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Field evaluation of a supervised control system for *Botrytis* leaf blight in spring sown onions in the Netherlands

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Abstract

Between 1988 and 1992 two existing weather based advisory models to control leaf blight in onions, were evaluated in the Netherlands. The first model, BOTCAST, can be used to time the initial spray while the second model, SIV, can be used to advise on every subsequent spraying. The evaluation based on field trials showed that application of both BOTCAST and SIV can reduce the number of sprays by 54% compared to a weekly spraying program without any yield loss or a higher disease severity. There was no relation between yield losses of untreated plots and disease severity expressed as lesion counts or leaf dieback. Relative disease growth rate was significantly but not closely related to weather based model characteristics or the observed crop micro-climate using linear regression analysis. The model characteristics did not yield better regressions than the climatological characteristics. Two changes to improve BOTCAST are proposed. Introduction of a supervised control system based on BOTCAST and SIV seems only economically feasible when the system is used as a regional warning system.

Introduction

Leaf blight in onions is primarily caused by the fungus *Botrytis squamosa*. In the Netherlands the disease was first found in 1965 (Tichelaar, 1966). The development of lesions on the green leaves (leaf spots) followed by blighting of the leaves are characteristic for this disease (Hancock and Lorbeer, 1963; Sutton et al., 1990). To control the disease, farmers are advised to apply preventive fungicides on a weekly basis from the moment that onion plants touch each other between rows until the leaves fall over. Depending on the development rate of the onion crop this amounts to 6–8 sprays per year. In trials carried out by Shoemaker and Lorbeer (1977a) the yield loss on untreated plots caused by *Botrytis squamosa* ranged from 7 to 30%. In fungicide trials carried out in the Netherlands between 1976 and 1987 the yield depression in untreated plots varied from 0% when disease was not present to a maximum of 26% (Hoek, pers. com.). The large variation in yield depressions can be partly explained by variation in the extent to which circumstances are favourable for the development of lesions or for leaf blighting.

Weather conditions influence disease development to a large extent (Alderman et al., 1987). Therefore weather based supervised control systems have been developed to rationalise and thus reduce pesticide use. Sutton et al. (1986) developed the disease forecasting model BOTCAST which can be used to time the first spray. After applying the first spray a weekly spraying schedule was advised. Earlier Lacy and Pontius (1983) developed a sporulation forecasting model, named SIV, that can be used to time the subsequent sprayings. In this advisory model the first spray was applied when leaves touch each other between rows.

The combinaton of both models might offer a useful integrated supervised control system for leaf blight in spring sown onions in the Netherlands. It was expected that this combination would provide farmers with a tool to meet the government goal that aims at a reduction of pesticide applications in arable farming by 25% from 1988 to the year 2000 and at the same time reduce the costs of onion growing.

In this paper BOTCAST, SIV and their combination are evaluated with respect to the number of sprays applied, the yield reached, the disease severity developed and the relation between relative disease growth rate and model characteristics.

Materials and methods

Structure of BOTCAST and SIV

On the basis of hourly measured data on temperature, relative humidity, leaf wetness and rainfall BOTCAST calculates a Daily Inoculum Value (DINOV), which indicates whether or not the circumstances were suitable for spore production, and a Daily Infection Value (DINFV), which represents the extent to which the circumstances were suitable for infection. The values of DINOV (0 or 1) and DINFV (0, 1 or 2) on day i are multiplied to give a Daily Disease Severity Index (DSI). The longevity of spores is accounted for by multiplying $DINFV_i$ by $DINOV_{i-1}$ when $DINOV_i$ is 0, $DINOV_{i-1}$ equals 1 and the spores produced on the preceding day have not led to infection ($DINFV_{i-1}$ = 0). Essentially the DSI is not an expression of disease severity, but an indication of probability of disease increase. However, the original term is used throughout the paper. From the day that 50% of the onions have emerged the DSI is accumulated to give the Cumulative Disease Severity Index (CDSI). A spray is advised as soon as a threshold value is exceeded. Sutton et al. (1986) proposed two threshold values. As soon as a CDSI-value of 30 was reached the authors advised a frequent monitoring of the disease. This value preceded rapid disease increase by 2–3 weeks. At a CDSI value of 40 a spray was advised as this value preceded rapid disease increase only by a few days. Subsequent sprays are not supported by BOTCAST.

