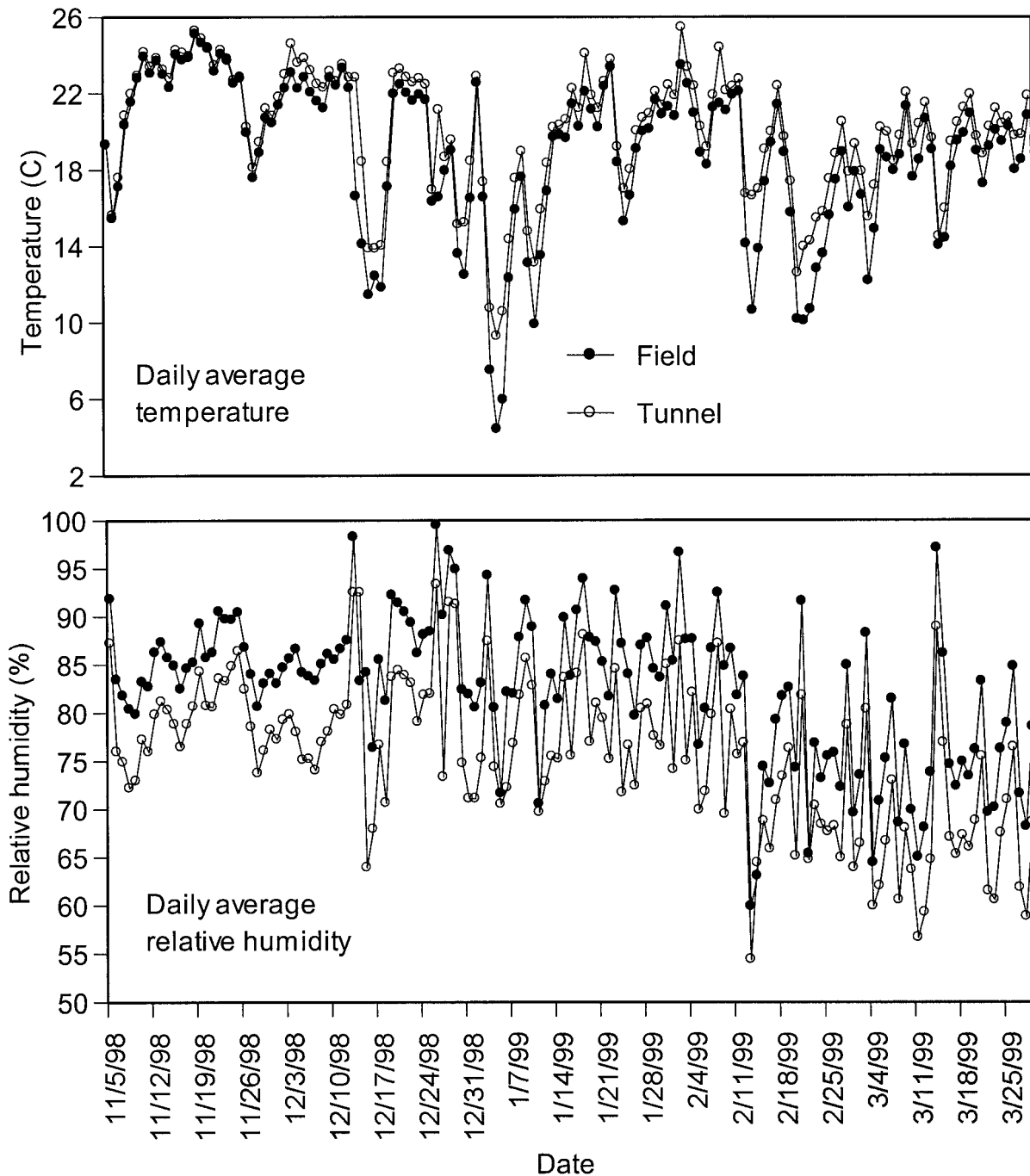


Fig. 3. Daily average temperatures and daily average relative humidities in the field and tunnel in the 1998-99 season.

on fruit was much higher in tunnels than in the field. The conditions required for fruit and leaf infection might be different. Powdery mildew can be a limiting factor for strawberry fruit production in tunnels, although effective organic products such as sulfur or other labeled fungicides can provide good control of powdery mildew (8) or resistant cultivars such as Sweet Charlie, which in turn may reduce or eliminate the reliance on fungicides for powdery mildew control in tunnels.

High early-season marketable yields are very important to the profitability of producing strawberries because the market value of fruit in December and January can be four to five times greater than the market value later in the season. Temperature is an important factor affecting early production (18), and the higher early-season

yield might be attributed to elevated temperatures in tunnels. Early-season production also depends upon the flowering and fruiting patterns of individual cultivars and their interactions with the environment. Sweet Charlie produces fruit earlier than Camarosa. In tunnels, a 24 to 35% increase of early production was observed on Sweet Charlie compared with the field. No marketable yield differences were observed between the 7- and 14-day captan schedules in 1998-99 and between the 7-day captan schedule and the untreated control during the early period in 1999-2000. This could be the result of a lack of differences in *Botrytis* fruit rot incidence among fungicide treatments during the corresponding periods.

