Netherlands Journal of Agricultural Science 47 (1999) 29-49

Crop management and anthracnose development in caraway (*Carum carvi* L.)

A. EVENHUIS[1,3,*], B. VERDAM[2] AND J.G.N. WANDER[1]

[1] Applied Research for Arable Farming and Field Production of Vegetables, P.O. Box 430, NL-8200 AK Lelystad, The Netherlands
[2] DLO Research Institute for Plant Protection (IPO-DLO), P.O. Box 9060, NL-6700 GW Wageningen, The Netherlands
[3] Present address: Applied Research for Arable farming and Field Production of Vegetables, South East Netherlands, P.O. Box 6077, NL-5960 AB Horst, The Netherlands

* Corresponding author (fax: +31-77-3970180; e-mail: a.evenhuis@pav.agro.nl)

Received 25 November 1997; accepted 17 December 1998

Abstract

Anthracnose of caraway is caused by the fungus *Mycocentrospora acerina* (Hart.) Deighton. A reduction of leaf wetness duration was positively correlated ($r^2 = 0.71$; $P < 0.001$) with a decrease of disease severity. Lodging and higher plant density prolonged leaf wetness duration. Disease incidence and severity of anthracnose were reduced by crop management activities minimizing leaf wetness duration. Reduction of nitrogen levels reduced the risk of anthracnose development in spring and biennial caraway. Decreasing the sowing rate from 8 to 4 kg per hectare resulted in a lower disease severity and an increase of seed yield in spring caraway, but not in biennial caraway. In biennial caraway disease severity decreased with wider row spacing. A damage threshold between 6% and 12% disease severity is proposed. Positive financial results of crop management activities are indicated.

Keywords: crop protection; *Mycocentrospora acerina*; leaf wetness duration; nitrogen application; phytopathology; row spacing; sowing rate; plant density

Introduction

Caraway (*Carum carvi* L.) is an arable crop grown for seeds and essential oil, especially carvone. A commercial sprout inhibitor of potatoes, based upon carvone, was brought to the market in 1995 (Hartmans *et al.*, 1995). In the Netherlands, farmers usually grow biennial or winter cultivars. In the first year caraway is grown under a cover crop. If the root collar reaches a diameter of about 6 mm at the end of the growing period of the first year, the plant will bolt in April and flower in May of the following year (Bernelot Moens *et al.*, 1973). If the required root diameter is not reached, the plants will remain vegetative for one more year. On heavy clay soils a high sowing rate is usually applied to ensure crop establishment under difficult con-

ditions. When, however, conditions are favourable for germination more plants than necessary will emerge and competition among caraway plants may occur, and root growth may be hampered.

Spring caraway is an annual type, grown without a cover crop. In the Netherlands, spring caraway has only been grown by a few farmers. From bolting until harvest spring caraway is very similar to biennial caraway. Spring caraway flowers in July and is harvested in September, approximately two months later than biennial caraway.

Caraway yields vary from 600 to 2500 kg ha^{-1}, depending on year, region and field (Bouwmeester *et al*., 1995). Part of this variation may be caused by *Mycocentrospora acerina* (Hart.) Deighton, the causal agent of anthracnose in caraway. Crop and disease management, essential to increase the crop's yield stability, demand better knowledge of disease/crop interactions. In this paper, experiments to study the effect of nitrogen rate, sowing rate and row spacing on anthracnose are described.

Materials and methods

General information on thirteen field experiments is given in Table 1. The locations of the experimental sites are shown in Figure 1. Information on inoculation, disease assessment, leaf wetness duration and agronomical observations is given first and in general applies to all experiments. Treatments per experiment are described later.

Inoculation. Spring caraway was inoculated at the end of spring, just before bolting. Biennial caraway was inoculated in March, also just before bolting. Inoculum was produced by blending a 3 to 4 week old culture of *M. acerina* on Potato Dextrose Agar (18 °C) in tap water. The suspension was sieved through double cheesecloth. The final inoculum density was adjusted to 10^4 chlamydospore chains per ml suspension. Inoculum or water (500 l ha^{-1}) was added to each plot using a knapsack sprayer. Inoculations were performed on rainy days. Control plots were sprayed with water.

Disease assessments. In biennial caraway disease levels were estimated weekly from bolting till harvest. Disease incidence was observed on 25 plants per plot and expressed as the percentage of caraway plants infected by *M. acerina*. Disease severity was determined by estimating the percentage of the main stem surface covered with lesions caused by *M. acerina*, on the same 25 plants per plot. Final disease assessments were made about four weeks before harvest, sampling 25 plants at 5 positions per plot (125 plants per plot). In spring caraway, only the final disease assessments were made.

Leaf wetness duration. In 1993 and 1994, 'Lufft' leaf wetness sensors (G. Lufft Meß- und Regeltechnik GmbH, Stuttgart) were used to assess daily leaf wetness duration, from bolting until harvest, in the nitrogen experiments. Each week, the sensors were moved from one block to another and from one nitrogen level to another. Displacements were made to avoid confounding effects of sensors and sensor posi-

Table 1.General information on field experiments. Biennial caraway is sown one year before the harvest year.

Experiment	1	2	3	4	5	6	7	8	9	10	11	12	13
Harvest year	1992	1993	1994	1992	1992	1993	1993	1993	1993	1994	1994	1993	1994
Location[a]	L	L	R	NB	W	NB	W	NB	W	NB	W	W	Ln
Soil type	clay	clay	clay	clay	sand	clay	sand	clay	sand	clay	sand	clay	clay
Caraway crop[b]	S	S	B	S	S	S	S	B	B	B	B	B	B
Cover crop[c]	none	none	SB	none	none	none	none	OSF	SB	SB	SB	P	P
Sowing date	9/3	5/4	28/4	9/4	22/4	15/4	21/4	–/4	22/4	–/4	21/4	–/4	–/4
Sowing rate (kg/ha)[d]	7.5	7.5	8	t	t	t	t	t	t	t	t	t	t
Row spacing (cm)[d]	25	25	25	t	t	t	t	t	t	t	t	t	t
Nitrogen rate (kg/ha)[d,e]	t	t	t	100	100	100	100	100	100	100	100	100	70
Inoculation date	18/6	16/6	6/4	24/7	24/7	16/6	–[f]	10/92	–	9/93	–[f]	–	–
Lodging assessment	17/6	6/7	7/7	–	–	13/8	–	–	9/6	–	30/6	–	23/6
Disease assessment[g]	31/8	17/8	16/6	20/8	7/9	13/8	25/8	–	9/6	–	15/6	17/6	30/6
Harvest date	31/8	6/9	18/7	9/9	12/10	20/9	29/10	none	8/7	none	19/7	–/7	20/7
(Sub) Plot size (m)	6*6	6*6	3*15	6*18	6*15	6*18	6*15	6*18	6*15	6*18	6*15	5*5	5*5

[a] Field experiments were located at Lelystad (L), Lienden (Ln), Nieuw Beerta (NB), Randwijk (R), and Wageningen (W).
[b] S and B are spring caraway and biennial caraway, respectively.
[c] SB spring barley, P = peas, OSF = oil seed flax.
[d] For t = treatments, see Materials and Methods.
[e] Nitrogen rate applied in spring, for biennial caraway nitrogen rate applied in autumn depended on soil type and cover crop.
[f] Not relevant.
[g] The date indicates when comprehensive and final disease assessments were made.