Like BOTCAST, the SIV-model is based on historical weather data. The model produces a Sporulation Index Value (SIV) that is based on hourly measurements of temperature and relative humidity. The SIV represents the extent to which the weather has been favourable for sporulation of *Botrytis squamosa*. Infection is not considered in this model. Lacy and Pontius (1983) used hourly data on relative humidity and temperature to calculate the vapour pressure deficit (VPD). The authors measured temperature and VPD data during a three day period and related these values empirically to spore catches to give the SIV-value. Contrary to the CDSI, the SIV is not a cumulative figure. Whenever the SIV passes the threshold value and 7 or more days have elapsed since the preceding spraying, a new spray should be applied within 24 hours. Lacy and Pontius (1983) advised a SIV threshold value of 50, but stated that this value should be adapted to local conditions.

Table 1. Spraying programs evaluated in the trials

Start of spraying	Subsequent spraying	Year 1988	1989	1990	1991	1992
Closed crop[1]	Weekly	x	x	x	x	x
	SIV = 40	x	x	x	–	–
	SIV = 80	x	x	x	x	x
CDSI = 30	Weekly	x	x	x	–	–
	SIV = 40	x	x	x	–	–
	SIV = 80	x	x	x	–	–
CDSI = 40	Weekly	x	x	x	x	x
	SIV = 40	x	x	x	–	–
	SIV = 80	x	x	x	x	x

[1] closed crop = the time when onion leaves touch each other between rows. This is the standard advice to farmers to start spraying.

Treatments in field trials

Between 1988 and 1992 five field trials were conducted to evaluate both BOTCAST and SIV. In our trials the CDSI-thresholds of 30 and 40, advised by Sutton et al. (1986), were tested together with arbitrarily chosen SIV thresholds of 40 and 80. In the field trials several possible combinations to time both the initial and the subsequent sprays as indicated in Table 1, were tested. An untreated control was added. Spraying stopped when 50% of the leaves had fallen over (foliar collapse) as is the current practice in the Netherlands. In the years 1988–1991 the fungicide chlorothalonil/vinchlozolin (50/16.7%) at a rate of 1 kg ha^{-1} was used to control leaf blight. In 1992 2.5 kg ha^{-1} maneb/vinchlozolin (64/10%) and 2 kg ha^{-1} maneb/chlorothalonil (50/25%) were applied in an alternating spray schedule.

In 1991 the spraying strategies were applied on plots receiving a low or a high amount of nitrogen fertiliser (50 or 200 kg N ha^{-1}). In 1992 the spraying strategies were tested in early and late sown plots (9 or 29 April). The nitrogen and sowing date treatments were added to enlarge the crop types and thereby the range of micro-climates tested. In 1988, 1989, 1990 and 1991 these plots were distributed over 4 replications in a complete randomised block design. The trial in 1992 was set up as a split plot design with the fac-

Table 2. Characteristics of the onion crops in the five trials

	1988	1989	1990	1991 N rate (kg ha^{-1})		1992 Sowing	
				50	200	Early	Late
Plant density (m^{-2})	78	103	63	100	100	99	85
Plot size (m × m):							
– Total	3 × 7.5	3 × 7.5	3 × 7.5	3 × 10	3 × 10	4.5 × 13	4.5 × 13
– Net	1.8 × 6	1.8 × 6	1.8 × 6	1.8 × 8	1.8 × 8	1.5 × 11	1.5 × 11
Sowing date	19/4	10/4	10/4	3/4	3/4	9/4	29/4
Date of 50% emergence	6/5	2/5	7/5	24/4	24/4	30/4	15/5
Date that crop closed[1]	29/6	15/6	26/6	5/7	5/7	11/6	29/6
Date of 50% foliar collapse	23/8	31/7	4/9	20/8	20/8	7/8	24/8
Harvest date	6/9	23/8	3/10	12/9	12/9	24/8	10/9
date at CDSI-threshold:							
– 30	12/7	–[2]	25/6	27/6	26/6	9/6	16/6
– 40	18/7	–[2]	6/7	10/7	10/7	26/6	27/6
% days[3] with:							
– SIV $\geq$ 40	95	26	46	74	72	66	84
– SIV $\geq$ 80	68	11	15	38	43	38	61

[1] Closed crop = the time when onion leaves touch each other between rows. This is the standard advice to farmers to start spraying.
[2] The value of the CDSI at harvest was only 19.
[3] The days between the day when onion leaves touched each other between rows and the day of 50% foliar collapse are taken into account, because in this time period sprays are applied.

tor sowing time randomised over the main plots and spraying programs randomised over the subplots. In all trials the cultivar Robusta was used. The onions were sown in beds of 1.5 m wide with 5 rows at 27 cm distance per bed. The distance between adjacent beds was 42 cm. Additional crop characteristics are given in Table 2.

