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Control of *Botrytis cinerea* in glasshouse fuchsia by specific climate management

S. Friedrich*, D. Gebelein and C. Boyle
*Institute for Plant Protection in Horticultural Crops, Federal Biological Research Centre for Agriculture and Forestry, Messeweg 11/12, D-38104 Braunschweig, Germany; *Address for correspondence: Lessingstrasse 26, D-02994 Wiednitz, Germany (E-mail: stephanie.friedrich@addcom.de)*

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Abstract

The effect of climate management as a tool for integrated control of *Botrytis cinerea* in fuchsia culture was studied in two glasshouse experiments. This included: (i) a conventional, temperature based (T) and (ii) a humidity/temperature based (HT) climate control. When neighbouring plants came in contact with one another, a novel, economical method of direct ventilation of the canopy was employed as an additional treatment in each glasshouse. Despite significant differences in plant growth, no distinct effects on the susceptibility of clonal fuchsia plants or on the growth rate of stem blight lesions within the canopy were found for the different climate managements. Using the HT strategy, the canopies were effectively dehumidified during the night in contrast to the T management. Towards the end of the cultivation, a period with dense canopies, direct ventilation was most effective in dehumidifying the canopy. The differences in microclimate were correlated with *B. cinerea* stem infection and sporulation incidence. Best results were achieved using a combination of the HT strategy with direct ventilation, reducing stem blight values to less than a third as compared to the T management. With regard to plant health, climate management in glasshouses can only be improved by specific manipulation of the canopy climate: in presence of susceptible plant tissue, a management providing vapour pressure deficit values within the canopy above 1 hPa, or more safely, 1.5 hPa, is recommended.

Introduction

Plant production under glass offers opportunities for specific control of climatic factors, both for the optimization of plant growth and for integrated control of pathogens (Tompkins and Hansen, 1948; Winspear et al., 1970; Meneses et al., 1994; Yunis et al., 1994; Hausbeck et al., 1996a, b). Despite the availability of climate control computers in horticulture, their potential for disease control is, in general, underexploited (Jarvis, 1989). This is due to the inadequate knowledge of the interrelationship of glasshouse climate management, canopy climate and plant susceptibility, and how these factors influence the population dynamics of the pathogen (Weritz, 1992; O'Neill, 1994). This information, however, is necessary to determine precisely which environmental conditions should be prevented in order to avoid an excessive and costly reduction of humidity by heating of the glasshouse (Nicot and Allex, 1991).

Disease control by specific climate management is most promising for pathogens which have critical climatic requirements for specific stages of development. Spore germination and infection of *Botrytis cinerea* was found to depend on air humidity values close to vapour saturation (Wilson, 1937; Nelson, 1951; Sirry, 1957; Kerssies, 1994; Williamson et al., 1995), or even on leaf wetness (Nair and Allen, 1993; Broome et al., 1995). This pathogen was therefore suitable to

develop a computer-aided climate management that inhibits disease development.

B. cinerea is an economically highly important pathogen in horticulture, usually controlled by frequent, prophylactic use of fungicides (Braun and Sutton, 1984; Bulger et al., 1987; de Visser, 1996; Raposo et al., 1996). This may lead to multiple resistance in the pathogen population (Moorman and Lease, 1992; Raposo et al., 1996).

The effects of different glasshouse climate strategies, alone or in combination with a novel direct canopy ventilation on microclimate, on plant growth and susceptibility as well as on disease progress are presented for the pathosystem *Fuchsia* × *hybrida*/*B. cinerea*.

Materials and methods

Climate management experiments to control *B. cinerea* in fuchsia culture were carried out in identical glasshouse compartments (120 m^2).

Plant material and culture

Four-week-old fuchsia plants (*Fuchsia* × *hybrida*, cv. Beacon), propagated from one mother plant, highly susceptible to *B. cinerea*, were planted in 11 cm plastic pots (substrate: Klasmann-Deilmann GmbH, Geeste-Großhesepe, Germany) (Table 1). The pots were placed on commercial aluminium benches (1.5 × 10 m) with an under-bench heating system. One bench per treatment was used. According to requirements, every 1–3 days drip irrigation was provided through three plastic tubes arranged lengthways on the benches covered with mats and a perforated polyethylene film surface. Plants were fertilized (75 mg l^{-1} N, 50 mg l^{-1} P_2O_5, 75 mg l^{-1} K_2O) during irrigation. They were spaced from an initial plant density of 49 to approximately 20 plants per square metre. The parasitic wasp *Encarsia formosa* was released prophylactically every two weeks to control white flies.

Table 1. Fuchsia culture time table of the climate control experiments in 1997 and 1998

Cultural measure	1997	1998
Striking	1st week of February	14 January
Planting of rooted cuttings	4 March	11 February
Pinching	10 March	19 February
Onset of differential climate control	10 March	23 February
Onset of fertilization	1 April	9 March
Start of the direct ventilation	4 April	25 March

Climate management

Glasshouse climate was controlled by climate computer (Micos 4000R, Sauter Cumulus AG, Freiburg, Germany). Conventional, temperature based (T) climate management was applied in one glasshouse compartment (Table 2). The strategy in the second compartment was a humidity/temperature based (HT) management, which consisted of controlled dehumidification combined with a drop of temperature in the morning (cool morning). Dehumidification of the glasshouse air took place by linear adjustment of the temperature threshold at which ventilation occurred according to the air humidity within the glasshouse. Thus, the greater the humidity within the glasshouse, the lower was the temperature at which ventilation was performed (Table 2). In order to reach the same mean temperature for a comparable plant development, the temperature threshold for heating had to be 1–1.5 °C higher in the HT strategy as compared to the T management.

