Journal of Agricultural Science (2003), **140**, 1–13. © 2003 *Cambridge University Press*
DOI: 10.1017/S0021859602002885 *Printed in the United Kingdom*

Effects of rate and timing of nitrogen fertilizer on disease control by fungicides in winter wheat. 1. Grain yield and foliar disease control

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(*Revised MS received 18 November 2002*)

SUMMARY

The effects of nitrogen (N) rate and timing on need for fungicide application in winter wheat (*Triticum aestivum*) were investigated in 3 years of field experiments on loamy sand soils in Denmark. A two-factor completely randomized experimental design was used, comprising seven combinations of different N fertilizer rates and application times, and five doses of fungicide (co-formulation propiconazole and fenpropimorph). Two different varieties of winter wheat with high susceptibility to powdery mildew (*Blumeria graminis*) were used, Florida in the first season and Pepital in the last two seasons. The severity of powdery mildew and septoria leaf spot (mainly *Septoria tritici*) varied between seasons from slight to moderate with powdery mildew dominating in the first season and septoria leaf spot in the last season. The severity of both powdery mildew and septoria leaf spot assessed as the Area Under the Disease Progress Curve (AUDPC) was increased by application of N in all years, and more so by early applied N. Grain yields increased with increasing N rate and fungicide dose. However, the observed grain yields did not reveal any N × fungicide interactions. Regression models were therefore fitted, relating grain yield to rate and timing of N fertilizer and to AUDPC of powdery mildew and septoria leaf spot, and relating AUDPC to rate and timing of N fertilizer and to fungicide dose. They demonstrated that septoria leaf spot had a considerably higher impact on grain yield than mildew. The optimal fungicide dose and N rate were defined as those giving the highest economic return. The regression models were used to estimate the effect of N rate and timing on optimal fungicide dose, and the effect of fungicide application on optimal N rate. The optimal fungicide dose increased almost linearly with N rate above a minimum N rate, but with a large dependency on price relations. Early applied N caused a higher demand for disease control. The fungicide applications in the model were mainly driven by the need to control septoria leaf spot, whereas powdery mildew gave a poor net return for control. The estimated optimal N fertilizer rate for untreated diseased crops was 60 kg N/ha lower than for crops without disease. The use of fungicides with an efficacy twice that of the EBI-fungicides used in this experiment would increase the optimal N rate by *c*. 20 kg N/ha.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is a dominating agricultural crop in northern Europe because of its high productivity and its nutritional and economic value. Yields have increased rapidly by about 0·15 t/ha/year in the north-western part of Europe over the past 20 years (Supit 1997). This increase can largely be attributed to higher-yielding varieties (Silvey 1994) and the introduction of effective fungicides for disease control (Orson 1995).

The increasing winter wheat yields have also required increasing fertilizer use, especially of nitrogen (N). Nitrogen has been found to enhance especially the epidemic development of several biotrophic

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fungal diseases in winter wheat, e.g. powdery mildew (*Blumeria graminis* (DC.) Speer) (Bainbridge 1974), yellow rust (*Puccinia striiformis* f.sp. *tritici* West) (Danial & Parlevliet 1995) and leaf rust (*Puccinia recondita* Rob. & Desm.) (Mascagni *et al.* 1997). Semi-biotrophic fungal diseases such as leaf spot (*Septoria tritici* Roberge in Desmaz (*Mycosphaerella graminicola* (Funckel) Schröter in Cohn)) and leaf blotch (*Stagonospora nodorum* (Berk.) Castellani & Germano (*Phaeosphaeria nodorum* (Müll.) Hedjaroude)) have also been found to increase with increasing N application (Howard *et al.* 1994; Leitch & Jenkins 1995; Lovell *et al.* 1997), although these diseases are considered to be influenced predominantly by climatic conditions, especially by rainfall which affects spore dispersal (Lovell *et al.* 1997). There are for instance several studies that report no effect of N rate on septoria leaf spot (Büschbell & Hoffmann 1992; Olesen *et al.* 2000).

Septoria leaf spot, powdery mildew and yellow rust are the most important foliar diseases in winter wheat in Denmark. Although fungicides are available, their use is under critical review from both an economic and an environmental point of view (Jørgensen & Secher 1996).

At the beginning of the 1980s the use of pesticides increased significantly, partly due to the development of effective fungicides. This led in 1986 to the introduction of the first Danish action plan for a reduction of pesticide use. The aim has been to reduce both the quantity and the frequency of full-dose treatments in agriculture, defined as the treatment frequency index (TFI) (Jørgensen & Secher 1996). The driving force for the action plans has been the detection of pesticides in ground and surface waters.

Calculations based on analyses of farm economy as well as farmers' experiences have shown that a reduction in total TFI for agricultural crops of 1·5–1·7 is possible without significant economic consequences for the growers (Anonymous 1999*b*). The TFI was reduced from 2·6 in 1981–85 (reference period) to 2·0 in 2000.

The increasing concentrations of nitrate in surface and ground waters have been of great environmental concern in Denmark (Børgesen *et al.* 2001). In 1987, an action plan on the aquatic environment was implemented with the aim of reducing N leaching from agricultural areas by 100 000 t N/year. The measures applied have been gradually adjusted over time in order to reach this target (Grant *et al.* 2000). From 1999 the maximum permitted N fertilizer rate was reduced to 10 % below the economically optimal rate. For continuous winter wheat on sandy loam soil this resulted in a reduction of the N-norm from 206 kg N/ha in 1998 to 183 kg N/ha in 2000 (Plantedirektoratet 1997, 1999). The N applied at farm level cannot legally exceed the weighted sum of the N-norms of the respective crops.

Several field experiments have shown that the yield increase due to fungicide application depended on N rate in some year–location combinations (Kelley 1993; Howard *et al.* 1994; Olesen *et al.* 2000). These interactions indicate that the optimal N fertilizer rate will depend on the success of the disease control. The general relationships reported in literature also suggest that a reduction in N fertilizer may reduce the need for disease control. However, there have been no attempts to quantify the effect of fungicide control on optimal rate of N fertilizer and vice versa.

