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Development of a downy mildew advisory model based on downcast

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Abstract

A downy mildew advisory model for use in practical onion growing was constructed according to DOWNCAST, an existing downy mildew forecasting model. The model was empirically improved after comparison between observed and calculated disease development. Onion plants grown in pots were placed as trap plants in artificially inoculated onion fields (one in 1995, three in 1996 and one in 1997) for 1–7 days, then removed and incubated outdoors in a sheltered place at 1 km distance from the onion field. Symptom development was observed. Hourly measurements of leaf wetness, temperature and relative humidity were taken in the crop and hourly data on rainfall were obtained from a nearby automatic weather station. Sporulation of the fungus was visually observed in the onion crop in the morning on several days in all three years. Sporulation-infection periods and sporulation as predicted by the model were compared with symptom development on the trap plants and observations on sporulation in the field. The initial model corresponded to the trap plant observations in only 18 out of 42 and to visual sporulation in 25 out of 40 occasions. Criteria in both the sporulation and infection submodels of the advisory model were subsequently calibrated to obtain a best fit between the model and observations. In 30 out of 42 occasions the improved model corresponded with trap plant observations while 30 out of 40 sporulation observations were now calculated correctly. The improved model needs to be evaluated with additional and independent data.

Introduction

In the Netherlands the onion leaf disease downy mildew, caused by *Peronospora destructor* reappeared in 1990 after an absence of almost 30 years, a phenomenon, which was also observed by Smith et al. (1985) in New York. To control this disease, farmers in the Netherlands tend to spray weekly, or even more frequently, with dithiocarbamates, such as maneb, zineb and mancozeb. This decreased the practical value of an advisory system on leaf blight (*Botrytis squamosa*) in spring-sown onions that was evaluated under Dutch conditions (de Visser, 1996) and introduced in practice in 1992. Indeed, farmers stressed that the usefulness of the leaf blight advisory system depended on the availability of an advisory system for downy mildew and its combination with the leaf blight advisory system. Moreover, the Dutch government, together with farmers' organisations, aims to reduce the fungicide use by the year 2000 to 40% of the average use during the period 1984–1988. The reappearance of downy mildew endangers the achievement of this aim not only because farmers currently spray frequently to control downy mildew, but also because the leaf blight advisory system cannot meet its expectations regarding the reduction of fungicide input. Therefore, it was necessary to provide farmers with a tool that rationalises downy mildew control. Jesperson and Sutton (1987) presented DOWNCAST, a model that determines whether or not the microclimate within an onion crop has been favourable to sporulation and infection by the fungus. Similar to the leaf blight advisory system, DOWNCAST is a weather-based system. According to the authors, DOWNCAST correctly determined sporulation favourability of the microclimate to a high degree. FitzGerald and O'Brien (1994) also evaluated

DOWNCAST with satisfactory results. DOWNCAST has also been evaluated in Sweden (Forsberg, pers. com.). This paper reports on the construction of a model according to DOWNCAST, the comparison between calculated and observed disease development and the subsequent empirical improvement of the model.

Materials and methods

Onion crops

Characteristics of the onion crops in which disease development was observed and the microclimate was measured, are summarised in Table 1. Disease development was studied in plots of onion trials that were not treated with fungicides. The trials were laid out in four replications as random block designs. Plots were 4.5 m wide and 10 m long. Onions were sown or planted on beds 1.5 m wide in five rows 27 cm apart leaving 42 cm between the outer rows of adjacent beds. In 1995 at Lelystad and 1996 at Colijnsplaat, the microclimate was measured in the same crop as where disease development was studied. In 1996 and 1997 at Lelystad, microclimate was measured in an onion crop 13.5 m wide and 20 m long at about 1 km distance from the diseased crop. These crops were planted on the same day using the same variety. This experimental set-up was chosen for practical reasons concerning on-line electronic data transfer to a personal computer that processed the data.