Micro-climate

To apply BOTCAST and SIV hourly values are needed for temperature, relative humidity (RH), leaf wetness and rain. RH and leaf wetness were measured in the onion crop while data on temperature (at 150 cm) were obtained from a permanent automatic weather station except for 1992 when temperature was measured within the crop. The weather station from which also rain data were obtained in all years, was situated within 1 km of the trials. In each trial the RH was measured with electronic sensors. During the first three years, an Eliwell EWHS-31 and a Rotronic YA-100/C80 sensor were used and in the last two years four Vaisala HMA-31 OTA sensors. In 1988 leaf wetness was measured with a DeWit sensor and in other years with electronic sensors that were made according to the specifications kindly provided by James (pers. com.) and that were used by Sutton et al. (1986) in some of their trials. The sensors were cylindrical, 20 cm long with a 1.3 cm outer diameter and 0.6 cm inner diameter and were made of plexiglas. The sensors were coated with white oil-based paint. Two spiral grooves 1.5 mm apart and 0.5 mm deep were cut in the sensor surface. Two nickel wires of 0.25 mm were wound in the grooves. The electronic leaf wetness sensors registered a voltage between 0 and 1 V. Measurements in the laboratory showed that the voltage increased according to a diminishing returns curve with an increasing number of water droplets. Leaves were arbitrarily assumed to be wet when at least two of the four registered values per hour were higher than 0.2 V. A Kaye Digistrip II Datalogger (1988–1990) or a Squirrel SQ 32-4V/84/41 datalogger (1991 and 1992) were used to register twice per hour the output of the electronic sensors that were situated in the onion crop. In 1988–1990 two electronic RH sensors and two leaf wetness sensors were used and four in 1991 and 1992 (two for each fertiliser treatment respectively each sowing date).

Yield level

In 1988–1991 the yield and the number of bulbs were determined by harvesting 6 m of 6 middle rows (10.62 m^2) of each plot that consisted of 10 rows, when approximately 50% of the leaves were dead. In 1992 10 m of the middle bed of each three beds wide plot were harvested (15 m^2). The onions were artificially dried at 30 °C until the necks were dry and subsequently weighed and counted.

Disease severity

In 1988 no observations on disease severity were made while in 1989 the disease was not present. In 1990 disease severity was scored by counting the number of lesions on the oldest green leaf of 12 randomly selected plants per plot. This was done on 10 occasions with an average interval of 10 days. The oldest green leaf was defined as the oldest leaf of which the surface was still more than 50% green. The one-sided leaf area of the collected leaves was measured with a LI-3100 area meter. In 1991 and 1992, 6 randomly chosen plants per plot were collected 8 and 10 times with average intervals of 9 and 7 days respectively. The number of lesions on each leaf was counted and the length of the green and dead part of the leaf was measured. On heavily infected leaves the number of lesions was estimated. Disease severity at any observation date was expressed as the number of lesions per dm^2 of green leaf surface. The disease severity during the season was calculated as the area under the disease progress curve according to Vincelli and Lorbeer (1989):

$$\mathrm{AUDPC}_i = \sum_{i=1}^{n-1} 0.5(\mathrm{lesions}_{i+1} + \mathrm{lesion}_i)(t_{i+1} - t_i) \quad (1)$$

where t_i is the daynumber and lesion_i is the number of lesions (dm^{-2}) on observation day i and n is the number of observation dates. Disease assessments after foliar collapse (fall-over of the leaves) were not included in the AUDPC-value (d dm^{-2}). Foliar collapse indicates maturity of the crop. The AUDPC-value referred to a period of 69 days in 1990, 52 days in 1991 for both fertiliser treatments and 35 and 49 days in 1992 for the early and late sowing date.

Relative disease growth rate

The relative disease growth rate (RGR) was calculated as follows (Zadoks and Schein, 1979):

$$\mathrm{RGR} = (t_2 - t_1)^{-1} * \ln(\mathrm{lesions}_2/\mathrm{lesions}_1) \quad (2)$$

where t_1 and t_2 are the day numbers of two successive dates of disease assessment and lesion_1 and lesion_2 represent the corresponding lesion densities (dm^{-2}) observed in 1990, in 1991 at both fertiliser levels and in 1992 in both the early and late sown crops. The RGR was related to SIV, DINOV, DINFV and DSI and to climatological characteristics averaged over the corresponding periods between successive dates of disease assessment. The characteristics were related according to a linear or quadratic model using linear regression analysis. It was expected that the model characteristics would yield better relations with RGR than the climatological characteristics.

Statistical analysis was performed using the Genstat 5 release 3 package (Payne et al., 1993).