The objective of the experiments presented in the current paper was to study the effects of timing and rates of N fertilizer and fungicide application on leaf diseases, grain yield and N uptake. These data were then used in regression models to estimate optimal fungicide dose and optimal N fertilizer rate and timing, and to estimate the influence of optimal N rate on efficiency of disease control and on farmer's income. The optimal fungicide dose and N rate was defined in the current paper as those giving the highest economic return.

MATERIALS AND METHODS

The experiments were carried out during three seasons on experimental stations in Denmark using the same experimental layout in all years. During the first two seasons (1992–93 and 1993–94) the experiments were carried out at Foulum (56°30′ N, 9°35′ E), where the soil is a Typic Hapludult with a clay content of about 10 % throughout the profile 0–100 cm. During the last season (1994–95) the experiment was carried out at Roskilde (57°38′ N, 12°03′ E), where the soil is a Typic Agrudalf with a clay content of about 13 % in the plough layer increasing to 20 % below 50 cm depth.

Two different cultivars of winter wheat were used, Florida in the first season and Pepital in the last two seasons. Both varieties are highly susceptibile to powdery mildew (Pedersen 1992). The sowing date was 18–22 September (Table 1) with a sowing rate aimed at achieving a density of 300 plants/m². The inter-row distance was 12·5 cm at Foulum and 12 cm at Roskilde. The previous crop was barley for the first two seasons and oat for the last season. These cereal crops were harvested at maturity and the straw was removed at Foulum, but incorporated at Roskilde. The soil was ploughed, packed with a cylinder roller and harrowed before sowing of the wheat.

PK-fertilizers were supplied in April, with 16, 17, 16 kg P/ha and 84, 87, 84 kg K/ha being applied in 1993, 1994 and 1995, respectively. In 1992–93 the weeds were controlled by spraying with metsulfuron-methyl in April, in 1993–94 by spraying with isoproturon and a mixture of mecoprop and ioxynil in October 1993, and in 1994–95 with one spraying in November with a mixture of mecoprop and

Table 1. *Crop calendar and occurrence of selected growth stages (GS) according to the BBCH scale (Lancashire et al. 1991)*

Event	1992–93	1993–94	1994–95
Sowing	18 September	20 September	22 September
Emergence (GS 09)	2 October	4 October	4 October
N-application at T1	5 April	30 March	21 March
N-application at T2	29 April	26 April	26 April
N-application at T3	13 May	10 May	17 May
Flag leaf emerged (GS 39)	20 May	28 May	1 June
N-application at T4	3 June	8 June	14 June
Ear emerged (GS 59)	6 June	16 June	15 June
Anthesis (GS 65)	10 June	22 June	20 June
Yellow ripeness (GS 87)	27 July	24 July	28 July
Harvest	24 August	8 August	15 August

Table 2. *Experimental treatments*

Factor and treatment
Nitrogen
N1. 50 % at T2 (in total 50 %)
N2. 100 % at T2 (in total 100 %)
N3. 33 % at T1 + 50 % at T3 (in total 83 %)
N4. 33 % at T1 + 67 % at T3 (in total 100 %)
N5. 33 % at T1 + 83 % at T3 (in total 117 %)
N6. 17 % at T1 + 83 % at T3 (in total 100 %)
N7. 33 % at T1 + 50 % at T3 + 17 % at T4 (in total 100 %)
Fungicide
F1. Untreated
F2. 25 % PCP
F3. 50 % PCP
F4. 75 % PCP
F5. 100 % PCP

T1, late March; T2, 240 °Cd; T3, 400 °Cd; T4, 700 °Cd; PCP, PC Plant Protection.

ioxynil. Irrigation was applied at Foulum with 58 mm in 1993 and 61 mm in 1994. No insecticides were applied.

Experiment treatments

The treatments comprised a full factorial combination of seven N strategies and five fungicide doses as outlined in Table 2. The experiments were laid out in a completely randomized block design with three blocks (replicates), in total 105 plots. The gross plot size at Foulum was 15 m × 3 m, and the net area for harvest at maturity was 10 m × 1·5 m = 15·0 m². At Roskilde the gross size was 15 m × 2·5 m, and the net area was 10 m × 1·44 m = 14·4 m². The net plot width for fertilizer application was 2·5 m at both sites.

Nitrogen was applied as CAN (calcium ammonium nitrate) containing 27 % N, with 50 % in each of the ammonium and nitrate form. The full N rates were adjusted relative to the recommended N rate according to Danish fertilizer practices (Plantedirektoratet 1997) and adjusted for measured soil mineral N content in spring, which for the depth 0–100 cm amounted to 32, 34 and 16 kg N/ha for 1993, 1994 and 1995, respectively. Thus, the full N rates were 189, 183 and 180 kg N/ha in 1993, 1994 and 1995, respectively. Several split N strategies were used with four dates of application (T1 to T4). The first N application was given as soon as possible after 20 March (T1). The subsequent applications were given when specified temperature sums (base temperature of 0 °C) had accumulated from 1 March (Tables 1 and 2). The temperature sum of 240 °Cd (T2) occurred before the beginning of stem elongation, 400 °Cd (T3) occurred between the beginning of stem elongation and flag leaf emergence, and 700 °Cd (T4) occurred between flag leaf emergence and ear emergence (Table 1).

Fungicide treatments followed recommendations from the decision support system 'PC Plant Protection' (PCP) (Secher *et al.* 1995). The use of PCP as reference makes it possible (a) to evaluate how N-strategies affect the recommendations given by PCP and (b) to evaluate whether the rules in PCP properly reflect the response of diseases and crop to N-strategies. Five different doses of fungicide were applied: 0, 25, 50, 75 and 100 % of the dose recommended by PCP. The recommended doses were based on assessments of powdery mildew frequency assessed individually in each of the seven N strategies treated with 100 % PCP. However, recommendations for spraying for septoria leaf spot were based on the number of days with precipitation > 1 mm. The fungicide treatments are shown in Table 3. The co-formulation propiconazole + fenpropimorph (125 + 375) belonging to the group of EBI-fungicides was used in all treatments (Tilt Top™).