Preliminary studies had shown that air humidity within the canopy is a crucial factor for disease progress. Therefore, a supplementary direct ventilation method was developed, allowing a specific and cost-effective reduction of the humidity within the canopy. On one of the two benches in each glasshouse compartment, three polyethylene pipes were laid lengthways onto the mats between the rows of the fuchsia plants. These pipes were 13.4 cm in girth with two holes of 2 mm diameter spaced at 20 cm intervals. They were connected to a radial ventilator (250 W, model: 52DSLG90 1 Ph., Airflow Lufttechnik GmbH, Rheinbach, Germany) on one end, the other end was closed. Beginning when neighbouring plants came in contact with one another (Table 1), the ventilator was automatically switched on at relative humidity values within the crop above 85% and turned off below 81%. The input air for the ventilator came from the same compartment from outside the canopy. Except for this direct ventilation, the fuchsia plants on both benches in each climate management zone were treated identically.

Table 2. Temperatures for heating and ventilation in two glasshouse compartments with different climate management in 1997 and 1998

Year	Start	Climate control	Time	Heating below (°C)	Ventilation above (°C)
1997	4 March	Both houses temperature based	all day	17	22
	10 March	Temperature based	all day	17	22
		Humidity/temperature based	7–9 am	4	5
			9–7 am	17	16 (at 90% RH)–24 (at 40% RH)
	10 April	Temperature based	all day	15	20
		Humidity/temperature based	7–9 am	4	5
			9–7 am	16	15 (at 90% RH)–23 (at 40% RH)
	9 May	Both houses temperature based	all day	8	12
1998	11 Febr.	Both houses temperature based	all day	17	22
	23 Febr.	Temperature based	all day	16	21
		Humidity/temperature based	7–9 am	3	5
			9–7 am	17	16 (at 90% RH)–24 (at 40% RH)
	3 April	Temperature based	all day	13.5	19
		Humidity/temperature based	7–9 am	3	5
			9–7 am	15	14 (at 90% RH)–22 (at 40% RH)
	30 April	Temperature based	all day	8	12
		Humidity/temperature based	7–9 am	3	5
			9–7 am	7	8 (at 90% RH)–16 (at 40% RH)

Climate measurement

Relative humidity and temperature within each canopy were recorded with a data logger (GERO Meßsysteme GmbH, Braunschweig, Germany) equipped with two combined sensors (Testoterm GmbH, Lenzkirch, Germany). The accuracy of the sensors was ±2% between 2 and 98% relative humidity and ±0.4 °C from 0 to 40 °C, respectively. Sensors were positioned 1 cm above the substrate surface as close to the main plant shoots as possible and, in order to minimize irradiation, facing to the north of the subject plant. Canopy climate was archived every 5 min and hourly mean values were calculated.

Hourly values of temperature and relative humidity of the glasshouse air, recorded by aspirated psychrometers approximately 15 cm above the canopy were supplied by the Institute for Plant Protection in Horticultural Crops of the Federal Biological Research Centre for Agriculture and Forestry.

Relative humidity provides information on the water vapour saturation percentage of the air at a given temperature and is, therefore, not suited to determine potential evaporation of surfaces of living tissue and possible moisture stress by itself (Stevens, 1916; Anderson, 1936; Delp, 1954). Consequently, the recorded relative humidity was converted into the corresponding water vapour pressure deficit (VPD) (Deutscher Wetterdienst, 1976). It was then possible to compare the epidemiologically relevant differences in the availability of water for the pathogen.

Plant growth

The growth of the plants exposed to the four different climate management and ventilation treatments was recorded weekly. At the end of the experiments (13 May 1997, 5 May 1998), the plant height, the number of nodes and the length of the internodes of the two upper stems, branching from the main stem, were assessed for 12 healthy fuchsia plants per treatment.

Plant susceptibility

On 8 and 22 April, 6 May 1997 healthy fuchsia plants, previously exposed to different climate conditions for 4, 6, and 8 weeks, were simultaneously removed from the glasshouses and tested for their susceptibility towards *Botrytis* stem blight by artificial inoculation.

To gain standardized inoculum, conidia of *B. cinerea*, obtained from a naturally infected fuchsia plant, were cultured on PDA medium for 10–14 days under laboratory conditions

(20–23 °C, day light). The conidia were formulated semi-solid: 20 g PDA medium and 40 g sterile glucose (100 g l^{-1})-Tween 80 (0.05%)-solution were heated until the agar was dissolved, cooled down to 35–40 °C and inoculated with *Botrytis* conidia (10^4 conidia ml^{-1}). The mixture was shaken in order to equally suspend conidia and to prevent the agar from gelling.

Four to six well-developed stems of fuchsia plants (8–12 plants per treatment) were inoculated in the middle of the shoots by applying 25 µl of this inoculum formulation to the stem surface from one axil to the opposite one. The tip of the Eppendorf pipette used was shortened to avoid wounding. Following inoculation all plants were exposed to the same infection-promoting conditions (air humidity about 100%) beneath a transparent film tent in a shaded glasshouse. Thus, differences in disease could be attributed to the effect of different culture conditions. Length of resulting stem blight lesions – non-inoculated control plants never showed stem lesions in the middle of the shoots – was recorded after 2, 6, and 8 or 9 days. The number of inoculated stems per plant was not always identical. Prior to statistical analysis, therefore, mean lesion length of each plant was calculated.

Disease assessment

One row of fuchsia along the perimeter of each bench served as a border to the assayed plants. Thirty healthy plants per treatment were marked 14 days after planting. The number of side stems naturally infected by *B. cinerea* was assessed weekly for each plant and the percentage of fuchsia with stem blight was calculated. The numbers of necrotic lower leaves and of leaves showing sporulation of *B. cinerea* were recorded weekly for each plant.

Additionally, the length of naturally occurring lesions on the marked four upper stems of each of these plants was measured. For each individual stem lesion, the weekly extension was calculated for the last two weeks of disease assessment. After lesions had been classified into size classes of >0–1, >1–2, >2–4, >4–7, and >7 cm, the mean lesion size and the weekly lesion extension rate were calculated for each size class and each treatment.