Results

Yield and number of sprays applied in 1988 and 1989

In 1988 untreated plots yielded 9.8% less than treated plots (Table 3). Application of BOTCAST at both thresholds did not influence yield compared to the standard advice. The lower SIV-threshold resulted in a higher yield than the higher threshold or the weekly spraying schedule: 66.2 resp. 63.8 and 62.5 t ha^{-1}. However, the number and timing of sprays did not differ between the lower threshold value and the weekly spraying schedule. Application of BOTCAST at CDSI-thresholds of 30 or 40 decreased the number of sprays by two and three while the SIV-threshold of 80 additionally lowered the number of sprays by two.

In the warm and dry year of 1989 no significant differences in yield levels between treatments could be detected (Table 3) and there was no disease. Using BOTCAST spraying was never advised. However, the application of SIV after sprays started according to the practical advice, resulted in three sprays at both the SIV thresholds.

Yield, number of sprays and disease severity in 1990

In 1990 drought stress during germination and emergence of the crop led to a low plant density (Table 2) and thus a late maturing crop. This explains the high number of sprays according to the weekly spray schedule (Table 4). The significantly higher AUDPC-value of the untreated plots compared to the treated plots was not followed by a corresponding difference in yield level. The application of the CDSI-threshold of 40 resulted in a 5.9% higher yield compared to the CDSI-value of 30 and the practical advice, while the corre-

Table 3. Onion yield (t ha^{-1}) and number of sprays applied in 1988 and 1989 depending on the treatment

Treatment		Yield (t ha^{-1})		Number of sprays applied	
Start of sprays	Subsequent sprays	1988	1989	1988	1989
No	No	57.9	72.7	0	0
Closed crop	Weekly	64.5	71.4	8	6
	SIV=40	67.4	74.9	8	3
	SIV=80	62.1	70.9	6	3
CDSI=30	Weekly	64.1	70.5	6	0
	SIV=40	64.2	70.9	6	0
	SIV=80	62.0	74.7	4	0
CDSI=40	Weekly	62.8	73.5	5	0
	SIV=40	67.0	73.6	5	0
	SIV=80	63.3	74.7	3	0
Effects[1]:					
Untreated vs treated		****	ns	–	–
Start of sprays		ns	ns	–	–
Subsequent sprays		****	ns	–	–

[1] **** = $p < 0.001$; *** = $0.001 < p < 0.01$; ** = $0.01 < p < 0.05$; * = $0.05 < p < 0.01$; ns = $p > 0.01$.

Table 4. Onion yield, area under the disease progress curve (AUDPC-value) between 27 June and 4 September and number of sprays applied in 1990 depending on the treatment

Treatment		Yield	AUDPC-value	Number
Start of sprays	Subsequent of sprays	(t ha^{-1})	(d dm^{-2})	sprays
No	No	55.9	1012	0
Closed crop	Weekly	55.9	313	10
	SIV=40	58.1	381	6
	SIV=80	57.0	471	5
CDSI=30	Weekly	55.8	320	9
	SIV=40	56.3	397	5
	SIV=80	56.4	456	5
CDSI=40	Weekly	60.8	451	8
	SIV=40	60.5	577	4
	SIV=80	59.1	563	4
Effects[1]:				
Untreated vs treated		ns	****	–
Start of sprays		**	***	–
Subsequent sprays		ns	**	–

[1] **** = $p < 0.001$; *** = $0.001 < p < 0.01$; ** = $0.01 < p < 0.05$; * = $0.05 < p < 0.01$; ns = $p > 0.10$.

sponding average AUDPC-values were 530 resp. 390 (d dm^{-2}). These results suggest that the observed disease levels found did not influence yield. With BOTCAST one or two sprays could be saved in 1990 at CDSI-thresholds of 30 or 40 while four additional sprays were saved when further spraying was based on either of the two SIV-thresholds.