Table 3. *Applied fungicide (l/ha of Tilt Top) in the full dose treatments (100% PCP) for the seven different nitrogen treatments*

Date	N1	N2	N3	N4	N5	N6	N7
1993							
5 May	0·23	0·23	0·45	0·38	0·38	0·30	0·45
27 May	0·50	0·60	0·60	0·60	0·60	0·60	0·60
10 June	0·51	0·51	0·51	0·51	0·51	0·51	0·51
1994							
19 May	0·00	0·00	0·27	0·23	0·31	0·27	0·27
25 May	0·27	0·27	0·00	0·00	0·00	0·00	0·00
2 June	0·00	0·00	0·43	0·52	0·52	0·43	0·34
9 June	0·36	0·45	0·00	0·00	0·00	0·00	0·00
16 June	0·00	0·00	0·41	0·41	0·50	0·41	0·41
24 June	0·36	0·44	0·00	0·00	0·00	0·00	0·00
30 June	0·00	0·00	0·44	0·44	0·44	0·44	0·44
1995							
15 May	0·00	0·00	0·22	0·22	0·22	0·00	0·22
8 June	0·45	0·45	0·45	0·45	0·45	0·45	0·45
Total							
1993	1·24	1·34	1·56	1·49	1·49	1·41	1·46
1994	0·99	1·16	1·55	1·60	1·77	1·55	1·46
1995	0·45	0·45	0·67	0·67	0·67	0·45	0·67

Measurements

Crop growth stages were recorded every second day (Table 1). Ears were counted after anthesis in four 0·1 m² circular areas in each plot. The grains were harvested at maturity using a plot combine harvester for yield determination.

The grain dry matter content was determined in a subsample after oven-drying at 80 °C for 24 h. Total N in the grain was determined by the Dumas method (Hansen 1989). Grain weight was determined by weighing 1000 grains from each plot.

Percentage of leaf area covered by powdery mildew or septoria leaf spot (mainly *Septoria tritici*) on leaves, stems and ears was recorded weekly in each plot from 22 April to 15 July 1993, 4 May to 20 July 1994 and 8 May to 17 July 1995. Assessments were made on a 'whole-plot' basis by making an overall assessment of the mean percentage infection at a minimum of four positions selected randomly within each plot. At each position, disease was assessed on all green leaves (Anonymous 1999*a*).

Calculations

The observed disease severity was converted to Area Under the Disease Progress Curve (AUDPC) (Teng & Johnson 1988) by linear interpolation of fractional disease coverage between observation dates and summing all resulting daily values from the first to the last observation date.

The yield and disease severity data were analysed by an analysis of variance (ANOVA) separately for each year using the MIXED procedure of the SAS statistical analysis system (SAS Institute 1996). The MIXED procedure uses the method of residual maximum likelihood (REML) (Searle *et al.* 1992), and the number of degrees of freedom was calculated approximately using Satterthwaites method (Satterthwaite 1946). Data from five of the plots from 1995 were discarded because of mistakes in the N applications. These discarded plots included one plot of N1, three of N2 and one of N5. Four different fungicide treatments were represented in the discarded plots.

In addition, the following model was fitted to the yield data jointly for all three years:

$$Y = a_y + bN_1 + cN_2 + dN_3 + eN_4 + fN_T^2 + gA_m + hA_s \quad (1)$$

where Y is the grain dry matter yield (t/ha), N_1, N_2, N_3 and N_4 are the amounts of N fertilizer (kg N/ha) applied at T1, T2, T3 and T4, respectively, and N_T is the total amount of N fertilizer applied (kg N/ha). A_m and A_s are AUDPC of powdery mildew and septoria leaf spot, respectively. a_y is a constant that depends on year, and b, c, d, e, f, g and h are constants. The model was also fitted to the data for grain N content (kg N/ha), omitting the quadratic term for N_T. The constants in Eqn (1) were estimated for grain yield using the MIXED procedure of SAS.

The following model was fitted to the disease data:

$$A = \max(a_y + bN_1 + cN_2 + dN_3 + eN_4, 0) \times \exp(-kF) \quad (2)$$

where A is AUDPC of either powdery mildew or septoria leaf spot, N_1, N_2, N_3 and N_4 are the amounts of N fertilizer (kg N/ha) applied at T1, T2, T3 and T4 respectively, and F is the applied dose of fungicide (l/ha). a_y is a constant that depends on year and b, c, d, e and k are constants. The constants in this equation were estimated for each disease using the NLIN procedure of SAS (SAS Institute 1996).

Scenarios

Scenarios were set up to analyse the effect of rate and timing of N fertilizer on optimal fungicide dose. The optimal fungicide dose was calculated as the point where the change in income with increasing fungicide dose balances the increasing costs of the fungicides and its application. The income and costs were calculated as

$$I = p_g Y_g / 0{\cdot}85 \quad (3)$$

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$$C = p_f F + p_a \min(1, 2F) \quad (4)$$

where I is income from selling the cereal grains (€/ha), C is the sum of fungicide and application costs (€/ha), and F is the total amount of fungicide applied during the season (l/ha), Y_g is grain yield (t DM/ha), p_g is the price of grain with 15% moisture (€/t), p_f is the fungicide cost (€/l) and p_a is the cost per fungicide application (€/ha). It was assumed that the number of applications depended linearly on total fungicide dose, but that at least one application was needed. Separate price scenarios were used for 1994 and 2000 reflecting changes in prices of grain and fungicide. The following prices were used for 1994: $p_g = 125$ €/t, $p_f = 40$ €/l, and $p_a = 8$ €/l (Pedersen 1994), and for 2000: $p_g = 100$ €/t, $p_f = 45$ €/l, and $p_a = 8$ €/l (Pedersen 2000).

The optimal fungicide dose was calculated by increasing the dose F from 0 in steps of 0·01 l/ha until the costs (C) exceeded the income (I). The costs were calculated directly from Eqn (4). The income was calculated from Eqn (3) using the grain yield from Eqn (1), where the AUDPC of powdery mildew and septoria leaf spot was calculated from Eqn (2) using the fungicide dose (F).