Conidia trapping

Conidial dispersal was monitored within the canopy of the different climate and ventilation treatments from 4 April to 13 May 1997 and 25 March to 10 May 1998. Every day between 9 and 10 am, 9-cm plastic Petri dishes (2 replicates per treatment) containing a selective medium for *B. cinerea* (Kerssies, 1990) were placed between the plants 10 cm below the top of the canopy. After 24 h of exposure, the plates were covered, incubated at room temperature (20–23 °C) for 6–10 days, and the number of colony-forming units per plate counted.

Results

Glasshouse climate

As compared to conventional, temperature based (T) climate management, the temperature drop in the humidity/temperature (HT) based strategy caused a short-term reduction in temperature of 6–7 °C at 8 am in both years (Figure 1a). This led to an approximately 0.5 °C lower mean temperature in the glasshouse with the HT strategy than in the T managed compartment (Table 3).

By the controlled dehumidification as well as the drop of temperature in the morning in the HT strategy, mean vapour pressure (VP) of the air was reduced throughout the day in both experiments (Figure 1b) compared to the T management. Thus using the HT strategy, the higher VPD during the night is not only due to the higher night temperature but also to a generally dryer glasshouse air. Due to frequent rainy weather with an overcast sky in 1998, glasshouse dehumidification was less effective and the differences between the climate strategies smaller than in 1997 (Figure 1b, c). Using the HT strategy, glasshouse VPD during the night was about 2 hPa higher in 1997 but only 1 hPa higher in 1998 compared to the T management.

Canopy climate

Whereas the air temperature within the fuchsia canopy differed only slightly from that of the surrounding air in the glasshouse, the epidemiologically relevant VPD during the night and early

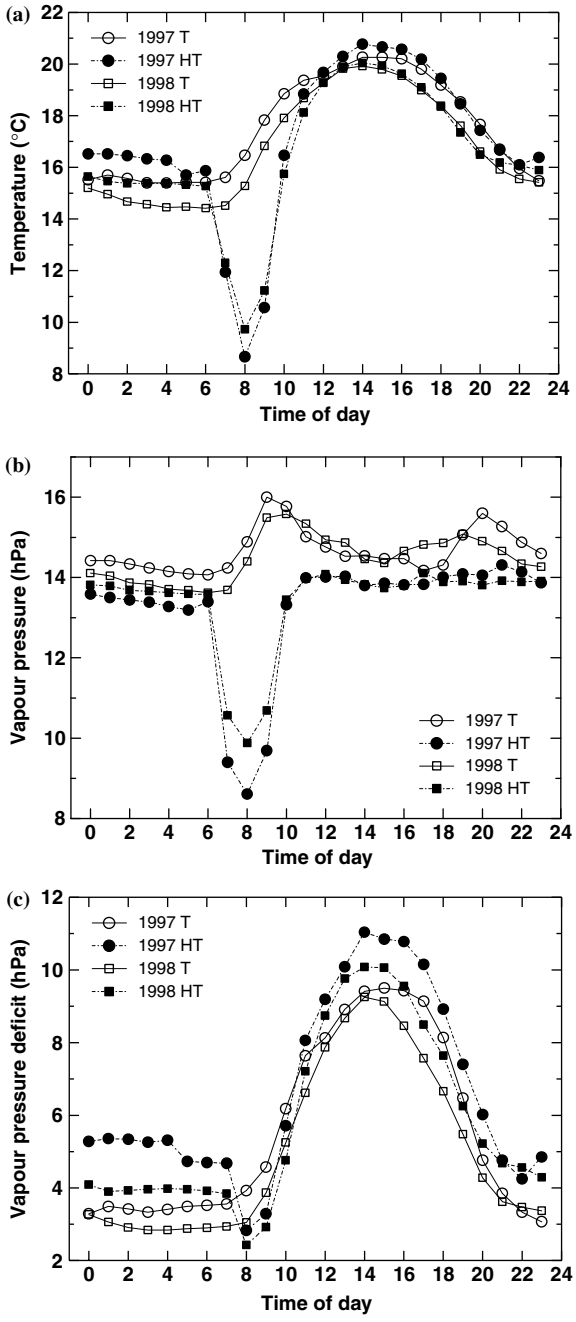

Figure 1. Mean diurnal temperature (a), vapour pressure (b) and vapour pressure deficit (c) within the glasshouse at two different climate managements (T = temperature based, HT = humidity/temperature based) in 1997 (11 March to 15 May) and 1998 (24 February to 12 May).

morning was several times less within the crop than in the glasshouse (Figure 2a). Using the HT strategy, the canopies were more effectively dehumidified at night in contrast to the T management (Figure 3). The temperature drop in the morning used for the HT strategy led to a distinct, though short-term VPD increase within the canopy and thus shortened the period of low VPD during the night and in the morning (Figures 2b and 3).

The additional direct ventilation of the canopy led to a distinct increase of VPD within the canopy compared to the non-ventilated treatment within the same glasshouse (Figures 2b and 3). Direct ventilation of the canopies mainly occurred at night and during the morning. As the difference between the VPD of the air in the glasshouse and in the canopy increased, the humidity-reducing effect of direct ventilation also increased (Figure 3b). A low VPD within the canopy could not be prevented in cases when the VPD within the glasshouse was low, too, such as on 18 April 1998 in the T treatment (Figure 3a).

Throughout the experiments, the direct ventilation of the canopy in the glasshouse with T management was more effective at dehumidification than the HT strategy applied for that same purpose. Especially towards the end of the cultivation, a period with dense canopies, it was only possible to ensure a proper dehumidification of the canopy by its direct ventilation (Figure 2b).