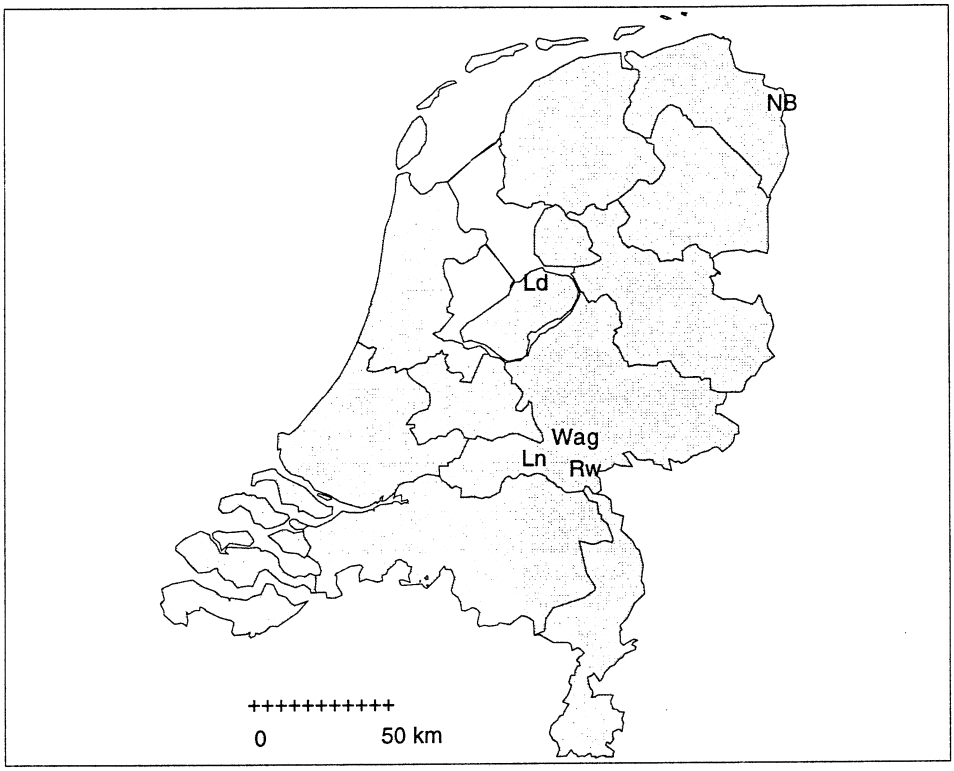

Figure 1. Map of the Netherlands with the sites of the field experiments; NB: Nieuw Beerta; Ld: Lelystad; Ln: Lienden; Rw: Randwijk; W: Wageningen.

tions on the evaluation of leaf wetness duration. In Wageningen, leaf wetness duration was estimated by 'De Wit' leaf wetness recorders, from bolting until harvest. Differences in leaf wetness duration between treatments were analysed by considering daily leaf wetness durations to be sequential replicates. Analysis of variance was applied to leaf wetness data.

Plant density. Plant density of caraway was determined by counting caraway stem bases in two or four, depending on row spacing, adjacent rows of one meter length at four positions in each plot (approximately 2 m^2 per plot), directly after harvest.

Lodging. Lodging of caraway was assessed whenever it occurred (Table 1). The percentage of lodged crop area was estimated per plot. Plants were considered to be lodged when the stem's angle of inclination deviated more than 45 degrees from the upright position.

Yield. Caraway was harvested using a combine harvester (Wintersteiger, Nurserymaster Elite, Austria) designed for field experiments. Seed lots per subplot were

weighed after drying to 12% water content and removal of trash. The result was converted to seed yield in kg per hectare.

Effect of nitrogen rate on anthracnose (Experiments 1, 2, 3)

Treatments. In spring 1992 either 40 or 100 kg ha^{-1} fertilizer nitrogen was given to spring caraway. Nitrogen fertilization of spring caraway was 40, 100 and 160 kg ha^{-1} in 1993. Nitrogen levels applied to biennial caraway in March 1994 were 40, 100 and 160 kg ha^{-1}. Each of the three experiments consisted of four blocks in a split-plot design. A block consisted of two plots, which were either inoculated with *M. acerina* or treated with water. Each plot consisted of two (1992) or three (1993 and 1994) subplots to which the nitrogen level was allotted randomly. The plots and subplots were surrounded by a 3 m buffer zone of barley in 1992 and of caraway in 1993 and 1994. The buffer zone was intended to reduce the spread of the fungus from inoculated to non-inoculated subplots.

Effect of sowing rate and row spacing on anthracnose (Experiments 4-13)

Treatments in spring caraway (Experiments 4–7). The row spacing was 12.5, 37.5 and 50 cm at Nieuw Beerta and 12, 36 and 48 cm at Wageningen. The sowing rates were 4 and 8 kg seed per hectare. Each combination of sowing rate and row spacing (plot) was applied in a block, four blocks per experiment. Each plot had two subplots of which one was inoculated as described above. Inoculations were carried out at the end of spring, just before bolting of the caraway crop. No inoculation was carried out in Experiment 7 at Wageningen in 1993, because a natural inoculum source was present in the field. No buffer zones between plots were applied in these experiments.

Treatments in biennial caraway (Experiments 8–11). The cover crops were sown with a row spacing of 25 cm. The row spacing of caraway was 12.5, 37.5 and 50 cm at Nieuw Beerta (Experiments 8, 10) and 12, 36 and 48 cm at Wageningen (Experiments 9, 11). The sowing rates were 6 and 12 kg ha^{-1}. The experimental design was as in spring caraway. At Nieuw Beerta half of the plots were inoculated with *M. acerina* in October 1992 (Experiment 8) and September 1993 (Experiment 10). No inoculations were carried out at Wageningen (Experiments 9, 11), since a natural inoculum source was present.

Supplementary experiments (12 and 13). Disease assessments were made in two field experiments not specifically designed to investigate the effect of row spacing on *M. acerina* development. The experiments were located on clay soils at Wageningen (Experiment 12) and Lienden (Experiment 13) in 1992/93 and 1993/94, respectively (Table 1). In these experiments row spacings were 25, 37.5 and 50 cm at Wageningen and 25 and 50 cm at Lienden.

Statistics. Data were analysed with Genstat 5, release 3.1. Analyses of variance were

conducted on disease assessment data and agronomical data. Least significant differences (lsd) at $P = 0.05$ were calculated from s.e.d. values generated in the analyses. Logit transformation of disease incidence and disease severity usually improved the discriminative capacity of the analyses. Disease severity was square root transformed in Experiment 12.

Linear regression was conducted to demonstrate the correlation of lodging and disease severity in the nitrogen experiments (Experiments 1–3). To compare these experiments, partial normalisation of data was applied. Instead of the values x_{ij}, with x for the variate, i for the experiment and j for the j^{th} observation in experiment i, we used the deviation from the mean per experiment, $y_{ij} = x_{ij} - x_i$, with y for the partially normalised variate (complete normalisation requires division of y_{ij} by s_i). The correlation of disease severity and caraway yield was also described by linear regression. Yield was log transformed. Leaf wetness duration was measured in six experiments (Experiments 2, 3, 5, 7, 9, 11). The correlation of leaf wetness duration and disease severity was studied by linear regression, after partial normalisation of the data.

Gompertz curves were calculated to describe disease development with time (Evenhuis & Verdam, submitted) in Experiment 3. Curves were fitted to individual plots, and plot parameter values were averaged per treatment.

Results

Effect of nitrogen rate on anthracnose

Experiments 1 and 2 were carried out with spring caraway and Experiment 3 with biennial caraway (Table 1). The soil nitrogen rate (0–90 cm) in early spring was 20, 18, and 30 kg ha^{-1} in Experiments 1-3, respectively.