Artificial inoculation

The crops, in which disease was studied, were artificially inoculated with downy mildew. In 1995 this was realised by transplanting diseased plants from a shallot crop (27 June) and a crop grown from onion sets (5 July). In 1996 and 1997 inoculation was realised with small onion bulbs (<21 mm) that were injected with a spore suspension of *Peronospora destructor* the preceding year (e.g. Hildebrand and Sutton, 1982). The spores were collected from sporulating onion leaves in the field. In 1996 these bulbs were planted and raised in pots before transferring the pots to the onion crops. In 1997 the inoculated bulbs were planted directly in the crop. In 1995 secondary infections on plants surrounding the transplants were observed on 31 July. In 1996 at Lelystad, plants grown from inoculated bulbs were placed in the crop on 3 May resulting in secondary infections visible on 6 June. In 1997 at Lelystad, the primary inoculated bulbs were planted in the crop on 25 March and secondary infections were first visible on 16 May. In 1996 at Colijnsplaat, plants grown from inoculated bulbs were transferred to the onion crop grown from sets on 15 May. Secondary infections around the pots were first observed on 11 June. On 19 June diseased plants were transferred from the onion crop grown from sets to the spring-sown onions. In this crop diseased plants were first noticed around these transplants on 24 July.

Weather data

Hourly data of temperature, relative humidity and leaf wetness within an onion crop were measured in the periods mentioned in Table 2. The temperature and relative humidity were measured with two Vaisala HMA-31 OTA sensors that were placed at 10 cm above soil level. Leaf wetness was measured with two tubular formed plexiglas electrical resistance sensors as used by Sutton et al. (1986) in the development of BOTCAST, a leaf blight forecasting model for use in onions and by De Visser (1996) to evaluate this model under Dutch conditions. The sensors were constructed following specifications kindly provided by James (pers.com.). The sensors were 20 cm long with a 1.3 cm outer and a 0.6 cm inner diameter and were

Table 1. Onion crop characteristics during 1995–1997

Year	Crop	Location	Planting date	Harvest date	Variety	Plant density (m^{-2})
1995	spring sown onions	Lelystad	14 April	14 September	Hyfield	58
1996	onions grown from sets	Lelystad	21 March	15 August	Centurion	80
1996	onions grown from sets	Colijnsplaat	18 March	29 July	Centurion	72
1996	spring sown onions	Colijnsplaat	27 March	28 August	Summit	91
1997	onions grown from sets	Lelystad	24 March	30 July	Centurion	90

Table 2. Period of measurement of micrometeorological data and number of batches of onion trap plants and the range of time periods of their exposure to downy mildew

Year	Crop	Location	Period of measurement	Number of batches of 8 trap plants	Range of time periods (*d*)
1995	spring sown onions	Lelystad	4 May–30 August	6	7
1996	onions grown from sets	Lelystad	4 May–9 August	12	3–4
1996	onions grown from sets	Colijnsplaat	1 May–26 June	5	7
1996	spring sown onions	Colijnsplaat	27 June–20 August	4	7
1997	onions grown from sets	Lelystad	7 April–5 August	15	1–3

coated with white oil-based paint. Two spiral grooves 1.5 mm apart and 0.5 mm deep were cut in the sensor surface. In these grooves two nickel wires of 0.25 mm were wound. These wetness sensors produced an output ranging from 0 to 1000 mV and were placed at a height of 10 cm above the soil surface at an angle of 45° to reflect the height and angle of implantation of the onion leaf blades to the pseudo stem. Squirrel SQ 32-4V/84/41 dataloggers were used to register the data. Hourly amounts of rainfall were obtained from an automatic weather station situated within 1 km of the onion plots.