Leaf wetness and guttation were not observed during the experiment in the first year, however, both occurred during two humid periods in 1998. Condensation of water close to the stem base was never observed.

Plant growth

The development of fuchsia plants was similar in the four different climate management treatments and no significant differences were found for the number of nodes originating from the main stem (Table 4). Fuchsia plants subjected to the HT strategy, including a drop of temperature in the morning, however, were significantly shorter, as compared to those under T management, a criterion for better quality. In both trials, the first two internodes of the plants from the HT strategy were significantly shorter than those of the plants from the T management. Plants treated with the additional direct ventilation were approximately 1–3 cm shorter than non-ventilated plants of the same strategy.

Table 3. Mean temperature, vapour pressure and vapour pressure deficit within in the two glasshouse compartments with different climate management in 1997 (11 March to 15 May) and 1998 (24 February to 12 May)

Climate control	1997			1998		
	Temperature (°C)	Vapour pressure (hPa)	Vapour pressure deficit (hPa)	Temperature (°C)	Vapour pressure (hPa)	Vapour pressure deficit (hPa)
Temperature based	17.5[a1]	14.7[a]	5.5[a]	16.8[a]	14.5[a]	5.0[a]
Humidity/temperature based	17.0[b]	13.2[b]	6.6[b]	16.4[b]	13.4[b]	5.8[b]

[1] Means followed by the same letter within a column do not differ ($P < 0.05$) according to the paired samples t test.

Susceptibility of plants following climate management

In comparing fuchsia plants subjected to different climate management treatments for 4, 6, and 8 weeks prior to simultaneous artificial inoculation, however, no clear and consistent differences in lesion extension of the genetically identical plants could be detected. When inoculated after 4 weeks of exposure to different climate

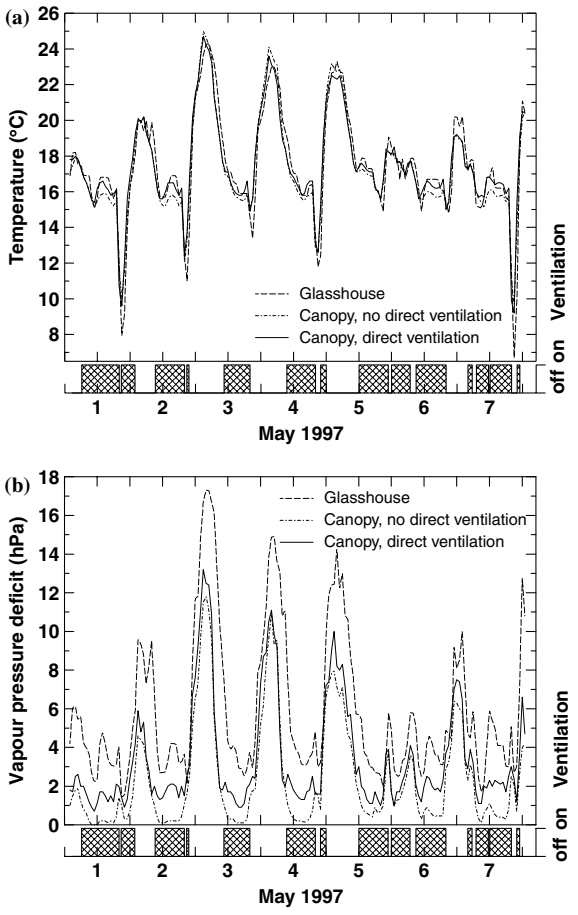

Figure 2. Temperature (a) and vapour pressure deficit (b) within the glasshouse and inside the fuchsia canopies (no direct ventilation, direct ventilation) using a humidity/temperature based climate management, beginning of May 1997.

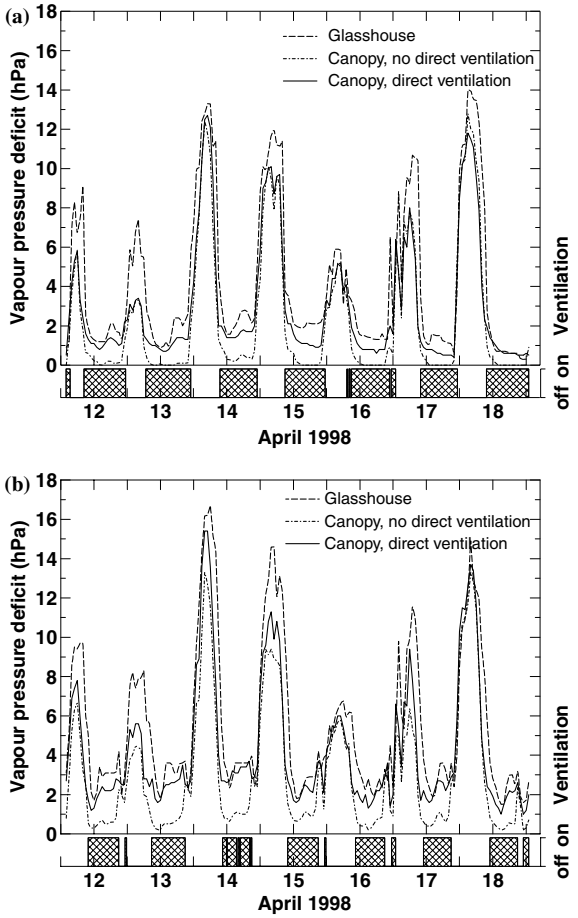

Figure 3. Vapour pressure deficit within the glasshouse and inside the fuchsia canopies (no direct ventilation, direct ventilation) using a temperature based (a) and a humidity/temperature based climate management (b), 12–18 April 1998.

