

EFFECTS OF CULTURAL MANAGEMENT ON THE FOOT AND ROOT DISEASE COMPLEX OF DURUM WHEAT

M. Montanari¹, G. Innocenti¹ and G. Toderi²

¹ *Dipartimento di Protezione Valorizzazione Agroalimentare, Alma Mater Studiorum, Università di Bologna, Via Fanin 46, 40127 Bologna, Italy*

² *Dipartimento di Scienze e Tecnologie Agroambientali, Alma Mater Studiorum, Università di Bologna, Via Fanin 44, 40127 Bologna, Italy*

SUMMARY

The effects of three tillage techniques (minimum tillage [chisel ploughing], and mouldboard ploughing to a depth of 25 and 50 cm) and four 2-year crop rotations (continuous wheat, wheat/barley, wheat/sugar-beet and wheat/fallow) on the foot and root disease complex of durum wheat were studied from 1999 to 2001 in an experimental field at the Bologna University farm. Brown foot rot (BFR) caused by *Fusarium* species and *Bipolaris sorokiniana*, and eyespot caused by *Oculimacula* spp. were the major components of the foot and root disease complex.

Ploughing was significantly more effective than chiselling in controlling eyespot disease over the whole period of observation, whereas ploughing significantly reduced BFR only in 1999 when the incidence of the disease was the highest. Wheat/sugar-beet was generally less favourable for development of the foot and root disease complex than the other rotations tested. The effects of tillage techniques and crop rotations on disease were year-dependent. A more detailed analysis carried out in 2000 to evaluate the effect cultural practices on fungi associated with brown foot rot disease, indicated that *F. culmorum* was predominant with minimum tillage and scarce in ploughing, whereas *B. sorokiniana* was predominant in plots that were ploughed.

Key words: durum wheat, crop rotation, tillage, foot and root fungi.

INTRODUCTION

The main components of the foot and root disease complex of winter cereals in temperate areas are brown foot rot (BFR) (*Fusarium* species and *Bipolaris sorokiniana* [Sacc. in Sorok.] Shoem), eyespot (*Oculimacula acuminata* [Boerema, Pieters & Hamers] Crous & Gams, and

O. yallundae [Wallwork & Spooner] Crous & Gams), sharp eyespot (*Rhizoctonia cerealis* van der Hoeven) and take-all (*Gaeumannomyces graminis* von Arx & Olivier var. *tritici* Walker). The main sources of inoculum for all these soil-borne fungi are infested crop residues, where the fungi survive as mycelium or resting structures in the inter-crop period (Wiese, 1987). Survival of the pathogens depends on several factors, such as the nature and position of crop residues in the soil profile, and the presence or absence of antagonistic, competitive biota (Garrett, 1970; Hornby *et al.*, 1998).

The complex aetiology of the diseases suggests different control methods, including the use of biological, chemical and agronomic treatments (Cook, 2000; Roberti *et al.*, 1992, 2000). Cultural practices, particularly tillage techniques and crop rotations, can reduce the amount of primary inoculum by correct management of the residues in the soil profile and by their effect on antagonistic organisms living in the soil as saprotrophs, weak plant parasites or mycoparasites (Sumner *et al.*, 1981; Colbach *et al.*, 1996; Cook, 2000). However, the effects of tillage on plant-pathogen interactions change in relation to soil and climatic conditions, crop succession and tillage technique/crop rotation interactions.

Generally, ploughing can reduce inoculum by burial and fragmentation of infectious residues. However, especially in light soil, ploughing has several negative effects, such as increasing erosion and topsoil loosening, with associated deterioration of soil quality (Phillips *et al.*, 1980). Conversely, minimum tillage and particularly no-till generally have a positive effect on soil microbial activity, by increasing organic matter (Sumner *et al.*, 1981; Wardle, 1995). However, in heavy soil, no till or reduced cultivation can cause water logging, which is favourable to the survival of pathogens on residues distributed in the upper soil layer, thus increasing infection of crowns and roots (Cook, 1973). The success of crop rotation in controlling foot and root disease depends on the relationship between pathogens and the crop growing in the absence of the cereal, which can be host, non-host or amplifier crop (Colbach and Meynard, 1995).

In Italy, brown foot rot is the major component of the foot and root disease complex of durum and soft wheat and causes severe yield losses (Innocenti, 1985;

Corazza *et al.*, 1987; Cariddi *et al.*, 1991; Balmas and Corazza, 1992; Rossi *et al.*, 1994; 1995; Balmas *et al.*, 2000; Innocenti *et al.*, 2000b; Covarelli and Nicholson, 2002). Take-all has been an important component of the disease only in particular years (Innocenti *et al.*, 1992); eyespot and sharp eyespot do not usually play an important role in the foot and root disease complex (Rossi *et al.*, 1995; Innocenti *et al.*, 2000b), although, recently, a higher incidence of eyespot has been observed in some areas of central and northern Italy (Innocenti *et al.*, 2000a).