Trap plants

Disease development to evaluate DOWNCAST was studied using the technique described by FitzGerald and O'Brien (1994). Trap plants were raised outdoors, isolated from any other onion crop, in black 6l pots by planting four plants per pot. In 1995 and 1996 seeds were used and in 1997 sets. For time periods mentioned in Table 2, 8 pots were periodically transferred to the onion trials. In each of the four plots that were not treated with fungicides, two pots were placed. The plants were 8 weeks old in 1995 and 11 weeks in 1996 and 1997 at the moment of their exposure to downy mildew infection in the field. Timing of planting of the trap plants was undertaken accordingly. At the end of the exposure periods in 1995 and 1996, pots were brought back to a sheltered place isolated from any onion crop. Following their one day exposure time in 1997, pots were transferred to the disease free onion field in which the microclimate was measured (1 km away distant from the diseased crop), to expose the plants to a crop microclimate for three days accounting for the longevity of downy mildew spores. After this period, pots were transferred to a sheltered place isolated from any onion crop. Fourteen days after exposure to downy mildew, symptom development on the leaves was observed. As a control for each batch of 8 pots, 2 unexposed pots remained at the location where trap plants were raised. These control pots were transferred to the sheltered place at the same time as the exposed pots with trap plants. The transfers of the trap plants were always made at 12:00 h.

Visual assessment of sporulation

During the growth of the crops in which disease development was studied, the extent of sporulation visible on the leaves was visually assessed on several occasions as 'no sporulation occurring', light, moderate or heavy sporulation based on the intensity of sporulation. Sporulation was observed at Lelystad during morning hours on 13 days between 4 August and 31 August in 1995, on 9 days in the period between 10 June and 23 July in 1996 and on 13 days between 16 May and 10 July in 1997. At Colijnsplaat in 1996 sporulation was observed only on two occasions both in the onions grown from sets (11 and 26 June) and in the spring-sown onions (24 and 30 July).

The initial model based on DOWNCAST

The model used in our experiments was constructed according to the description of DOWNCAST as presented by Jesperson and Sutton (1987). Criteria that were not an exact copy of the original criteria are described here. The parameter names, their descriptions and values that are used throughout the text, are listed in Table 3.

Sporulation was assumed to be inhibited by high temperatures between 8:00 and 20:00 h during the preceding day according to the refined criterion as proposed by Jesperson and Sutton (1987): no sporulation occurs when temperature exceeded 27, 28 or 29 °C

Table 3. DOWNCAST parameter names, their description and value

Name	Description	Value
HIGHRH	Minimum value of relative humidity favourable to sporulation	95%
MORT	Maximum sum of leaf wetness value of 5 consecutive hours allowing for spores to survive	1500 mV
RAINDARK	Maximum amount of rain between RAINSTART and RAINEND still permitting sporulation to occur	0 mm
RAINSTART	Starting time of period during which RAINDARK is still allowing sporulation to occur	0:00 h
RAINEND	Last hour of period during which RAINDARK is still allowing sporulation to occur	06:00 h
STARTHOUR	Starting hour for the 72 h period of potential spore survival	05:00 h
SURF1	Minimum sum of leaf wetness value of 5 consecutive hours ensuring rapid increase of leaf wetness values	2500 mV
SURF2	Minimum sum of leaf wetness value of 3 consecutive hours to ensure infection after rapid increase of leaf wetness values	2400 mV
WETLIMIT	Minimum value indicating leaf wetness	800 mV

during more than 8, 4 and 2 h respectively. Apart from high temperature, sporulation is inhibited by rainfall between RAINSTART and RAINEND. Although Jesperson and Sutton (1987) used a value of 01:00 h for RAINSTART, we applied a more conservative value of 0:00 h.

Hildebrand (1983) showed that sporulation intensity is depending on the time of onset of high relative humidity (HIGHRH) and on the mean temperature during the period of high relative humidity. DOWNCAST only accounts for the influence of relative humidity. Therefore, the data presented by Hildebrand (1983) have been integrated in the model according to Table 4.

The criterion allowing infection to take place during the morning directly following sporulation was refined, based on Hildebrand and Sutton (1984b) (Table 5). Their results showed that at temperatures between 16 and 20 °C and between 20 and 24 °C longer leaf wetness periods are necessary for infection than assumed in DOWNCAST.