Disease incidence and disease severity increased significantly with the nitrogen level applied in the inoculated plots (Experiments 1–3; Tables 2 and 3). In the control plots no effect of nitrogen rates on disease incidence and disease severity was found in Experiment 1. In Experiments 2 and 3 disease incidence and disease severity increased significantly with nitrogen rate in the control plots, although the effect was less pronounced than in inoculated plots (Table 3).

In Experiment 1, seed germination was moderate (65 plants m^{-2}) and growth was rather poor which resulted in an open crop and no lodging. In Experiments 2 and 3, the caraway crops lodged after heavy rainfall in early July and June, respectively. Lodging increased with the nitrogen rate applied. Inoculation had no effect on lodging. Disease severity and lodging increased with N-fertilization (Tables 2 and 3). To be able to compare the correlation of lodging and disease severity in spring (Experiment 2) and biennial caraway (Experiment 3) partial normalisation was applied. Figure 2 shows that after normalisation an increase of lodging correlated strongly with an increase of disease severity, in spring and biennial caraway. *M. acerina* disease progress curves were fitted to Gompertz equation. Disease incidence increased to 100% in inoculated plots, though the epidemic was delayed by approximately a week

Table 2. *Experiments 1 and 2.* Effect of three nitrogen levels and inoculation with *M. acerina* (*M.a.*) on lodging, plant density, disease incidence and severity of *M. acerina*, yield and daily leaf wetness duration in spring caraway at Lelystad in 1992 and 1993.

Nitrogen rate (kg ha^{-1})	*M.a.*[a]	Lodging (%)		Plant density (m^{-2})		Disease incidence (%)		Disease severity (%)		Yield (kg ha^{-1})		Mean[b] daily leaf wetness duration (h.min day^{-1})
		1992	1993	1992	1993	1992	1993	1992	1993	1992	1993	1993
40	–	0	13	65	89	1	73	0.1	8	541	1169	14h.14
100	–	0	63	60	90	1	89	0.1	11	741	1060	15h.20
160	–	–	78	–	87	–	93	–	14	–	1063	15h.55
40	+	0	10	68	84	13	99	0.7	31	554	792	–[c]
100	+	0	55	63	82	30	100	1.3	44	733	531	–
160	+	–	83	–	83	–	100	–	41	–	504	–
LSD I*n (0.05)[d]			28[e]	9[e]	12[e]	3	5	0.4[e]	6	164[e]	321[e]	55 min
all	–	0	51	63	88	1	85	0.1	11	641	1087	–
all	+	0	49	66	83	22	100	1.0	39	644	609	–
LSD I (0.05)[f]			18[e]	7[e]	13[e]	2	4	0.3	5	116[e]	290	–
40	–/+	0	11	67	86	7	86	0.4	20	548	981	–
100	–/+	0	59	62	85	15	94	0.7	27	737	796	–
160	–/+	–	80	–	85	–	96	–	27	–	783	–
LSD n (0.05)[g]			27	7[e]	7[e]	2	3	0.3	3	116	120	–

[a] Caraway sprayed with water (–) or inoculated with *M. acerina* (+).
[b] Leaf wetness was measured at Lelystad in 1993, only.
[c] No data available.
[d] LSD given for the inoculation and nitrogen interaction.
[e] No significant differences at $P < 0.05$.
[f] LSD given for the inoculation effects.
[g] LSD given for the nitrogen effects.

Table 3. *Experiment 3*. Effect of three nitrogen levels and inoculation with *M. acerina* (*M.a.*) on lodging, disease incidence and severity of *M. acerina*, yield and leaf wetness duration in biennial caraway at Randwijk in 1993/94.

Nitrogen rate (kg ha^{-1})	*M.a.*[a]	Lodging (%)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})	Mean total leaf wetness duration (h.min day^{-1})
40	–	0	46	16	0.3	2105	–
100	–	19	50	23	0.7	2621	–[d]
160	–	53	51	35	1.2	2304	–
40	+	0	56	86	3.3	2065	13h.40
100	+	13	51	96	10.5	1384	–
160	+	85	51	99	14.2	1292	16h.02
LSD i*n (0.05)		21	12[c]	17[c]	3.5	565	57 min
all	–	24	49	25	0.7	2343	–
all	+	33	53	94	9.3	1580	–
LSD i (0.05)		19[c]	8[c]	18	3.6	383	–
40	both	0	51	51	1.8	2085	–
100	both	16	51	60	5.6	2003	–
160	both	69	51	67	7.7	1798	–
LSD n (0.05)[b]		14	9[c]	11	2.2	433[c]	–

[a] Caraway sprayed with water (–) or inoculated with *M. acerina* (+).
[b] LSD given for the nitrogen effects, the inoculation effects and the interaction, respectively.
[c] No significant differences at $P < 0.05$.
[d] No data available.

at the lowest nitrogen level. In the control plots, *M. acerina* disease incidence increased with increasing nitrogen rate (Figure 3).

Yield was negatively correlated with disease severity in Experiments 2 and 3. Caraway yield of inoculated plots was 44% (Experiment 2; Table 2) and 33% (Experiment 3; Table 3) lower than of non-inoculated plots. In Experiment 1, disease severity levels were less than 2%, probably too low to cause yield loss by anthracnose. Under low disease pressure, an increase of the spring caraway yield from 540 to 740 kg ha^{-1} was found with an increase of nitrogen rate from 40 to 100 kg ha^{-1}. A similar effect was found in Experiment 3 in the control plots. Yield of biennial caraway increased from 2100 kg ha^{-1} to 2600 kg ha^{-1} with an increase of N-fertilization of 40 to 100 kg ha^{-1}. Under high disease pressure (Experiment 2 and inoculated plots of Experiment 3) yield dropped with N-fertilization, lodging increased and anthracnose became more severe.

Lower nitrogen levels led to shorter leaf wetness duration in spring caraway (Table 2) and biennial caraway (Table 3).

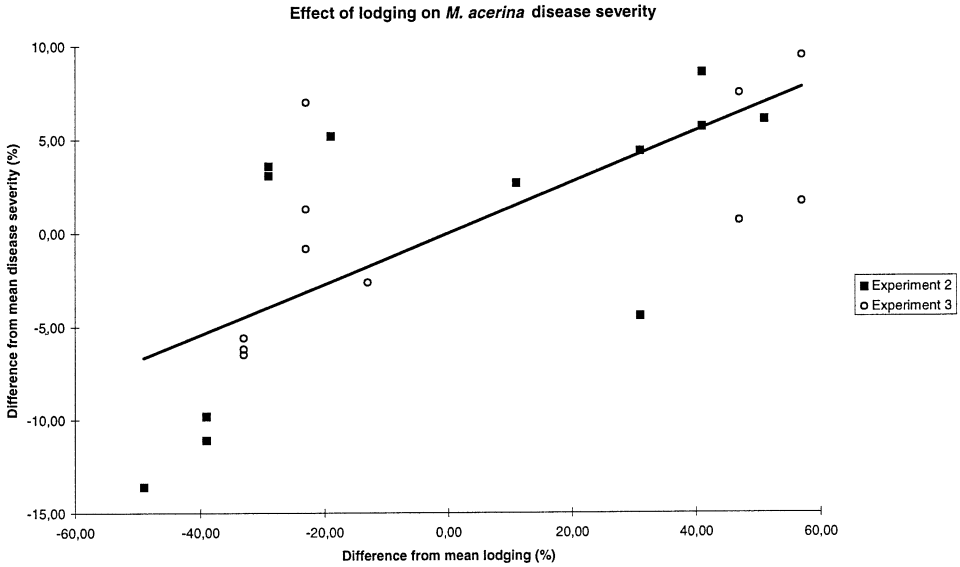

Figure 2. The correlation of lodging (L) and disease severity (S) of anthracnose in caraway at Lelystad (Experiment 2) in 1993 and Randwijk (Experiment 3) in 1994 (n = 24, $P < 0.001$, $r^2 = 0.42$), with standard errors between brackets: S = 0.06 (1.06) + 0.117 (0.028) * L
S and L are rendered as partially normalized variates (see text).