Yield, number of sprays and disease severity in 1991

In 1991 disease severity (AUDPC-value) in the untreated plots (1865 lesion days dm^{-2}) was greater than in the treated plots (333 lesion days dm^{-2}) (Table 5). The treated plots yielded on average 4.2% more than the untreated plots. Application of BOTCAST resulted in a 3.3% higher yield compared to the practical advice, but a corresponding difference in the AUDPC-value was not observed. Spraying according to BOTCAST started one day later than according to the practical advice. The plots sprayed according to the SIV model yielded 6.2% more than the weekly sprayed plots without any difference in disease severity observed. Only one spray was saved with the SIV model. The crops fertilised with 200 kg ha^{-1} of nitrogen yielded 3.3% more than the crops fertilised with 50 kg ha^{-1}. A difference in disease severity was not observed and there was only a small difference in the percentage of days that the SIV-threshold of 80 was exceeded (Table 2). Probably the larger yield at the high nitrogen fertiliser rate was due to a difference in the leaf area duration (LAD, m^2 m^{-2} d). The LAD was calculated as the area under the LAI progress curve, which was based on the leaf area of the plants at each observation date and the plant density observed at harvest. The LAD of the crops fertilised with 200 kg ha^{-1} of nitrogen was 17.8% higher than the LAD of the low fertilised crops. As an estimate for leaf dieback the total dead leaf length per plant was expressed relative to the total green plus dead leaf length. This percentage of dead leaf length on the first disease assessment day after the last spray was the same in all treatments. At the moment of fall-over of the onion leaves the disease had probably not entered the leaf blight phase.

Yield, number of sprays and disease severity in 1992

On average the treated plots in the 1992 trial yielded 4.1% more than the untreated plots ($p = 7.5\%$). This percentage was 5.3 and 2.6 for the early and late sown crop, but the interaction was not significant. The larger yield of the treated plots corresponded to a lower AUDPC-value (Table 6). On average this value was 158 on the treated and 328 on the untreated plots. Untreated plots also had a slightly higher percentage of

Table 5. Onion yield, area under the disease progress curve (AUDPC-value) between 24 June and 15 August, percentage of dead leaf length on 15 August and number of sprays applied in 1991 depending on the treatment

Treatment			Yield	AUDPC-value[1]	Dead leaf	Number of
N rate (kg ha^{-1})	Start of sprays	Subsequent sprays	(t ha^{-1})	(d dm^{-2})	length (%)	sprays applied
50	No	No	61.2	1775	11.9	0
	Closed crop	Weekly	59.2	372	10.8	6
		SIV=80	63.3	342	11.2	5
	CDSI=40	Weekly	60.4	335	10.9	6
		SIV=80	66.0	361	11.1	5
200	No	No	60.9	1956	7.9	0
	Closed crop	Weekly	62.8	282	11.9	6
		SIV=80	64.8	317	8.5	5
	CDSI=40	Weekly	64.1	287	12.3	6
		SIV=80	67.8	369	7.7	5
Effects[2]:						
Treated vs untreated			**	****	ns	–
Nitrogen applied			**	ns	ns	–
Start of sprays			****	ns	ns	–
Subsequent sprays			****	ns	ns	–

[1] Due to skewness of the residuals the AUDPC was analysed after log-transformation.
[2] **** $= p < 0.001$; *** $= 0.001 < p < 0.01$; ** $= 0.01 < p < 0.05$; * $= 0.05 < p < 0.01$; ns $= p > 0.10$.

dead leaf length on 10 August(22 resp. 26%). Contrary to 1991, disease development had apparently entered the leaf blight phase at the time of observation. The difference was observed after fall over of the leaves. Yield differences related to BOTCAST and SIV could not be detected nor could differences in disease severity be observed. However, the application of both models reduced the number of sprays from 7 to 4 in the early and from 6 to 5 in the late sowing. In the early and late sown crops the CDSI-threshold of 40 advised on the first spray 15 days later and 3 days earlier respectively than the practical advice (Table 2), which largely accounted for the difference in spray reduction between both sowing dates.

Relative disease growth rate in relation to model- and climatological characteristics

In addition to yield, disease severity and number of sprays, the advisory models were evaluated on the basis of their relation with relative disease growth rate (RGR). The estimates, their standard deviations and the percentage of variance accounted for are listed in Table 7. The quadratic term is only listed when the P-value of the corresponding estimate was less than 0.1. None of the models in Table 7 were significantly influenced by crop conditions (N fertiliser, sowing time, year). The SIV accounted for a higher percentage of the variance than DINOV, although both are sporulation models. DINFV showed a poor relationship with RGR. It could be expected that a combination of a sporulation and an infection index, as is realised in the DSI, would give a better correlation. However, the DSI only accounted for 16% of the variance. This low percentage was partly caused by a high RGR in the period between 10 and 17 August in 1992 (both sowings) and a corresponding low average value of DSI. The average value of the DSI was low due to high temperatures in this period. After increasing the temperature that prevents sporulation in BOTCAST from 30 to 34 °C, the percentage variance accounted for by DSI increased from 16 to 31%. A further increase was realised by replacing DINOV by an index based on SIV having a value of 0 or 1 when the SIV remained below or exceeded a threshold value. From four possible threshold values (50, 60, 70 and 80) the value of 70 produced the best statistical relationship with RGR.