The aim of this study was to evaluate the influence of three tillage techniques and four crop rotations on the foot and root disease complex of durum wheat in a typical Italian cereal-growing area.

MATERIALS AND METHODS

Field site and sampling. The study was carried out at the University farm located in the Po Valley near Bologna (northern Italy), in a wheat-growing area, on clay soil classified as Inceptisol, Udertic Ustochrepts, Fine, Mixed, Mesic (FAO classification). The trial was set up in 1985. Our data refer to the period 1999-2001. Three tillage techniques (mouldboard ploughing to a depth of 50 cm [T50] and 25 cm [T25]) and minimum tillage (chisel ploughing [MT]), continuous winter durum wheat [W] and three 2-year crop rotations (wheat/barley [W/B], wheat/fallow [W/F] and wheat/sugar-beet [W/S]) were tested in a two-factor split-plot design with three replicates, where tillage was the main factor (plot: 42 × 8 m) and crop rotation the secondary factor (subplot: 6 × 8 m). Wheat/fallow was introduced into the trial in 1995 after continuous oats. In the fallow year, weeds were controlled by herbicide application in autumn and shallow cultivation in the spring. In each year *Triticum durum* Desf. cv Creso was sown in mid October at 200 Kg per ha; 200 Kg per ha of nitrogen in wheat in W, W/F and W/B treatments and 160 Kg per ha in W/S were applied at sowing. All treatments also received 150 Kg per ha of phosphorus as P₂O₅. Fungicides were applied to control leaf diseases, but not foot and root diseases. A more detailed description of the agronomic treatments can be found in Toderi *et al.* (2000). To evaluate the effects of agronomic treatments on foot and root diseases, 20 plants were randomly collected at the late milk-early dough development stage (85-87 of the Zadoks plant growth stage (ZGS); Zadoks *et al.*, 1974) along two diagonals per sub-plot (replicate) giving a total of 60 plants per treatment. To analyse the fungi associated with brown foot and root rot disease, 15 plants were collected from each subplot at the stem elongation stage (ZGS 29-30), in W and W/F under MT and T25. Later, 15 plants were collected at the late milk-early dough development stage (ZGS 85-87) in W

and W/F under MT and T25 in each subplot. Meteorological data (air-temperature and precipitation) were provided by Department of Agroenvironmental Science and Technology, University of Bologna (Italy).

Disease assessment. Plants, including roots, were assessed for disease after separating stems from sheaths and washing under running water. Each disease was expressed as incidence: the percentage of diseased plants (plants with symptoms) per replicate per treatment. The incidence was calculated as: (infected plants/total plants) × 100. Isolation was used to verify the pathogens associated with disease symptoms. Segments from roots (each approximately 0.5 cm) and portions of stems (each approximately 1 cm) were surface-sterilised for 1 min in aqueous 10% ethanol, 8% sodium hypochlorite rinsed twice with sterile distilled water and dried on sterile filter paper. Roots or stem portions were then placed on 1.8% Bacto agar (Becton, Dickinson and Company, Sparks, Md, U.S.A.) amended with 160 mg l⁻¹ streptomycin sulphate. Fungi growing out were transferred separately to plates containing 3.9% Difco potato dextrose agar (PDA, Becton, Dickinson and Company, Sparks, Md, U.S.A.). To isolate *G. graminis* var. *tritici*, root segments were placed on the Ggt semi-selective medium described by Juhnke *et al.* (1984). For *Oculimacula* the isolation method suggested by Murray (1992) was used: surface sterilised stem pieces were placed on 2.0% Bacto agar + 50 mg l⁻¹ rifampicin in Petri dishes. Plates were incubated for 10 days at 15°C under near-ultraviolet light (NUV), colonies were then sub-cultured on 0.2 PDA + 50 mg l⁻¹ rifampicin and incubated at 15°C. No distinction was made between the two species of *Oculimacula*. Isolations were also made from plants with no specific symptoms as controls.

Isolation and identification of fungi associated with brown foot rot disease. To isolate fungi associated with BFR, diseased plants collected at ZGS 20-30 and the basal portion (0-20 cm) of main stems and fertile tillers with disease symptoms collected at ZGS 91-92, were washed under running water for 1 h, surface-sterilised, rinsed and dried as above. Plants or stem portions were then placed in sterile trays on modified potato dextrose agar (MPDA) containing 25 g l⁻¹ PDA, 160 mg l⁻¹ streptomycin sulphate, 60 mg l⁻¹ chlortetracycline hydrochloride and 6 mg l⁻¹ dichloronitroaniline. Trays were put into polyethylene bags and incubated at room temperature for 4-5 days. Mycelia growing out were separately transferred onto PDA in Petri dishes and incubated at 24°C in the dark for 4-7 days. Thereafter, mycelial plugs from each colony were transferred onto low nutrient agar (SNA; Spezieller Nährstoffarmer Agar) (Nirenberg 1981) and maintained at 17°C under NUV for 7-15 days. Fungal species were identified on the basis of their cultural, morphological and biological features accord-

Table 1. Total monthly precipitation (mm) and mean monthly temperature (°C) over the period of observation.