Effect of sowing rate and row spacing on anthracnose in spring caraway

Experiment 4. The disease severity (*M. acerina*) was 0.2% in 1992 at Nieuw Beerta, and the experiment was therefore excluded from the analysis. Under low disease pressure a reduction of the sowing rate from 8 to 4 kg ha^{-1} led to a small (9%) but significant decrease ($P = 0.001$) of the caraway yield from 1304 to 1186 kg ha^{-1}. Plant density was 53 and 100 plants m^{-2} at a sowing rate of 4 and 8 kg ha^{-1}, respectively. No significant effect of row distance on yield was found.

Experiments 5–7. Disease incidence and severity of *M. acerina* were higher in inoculated spring caraway than in the uninoculated controls of Experiments 5 and 6. No interaction was found between inoculum level and sowing rate or row spacing. No significant interactive effects of sowing rate and row spacing on disease incidence, disease severity, plant density, lodging and yield were found. Therefore the aspects of sowing rate and row spacing in spring caraway were analysed separately.

In Experiment 5, a low sowing rate resulted in lower plant densities, shorter leaf wetness duration, and lower disease levels in spring caraway (Table 4). Averaged over Experiments 5 – 7 similar results were obtained (Evenhuis & Verdam, 1995). At Wageningen (Experiments 5 and 7), daily leaf wetness duration was approximately one hour shorter in caraway with a sowing rate of 4 kg ha^{-1} compared to a sowing rate of 8 kg ha^{-1}.

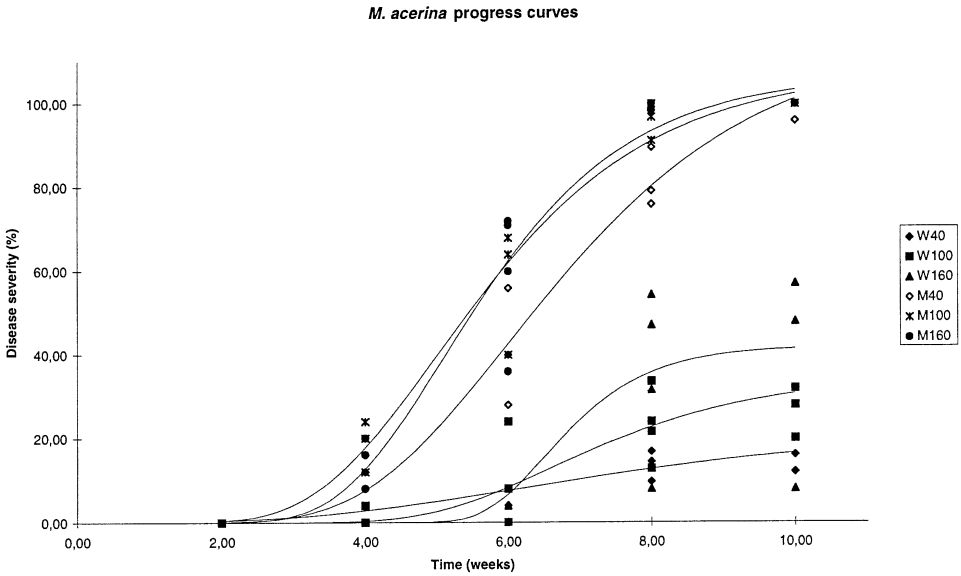

Figure 3. Disease incidence progress curves for *M. acerina* in caraway at Randwijk in spring 1994 were fitted to Gompertz curves (Y = A + C * EXP (EXP (-B*(X-M)))). At X = 0 bolting just began. Disease incidence was assessed in plots treated with water (W) or inoculated with *M. acerina* (M) with nitrogen rates of 40, 100 and 160 kg ha^{-1}. Parameter A was set to zero. Least significant differences for the parameter C was 14. Standard errors are given between brackets in an italic letter type.

Y_{W40} = 22 *(23)* * EXP(-EXP(–0.33 *(0.50)* * (X-6.2 *(4.1)*)))
Y_{W100} = 35 *(6)* * EXP(-EXP(–0.60 *(0.84)* * (X-6.6 *(0.5)*)))
Y_{W160} = 42 *(5)* * EXP(-EXP(–1.22 *(0.65)* * (X-6.5 *(0.3)*)))
Y_{M40} = 116 *(11)* * EXP(-EXP(–0.50 *(0.11)* * (X-6.0 *(0.3)*)))
Y_{M100} = 108 *(6)* * EXP(-EXP(–0.59 *(0.11)* * (X-5.0 *(0.2)*)))
Y_{M160} = 107 *(5)* * EXP(-EXP(–0.69 *(0.11)* * (X-5.1 *(0.2)*)))

In Experiment 5, plant density and lodging were significantly affected by row spacing, but not yield, disease incidence and severity (Table 5). But, averaged over Experiments 5–7 yield increased significantly with smaller row spacing.

Yield was significantly correlated with disease severity (highest observed level was 79%) in Experiment 6 at Nieuw Beerta, 1993. Caraway yield was significantly (n = 48; P < 0.001; LSD = 105) higher in control plots (1090 kg ha^{-1}), than in plots inoculated with *M. acerina* (300 kg ha^{-1}) in Experiment 6. No correlation was found of disease severity (highest observed levels were 16% and 39%) and yield, analysed by linear regression in Experiments 5 and 7, at Wageningen, in 1992 and 1993.

Effect of sowing rate and row spacing on anthracnose in biennial caraway

Experiments 8 and 10. The Experiments 8 and 10, on sowing rate and row spacing at Nieuw Beerta, met with misfortune. In autumn/winter of 1992/93 (Experiment 8), many caraway plants did not produce a root large enough (diameter 6 mm) to permit

Table 4. *Experiment 5*. Effect of sowing rate on lodging, plant density, disease incidence and mean severity of *M. acerina* and yield in spring caraway. Observations were averaged over row spacings at Wageningen in 1992. Row spacings varied from 12 to 48 cm.

Sowing rate (kg ha^{-1})	Inoculation	Lodging (%)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})
4	+/–	20	67	44	4.3	483
8	+/–	33	112	58	6.3	370
LSD (0.05)		16[a]	12	11	1.9	99
4 /8	water	25	91	45	4.4	405
4 /8	*M. acerina*	28	88	57	6.2	444
LSD (0.05)		4 [a]	6 [a]	8	1.3	109 [a]
4	water	21	67	37	3.5	441
8	water	29	115	53	5.3	369
4	*M. acerina*	19	67	52	5.1	517
8	*M. acerina*	37	110	63	7.3	371
LSD (0.05)		23 [b]	24 [a]	13 [a]	2.3 [a]	137 [a]

[a] No significant difference at $P < 0.05$.
[b] No significant difference at $P < 0.05$, except when comparing means with the same level(s) of sowing rate, than the l.s.d. becomes 5.7.