From the climatological variables listed in Table 7, the relative humidity, the number of rainy hours and the percentage of days with a leaf wetness duration longer than 16 or 20 hours produced the best relationship. The relation between the climatological variables and RGR was further analysed by multiple regression analysis.

Table 6. Onion yield, area under the disease progress curve (AUDPC-value) between 29 June and 3 August (early sowing) or between 6 July and 10 August (late sowing), percentage of dead leaf length on 10 August and number of sprays applied in 1992 depending on the treatment

Treatment			Yield	AUDPC-value	Dead leaf	Number of
Sowing	Start of sprays	Subsequent sprays	(t ha^{-1})	(d dm^{-2})	length (%)	sprays applied
Early	No	No	71.4	311	33.9	0
	Closed crop	Weekly	75.4	141	28.0	7
		SIV=80	74.3	139	24.6	5
	CDSI=40	Weekly	76.3	144	24.6	5
		SIV=80	75.6	173	25.9	4
Late	No	No	64.5	1295	18.8	0
	Closed crop	Weekly	65.6	610	18.8	6
		SIV=80	66.1	534	16.0	5
	CDSI=40	Weekly	66.6	550	16.5	6
		SIV=80	66.3	617	18.2	5
Effects[1]:						
Treated vs untreated			*	****	**	–
Sowing time			****	****	****	–
Start of sprays			ns	ns	ns	–
Subsequent sprays			ns	ns	ns	–

[1] **** $= p < 0.001$; *** $= 0.001 < p < 0.01$; ** $= 0.01 < p < 0.05$; * $= 0.05 < p < 0.10$; ns $= p > 0.10$.

Table 7. Relation between relative disease growth rate (RGR) and model- or climatological characteristics (X) according to the model: RGR = a + b*X + c*X^2 (n = 39)

Characteristic	Regression parameters (x 10^{-2})						%vaf[3]
	a		b		c		
	Estimate	Standard error	Estimate	Standard error	Estimate	Standard error	
Model characteristic							
SIV	–1.36	7.24	–0.35	0.31	0.0067	0.0029	40
DINOV	–0.97	4.10	16.76	6.63	–	–	12
DINFV	–13.95	5.69	18.57	4.58	–	–	29
DSI original	–1.60	3.95	10.68	3.75	–	–	16
DSI adapted 1[1]	–6.77	3.99	14.88	3.53	–	–	31
DSI adapted 2[2]	–6.96	3.33	16.72	3.13	–	–	42
Climatological characteristic							
Leaf wetness (h)	–18.85	6.17	2.39	0.53	–	–	34
Temperature (°C)	61.9	23.1	–3.08	1.30	–	–	11
RH (%)	536.0	228.0	–14.66	5.67	0.099	0.035	45
Rain (mm)	4.83	3.61	–1.26	2.47	0.534	0.263	29
Rainy hours (h)	0.51	3.70	–0.19	3.07	0.813	0.458	43
Hours with RH<70% (h)	28.01	5.09	–5.81	1.73	0.247	0.122	37
Hours with RH>90% (h)	–19.13	6.56	2.30	0.54	–	–	31
Days with leaf wetness							
> 16 h	–4.73	3.09	92.90	24.60	–72.70	34.80	41
> 20 h	0.76	2.27	68.70	12.50	–	–	44

[1] Temperature that prevents sporulation increased from 30 to 34 °C.
[2] Sporulation submodel DINOV replaced by SIV with threshold value 70%.
[3] %vaf = percentage variance accounted for.

The relation which accounted for the highest percentage of variance and of which the P-value of each of the parameter estimates was lower than 0.1, was:

$$\begin{aligned} RGR = {} & 0.13 - 0.062 * RAIN + \\ & 0.565 * WET20 - 0.014 * RHlow + \\ & 0.0089 * RAIN^2 \end{aligned} \qquad (3)$$

where RAIN equals the average daily rainfall (mm d^{-1}), WET20 represents the percentage of days on which the leaf wetness duration exceeded 20 hours and RHlow is the average number of hours per day with a relative humidity lower than 70%. This model accounted for 77% of the variance. The amount of rain is not taken into account in calculation of the SIV and is only of minor importance in BOTCAST.

Discussion

Yield and number of sprays

The evaluation trials carried out in the Netherlands between 1988 and 1992 showed that application of a combination of a CDSI-threshold of 40 and a SIV-threshold of 80 resulted on average in a 54% reduction in the number of sprays compared to a weekly spraying schedule without an observed yield loss and without a significant increase in disease severity.