Table 4. Influence of the different climate management and ventilation treatments on plant growth at the end of the experiments in 1997 and 1998

Year	Climate control	Direct ventilation	Plant height (cm)	Node number	Length of internode (cm)					
					1[1]	2	3	4	5	6
1997	Temperature based	No	47.7[a 2]	7.5[a]	2.7[a]	4.9[a]	5.2[a]	5.9[a]	6.0[a]	6.2[a]
		Yes	43.0[b]	7.5[a]	2.7[a]	5.1[a]	5.2[a]	5.9[a]	6.1[a]	6.0[a]
	Humidity/temperature based	No	41.0[b]	6.5[a]	2.0[b]	4.6[b]	5.1[a]	5.9[a]	6.0[a]	5.4[b]
		Yes	37.7[c]	7.0[a]	2.2[b]	4.3[c]	4.6[b]	5.3[b]	5.5[b]	5.2[b]
1998	Temperature based	No	56.3[a]	8.5[a]	2.5[a]	5.2[a]	5.2[a]	5.8[a]	6.2[a]	6.4[a]
		Yes	55.3[a]	8.6[a]	2.5[a]	4.9[b]	5.3[a]	5.5[ab]	6.2[a]	6.3[ac]
	Humidity/temperature based	No	52.0[b]	8.0[a]	1.7[b]	3.8[c]	5.0[a]	5.9[a]	7.1[b]	7.3[b]
		Yes	49.6[c]	8.1[a]	2.0[c]	3.7[c]	4.3[b]	5.0[b]	5.5[c]	5.8[c]

[1] Internode number one corresponds to the first internode formed at the pinched main stem and so on.
[2] The significance of differences between the treatments was tested for each year. Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

managements, no significant difference in plant susceptibility was found (Table 5), plants exposed to the T management for 6 weeks tended to be less susceptible, however the opposite could be stated after 8 weeks of exposure. Direct ventilation had no effect on host susceptibility in any of the two strategies.

Stem infection

Up to two weeks after planting, stem infection leading to individual plant death was observed in approximately 1% of the crop. This was attributed to injuries during planting. The climate management was identical in all treatments up to that time (Table 1).

On the symptomless plants marked 14 days after transplanting in order to exclude an effect of wounding, the first stem blight lesions appeared 6–7 weeks after planting, at the beginning or in the middle of April. At this time, the epidermis of the fuchsia plants began to split open from the stem base upwards and died off at the edges as a natural process of secondary thickening. Reimann et al. (1999) showed that even under massive infection pressure, conidia of *B. cinerea* could only induce stem lesions at areas with dead tissue, like those occurring due to secondary thickening. During the experiments, the majority of stem blight lesions originated from these locations close to the substrate and successively expanded over the stems.

From 25 April to 6 May 1997, a very high humidity with values below 2 hPa was prevalent in the glasshouse, and values of approximately 0 hPa were measured within the canopy of the T management during the night and early morning. Rapid disease development was detected during this period in the corresponding treatment (Figure 4a). Using the HT strategy, humidity values of about 4 hPa were found for the glasshouse air with corresponding values within the dense canopy between 0 and 1 hPa during the night. Disease increase was reduced to half of that of the T treatment during this period. Due to direct

Table 5. Stem lesion length (mm) of clonal *Fuchsia* × *hybrida* plants treated with different climate and ventilation managements for 4, 6, and 8 weeks in 1997. Healthy plants were simultaneously removed from the greenhouse, inoculated with *B. cinerea* and incubated at identical infection-promoting conditions

Climate control	Direct ventilation	Date of plant removal		
		8 April	22 April	6 May
Temperature based	No	35.7[a1]	50.0[a]	70.5[a]
	Yes	27.0[a]	56.6[ab]	73.9[a]
Humidity/temperature based	No	23.7[a]	63.7[b]	64.7[ab]
	Yes	28.2[a]	59.9[ab]	59.4[b]

[1] Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

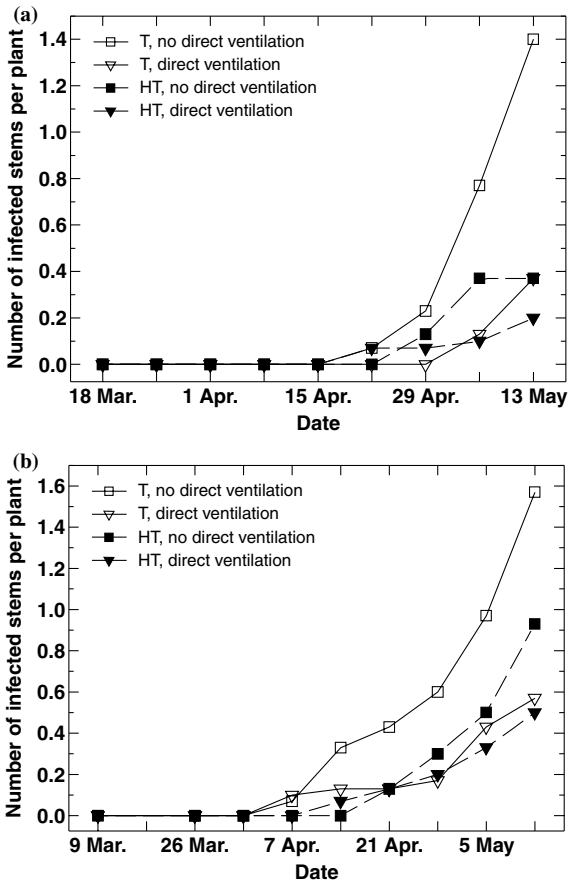

Figure 4. Influence of climate management (T = temperature based, HT = humidity/temperature based) and direct ventilation on stem infection in 1997 (a) and 1998 (b).

ventilation the canopy humidity could be reduced to 1–2 hPa during the night in this critical period (Figure 2b). In both compartments disease progress was minimized.