The DOWNCAST model accounts for a maximum survival period for spores of three days. Infection can take place on the condition that the rate of dew deposition in the first five hours of leaf wetness is rapid and that leaf wetness persists at least three hours thereafter (Hildebrand and Sutton, 1984a). The application of these findings in DOWNCAST was based on the use of a mechanical leaf wetness sensor. However, an electronic resistance sensor is more suitable regarding a future introduction of the model in practice taking into consideration that automation is then obligatory. The use of the resistance sensor required an adaptation of the corresponding DOWNCAST rules. The sum of leaf wetness values for five consecutive hours (SUM1) and the leaf wetness sum of three subsequent hours (SUM2) were calculated starting from the first hour after STARTHOUR with a leaf wetness value exceeding 200 mV. Subsequently, SUM1 and SUM2 were compared to three threshold values (SURF1, SURF2 and MORT). SURF1 was determined on the basis of a linear increase of leaf wetness values from 200 mV to 800 mV, which value is assumed to coincide with leaf wetness (WETLIMIT, see Table 3), during five hours (200, 350, 500, 650 and 800 mV respectively) while SURF3 equalled three times WETLIMIT. MORT was arbitrarily set to 1500 mV. If SURF1 did not exceed MORT, spores were supposed to survive and the next hour was considered. Spores infected onion leaves when SUM1 and SUM2 equalled or exceeded SURF1 and SURF2 respectively. In all other combinations spores were assumed to have died.

Results

Trap plants: comparison between observation and calculation

The results observed for the trap plants corresponded in 18 of 42 occasions with the calculations by DOWNCAST. No symptoms developed on leaves when DOWNCAST calculated no sporulation-infection period (8 occasions) or the disease was at least present on some leaves when according to DOWNCAST disease spread would have occurred on at least one day

Table 4. Onion downy mildew sporulation value depending on time of onset of high relative humidity (HIGHRH) and mean temperature during the period of high relative humidity

Time of onset of high relative humidity (h)	Mean temperature during period of high relative humidity (°C)																							
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
22:00	0	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2	1	1	1	0
23:00	0	0	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	0	0
24:00	0	0	0	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	1	1	1	1	0	0	0
01:00	0	0	0	0	0	0	1	1	1	2	2	2	2	2	2	2	2	1	1	1	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Criteria based on onion leaf wetness duration and mean temperature during wet period, to allow for downy mildew infection directly following sporulation

Range of mean temperature (°C)		Period with leaf wetness readings > WETLIMIT
Lower limit	Upper limit	
6	16	06:00–08:00 or 09:00 h
16	20	06:00–11:00 h
20	24	06:00–12:00 h

(10 occasions) (Table 6). Disease spread was not calculated on 19 occasions (unforeseen disease spread) while in 5 further occasions disease spread did not take place and according to DOWNCAST conditions favoured disease spread (unjust calculation). Study of the criteria involved in 19 occasions of unforeseen disease spread were WETLIMIT (10x), STARTHOUR (2x), RAINDARK (4x), HIGHRH (2x) and RAINSTART (1x). Of the 5 occasions of unjust calculation of sporulation-infection, one took place in 1996 at Lelystad (between 7 and 10 June) and the other four occurred in the spring sown onions in 1996 at Colijnsplaat (between 20 July and 16 August). In 1996 at Lelystad this contradiction could have been the consequence of an insufficient sensitivity of the trap plant technique; secondary infections within the crop were not observed until 6 June. Furthermore, crop microclimate favoured disease development strongly. Leaf wetness values between 06:00 and 08:00 h on 10 June were >900 mV, while relative humidity was >95% between 22:00 and 09:00 h with temperatures between 8 and 9 °C. The reason for the absence of sporulation on trap plants exposed to disease spread in the spring sown onions in 1996 at Colijnsplaat is not evident. Microclimatic measurements indicated favourable circumstances that amply met the DOWNCAST criteria. One possible explanation could be a low growth rate of the crop due to drought stress (rainfall between 01 June and 10 August was only 45 mm of which 30 mm fell after 20 July), which was underlined by the low final yield of 44 tonnes ha^{-1}. This could have caused a too low availability of assimilation products in the leaves for sporulation and thus disease development to take place (Yarwood, 1943). Another possible explanation could be an unfavourable leaf surface microclimate of the drought stressed plant tissue.