Table 5. *Experiment 5*. Effect of row spacing on lodging, plant density, disease incidence and severity of *M. acerina* and yield in spring caraway. Observations were averaged over sowing rates at Wageningen in 1992. Sowing rates were 4 and 8 kg ha^{-1}.

Row spacing (cm)	Inoculation	Lodging (%)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})
12	+/–	6	108	56	6.4	406
36	+/–	24	80	52	5.2	404
48	+/–	50	82	45	4.2	469
LSD (0.05)		19	14	13[a]	2.4 [a]	121[a]
36	water	25	91	45	4.4	409
48	*M. acerina*	28	88	57	6.2	445
LSD (0.05)		4 [a]	5 [a]	7	1.2	130 [a]
12	water	6	111	48	4.8	359
36	water	20	79	45	4.4	418
48	water	49	83	43	3.9	448
12	*M. acerina*	5	104	65	8.0	442
36	*M. acerina*	28	81	59	6.1	402
48	*M. acerina*	51	80	48	4.5	490
LSD (0.05)		21 [a]	31 [a]	17 [a]	2.8 [a]	182 [a]

[a] No significant differences at $P \leq 0.05$.

bolting and flowering. Between 5 and 50% of the plants flowered in 1993, depending on sowing rate and row spacing (Table 6). The higher sowing rate and the smallest row spacing gave the highest number of flowering plants. A significantly ($P < 0.001$) higher percentage of flowering plants was achieved with a sowing rate of 6 compared to 12 kg seed ha^{-1}. The poor bolting was probably caused by the cover crop. Oil seed flax (linseed) was harvested late, and started regrowth, and thus hampered caraway root growth. In 1993/94 (Experiment 10), the number of caraway plants was very low after harvest of the cover crop and plant densities patterns were irregular throughout the field. Nevertheless the highest numbers of plants were found with the higher sowing rate and the smallest row spacing. The effect of plant density on disease severity could not be assessed at these low plant densities and irregular plant density pattern. Both Experiments were excluded from the analysis of the relationship between disease development and plant density.

Experiments 9 and 11–13. The sowing rate had no effect on disease incidence and disease severity of reproductive plants at Wageningen. Mean densities of total plants were 122 and 198 plants m^{-2} in 1993 (Experiment 9) at sowing rates of 6 and 12 kg ha^{-1}, respectively, and 67 and 101 plants m^{-2} in 1994 (Experiment 11). Mean plant densities of reproductive plants were 91 and 114 in 1993 and 56 and 58 in 1994 at sowing rates of 6 and 12 kg ha^{-1}, respectively. At the higher sowing rate a smaller percentage of the plants flowered (Table 6).

Table 6. *Experiments 8–11*. The interactive effect of sowing rate and row spacing on plant density of biennial caraway at Nieuw Beerta and Wageningen.

Row spacing (cm)	Sowing rate (kg ha^{-1})	Total plant density (m^{-2})				Reproductive plant density (m^{-2})			Percentage reproductive plants (%)		
		8	9	10	11	8	9	11	8	9	11
12	6	120	117	29	72	30	98	72	25	85	100
36	6	94	125	20	66	27	85	55	29	69	87
48	6	88	123	26	62	12	89	41	13	72	68
12	12	178	213	42	132	35	136	75	20	65	61
36	12	149	183	29	96	14	109	48	9	60	51
48	12	137	199	27	76	2	98	51	1	50	71
LSD r*s (0.05)		37[a]	42[a]	10[a]	26[a]	21[a]	21[a]	14[a]	19[a]	11[a]	29[a]
all	6	101	122	25	67	23	91	56	22	75	85
all	12	155	198	33	101	17	114	58	10	58	61
LSD s (0.05)		22	24	5[a]	15	14[a]	18	8[a]	11	6	17
12	both	149	165	35	102	33	117	73	22	75	81
36	both	122	154	25	81	20	97	51	19	64	69
48	both	113	161	27	69	7	93	46	8	61	69
LSD r (0.05)		27	29[a]	6[a]	19	17	22[a]	10	13[a]	8	20[a]

[a]: No significant differences at $P < 0.05$.

Since the effect of sowing rate on reproductive plant density was non-significant, only the effect of row spacing was analysed. In both experiments (9 and 11), disease incidence and disease severity decreased with increasing row spacing (Table 7). In Experiment 12, disease severity of biennial caraway was significantly lower at 37.5 cm row spacing than at 50 cm (Table 8). A row spacing of 25 cm led to intermediate levels of *M. acerina* infection. In experiment 13 (Table 9) no significant differences were found in disease severity of caraway at 25 and 50 cm row spacing. Row spacing of 48 cm seemed to increase the risk of lodging (Experiments 9, 11–13), though the effect on lodging was non-significant in these experiments.

Correlation between M. acerina disease severity and caraway yield on clay soils. Seven experiments (1, 2, 3, 4, 6, 12 and 13) were carried out in which both disease severity and yield were determined. Yield decreased with increasing disease severity. Linear regression of yield on disease severity gave a coefficient of determination $r^2 = 0{,}36$ with n = 214 and $P < 0.001$. Linear regression of the log transformed yield

Table 7. *Experiments 9 and 11*. Effect of row spacing on mean lodging, plant density, disease incidence and severity of *M. acerina*, yield and leaf wetness duration in biennial caraway at Wageningen in 1992/93 and 1993/94, analysed together. Data from plots with sowing rates of 6 and 12 kg ha^{-1} were taken together.

Row spacing (cm)	Lodging (%)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})	Leaf wetness duration (h.min.day^{-1})
12	23	92	75	12.3	1274	9h.13
36	23	71	70	8.3	1372	--[a]
48	28	64	67	6.9	1300	8h.20
LSD (0.05)	11[b]	14	4	3.0	84[b]	28 min

[a] No data available.
[b] No significant differences at $P < 0.05$.

Table 8. *Experiment 12*. Effect of row spacing on plant density (reproductive plants), disease incidence and severity of *M. acerina* and on yield of biennial caraway at Wageningen in 1993. The sowing rate was 8 kg ha^{-1}. Lodging was not assessed.

Row spacing (cm)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})
25	50	62	4.4 ab	1398
37	43	51	2.6 a	1689
50	40	68	6.1 b	1498
LSD (0.05)	6	13	2.3[a]	232

[a]: Different characters indicate significant differences at $P \leq 0.05$. Disease severity was square root transformed before analysis of variance.

Table 9. *Experiment 13*. Effect of row spacing on means of lodging, reproductive plant density, disease incidence and severity of *M. acerina*, and yield in biennial caraway at Lienden in 1994. The sowing rate was 8 kg ha^{-1}.

Row spacing (cm)	Lodging (%)	Plant density (m^{-2})	Disease incidence (%)	Disease severity (%)	Yield (kg ha^{-1})
25	19	94	95	13.6	1947
50	23	54	89	10.0	1996
LSD (0.05)	22[a]	11	6.7[a]	9.0[a]	298[a]

[a] No significant difference at $P \leq 0.05$.

on disease severity gave $r^2 = 0.60$ (n = 214; $P < 0.001$; Figure 4). In two experiments (8 and 10) yield was not determined. In Experiments 1 and 4 disease severity was less then 2% and only small effects on disease severity were found.