Between 1 and 9 April 1998, VPD values were about 0 hPa throughout the night and morning within the canopy with no additional ventilation under T management. This is correlated with an increased disease severity in the middle of April (Figure 4b). The reduction in humidity within the canopies of the other three treatments was sufficient to prevent new stem lesions during this period. A second infection phase occurred after a very humid period on 28 and 29 April during which a noteworthy reduction in humidity could only be achieved within the canopies by direct ventilation. Subsequent disease progress was lowest in these treatments.

Throughout both experiments, there was no substantial disease increase when VPD values within the canopy were above 0.5–1 hPa during the night and early morning. Disease progress was usually most rapid during the last 2–3 weeks of fuchsia culture. This was due to the simultaneous presence of necrotic tissue (senescent leaves, dead epidermal stem cells) and abundant inoculum, combined with dense canopies. During this period, reliable and effective dehumidification of the crop could only be achieved by direct ventilation (Figure 2b). It resulted in a substantially slower stem infection rate than in non-ventilated crops, culminating in a 2–3 times lower final disease level as compared to the corresponding non-ventilated treatments (Figure 4, Table 6).

In contrast to the first year it was cloudier during 1998, leading to lower VPD values within the glasshouses for both climate strategies (Table 3). Thus, it was more difficult to ensure a proper reduction in canopy humidity by the different indirect and/or direct dehumidification

Table 6. Number of infected stems per plant and percentage of fuchsia with stems infected by *B. cinerea* at the end of the climate management and ventilation experiments in 1997 and 1998

Climate control	Direct ventilation	1997		1998	
		Infected stem			
		Number	(%)	Number	(%)
Temperature based	No	1.40[a1]	43.3[a]	1.57[a]	60.0[a]
	Yes	0.37[b]	16.7[b]	0.57[b]	30.0[b]
Humidity/temperature based	No	0.37[b]	6.7[b]	0.93[b]	46.7[ab]
	Yes	0.20[b]	10.0[b]	0.50[b]	23.3[b]

[1] Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

treatments, resulting in a smaller effect on the final disease level in 1998 as compared to 1997 (Figure 4).

The highest stem infection of fuchsia by *B. cinerea* at the end of the cultivation period was always assessed with the T management, where 43 and 60% of the fuchsia were infected in the first and second year, respectively (Table 6). All dehumidification treatments reduced stem infection considerably, differences were significant with one exception. The effect of HT strategy and direct ventilation on stem blight occurrence and severity are comparable, with an advantage for direct ventilation during the second, more humid investigation period. The best results were achieved using a combination of HT strategy and direct ventilation, what reduced the number of infected stems to 14% or 32% of the values with T management alone.

Blight progression in naturally infected stems

The extension rate of stem blight lesions increased with increasing lesion length (Figure 5) and differed significantly for the lesions of different size classes in both years (Table 7). Comparing the climate management and ventilation treatments, however, there was no statistically significant difference in the extension rate of lesions of the same size class in both years. The classification into size classes was necessary. Lesions occurring on the highly infected plants of the T management without direct ventilation were on average much longer than those on plants from directly ventilated canopies. By calculating the arithmetic mean of weekly stem lesion extension for each treatment, results would have been distorted due to higher growth rates for longer lesions (Table 7).

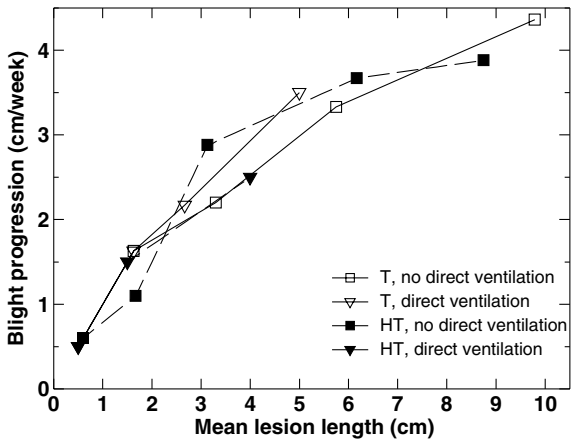

Figure 5. Weekly extension of *Botrytis* stem blight lesions within the fuchsia canopies of different climate management (T = temperature based, HT = humidity/temperature based) and ventilation treatments in relation to mean lesion length in the period from 29 April to 13 May 1997.

Table 7. Weekly extension of naturally infected stem blight lesions (mm) in dependence of the lesion size in 1997 and 1998

Size class (cm)	1997	1998
> 0–1	0.58[a] [1]	0.52[a]
> 1–2	1.52[b]	1.02[b]
> 2–4	2.33[c]	2.22[c]
> 4–7	3.45[d]	2.56[cd]
> 7 cm	4.18[e]	2.87[d]

[1] Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

Incidence of fuchsia plants with B. cinerea *sporulating on necrotic leaves*

Only naturally senescent and necrotic lower fuchsia leaves were visibly colonized by the pathogen, except during two very humid periods in 1998, which led to leaf wetness and guttation in the glasshouse with T management, when healthy upper leaves were also invaded by the pathogen, starting from the margin. Leaves were also colonized secondarily by mycelium growing from stem blight lesions into the petiole.

Plants with *B. cinerea* sporulating on necrotic leaves were considerably less in both years when exposed to treatments which reduced canopy humidity as compared to plants of the T management (Table 8). As for stem infection a rapid increase in sporulation incidence was always observed after a period with VPD values close to saturation within the canopy during the night and early morning. For example, a greatly increased incidence of fuchsia plants showing sporulation of *B. cinerea* on necrotic leaves was observed on 14 April 1998 for the T management, after a period with canopy VPD values of about 0 hPa throughout the night and morning from 1 to 9 April 1998. The reduction in humidity within the canopies of the other three treatments during this period was sufficient to prevent sporulation.