In Florida, a calendar-based fungicide spray program with weekly applications of

captan is the standard practice for commercial strawberry production. Such a program costs approximately \$1,400/ha (16). Even with standard fungicide applications, *Botrytis* fruit rot can still cause 10 to 15% losses of marketable yield on highly susceptible cultivars such as Sweet Charlie (7,9). In this study, tunnel culture reduced the incidence of *Botrytis* fruit rot to less than 2%, without fungicides. Thus, in addition to saving costs on fungicides, the use of tunnel culture could increase marketable yield compared with the standard conventional production system. During these experiments, yields of Sweet Charlie were 8 to 13% higher in tunnels than in the field, which adds up to \$2,000 to \$3,250/ha in farm gate revenue. The cost of building plastic tunnels with a metal frame is approximately \$28,000/ha, but the plastic

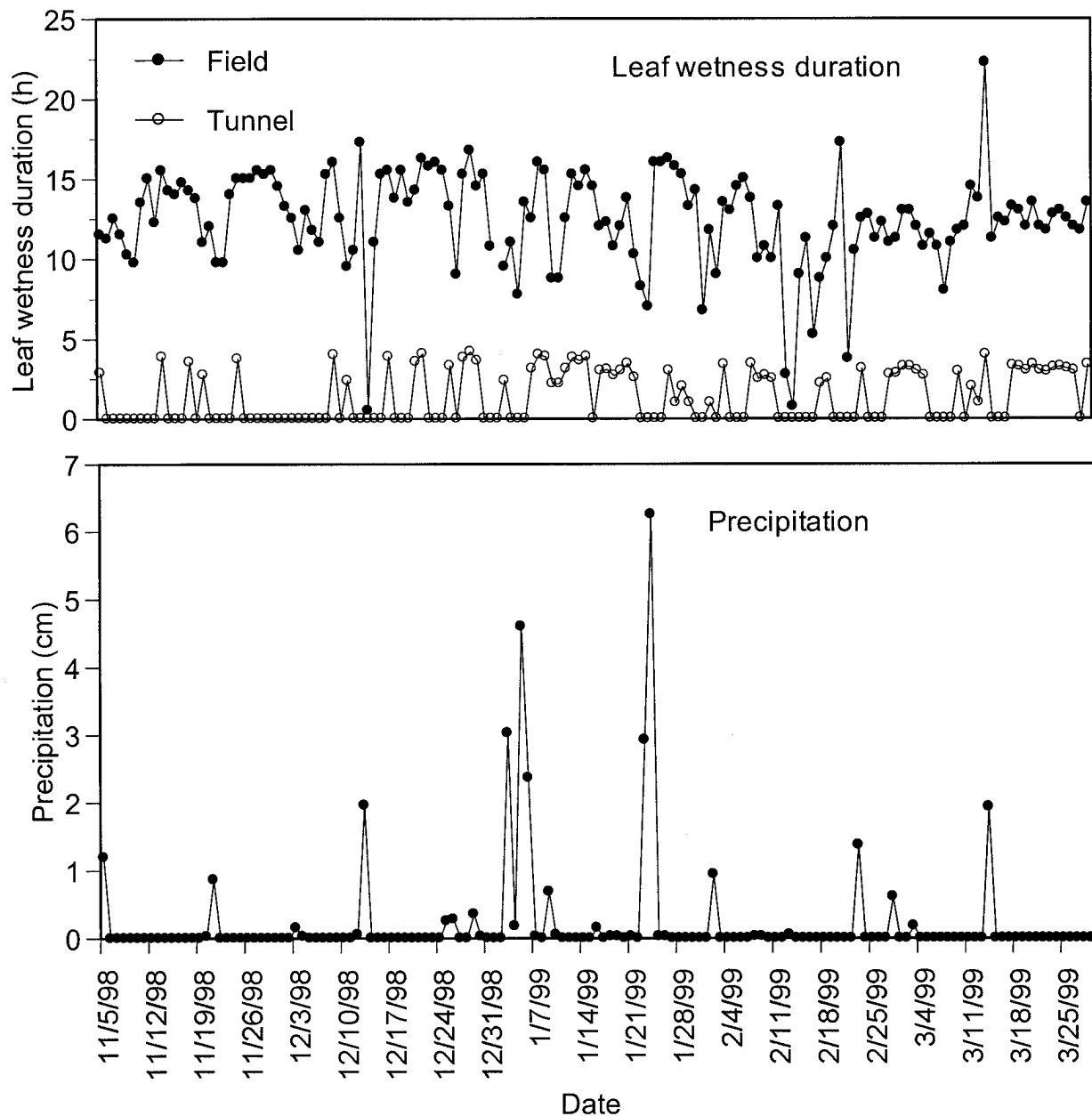


Fig. 4. Daily leaf-wetness durations and precipitation in the field and tunnel in the 1998-99 season (no precipitation observed in the tunnel).

cover can be used for 2 to 3 years and then replaced at a cost of \$8,000/ha. Apparently, the economic feasibility of tunnel production in Florida is questionable as a result of high start-up costs. Additional restrictions on fungicide use as a result of food safety concerns and the reduced availability of water for freeze protection in the region may force changes in production practices in Florida, which could make tunnel culture an attractive alternative.

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