Trap plants: empirical improvements

WETLIMIT was lowered from 800 to 550 mV and as a consequence SURF1 was decreased from 2440 to 1876 mV and SURF2 from 2400 to 1650 mV. This modification allowed DOWNCAST to calculate sporulation-infection periods on 8 of 10 occasions of unforeseen disease spread. On one of the two remaining occasions, the leaf wetness readings were too low for infection directly following sporulation (155–240 mV between 06:00 and 09:00 h), as well as for infection in the following night (264–354 mV between 23:00 and 08:00 h). On the other occasion, leaf wetness value was 541 mV at 06:00 h and 125 mV at 09:00 h, while leaf wetness values during the following night were not high enough for infection to take place. A further decrease of

Table 6. Percentage of onion leaves of trapplants with sporulation by *Peronospora destructor* and number of days with favourable weather according to DOWNCAST before and after application of modifications

Trial		Lelystad 1995						Lelystad 1996										
time period		25/7 — 31/7	01/8 — 07/8	08/8 — 14/8	15/8 — 21/8	22/8 — 28/8	29/8 — 04/9	04/6 — 06/6	07/6 — 10/6	11/6 — 13/6	14/6 — 17/6	18/6 — 20/6	21/6 — 24/6	25/6 — 27/6	28/6 — 01/7	02/7 — 04/7	05/7 — 08/7	09/7 — 11/7	12/7 — 15/7
% leaves infected		22	15	30	70	0	9	0	0	0	0	0	0	9	3	0	43	24	60
DOWNCAST	model as described	2	2	0	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0
	modified model	3	2	2	2	1	2	1	1	0	0	0	0	1	1	0	2	1	4

Trial		Colijnsplaat 1996									Lelystad 1997								
time period		11/6 — 17/6	18/6 — 24/6	25/6 — 01/7	02/7 — 08/7	09/7 — 15/7	20/7 — 26/7	27/7 —- 02/8	03/8 —- 09/8	10/8 — 16/8	10/6	11/6	12/6	13/6	14/6 — 16/6	24/6	25/6	26/6	27/6
% leaves infected		0	0	2	23	4	0	0	0	0	62	15	52	99	100	22	9	7	2
DOWNCAST	model as described	0	0	1	2	4	2	4	4	2	0	0	0	0	1	0	0	0	0
	modified model	0	0	3	2	6	3	5	5	3	1	0	1	1	3	0	1	1	1

Trial		Lelystad 1997					
time period		28/6 — 30/6	08/7	09/7	10/7	11/7	12/7 — 14/7
% leaves infected		16	24	11	15	66	95
DOWNCAST	model as described	0	0	0	0	0	0
	modified model	2	0	0	1	0	1

WETLIMIT was not applied because several observations of the crop during early morning hours in 1995 at Lelystad showed that the crop canopy was dry or drying at leaf wetness values between 450 and 550 mV. As a comparison, Scherm and Van Bruggen (1993) defined leaf wetness at a value of 5.0 of an electronic resistance sensor programmed to record readings between 0 and10 during their studies on dew simulation.

STARTHOUR was changed from 05:00 to 08:00 h. This allowed sporulation-infection to be calculated on both the occasions of unforeseen disease spread related to this criterion. This modification implied that leaf wetness duration in the morning hours directly following sporulation with insufficient length did not contribute to mortality of the spores.

RAINSTART was set at 01:00 h. On 12 June 1997 light rainfall (0.3 mm) between 0:00 and 01:00 h prevented DOWNCAST to calculate sporulation-infection, while a substantial disease spread occurred. According to Hildebrand and Sutton (1982), sporulation did occur in nights when light rain fell until 01:00 h.