In three years, the use of a CDSI or SIV threshold resulted in a higher yield compared to the weekly spraying schedule. An explanation for these results cannot be given. Probably, phytotoxicity of the fungicides did not play a role because less sprayings did not always result in a higher yield (for example in 1989).

The contribution of either BOTCAST or SIV to the spray reduction varied between years. In 1989 the CDSI-threshold of 40 was never reached so that BOTCAST alone accounted for the total spray reduction. In 1990 application of the SIV-threshold of 80 saved 4 sprays while the use of BOTCAST resulted only in a limited spray reduction (1–2 sprays). This indicates the importance of a combination of both BOTCAST and SIV rather than one of the models alone.

Based on 5 trials Sutton et al. (1986) reported an average reduction in the number of sprays of 53% reached by application of a CDSI-threshold of 40. Publications on trials in which the SIV is evaluated as an advisory system are not known. Sutton et al. (1986) found that the lower three leaves had developed 6–15 lesions at the moment the CDSI-threshold of 40 was reached. In 1991 7 lesions were counted on the lower three leaves at a CDSI-value of 40 for both the low and the high nitrogen fertilisation rate. In 1992 this CDSI-value was reached three and two days prior to the first disease assessment in the early and late sowing. At this time 2 and 1 lesions were counted on the lower three leaves in the early and the late sowing. Therefore, in 1992 the CDSI increased at a higher rate than the disease compared to 1991 and to findings of Sutton et al. (1986).

Disease severity and its relation to yield

A close relation between disease severity based on lesion counts (AUDPC-value) and leaf dieback (percentage of dead leaf length) or yield could not be established. In 1990 a significantly higher AUDPC-value of the untreated plots compared to the treated plots did not result in a significant yield loss. In 1991 the observed difference in the AUDPC-value between untreated and treated plots (1865 resp. 333 lesion days) corresponded to a 4.2% yield loss of the untreated plots. In 1991 leaf blight was not observed (Table 5). In 1992 the number of lesion days on the untreated and treated plots was 328 and 158 respectively, while some leaf blight was observed (Table 6). The yield loss of the untreated plots (4.1%) was comparable to 1991. Comparing 1991 with 1992 makes it clear that the number of lesion days is not directly related to yield. The relation between disease severity based on lesion counts and yield could have been influenced by two factors.

The first factor could have been the occurrence of *Botrytis cinerea*. According to Hancock and Lorbeer (1963) this fungus can cause leaf spots but cannot induce leaf dieback and can thus be considered to be less harmful to the onion crop. Indeed, observations on spores trapped over an onion crop in 1991 in the Netherlands by Köhl et al. (1995) showed the prevalent occurrence of *Botrytis cinerae* over *Botrytis squamosa*.

The second factor could have been the influence of weather conditions on the development of the leaf blight phase of the disease (Sutton, 1990). The leaf blighting phase of the disease can be considered to be more harmful to the crop than the leafspotting phase. Leaf blighting lowers the leaf area index of the crop and can thus be expected to decrease yield (Alderman et al., 1987). According to Alderman and Lacy (1983) and Shoemaker and Lorbeer (1977b) leaf blighting is induced after leaf wetness periods prolonging for 4 and 3 days. Wetness periods of this duration have not been observed in our trials.

Due to both factors an increase in the number of lesions will not necessarily result in yield loss. Nevertheless, the concept of disease severity based on the number of lesions is useful in studies on leaf blight management in onions, because lesions can potentially result in yield loss.

Relation between RGR and model- or climatological characteristics
Sutton et al. (1986) related $\log_{10}$ lesion counts on $\log_{10}$ cumulative CDSI-value and found significant regressions in 7 out of 11 trials carried out in 9 different years. However, lesion counts and cumulative CDSI-values are not independent because both are likely to increase as the season progresses. Moreover, it was not clear to what extent years and trials influenced the regression. In this paper we have regressed data on relative disease growth rate (RGR) between disease assessment days in both 1990, 1991 (both nitrogen fertilisation rates) and 1992 (both sowing dates) on model and climatological characteristics referring to the same restricted periods. On any of the characteristics tested the origin of the data set had no significant influence on the regression. The results in Table 7 showed that the average DSI was poorly correlated with the RGR (low percentage variance accounted for). The SIV which only predicts sporulation was better correlated to the RGR, which is the result of both sporulation and infection. Moreover, simple climatological variables like leaf wetness duration, relative humidity and number of hours with rain yielded better regressions than the DSI. The regression of DSI on RGR was improved after increasing the temperature that prevents sporulation and replacing DINOV by SIV in the calculation of DSI. When integrating BOTCAST and SIV into one supervised control system, it seems consistent that the sporulation model SIV and the sporulation submodel in BOTCAST are the same. However, the percentage variance that was accounted for by the regression model of the adapted DSI was not larger than some of the climatological parameters. This suggests that a more simple model could lead to the same result in terms of the number of sprays applied.