Table 8. Percentage of fuchsia plants with necrotic leaves showing/not showing *B. cinerea* sporulation during the different climate management and ventilation treatments in 1997 and 1998

Climate control	Direct ventilation	Necrotic leaves with sporulating *B. cinerea*	1997				1998				
			22 Apr.	29 Apr.	6 May	13 May	7 Apr.	14 Apr.	21 Apr.	28 Apr.	5 May
Temperature based	No	No	6.7^{a1}	6.7^{a}	20.0^{a}	43.3^{a}	23.3^{a}	33.3^{a}	33.3^{ab}	36.7^{abcd}	63.3^{a}
	No	Yes	6.7^{a}	10.0^{a}	20.0^{a}	30.0^{ab}	6.7^{b}	40.0^{a}	46.7^{a}	50.0^{ab}	63.3^{a}
	Yes	No	0.0^{a}	0.0^{a}	10.0^{a}	23.3^{bc}	0.0^{b}	0.0^{b}	13.3^{c}	23.3^{cd}	33.3^{b}
	Yes	Yes	3.3^{a}	3.3^{a}	3.3^{a}	13.3^{bc}	3.3^{b}	3.3^{b}	3.3^{c}	16.7^{cd}	26.7^{b}
Humidity/tempera-ture based	No	No	0.0^{a}	3.3^{a}	6.7^{a}	10.0^{c}	0.0^{b}	10.0^{b}	36.7^{a}	53.3^{a}	76.7^{a}
	No	Yes	0.0^{a}	3.3^{a}	3.3^{a}	6.7^{c}	0.0^{b}	3.3^{b}	10.0^{c}	26.7^{bcd}	60.0^{a}
	Yes	No	0.0^{a}	6.7^{a}	6.7^{a}	10.0^{c}	0.0^{b}	10.0^{b}	16.7^{bc}	40.0^{abc}	63.3^{a}
	Yes	Yes	3.3^{a}	3.3^{a}	3.3^{a}	6.7^{c}	0.0^{b}	0.0^{b}	3.3^{c}	13.3^{d}	23.3^{b}

[1] Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

Throughout both experiments no substantial increase in sporulation incidence took place when VPD values within the canopy were above 0.5–1 hPa. Comparing the experimental years the incidence of *B. cinerea* sporulating on necrotic leaves in 1997 was half of that recorded in 1998.

In canopies with dehumidification measures (HT strategy, direct ventilation), it was observed that senescent/infected leaves dried more rapidly than under T management. This was accompanied by a reduced sporulation on dead plant material: The incidence of plants with necrotic leaves showing *B. cinerea* sporulation was lower than the corresponding incidence of plants with symptomless necrotic leaves. On 21 and 28 April 1998, for example, significantly less plants with leaves showing sporulation occurred in the HT strategy compared to the T treatment, despite a comparable incidence of plants with symptomless necrotic leaves in both compartments (Table 8). Close to the humid substrate surface, however, sporulation of the pathogen could not be totally prevented by the dehumidification techniques used.

B. cinerea *conidial dispersal*

The number of colony-forming units of *B. cinerea* recorded on the two replicate plates per treatment and day was very similar. High numbers of conidia were typically associated with human activity within the crop. The total number of colony-forming units recorded within the canopies of the T management was significantly higher as compared to the HT treatment in both experiments (Table 9). Irrespective of ventilation treatment, the number of conidia trapped daily in each glasshouse was very similar. Comparing the experimental years, regardless the climate management, half as many conidia were trapped in 1997 as compared to 1998, in which also the disease level was much higher.

Discussion

To develop an epidemiologically based climate management strategy as a tool for integrated control of *B. cinerea*, the interrelations between climate management of the glasshouse, canopy climate, plant predisposition, as well as their

Table 9. Number of colony-forming units of *B. cinerea* recorded within the fuchsia canopies of the different climate management and ventilation treatments during the exposure periods in 1997 and 1998

Climate control	Direct ventilation	1997	1998
Temperature based	No	333[a] [1]	718[a]
	Yes	250[a]	709[a]
Humidity/ temperature based	No	125[b]	209[b]
	Yes	121[b]	173[b]

[1] Means followed by the same letter within a column do not differ significantly according to the Waller–Duncan Bayesian *k*-ratio of 100, corresponding to alpha = 0.05.

influence on sporulation, infection, and lesion extension of the pathogen had to be studied.

The different climates within the glasshouses led to distinct differences in plant growth with a better quality for the plants from the HT strategy. However, no differences in susceptibility towards *B. cinerea* could be detected in the clonal fuchsia plants. Preliminary studies in 1996 with the same cultivar and management indicated the same results. This was not due to the used method, which displayed differences in the susceptibility of fuchsia plants from differently dense stands or with a different nutrient supply (S. Friedrich, D. Gebelein, and C. Boyle, unpublished). In other studies similarly, no significant correlations were found between environmental factors and the susceptibility of gerbera (Kerssies, 1996) and rose flowers (Hammer and Evensen, 1996; Kerssies, 1996) to postharvest infection by *B. cinerea*. In another study, the susceptibility of rose flowers to this pathogen, however, was inversely correlated to the overall mean VPD from 08:00 to 19:00 h for the 5-week growth period before harvest during different seasons of the year (Marois et al., 1988). A linear correlation was also found between the mean air velocity during the 5-week periods before each harvest and the postharvest susceptibility of rose flowers (Hammer and Evensen, 1996). In our study, however, differences of the climatic factors due to different climate managements during the same season were much smaller as compared to differences in glasshouse climate during different seasons.

In both experiments, no significant differences in growth rate of stem blight lesions occurring naturally within the fuchsia canopies of different climate management/ventilation treatments were found. This implies that expansion of *B. cinerea* within the stems of equally susceptible plants was not influenced by differences in the microclimate. Our results are in accordance to O'Neill et al. (1997) who stated that tissue rotting of tomato stems inoculated with *B. cinerea* was not increased by incubation at higher air humidity. Blowing forced heated air into the canopy of pelargonium plants did not reduce *Botrytis* stem blight progression (Hausbeck et al., 1996a) either.