The four unforeseen occasions of disease spread due to RAINDARK all took place in 1997 at Lelystad: 13, 24, 26 and 27 June. On these days 0.1, 0.3, 0.1 and 0.1 mm of rain fell between 01:00 and 06:00 h. Based on these results RAINDARK was increased from 0 to 0.1 mm. A further increase to 0.3 mm would allow sporulation-infection to be calculated between 2 and 4 July 1996; i.e. during a period in which disease spread was not observed in trap plants (Table 6). Furthermore, increasing the criterion to this level would not be in agreement with Hildebrand and Sutton (1982) who found light rains of 0.3 mm between 01:00 and 06:00 h to prevent sporulation.

Modification of HIGHRH is not proposed despite the two occasions of unforeseen disease spread (both in 1997 at Lelystad) where this criterion was not met. On 11 June relative humidity at night did not exceed 90%, while on 8 July the relative humidity decreased to 94% at 01:00 h and even further to 93% at 04:00 h.

Visual assessment of sporulation on leaves: comparison between observation and calculation

The visual assessments on sporulation on leaves were compared to the sporulation value calculated with DOWNCAST (Table 7). On 15 out of 40 observations a contradiction was found between the visual observation and corresponding DOWNCAST calculation. Unforeseen sporulation occurred on 13 days, while on 2 days sporulation was calculated but not observed. The criteria involved in the 13 unforeseen sporulations are HIGHRH (5x), high temperatures during the preceding day (2x), RAINDARK (1x), RAINSTART (1x) and Table 4 (4x). The two occasions where calculated sporulation did not coincide with visual sporulation on the leaves both took place in the spring-sown onions in 1996 at Colijnsplaat. Similar results were reached in this crop for sporulation-infection periods (Table 6). As with the trap plant observations in this crop, growing conditions could have prevented sporulation to occur.

Visual assessment of sporulation on leaves: empirical improvements

The five days of unforeseen sporulation related to HIGHRH all occurred in 1995 at Lelystad. On 9 August a heavy sporulation was observed, while DOWNCAST did not calculate this event. On 7 August only a few infected leaves showed sporulation, while relative humidity during the night of 8 August reached a maximum value of 75% and therefore did not favour sporulation. This implies that the spores observed on 9 August are not a remainder of an earlier sporulation. Between 01:00 and 02:00 h the relative humidity averaged 94% and increased to 95% in the next hour. A decrease of HIGHRH from 95 to 94% allowed sporulation to be calculated without producing a sporulation value on another day with no sporulation observed. Unforeseen sporulation on the other 4 days was caused by lower values of relative humidity. On 7 August 1995 relative humidity decreased to 89% between 05:00 and 06:00 h. On 14 August and 1 September 1995, relative humidity did not exceed 90% during the entire night. On 17 August relative humidity declined to 93% after 03:00 h. Only on 7 and 17 August the observed sporulation could have been a remainder of the preceding day.

On 22 August 1995 at Lelystad a heavy sporulation was observed while no spores were seen on the preceding day. The criterion concerning high temperatures during the preceding day prevented sporulation to be calculated. On 21 August mean hourly temperatures exceeded 28 °C for 4 h and 29 °C for 3 h. Based on this result the criterion was modified: sporulation was not calculated when mean hourly temperatures on the preceding day exceeded 27, 28, 29 or 30 °C during 8 or more, 6 or more, 4 or more or 2 or more hours respectively. This modification triggered calculation of sporulation on 4 August 1995 when no sporulation was observed, because mean hourly temperature

Table 7. Visual assessment of sporulation by *Peronospora destructor* on onion crop leaves and value of sporulation calculated by DOWNCAST before and after application of modifications. Sporulation was assessed no sporulation occurring (0), light (1), moderate (2) or heavy (3)