The effect of N rate on disease control using fungicide was estimated by varying N from 0 to 200 kg N/ha in steps of 1 kg N/ha. A split N application was used with 33% applied at T1 and 67% at T3. For each N rate the AUDPC of powdery mildew and septoria leaf spot was calculated using Eqn (2), with varying initial severities (a_y in Eqn (2)). a_y for powdery mildew was allowed to vary from −6 to 0 in steps of 0·2, and a_y for septoria leaf spot was allowed to vary from −0·6 to 0·8 in steps of 0·05. These intervals capture the interannual variation in disease pressure observed in the present experiment, taken as representing the interannual variation in a_y in Eqn (2) (Table 7). For each N rate and combination of a_y values for the diseases, an optimal fungicide dose was calculated as described above. The mean optimal fungicide dose was then calculated for each N rate. This essentially gives the mean optimal fungicide dose under a range of base levels of AUDPC for powdery mildew and septoria leaf spot.

The effect of N rate and timing of N application was estimated in a similar way. Nitrogen rate was allowed to vary from 0 to 200 kg N/ha in steps of 10 kg N/ha and the proportion of N applied at T1 from 0 to 50% in steps of 5%. The remaining N was applied at T3.

The effect of fungicide dose on optimal N rate was estimated in a similar way for four different scenarios differing in disease control: (1) a scenario without disease, (2) a scenario without disease control, but with disease, (3) a scenario with optimal disease control, (4) a scenario with optimal disease control using a fungicide with higher efficacy, simulated by arbitrarily doubling the k-values in Eqn (2). In all scenarios the N rate was varied from 0 to 250 kg N/ha in steps of 1 kg N/ha. A split N application was used with 33% being applied at T1 and 67% at T3. The net income was calculated by adding the N fertilizer costs to the costs in Eqn (4). The price for N fertilizer was set to 0·5 €/kg N (Pedersen 1994, 2000).

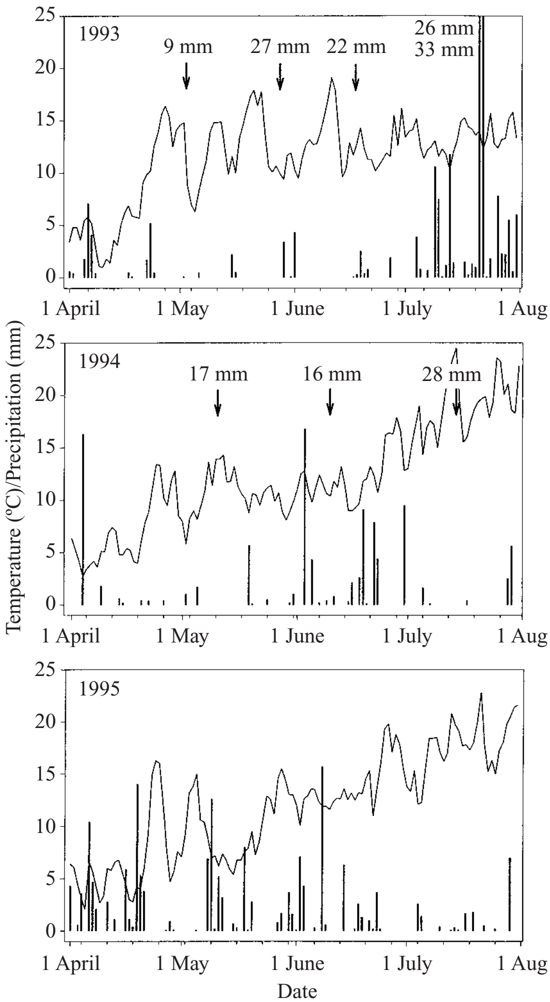

Fig. 1. Daily mean air temperature (lines) and precipitation (bars) for the growing season April to July of each of the three years. The arrows show the dates of irrigation.

RESULTS

Climatic conditions

The temperature and precipitation varied during the three growing seasons (Fig. 1). The 1993 season was dominated by dry weather until early July. 1994 was

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Table 4. *Grain yield and yield components. Grain yields and grain weights are based on dry matter*

Factor and treatment	Grain yield (t DM/ha) 1993	1994	1995	Grain weight (mg DM/grain) 1993	1994	1995	Ears (number/m^2) 1993	1994	1995
Nitrogen									
N1. 0+50+0+0=50%	4·98	5·93	6·65	47·5	43·0	36·7	353	426	455
N2. 0+100+0+0=100%	6·03	6·37	7·54	49·8	38·3	36·4	378	501	515
N3. 33+0+50+0=83%	6·23	6·48	7·38	47·4	40·0	35·7	384	463	489
N4. 33+0+67+0=100%	6·51	6·51	7·63	48·0	38·7	35·3	402	517	512
N5. 33+0+83+0=117%	6·66	6·51	7·68	48·0	37·5	35·2	410	515	510
N6. 17+0+83+0=100%	6·18	6·55	7·38	47·5	38·5	35·4	389	516	493
N7. 33+0+50+17=100%	6·40	6·63	7·57	47·6	40·0	36·3	405	489	483
S.E.D.	0·217	0·124	0·098	0·53	0·66	0·37	15	13	14
D.F.	68	68	63	68	68	63	68	68	63
Fungicide									
F1. Untreated	6·01	6·10	7·15	47·0	37·7	35·1	374	501	493
F2. 25% PCP	6·03	6·20	7·36	47·6	38·6	35·6	393	488	491
F3. 50% PCP	6·20	6·45	7·51	47·8	39·7	35·9	402	480	495
F4. 75% PCP	6·32	6·72	7·47	48·7	40·5	36·5	389	483	496
F5. 100% PCP	6·14	6·67	7·54	48·8	40·7	36·1	386	489	494
S.E.D.	0·183	0·105	0·080	0·45	0·56	0·30	13	11	12
D.F.	68	68	63	68	68	63	68	68	63
Overall mean	6·14	6·43	7·41	48·0	39·4	35·9	389	488	495

DM, dry matter; PCP, PC Plant Protection.

also dominated by dry weather during the whole growing season, whereas 1995 experienced extended periods of rain in April, May and early June.