A maximum of 77% of the variance in the RGR could be accounted for by multiple regression analysis resulting in equation (3). In this equation the average daily rainfall was one of the independent variables. However, according to this equation rainfall increased RGR only when daily rainfall exceeded 7 mm and decreased RGR to a small extent at lower amounts. Average daily rainfall exceeded 7 mm only in two periods between observation days. In both periods a high RGR value (>0.35) was found. A similar high value of RGR was only found in one period during which daily rainfall was 5 mm on average. In BOTCAST rainfall can only influence the CDSI through leaf wetness duration. High amounts of rainfall may possibly exert an influence on RGR that is not accounted for by the measurements of leaf wetness duration. James et al. (1984) reported that *Botrytis squamosa* sporulated after a shorter humid period when dead leaves had a higher moisture content at the start of the humid period. This could explain for the effect of high amounts of rainfall on the RGR.

Modifications of BOTCAST

Based on the linear regression analysis two changes of BOTCAST are proposed: an increase in the temperature that prevents sporulation and the substitution of DINOV by an SIV based index with a threshold of 70 when calculating DSI. The performance of the original and adapted BOTCAST model was evaluated by relating the CDSI to the number of lesions observed.

First the CDSI was considered at a disease severity of 10 lesions on the oldest green leaf. Using linear interpolation this CDSI was calculated for 1990, both nitrogen fertilisation rates in 1991 and both sowing dates in 1992. The average CDSI was 56 with a standard deviation of 10 (n = 5) with the original model. Applying both adaptions in the calculation of the DSI as indicated in Table 7 the average CDSI was 44 with a decreased standard deviation (s.d. = 2).

Secondly the number of lesions on the oldest three green leaves at the CDSI-threshold of 40 was determined with linear interpolation. Sutton et al. (1986) counted 6 to 15 lesions on the oldest three green leaves at this threshold value. As mentioned before, the number of lesions counted at a CDSI of 40 in 1991 was 7 at both fertilisation rates using the original model, while in 1992 less than 2 and 1 lesions were found at the early and late sowing date. The modified model gave lesion numbers at a CDSI of 40 of 9, 10, 15 and 21 in 1991 at the low and high nitrogen fertilisation rate and in 1992 at the early and late sowing time respectively. The suggested modifications to BOTCAST model would have led to fewer sprays 1991 and 1992. Also, in 1990 fewer sprays would have been advised and spraying would have started when 6 lesions were counted on the oldest green leaf. In 1988 and 1989 the modified model would have made no difference.

Vincelli and Lorbeer (1988) found that the BOTCAST sporulation submodel DINOV forecasted minor spray episodes better than the SIV model at a threshold of 50%. However, other threshold values were not considered. The authors developed an alternative sporulation model (IPI) that was superior to SIV and DINOV in forecasting spore episodes. Replacing the DINOV submodel of BOTCAST by the IPI model could possibly lead to a further improvement of BOTCAST.

According to equation (3) daily rainfall exceeding 7 mm is important in disease growth rate. This finding could be used to improve BOTCAST, for example by giving a higher DINOV value on days with high amounts of rainfall.

Economic feasibility

Introduction of a supervised control system in onions based on BOTCAST and SIV in practice has the advantage that farmers do not need to make laborious field observations. However, the system should be economically feasible. In the Netherlands onion farmers grow 4 ha of this crop on average. Assuming an application of 7 sprays per year resulting from a weekly spraying program, an average reduction of 54% on the number of sprays and fungicide and application costs of US$45 per spray per ha, the use of the supervised control system is only economically feasible when the annual costs of using the system are lower than US$680. The annual costs are likely to exceed this figure largely when the advisory system would only be applicable to the crop in which the micro-climate is measured. Therefore, application of the advisory system as a regional warning system seems necessary. This is only possible when the crop micro-climate within a certain region is comparable from one crop to another. When introducing BOTCAST and SIV in practice this aspect should be attended to.

Furthermore, the economic feasibility of the system is lowered by the recent reappearance of downy mildew in the Netherlands. Because farmers spray on a weekly basis to control downy mildew, the supervised control system for leaf blight will be less profitable. Therefore, research has started to evaluate DOWNCAST (Jesperson and Sutton, 1987) as a supervised control system for downy mildew. Both systems should then be combined into one supervised control system for spring sown onions.

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