Trial		Lelystad 1995													
date		04/8	07/8	09/8	14/8	16/8	17/8	21/8	22/8	25/8	29/8	30/8	31/8	01/9	
Sporulation assessment		0	1	3	2	2	1	0	3	0	0	0	3	1	
DOWNCAST	model as described	0	0	0	0	2	0	0	0	0	0	0	1	0	
	modified model	0	0	1	0	2	0	0	2	0	0	0	1	0	
Trial		Lelystad 1997							Lelystad 1996		Colijnsplaat 1996				
date		10/6	14/6	18/6	20/6	25/6	26/6	28/6	22/7	23/7	11/6	26/6	24/7	30/7	7/8
Sporulation assessment		2	0	0	0	2	3	3	0	0	3	3	0	0	0
DOWNCAST	model as described	2	0	0	0	0	2	1	0	0	0	1	0	2	2
	modified model	2	0	0	0	0	2	1	0	0	0	1	3	2	2
Trial		Lelystad 1997													
date		16/5	4/6	5/6	9/6	11/6	12/6	16/6	18/6	20/6	24/6	1/7	7/7	10/7	
Sporulation assessment		3	3	3	1	0	1	3	2	0	0	2	3	3	
DOWNCAST	model as described	0	0	0	1	0	0	1	0	0	0	3	2	2	
	modified model	2	1	1	3	0	3	1	0	0	0	3	3	2	

on 3 August exceeded 29 °C for 3 h. However, in the period between 30 July and 2 August the temperature exceeded 34 °C for 4 h or more. To prevent sporulation to be calculated on 4 August the following criterion was added: sporulation was prevented when mean hourly temperatures in the crop on at least 3 of the preceding 5 days was 34 °C or higher for at least 4 h. On 11 June 1996 at Colijnsplaat the calculation of sporulation was prevented by four hours of temperatures over 30 °C on 10 June. The spores could have been a remainder of a sporulation calculated on 10 June.

On four occasions in 1997 at Lelystad the criterion presented in Table 4 prevented sporulation to occur, whereas heavy (3x) or moderate sporulations were observed. On 16 May and on 4 and 5 June, relative humidity exceeded 95% between 02:00 and 06:00 h when average temperatures were 11.5, 9.7 and 10.8°C respectively. The spores observed on the crop leaves on 16 May could have been a remainder of the two preceding days when sporulation was calculated. However, on the days preceding 4 June relative humidity during the night was too low to calculate sporulation. A modification of Table 4 is proposed: a sporulation value of 1 was assigned to the combinations of periods with high relative humidity starting at 02:00 h and corresponding mean temperatures of 10, 11 or 12 °C. On 18 June (moderate sporulation) a start of the period of high relative humidity at 01:00 h was combined with a mean temperature of 8 °C. A modification of Table 4 was not applied because the spores observed could have originated from a 3-day period of continuing sporulation between 14 and 16 June.

On the day that RAINSTART prevented sporulation to be calculated (12 June 1997), rain was registered between 00:00 and 01:00 h. As already proposed earlier, RAINSTART was set at 01:00 h.

The unforeseen sporulation on 25 June 1996 at Lelystad was caused by 0.5 mm of rainfall between 04:00 and 06:00 h. Also, sporulation was not calculated on the 15 preceding days indicating the failure of DOWNCAST regarding the sporulation event on that date. A modification to account for this contradiction is not proposed