Fungicide treatments in 1993 and 1994 were prompted by the appearance of powdery mildew, whereas treatments in 1995 were initiated partly by powdery mildew and partly by the high frequency of rainy days (Fig. 1). The total amount of fungicide applied in the 100% PCP treatments was approximately 1.5 l/ha of Tilt Top in 1993 and 1994, and about 0·75 l/ha in 1995 (Table 2). Slightly lower doses were applied in the N1 and N2 treatments (Table 2). This was mainly because the powdery mildew epidemics started later in these treatments (Olesen *et al.* 2003).

Grain yield and disease responses

The effects of both N and fungicide on grain yield were significant in all years (Table 4). However, there were no significant interactions between N and fungicide on grain yield. Grain weight increased with increasing fungicide dose, but was not affected by N treatments. Contrary to this, ear density was unaffected by fungicide dose, but increased with increasing N rates in all years (Table 4).

Both grain N concentration and N content increased with increasing N rates (Table 5). Single N application tended to increase grain N concentration at the expense of grain yield (Tables 4 and 5), and increasing N rate applied at T3 also increased grain N concentration (compare treatments N4, N6 and N7 in Table 5). However, the timing of N applications did not influence grain N content (compare treatments N2, N4, N6 and N7 in Table 5). Fungicide dose did not affect grain N concentration, but there was a small increase of 2–12 kg N/ha in grain N content from none to full fungicide dose due to the higher dry matter yields (Table 5).

Powdery mildew dominated in 1993 and 1994 resulting in the highest values of AUDPC, whereas septoria leaf spot dominated in 1995 (Table 6). Increasing N rates significantly increased AUDPC in all years for both diseases. However, the effect was largest for powdery mildew, which is illustrated by the coefficients *b*, *c* and *d* in Eqn (2) being 5–9 times larger for powdery mildew compared with septoria leaf spot (Table 7). For both diseases, the effect of N decreased with later application of the fertilizer, as can be seen from the parameter estimates in Table 7. Increasing the fungicide dose reduced AUDPC of both diseases, but with lower efficiencies in 1995 (Table 6). There was a tendency for a saturation of the response at full fungicide dose, especially for septoria leaf spot. However, full disease control was not obtained in any of the years. Full fungicide dose gave a maximum of 55% control of powdery mildew in 1993 and 1994 and 57% control of septoria leaf

Table 5. *Nitrogen concentration and content in grains*

Factor and treatment	Grain N concentration (g/kg of DM) 1993	1994	1995	Grain N content (kg N/ha) 1993	1994	1995
Nitrogen						
N1. 0+50+0+0=50%	19·6	17·5	15·0	99	104	99
N2. 0+100+0+0=100%	23·0	22·1	20·1	139	141	151
N3. 33+0+50+0=83%	20·5	19·7	16·8	128	128	124
N4. 33+0+67+0=100%	22·3	21·2	18·5	145	138	141
N5. 33+0+83+0=117%	23·3	22·6	0·20	155	147	157
N6. 17+0+83+0=100%	23·5	21·5	20·0	145	141	148
N7. 33+0+50+17=100%	21·9	21·2	18·9	140	141	143
S.E.D.	0·64	0·12	0·17	6·7	2·5	1·4
D.F.	68	68	63	68	68	63
Fungicide						
F1. Untreated	22·3	21·0	18·7	134	128	134
F2. 25% PCP	22·0	20·8	18·6	133	129	138
F3. 50% PCP	21·7	20·8	18·5	135	135	139
F4. 75% PCP	22·1	20·7	18·3	140	139	137
F5. 100% PCP	21·9	21·0	18·6	136	140	140
S.E.D.	0·54	0·10	0·14	5·7	2·1	1·2
D.F.	68	68	63	68	68	63
Overall mean	22·0	20·9	18·5	136	134	138

DM, dry matter; PCP, PC Plant Protection.

Table 6. *Area under the disease progress curve (AUDPC) for powdery mildew and septoria leaf spot as affected by main factors*

Factor and treatment	Powdery mildew 1993	1994	1995	Septoria leaf spot 1993	1994	1995
Nitrogen						
N1. 0+50+0+0=50%	2·02	1·10	0·09	0·12	1·02	0·80
N2. 0+100+0+0=100%	4·78	3·43	0·42	0·27	1·57	1·16
N3. 33+0+50+0=83%	4·01	2·58	0·25	0·19	1·24	1·10
N4. 33+0+67+0=100%	4·33	3·01	0·36	0·25	1·45	1·09
N5. 33+0+83+0=117%	4·75	3·25	0·35	0·26	1·51	1·17
N6. 17+0+83+0=100%	2·68	3·03	0·31	0·22	1·40	0·94
N7. 33+0+50+17=100%	4·47	2·82	0·24	0·24	1·39	1·11
S.E.D.	0·284	0·200	0·066	0·028	0·071	0·068
D.F.	68	68	63	68	68	63
Fungicide						
F1. Untreated	5·46	4·02	0·33	0·35	1·84	1·21
F2. 25% PCP	4·72	3·26	0·34	0·28	1·46	1·10
F3. 50% PCP	4·01	2·53	0·27	0·19	1·27	1·07
F4. 75% PCP	2·68	2·12	0·23	0·15	1·11	0·94
F5. 100% PCP	2·44	1·80	0·26	0·15	1·14	0·95
S.E.D.	0·240	0·169	0·055	0·024	0·060	0·058
D.F.	68	68	63	68	68	63
Overall mean	3·68	2·75	0·29	0·22	1·36	1·05

PCP, PC Plant Protection.