Effect of leaf wetness duration on anthracnose. Leaf wetness duration was measured in six experiments (2, 3, 5, 7, 9 and 11), including two nitrogen experiments (annual/biennial), two experiments on sowing rate in spring caraway and two experiments on row spacing in biennial caraway. In all experiments longer leaf wetness duration coincided with higher disease incidence and disease severity levels (Tables 2, 3, and 7). Figure 5 shows the correlation of leaf wetness duration on disease severity ($n = 15$, $r^2 = 0.70$; $P < 0.001$), when for each experiment deviations from the means were calculated.

Discussion

Spring caraway and biennial caraway. Crop management experiments were carried out with spring caraway and biennial caraway. Growth and development of a spring caraway crop is largely comparable to the growth and development of biennial caraway in the second year. However, in spring caraway there is no build-up of inoculum on vegetative plants in autumn, because the crop is sown in spring and harvested in September. Infested soil must be the main inoculum source for infection of spring caraway plants in spring and summer. In biennial caraway inoculum build-up takes place in autumn (Evenhuis, 1998). Infection of stems and flowers of biennial caraway takes place from April the next year. When no natural inoculum source was suspected caraway crops were inoculated to create some disease pressure. Both caraway types are highly susceptible to *M. acerina* (Evenhuis & Verdam, 1997). Disease development due to *M. acerina* on stems, umbels and seeds of spring caraway is much the same as in biennial caraway. A difference is that spring caraway bolts, flowers and matures approx. 2 months later in the season than biennial caraway. Whether *M. acerina* infection will be severe or not depends upon weather conditions. From 20 experiments, including biennial and spring caraway a positive corre-

lation (r^2=0.61; P <0.001) was found between mean disease severity and rainfall during the month of flowering (Evenhuis & Verdam, 1995). The crop management activities studied were expected to affect anthracnose in the reproductive phase. Therefore it was expected that the experiments could be performed with spring caraway as well as with biennial caraway.

Caraway is an arable crop with only a short past concerning domestication and breeding. Most of the varieties grown in the Netherlands are selections from landraces. At present only three Dutch biennial varieties and one annual variety are available. Caraway is predominantly a cross-fertilizer (protandry) and the crop is genetically very heterogeneous. The plant to plant variation in growth and plant structure is large and caraway canopies are irregular. Unfortunately the effect in field experimentation is that standard errors tend to be large. On top of that, caraway is by nature biennial. Field experiments with small plots and few replications are not desirable, especially for biennial caraway, but usually inevitable. By analysing many experiments part of this problem can be overcome.

Buffer zones. Inter-plot interference between inoculated and non-inoculated plots was not found when buffer zones were used. This is in accordance with the short distance dispersal of M. acerina found in other experiments (Evenhuis & Verdam, 1995). Usually a large inoculation effect was found on disease development. In 1993, weather conditions were conducive to M. acerina development. At Nieuw Beerta (Experiment 6), no buffer zones were applied and non-inoculated plots became infected, although less severely than inoculated plots. At Lelystad (Experiment 2), buffer zones were applied but non-inoculated plots became infected anyhow by *M. acerina*, probably by an unidentified, natural source of inoculum, among which are crops like carrots and spinach and several weed species (Hermansen, 1992; Evenhuis & Verdam, 1997).

Yield. Experiments 1-6 were both inoculated and harvested. In spring caraway, yield loss due to anthracnose was found to be significant at Lelystad in 1993 (Experiment 2; 44%) and Nieuw Beerta in 1993 (Experiment 6; 75%). In biennial caraway, yield was significantly reduced by *M. acerina* at Randwijk (Experiment 3; 33%). The mean disease severity in these experiments varied from 12 to 28%. Inoculation with *M. acerina* had no effect on yield in Experiments 1 and 4. Disease severity levels were less than 2%, which were probably too low to cause yield loss. Caraway grown on sandy soil was inoculated with *M. acerina* in only one Experiment (5). No significant effect of inoculation was found on yield (Table 4). The mean disease severity was 5%, with a maximum of 15% in one plot. No correlation between yield and disease severity was found in experiments with mean disease severity levels below approximately 6% (Experiments 1, 4 and 5). On clay soils, a significant correlation of disease severity and log transformed caraway yield was found (Figure 4). From the experiments inoculated with *M. acerina* we conclude that the damage threshold must be approximately between 6 and 12% for both biennial and spring caraway on clay soils. The damage threshold is defined as the minimum level at which disease adversely affects yield (Zadoks & Schein, 1979).

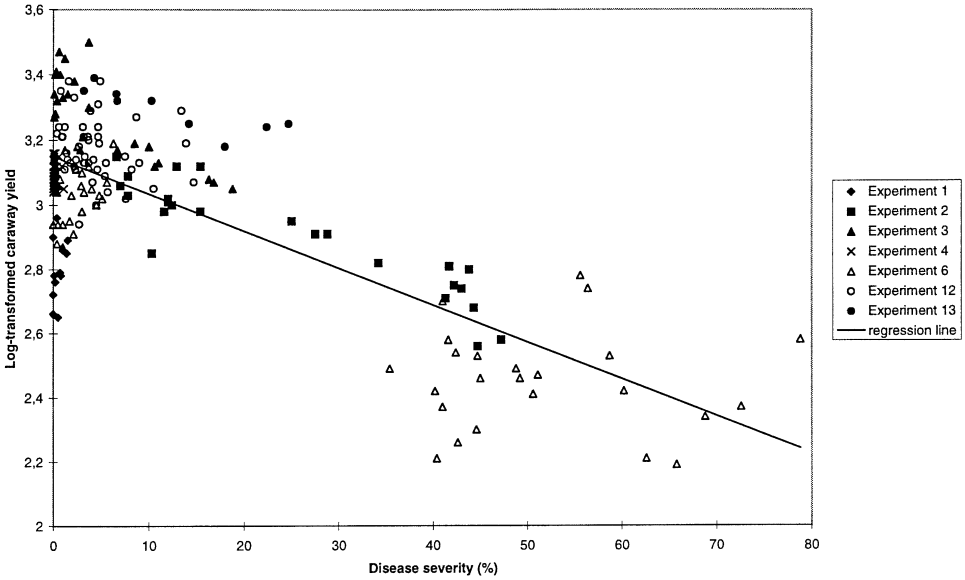

Figure 4. The correlation of disease severity (S) and log transformed yield (Y) of caraway in seven experiments on clay soils (n = 214; $r^2 = 0.60$), $P < 0.001$) with standard errors between brackets: Log(Y) = 3.15 (0.01) – 0.012 (0.0006) * S

Leaf wetness duration. Leaf wetness duration was measured with 'Lufft' recorders in the nitrogen experiments (2 and 3) and with 'De Wit' leaf wetness recorders in the plant density experiments (5, 7, 9 and 11). Differences in leaf wetness duration due to cultivation treatments within field experiments were significant. To compare the effect of leaf wetness duration on disease severity between experiments and between types of leaf wetness sensor, data were partially normalized. After normalization, an increase in leaf wetness duration was clearly correlated (n=15; r^2=0.70; $P < 0.001$) with an increase in disease severity (Figure 5). Differences between leaf wetness duration within experiments were caused by management factors. Experiments with different management factors led to the same result, therefore it is likely that a causal relationship exists between leaf wetness duration and disease severity. Lodging and higher plant density prolonged leaf wetness duration. In plots with these features conditions favouring *M. acerina* last longer. Spore production by *M. acerina* infection and colonization of the crop are facilitated. The damage threshold is reached earlier under these circumstances. Yield loss may be severe, especially if the crop lodges. Similarly, in carrot (*Daucus carota* L; *Umbelliferae*) the number of lesions increased with prolonged leaf wetness durations after inoculation with *Cercospora carotae* (Carisse & Kushalappa, 1992). *Mycocentrospora* spp. are related to *Cercospora* spp., and *Mycocentrospora acerina* was first described as a member of *Cercospora* family (Sutton & Gibson, 1977). In crops with higher plant densities, more infection sites are available, which may also accelerate the rate of an epidemic.