Discussion

The DOWNCAST model was evaluated by Jesperson and Sutton (1987) and FitzGerald and O'Brien (1994). Jesperson and Sutton (1987) only evaluated the sporulation submodel by comparing visual assessments of sporulation on leaves in two years to calculations by DOWNCAST and concluded that the model resulted in a good fit of the observations. FitzGerald and O'Brien (1994) evaluated the combination of sporulation and infection with a satisfactory result by using a trap plant technique in one year only. The trap plants were exposed to infection for a period of seven days. The authors did not make observations on sporulation incidence or severity. The work described in this paper can be considered as an evaluation of the initial model as described in the Materials and Methods section. This evaluation was based on both sporulation events and sporulation-infection periods as observed in five crops in three years. Furthermore, we exposed trap plants to disease spread for periods as short as one day. Especially the shorter periods seem more effective in evaluating sporulation-infection calculations than periods as long as seven days during which the probability of a sporulation-infection period and disease spread to occur is high. Our experiments resulted in a substantial number of contradictions between the initial model and the observations. Partly the assumptions and modifications that we applied when building the model in accordance with the description presented by Jesperson and Sutton (1987) could have caused this. For instance, these authors, as well as FitzGerald and O'Brien (1994), were not explicit on the criterion concerning the rate of dew deposition: we assumed a linear increase of the sensor readings. Moreover, these authors used a mechanical hemp string leaf wetness recorder whereas we used an electronic instrument for both practical reasons and because the same instrument was used to evaluate the onion leaf blight model (de Visser, 1996). Furthermore, we specified the temperature/relative humidity criteria at night regarding sporulation (Table 4). Also, the criteria determining infection on the same morning as sporulation, as proposed by Jesperson and Sutton (1987), were slightly refined (Table 5). However, partly the aforementioned contradictions could have been caused by an insufficient adaptation of the initial model to the simulated system.

The empirical improvement of the model resulted in an increase in the number of days with correspondence between model calculations and observations on trap plants from 18 to 30. The number of occasions with unforeseen disease spread decreased from

19 to 5. These 5 occasions were due to three criteria: WETLIMIT (2x), RAINDARK (1x) and HIGHRH (2x). The percentage infected leaves of the corresponding trap plants ranged from 15 to 66% and all occurred in 1997, a year with extreme high disease pressure (100% of the crop plants infected by 18 June). Under these circumstances a model is needed to identify conditions that are only marginally favourable to disease spread. Calculations of sporulation-infection periods without evidence of disease spread increased from 5 to 7. This increase was due to the calculation of sporulation-infection periods between 22 and 28 August in 1995 and between 4 and 6 June in 1996 at Lelystad. The contradiction of the latter time period could have been caused by an insufficient sensitivity of the trap plant technique, because the first secondary infections in the crop were not observed until 6 June. However, the contradiction of the first time period introduced by the modifications cannot be explained.

The modifications based on the comparison between model calculation and visual assessments of sporulation resulted in a decrease of the number of contradictions by 5. Of the 10 remaining contradictions, 7 concern unforeseen sporulations and 3 unjust sporulation calculations. The criteria involved in the 7 occasions of unforeseen sporulation were: HIGHRH (4x), RAINDARK (1x), high temperature on the preceding day (1x) and the criteria of Table 4 (1x). Corresponding sporulation events were classified as light to moderate. The category of unjust calculation of sporulation events (3 in total) was increased by one after applying the higher tolerance to high temperatures the preceding day. This situation occurred in spring-sown onions on 24 July 1996 at Colijnsplaat. In this crop other unjust calculations on sporulation-infection and sporulation are mentioned earlier in this paper.

After applying the modifications some contradictions remained unexplained. Further modifications of the criteria involved probably would result in less unforeseen events but also in more unjust calculations as was already clear from the unjust calculation of sporulation-infection between 22 and 28 August 1995 and 4 and 6 June 1996 at Lelystad, and of sporulation on 24 July 1996 at Colijnsplaat.

From the results presented in this paper, it can be concluded that the model does not offer a 100% fit with reality. However, after three years of empirical improvement, the model will be evaluated from 1998 onwards. This evaluation will not only be carried out on the basis of the techniques used in the present study, but also on the basis of field trials testing the efficacy of the advises produced by the model to control the disease.

In a situation where the downy mildew model is restricted to historic weather data, it can only be used in combination with curative fungicides that are currently not available to Dutch onion growers. True mildew predictions and, as a consequence, weather predictions are necessary for advises on the use of preventive sprays and are prerequisites for the successful combination of the downy mildew model with the leaf blight model. Therefore, a practical leaf wetness model has been constructed and evaluated that can be used to calculate leaf wetness based on predicted weather data. Furthermore, an empirical relation has been established to convert predicted values to microclimatic data. A following paper will be dedicated to these efforts.

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