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Table 7. *Parameter estimates of the model in Eqn (2) relating AUDPC to applied nitrogen (kg N/ha) at different times (T1–T4) during the growing season and to fungicide dose used (l/ha). The model was estimated for powdery mildew and septoria leaf spot separately. Standard errors of the estimates are shown in parentheses*

Parameter	Powdery mildew	Septoria leaf spot
a_y: Intercept (1993, 94, 95)	−0·4, −1·9, −6·2 (0·3)	−0·63, 0·84, 0·33 (0·09)
b: N rate at T1	0·070 (0·005)	0·008 (0·001)
c: N rate at T2	0·036 (0·002)	0·005 (0·001)
d: N rate at T3	0·019 (0·002)	0·004 (0·001)
e: N rate at T4	−0·021 (0·006)	−0·004 (0·001)
k: Fungicide dose	0·57 (0·03)	0·37 (0·03)
RMSE	0·69	0·21
R^2	0·88	0·87

RMSE, root mean squared error of model; R^2, multiple regression coefficient.

Table 8. *Parameter estimates of the model in Eqn (1) relating grain yield (t DM/ha) and grain N content (kg N/ha) to applied nitrogen (kg N/ha) at different times (T1–T4) during the growing season and to area under the disease progress curve (AUDPC) for powdery mildew and septoria leaf spot. Standard errors of the estimates are shown in parentheses*

Parameter	Grain yield	Grain N content
a: Intercept, mean	4·66 (0·42)	66·7 (5·0)
b: N rate at T1	0·029 (0·006)	0·45 (0·06)
c: N rate at T2	0·022 (0·006)	0·50 (0·03)
d: N rate at T3	0·020 (0·006)	0·49 (0·03)
e: N rate at T4	0·014 (0·008)	0·00 (0·07)
f: (Total N)^2	−0·00004 (0·00002)	
g: AUDPC, powdery mildew	−0·03 (0·02)	−0·8 (0·7)
h: AUDPC, septoria leaf spot	−0·76 (0·11)	−13·1 (3·2)
RMSE	0·42	12·2
R^2	0·74	0·65

RMSE, root mean squared error of model; R^2, multiple regression coefficient.

spot in 1993 (Table 6). The control of powdery mildew was generally better than that of septoria leaf spot as can be seen from the estimated k-values (Table 7).

The grain yield benefits from N fertilizer decreased considerably at the latest application date (Table 8). On the other hand there were no significant differences in the response of grain N content to N fertilizer among the three first application dates (T1 to T3). N applied on the last application date (T4) did not affect grain N content, and yields only slightly. Powdery mildew did not significantly affect grain yield or N content (Table 8), however, both were significantly reduced by septoria leaf spot.

Scenarios

The mean optimal fungicide dose as calculated from the regression equations (Eqns (1) and (2)) increased considerably with increasing N fertilizer rate (Fig. 2). This was mainly caused by septoria leaf spot, because powdery mildew on its own did not trigger a profitable fungicide application in any of the scenarios tested. However, the inclusion of powdery mildew increased the optimal dose somewhat. The simulated mean optimal fungicide doses were lower than the fungicide dose applied in the experiment for both the 1994 and 2000 price data (compare Fig. 2 and Table 2). The higher grain prices and lower fungicide price for 1994 compared with 2000 resulted in a higher optimal fungicide dose for 1994.

There was a non-linear response of optimal fungicide dose to N fertilizer, with increasingly higher dosages at higher N rates (Fig. 2). For example, reducing the N rate by 10% from 180 kg N/ha resulted in a decrease of optimal fungicide dose by 21% for 1994 price data and by 26% for 2000 price data.

There was an interaction between timing and rate of N fertilizer on optimal fungicide dose (Fig. 3). Increasing N fertilizer increased the need for fungicide application more if the fertilizer was applied at T1 compared with T3. This is mainly due to different relative effects of N rate at T1 and T3 on grain yield and attack of septoria leaf spot. These effects are mediated through the parameters for T1 (b) and T3 (d) in Eqns (1) and (2), and the ratio of d to b was 0·69 for grain yield, but only 0·50 for septoria leaf spot (see Tables 7 and 8). Powdery mildew was estimated to have little effect on grain yield, and even though this disease was considerably favoured by early N application, it did not trigger a profitable fungicide application.

The profitability of N fertilizer use was affected considerably by diseases and by efficiency of disease control (Fig. 4). The mean optimal N rate was

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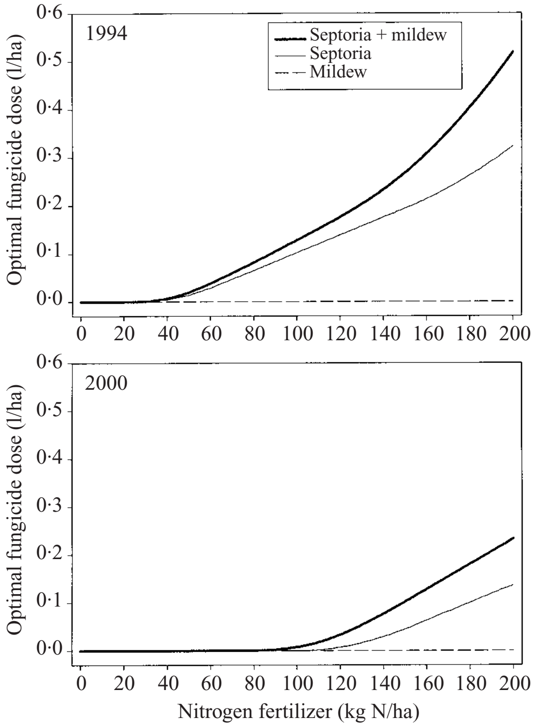

Fig. 2. Simulated response of mean optimal fungicide dose to increasing N fertilizer rate for 1994 and 2000 price scenarios. The N fertilizer was split with 33% applied at T1 and 67% at T3. The dose–response curves are shown for powdery mildew (– –) and septoria leaf spot (—) separately and for a mixture of powdery mildew and septoria leaf spot (**—**). The income and costs were calculated according to Eqns (3) and (4).

reduced by *c.* 60 kg N/ha for diseased crops compared with crops without disease (Table 9). A higher efficacy than for the EBI-fungicides used here simulated by doubling the *k*-values in Eqn (2) would increase the optimal N rate by *c.* 20 kg N/ha.