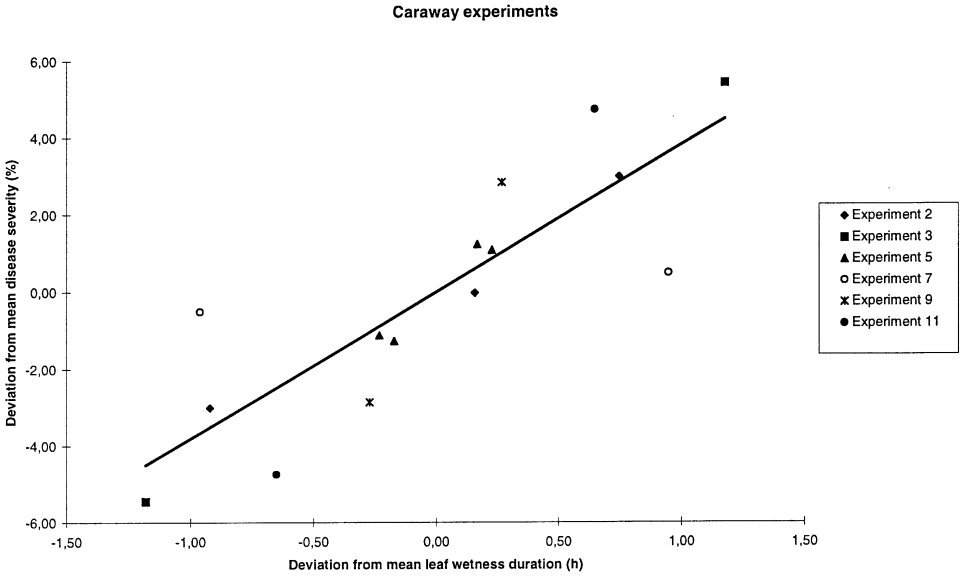

Figure 5. The correlation of mean daily leaf wetness duration (W) and disease severity (S; *M. acerina*) of caraway in six caraway experiments (n=15, r^2=0.70, P<0.001) with standard errors between brackets:
S = 0.005 (0.45) + 3,82 (0.65) * W
S and W are rendered as partially normalized variates.

In agricultural practice, activities to reduce the daily leaf wetness duration contribute to minimize yield loss due to *M. acerina* by slowing down the epidemic in the reproductive phase of the caraway crop.

Nitrogen. For good caraway growth and development, an adequate supply of nitrogen is necessary. However, over-application can easily result in lodging, as was found in Experiments 2 and 3. Lodging in combination with rainfall stimulated *M. acerina* development in caraway. In 1992, disease severity levels remained low in spring caraway due to a non-lodged crop and a dry and sunny summer (Experiment 1). In 1993, heavy summer rainfall stimulated anthracnose development in a lodged spring caraway crop (Experiment 2). The disease apparently spread into the non-inoculated plots, or a natural inoculum source was already present, since disease severity levels were rather high in these plots. Thus the interaction between nitrogen level and inoculation could not be demonstrated in 1993. The interactive effect was obvious in 1994, Experiment 3. High nitrogen application in the presence of *M. acerina* resulted in severe yield loss. Where no natural inoculum source was present and spread of anthracnose into non-inoculated plots was limited, yield increased up to an optimum nitrogen level.

These results clearly indicate that prevention of lodging also prevents *M. acerina* to develop towards levels causing yield loss. Lodging can be prevented by avoiding high nitrogen rates. Observations in Germany suggested that problems with *M. ace-*

rina in caraway occurred in wet and cool years, especially when crops were over-fertilized (Müller *et al*., 1989), which is in accordance with our results. In Poland, up to 200 kg N ha^{-1} is recommended for biennial caraway (Weglarz, 1983). The continental climate of Poland is in general dryer than the Atlantic climate of the Netherlands. Therefore under Polish conditions the microclimate in a caraway crop is less conducive to *M. acerina* development, so that higher nitrogen levels are less risky than under Dutch conditions. In the Netherlands, a nitrogen rate of 100–125 kg ha^{-1} minus the nitrogen available in the soil is recommended (Wander, 1994). Our results support this conclusion. Modest nitrogen application meets government policy, aimed at reducing environmental pollution by means of reducing agricultural inputs (here N), and promotes an environmentally sound image of caraway and its derivates such as a sprout inhibitor of potatoes based upon carvone.

Sowing rate. In biennial caraway manipulation of the sowing rate had little effect on anthracnose development. The effect of sowing rate was largely eliminated by competition between plants for light and nutrients in the autumn leading to nearly equal numbers of reproductive plants (Table 6). In contrast, spring caraway flowers without the need of producing a minimal root diameter. Therefore, in spring caraway manipulation of sowing rate is a good means to influence plant density (Table 4) and, indirectly, *M. acerina* development.

Row spacing. In biennial caraway row spacing is a means for indirect control of *M. acerina*. Narrow row spacing (12 cm) led to a denser crop, whereas a wide row spacing (48 cm) increased risk of lodging (Experiments 9, 11, 12 and 13). Thus, intermediate row spacing (25 – 36 cm) minimizes the risk of anthracnose development. These observations apply also to spring caraway. In Experiment 9, disease severity was relatively low and seed yield increased with narrower row spacing, probably because the distribution of the plants was better at a row spacing of 12 cm than at 48 cm. In Experiment 11, disease severity was higher and the effect of a better plant distribution on yield was counteracted by anthracnose development (Tables 6 and 7).

The percentage of biennial caraway plants remaining vegetative depends on plant density and root size before onset of winter. Plant density is influenced by sowing rate and row spacing (Table 6). Factors involved in root growth are the cover crop used, the harvest date of the cover crop and the weather conditions between harvest of the cover crop and the onset of winter. Vegetative plants do not contribute to seed production, but *M. acerina* infects these plants too. Thus, vegetative plants may enhance inoculum build-up in autumn and serve as inoculum sources for the reproductive plants in spring. The farmer should minimize the percentage of vegetative plants by lowering the sowing rate. But to guarantee plant establishment on heavy clay soils, work to ensure germination percentages to be adequate under all circumstances is still needed. Results from our study indicate that on a sandy soil a sowing rate of 6 kg ha^{-1} suits this purpose better than a sowing rate of 12 kg ha^{-1}. Experiments on clay soils in the Netherlands show that when caraway has to be harvested only once a sowing rate of 5 kg ha^{-1} results in an adequate plant density and a good yield (Wander, 1994). Experiments in Denmark with biennial caraway sown under

spring barley pointed to an optimal sowing rate as low as 4 kg ha^{-1} and a nitrogen application in spring of approximately 90 kg ha^{-1} (Nordestgaard, 1986). In Hungary optimum yield was achieved at a row spacing of 30 cm and a sowing rate of 6–8 kg ha^{-1} (Hornok & Csáki, 1982). In Poland a sowing rate of 5 kg ha^{-1} is recommended (Weglarz, 1983). Probably the results in Hungary and Poland were obtained with biennial caraway sown without a cover crop. Our results are in accordance with the results obtained by Nordestgaard (1986).