On the other hand, apparently slight differences in the VPD values within the crop, occurring within the same glasshouse due to direct ventilation for example, considerably influenced infection and sporulation of *B. cinerea*. In our experiments, disease progress was minimized when VPD values within the fuchsia canopy were above 0.5–1 hPa during the night and early morning. In climate chamber studies, *B. cinerea* infection was still observed at higher VPD values: After 5 days of incubation at 0.84 hPa (94% RH, 12 °C) dry-inoculated grape berries were highly infected, and even at 1.4 hPa (90% RH, 12 °C) successful infections were caused (Nelson, 1951). After 2 days of incubation at 1.0 hPa (94% RH, 15 °C) a high percentage of dry-inoculated rose petals showed *Botrytis* lesions, no symptoms could be observed following an incubation at 1.7 hPa (90% RH, 15 °C) (Williamson et al., 1995). Similar results were obtained for *B. cinerea* on bean leaflets (Wilson, 1937) and cabbage leaves (Yoder and Whalen, 1975). On bean leaflets, being comparable to fuchsia leaves in relation to their water-retaining capacity, sporulation of *B. fabae* was still observed after 6 days of incubation at 93% RH and 20 °C (Harrison, 1984), corresponding to a VPD of 1.6 hPa. In contrast to these *in vitro* data with continuous constant conditions for several days, periods of high humidity within the fuchsia canopy were usually interrupted at daytime. No information, however, is available on the effect of intermittent dry periods on infection and sporulation of *B. cinerea*. The water content of ungerminated *B. cinerea* conidia is low (Yarwood, 1950), thus they have to take up water for germination and infection. During shorter infection promoting periods higher humidity values will be required in the glasshouse compared to those found in climate chamber experiments.

High numbers of *B. cinerea* conidia were typically associated with human activity. The same was found for pelargonium stock plant (Hausbeck and Pennypacker, 1991) and strawberry culture (Jarvis, 1962). During our experiments, the total number of conidia trapped within fuchsia canopies in T managed glasshouses was 2–3 times as high as compared to the HT strategy. The reduction of humidity within the crop led to a rapid drying-out of senescent and infected plant material and, compared to the T management, led to a reduction of the incidence of plants with *B. cinerea* sporulating on necrotic leaves. Furthermore, the generally higher disease level within the glasshouses with T management as compared to the HT strategy will have contributed to the higher spore catches. Also Hausbeck et al. (1996b) reported that an application of forced heated air reduced sporulation of *B. cinerea* on necrotic leaves and blighted stems.

Due to micrometeorological effects close to the humid substrate surface, however, sporulation of the pathogen on necrotic/infected leaves could not be totally prevented by the dehumidification techniques used. A further reduction in inoculum potential will only be obtained by culture techniques leading to a dry substrate surface. The potential of the different climate strategies ought to be considerably enhanced by this culture measure. Hausbeck et al. (1996a) found that white plastic mulch on top of the pots in combination with forced heated air considerably reduced *B. cinerea* sporulation on necrotic lower leaves of pelargonium stock plants.

The lower *Botrytis* stem infection that occurred under the HT climate strategy resulted from the greater VPD during the night and early morning. The higher VPD was attained by the controlled dehumidification including a drop of temperature in the morning – what led to a generally lower vapour pressure – in combination with a slightly greater night time heating compared to the T management. The latter was necessary in order to achieve overall similar mean temperatures for a comparable plant development between the HT and T climate control regimes.

The HT strategy reached its limits, however, at the end of the culture period as soon as the canopies became dense. Within the same glasshouse, differences in canopy climate due to variation in the irrigation and heating system as well as plant density had an effect on stem blight of fuchsia (Lange, 1999). This explains why disease control by a climate management oriented towards the reduction of glasshouse humidity alone was not always sufficient.

A substantial improvement of climate management with regard to plant health can, therefore, only be achieved by the specific manipulation of the canopy climate. This ensures a sufficient dehumidification while an expensive, excessive reduction of humidity within the crop by exorbitant heating (Tompkins and Hansen, 1948; Winspear et al., 1970) can thus be avoided. In our experiments, a new method of direct ventilation was applied whenever humidity within the canopy exceeded 85% RH. Blowing dryer glasshouse air into the canopy through perforated pipes reduced air humidity specifically and more economically as compared to Hausbeck et al. (1996b) who irrespectively of the prevailing humidity values used continuous forced heated air from beneath the bench to dehumidify geranium canopies. The direct ventilation reduced stem blight to one-third and sporulation on necrotic leaves to half of that in the corresponding non-ventilated T management. Thus direct ventilation is considered to be a low cost tool to effectively reduce humidity and, as a result, *B. cinerea* incidence within dense canopies of any other low-growing culture. This includes ornamentals such as azalea, poinsettia, pelargonium, and cyclamen as well as horticultural crops as head lettuce.

It can be concluded, that a specific climate and/or ventilation management such as the HT strategy and/or direct ventilation is an effective tool with regard to integrated control of *B. cinerea*. The climate management should provide VPD values within the canopy above 1 hPa, or more safely, 1.5 hPa in order to substantially hamper sporulation as well as infection of the pathogen, not only on fuchsia. In the presence of senescent or infected plant tissue, culture techniques leading to a dry substrate surface should accompany climate management to reduce microclimatic effects of the substrate surface. No adverse effect of the changed climate on plant growth was observed and is to be expected due to the comparatively small changes in air humidity from the point of view of the plants. The 'cool morning' temperature control used in the HT strategy, additionally, is a standard method to obtain a better plant quality. In order

to determine the overall cost-effectiveness of the HT strategy alone or in combination with the direct ventilation compared to the T management, an analysis of heating costs would need to be carried out.

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