DISCUSSION

The disease severity of both powdery mildew and septoria leaf spot were enhanced by increasing rates of N fertilizer. This effect was considerably stronger for powdery mildew than for septoria leaf spot. This confirms the general finding that biotrophic pathogens like *B. graminis* are strongly affected by the N nutrition of the host (Bainbridge 1974; Tompkins *et al.* 1992), whereas the results for hemi-biotrophic pathogens like *S. tritici* may be more variable. However, in the literature cases showing that *S. tritici* is enhanced by N fertilizer (Broscious *et al.* 1985; Jordan *et al.* 1988; Howard *et al.* 1994; Leitch & Jenkins 1995; Lovell *et al.* 1997) outnumber the cases where there is no effect or even a decrease with increasing N rate (Tompkins *et al.* 1993; Olesen *et al.* 2000).

Darwinkel (1980) suggested that a split N application might reduce total seasonal powdery mildew infection levels. This hypothesis was confirmed in the current experiment, as all split N strategies comparable with a full single application resulted in lower values of AUDPC for powdery mildew. However, in the split strategies used here, a maximum of 33% of the N was applied in the early application. More N applied early would have promoted both powdery mildew and septoria leaf spot more, and have led to higher fungicide dose as indicated by our simulation model (Fig. 3). This effect of early N has also been found in other European field experiments (Darwinkel 1980; Jordan *et al.* 1988). A possible explanation could be that early infections increase the spore production and thus the infection pressure later in the season.

The higher simulated severity of powdery mildew and septoria leaf spot for early applied N resulted in higher optimal fungicide dose with more N applied in early season. However, there may still be good reason to apply at least part of the N early, because the yield response was also higher with early N application. This early N is required to promote tillering and development of an effective crop canopy (Darwinkel 1983; Ellen 1987).

The yield model in Eqn (1) used a linear relationship between yield and AUDPC. Similar yield models have been successfully applied for powdery mildew by Wright & Gaunt (1992) and for septoria leaf spot by Thomas *et al.* (1989).

Even though the effect of N rate on septoria leaf spot severity was weaker than for powdery mildew, the resulting impact on optimal fungicide dose was largely determined by the effect on septoria leaf spot, because yield was affected much more severely by septoria leaf spot than by powdery mildew (Table 8). The low impact of powdery mildew on yield was probably an effect of the rather low infection levels throughout the season (Olesen *et al.* 2002), which meant that the crop could compensate for the loss in green leaf area. Higher disease levels of powdery mildew would have been more harmful (Darwinkel 1980). However, it is generally known that powdery mildew is much less yield reducing than septoria leaf spot (Jørgensen *et al.* 2000). The larger yield losses due to septoria leaf spot were probably caused by accelerated senescence of the upper leaves (Shaw & Royle 1993; Lovell *et al.* 1997). This is supported by the fact that the yield improvement with fungicide treatment was mainly obtained through a higher grain weight (Table 4).

The statistical analyses of the yield data did not reveal significant N × fungicide interactions. This is partly caused by the experimental design, where fungicide dose depended on observations of powdery

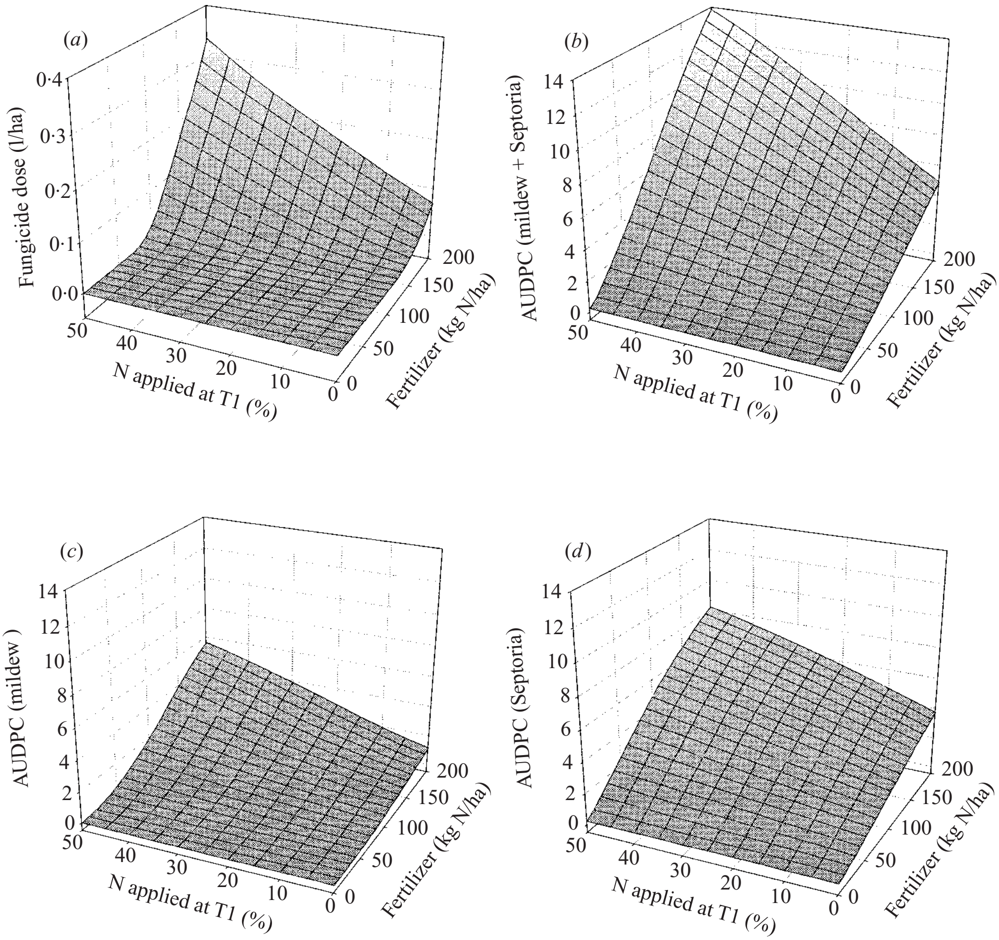

Fig. 3. Simulated response of mean optimal fungicide dose (*a*), severity of powdery mildew and septoria leaf spot (*b*), severity of powdery mildew (*c*) and severity of septoria leaf spot (*d*) to increasing N fertilizer rate and to proportion of the total N fertilizer being applied at T1. The remaining fertilizer was applied at T3. The price scenario for 2000 was used for calculating optimal dose. The income and costs were calculated according to Eqns (3) and (4).