The effect of *M. acerina* susceptible cover crops on caraway establishment is more profound than the effect of these cover crops on disease development in caraway (Evenhuis & Verdam, 1997) The choice of cover crop and the preparation of the land show to be more critical on clay than on sandy soils, as was observed in the establishment of the caraway crops in Experiments 10 and 11. A dry period after sowing resulted in poor germination and emergence and a very low plant density if biennial caraway is grown under spring barley on a clay soil. Instead of using a higher sowing rate to meet with adverse conditions, efforts should be made to improve caraway crop establishment. The effect of the species and the variety of the cover crop on the establishment of the undersown caraway has to be investigated further. Seed dressing improved crop establishment under adverse conditions, but is not permitted in the Netherlands (Evenhuis & Verdam, 1995). However, importation of caraway seeds dressed with fungicides is accepted.

Inoculum build-up. The results obtained in this study show that in spring caraway lower inoculum levels at the start of the reproductive phase led to lower disease severity levels and reduced risk of yield loss. Therefore, supplementary crop protection activities in biennial caraway should be aimed at the reduction of inoculum build-up in autumn, because a low inoculum level will delay the epidemic in spring. Furthermore, plant breeders should develop cultivars with higher levels of partial resistance to anthracnose, to reduce the rate of development of an epidemic. Some preliminary work was done to develop a method for the selection of partial resistance to anthracnose in caraway (Evenhuis & Verdam, 1995).

Economics of crop management activities. Experiments in which nitrogen levels varied from 75 to 165 kg N ha^{-1} had no significant effect upon caraway yield (Floot, 1990). From these results it is concluded that nitrogen application can be reduced from 160 to 100 kg ha^{-1}, leading to a saving in expenditure of approximately 50 Dutch guilders per ha^{-1}. Further reduction might lead to yield loss, since a nitrogen application of 75 kg ha^{-1} seemed to be sub-optimal for seed production (Floot, 1990).

Lowering the sowing rate from 10–15 kg ha^{-1} to 5 kg ha^{-1} did not result in smaller yields in biennial caraway (Nordestgaard, 1986). Lowering the sowing rate by 5 kg ha^{-1} saves the expenditure of 5 * 15 = 75 Dutch guilders ha^{-1}. In anthracnose management, reduction of sowing rate is especially appropriate for spring caraway. An indication was found (Experiment 4) that by lowering the sowing rate the yield of spring caraway decreases under disease free conditions, but the effect was small. The optimum sowing rate of spring caraway must be between 4 and 8 kg ha^{-1}, depending

on seedbed conditions and sowing date.

With an increase of the row spacing the plant density decreases. With lower plant densities the root diameter will be larger and yield will increase (Weglarz, 1982). In biennial caraway, the negative effect on yield of low plant density is compensated by larger roots. Therefore, medium row spacing as a tool to reduce anthracnose development in caraway is economically relevant.

Conclusions

A damage threshold between 6 and 12% disease severity level is proposed, which provides a range of disease severities for action to prevent yield loss of caraway due to *M. acerina*.

Activities preventing prolonged leaf wetness duration help to decrease the disease severity of *M. acerina* and consequently to increase yield stability. Reduction of nitrogen application and sowing rate, and a medium row spacing are relevant management activities.

Lodging seems to enhance the conditions favouring *M. acerina* and increases the probability of severe yield loss in the presence of *M. acerina*. In agricultural practice lodging should and can be prevented by avoiding over-fertilization.

Acknowledgements

We thank Dr. H.J. Bouwmeester (AB-DLO) for enabling us to carry out field experiments at Wageningen and Randwijk. We thank Dr. M. Gerlagh (IPO-DLO) for the possibility to assess anthracnose levels in two white mould field experiments at Wageningen and Lienden. Ir. W. van den Berg (PAV) gave statistical assistance. We thank Dr. J.C. Zadoks (WAU), Dr. A. Darwinkel (PAV), Dr. M. Gerlagh (IPO-DLO) and ir. W.J.M. Meijer (AB-DLO) for critically reading the manuscript.

References

Bernelot Moens, H.L., J. Kuizenga & G. Liefstingh, 1973. Caraway cultivation. Experimental Station for Arable Crops. In Dutch, Lelystad-Wageningen, 36 pp.

Bouwmeester, H.J., H.G. Smid, & E. Loman, 1995. Seed yield in caraway (*Carum carvi*). 2. Role of assimilate availability. *Journal of Agricultural Science* 124: 245–251.

Carisse, O. & A.C. Kushalappa, 1992. Influence of interrupted wet periods, relative humidity and temperature on infection of carrot by *Cercospora carotae*. *Phytopathology* 82: 602–606.

Evenhuis, A., 1998. On ecology and control of Mycocentrospora acerina in caraway (*Carum carvi*). PhD thesis, Wageningen Agricultural University, Wageningen, 193 pp.

Evenhuis, A. & B. Verdam, 1995. Possibilities to control anthracnose of caraway in order to increase yield stability. (In Dutch). Report 189, Research Station for Arable Farming and Field Production of Vegetables (PAGV), Lelystad, 166 pp.

Evenhuis, A. & B. Verdam, 1997. Effects of cover crops, weeds and plant debris on development of *Mycocentrospora acerina* in caraway, *Annals of Applied Biology* 131: 227–243.

Evenhuis, A. & B. Verdam. Effects of seed infection (*Mycocentrospora acerina*) on caraway *(Carum carvi)* crop establishment and yield. *Seed Science and Technology* (submitted).

Evenhuis, A., B. Verdam & J.C. Zadoks,1997. Splash dispersal of conidia of *Mycocentrospora acerina* in the field. *Plant Pathology* 46: 459–469.

Floot, H.W.G., 1990. Effect of nitrogen rate and split nitrogen application on caraway yield and quality. (In Dutch). Annual Report 1989/1990. Publication 54, Research Station for Arable Farming and Field Production of Vegetables (PAGV), pp 84–87.

Hartmans, K.J., P. Diepenhorst, W., Bakker & L.G.M. Gorris,1995. The use of carvone in agriculture: sprout suppression of potatoes and antifungal activity against potato tuber and other plant diseases. *Industrial Crops and Products* 4: 3–13.

Hermansen, A., 1992. Weeds as hosts of *Mycocentrospora acerina*. *Annals of Applied Biology* 121: 679–686.

Hornok, L. & G. Csáki, 1982. Effects of stand density on caraway *(Carum carvi* L.). *Herba Hungarica* 21: 59–65.

Müller, H.R., F. Pank, & A. Plescher, 1989. Anbauverfahren Kümmel (*Carum carvi* L.) 1. Mitteilung: Anbauverfahren Blanksaat. *Drogenreport* 3: 77–86.

Nordestgaard, A., 1986. Seed production of caraway (*Carum carvi* L.). Seed- and nitrogen rates. (Abstract) Beretning nr 1825. Statens Planteavlsforsog, Roskilde, pp. 37–44.

Sutton, B.C. & Gibson, I.A.S., 1977. *Mycocentrospora acerina*. CMI descriptions of pathogenic fungi and bacteria no. 357.

Wander, J.G.N., 1994. Caraway cultivation (In Dutch). Teelthandleiding 60. Research Station for Arable Farming and Field Production of Vegetables (PAGV), Lelystad, 39 pp.

Weglarz, Z., 1983. Effect of agricultural agents on the transition of *Carum carvi* L. from vegetative to generative phase III. Effect of time of sowing, amount of seeds per ha and fertilization level on the development and cropping of caraway. *Herba Polonica* 29: 103–111.

Zadoks, J.C. & R.D. Schein, 1979. Epidemiology and plant disease management. Oxford University Press, New York, 427 pp.