mildew frequency for each N-strategy (Table 2). In addition, such interactions can be difficult to obtain in experiments, where the experimental error often obscures the interactions. Mascagni *et al.* (1997) thus found significant N × fungicide interaction on grain yield at only one of 12 year–location environments in Louisiana, USA. In cases with significant N × fungicide interactions in the literature, grain yields increased more with fungicide application at high than at low N rates (Kelley 1993; Olesen *et al.* 2000). This interaction is also implied by the combined use of the regression Eqns (1) and (2).

The possible effect of the N × fungicide interaction is reflected in the simulated increase in optimal fungicide dose with increasing N rate (Fig. 2). The reductions of at least 10 % in N application rates imposed by the Danish action plan for the aquatic environment may thus have reduced the economically optimal requirements for fungicide application by up to 20 %. Since the plan was implemented in 1986 there has been a significant reduction in use of fungicides in winter wheat mainly due to farmers applying appropriate and reduced dosages for disease control (Secher & Jørgensen 1995). The TFI for fungicides has been reduced from 1.9 in 1985 to 0.7 in 2000. It can be difficult to judge if the reduction of N use by 10 % has already influenced this reduction. However, the imposed 10 % reduction in N-rate will facilitate the reduction of pesticide use.

The simulated optimal N rates were affected considerably by diseases and by fungicide use, and the optimal N fertilizer rate was lower when no fungicide was used. This confirms the general opinion that cereals in organic farming systems should be managed

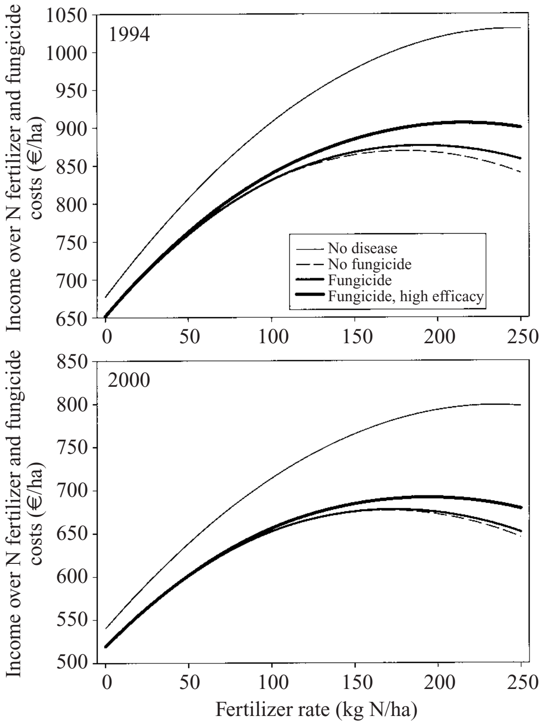

Fig. 4. Simulated mean response of net income to N fertilizer rate for situations without disease (—), without fungicide application (– –), and for optimal fungicide dose with normal (—) and double (—) (high efficacy) *k*-values in Eqn (2). The N fertilizer was applied as split N dressing with 33% at T1 and 67% at T3. The results are shown for 1994 and 2000 price scenarios. The income and costs were calculated according to Eqns (3) and (4).

at generally lower N input levels (Lampkin 1990). The optimal N rate is considerably higher for fungicides with higher efficacy than the EBI-fungicides used in this experiment. Compared with the EBI-fungicides, the use of strobilurins have resulted in an improved efficacy and increased yields elsewhere (Hanhart & Frahm 1996; Obst & Steck 1996). In particular, the strobilurin azoxystrobin has in many trials increased yields significantly compared with the level previously obtained with ergosterol inhibitors (Jørgensen & Nielsen 1998). It is thus likely that the adoption of new and more effective fungicides has increased the optimal N rate compared with the fungicides registered and used at the time when the experiments were carried out.

Table 9. *Simulated mean optimal N rates (kg N/ha) for price relations from 1994 and 2000. Four disease and fungicides scenarios were used: without disease, without fungicide application, optimal fungicide dose with normal and double (high efficacy) k-values in Eqn (2)*

Disease scenario	1994	2000
No disease	245	229
No fungicide, but disease	179	169
Optimal fungicide	190	173
Optimal fungicide, high efficacy	213	193

The simulated optimal fungicide dose was considerably lower than the full dose used in the experiments. The full dose was taken as the recommendation of the PC Plant Protection system. The fungicide applications were mainly triggered by observed powdery mildew frequency. However, the very small yield response to powdery mildew found in this experiment suggests that there is potential for reducing the recommended fungicide dose in PC Plant Protection under less conducive conditions.

CONCLUSIONS

The severity of both powdery mildew and septoria leaf spot were enhanced by increasing rates of N fertilizer. The effect was stronger for early applied N, especially for powdery mildew. Grain yield for a healthy crop was also enhanced most by early applied N. Septoria leaf spot had a considerably higher impact on grain yield than powdery mildew. The estimated optimal fungicide dose increased almost linearly with N rate above a minimum N rate, but with a large dependency on price relations. The highest fungicide doses were needed when N was applied early. The estimated optimal N fertilizer rate was reduced by *c.* 60 kg N/ha for untreated diseased crops compared with crops without disease. The use of fungicides with an efficacy twice that of the EBI-fungicides used in the experiment would increase the optimal N rate by *c.* 20 kg N/ha.

The work was financially supported by the Ministry of Food, Agriculture and Fisheries under contract BÆR-SP-15 of the research programme for Sustainable Agriculture, Reduction in Fertilizer and Pesticide Use.

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