Month	1998		1999		2000		2001	
	mm	°C	mm	°C	mm	°C	mm	°C
January			37.8	4.9	11.8	6.7	110.6	4.3
February			55.0	5.0	8.2	5.5	29.4	5.6
March			37.6	10.1	28.4	8.9	68.4	10.0
April			46.8	13.7	39.2	13.8	81.6	10.6
May			59.2	19.2	14.3	19.2	68.2	18.1
June			77.4	21.6	53.6	22.7	25.0	20.6
October	74.6	15.2	71.4	15.5	104.2	15.7		
November	26.8	7.5	221.6	7.4	84.2	12.7		
December	80.6	3.3	76.0	4.1	25.2	5.6		

ing to Nirenberg (1981), Nelson *et al.* (1983) and Domsh *et al.* (1993). The frequency of each species was calculated as the number of isolates of the species out of the total number of isolates.

Statistical analysis. All data are presented as untransformed but, before analysis of variance, they were subjected to angular (arcsin) transformation (Snedecor and Cochran, 1980).

Disease incidence data were subjected to analysis of variance (multifactor ANOVA) according to a two-factor split-plot design combined over years (year as random factor), where tillage technique was the main factor and crop rotation the second factor. Differences between the means were evaluated by the Least Significant Difference test (Statistical Analysis System, SAS Institute Inc, Cary, NC, U.S.A., 1997). To determine the effect of agronomic treatments on fungi associated with BFR in 2000, the percentages of fungal species responsible for the disease were subjected to multifactor ANOVA, according to a split split-plot design. Tillage technique was the main factor, crop rotation the second factor, and pathogenic species the third factor. Means were compared by LSD test. Regression analysis was used to describe the relationship between the incidence of BFR disease and the percentages of its causal agents, and the foot and root disease incidence and yield.

RESULTS

Meteorological data. The air-temperature was relatively warm over the whole period of observation (Table 1). Patterns of temperature distribution over the three years were slightly different. In particular, the 2001 spring weather was colder than that in the previous two years.

Total rainfall for the crop season (October-June) was 497 mm in 1998-1999, 524 mm in 1999-2000, and 596 mm in 2000-2001. Rainfall patterns over the three years were different. In particular, in the third year, the spring (March-May) was wetter (218.2 mm) than the same period in 1999 (143.6 mm) and in 2000 (81.9 mm).

Effect of the treatments on the disease. *Brown foot rot.* Wheat plants affected by brown foot rot disease (BFR) were found in all treatments over the whole period of observation. Mean disease incidence independent of tillage technique and crop rotation significantly decreased from 1999 to 2001 (1999: 59.5%; 2000: 46.5%; 2001: 24.4%). The effect of cultural practices on disease was particularly evident in 1999, when incidence was highest. In this year disease incidence was significantly higher with minimum tillage (MT) than with ploughing (T25 and T50). In 2000 and 2001 the effect of MT, T25 and T50 on the disease was similar (Table 2). Averaged

Table 2. Effect of tillage technique on brown foot rot disease of wheat expressed as percentage of diseased plants.

Tillage technique	1999	2000	2001	Means
MT	71.7 b	46.5 a	19.1 a	45.8 a
T25	60.6 a	43.9 a	26.4 a	43.7 a
T50	46.1 a	49.0 a	27.7 a	40.9 a

MT = minimum tillage; T25 = ploughing to 25 cm depth; T50 = ploughing to 50 cm depth. Percentage values were arcsin-transformed before statistical analysis. In the Table untransformed data are reported. Means in the same column followed by different letters were significantly different according the LSD test at $P < 0.01$. Tillage technique and tillage technique x crop rotation interaction were not significant; tillage x year interaction was significant at $P < 0.05$.

over the three years, there were no significant differences between tillage techniques. The incidence of BFR in 1999 was significantly higher in wheat grown after barley (W/B), fallow (W/F), and wheat (W) than in wheat succeeding sugar-beet (W/S) (Table 3). W/F significantly favoured disease development in 2001, whereas similar levels of disease were observed in all rotations in 2000. Averaged over the three years, sugar-beet significantly decreased disease incidence compared with W/F and W/B. The effects of tillage techniques as well as crop rotation on BFR disease development were year-dependent.

Table 3. Effect of crop rotation on brown foot rot disease of wheat expressed as percentage of diseased plants.

Previous crop	1999	2000	2001	Means
Wheat	58.9 b	43.5 a	21.3 a	41.2 ab
Barley	74.3 c	53.9 a	17.6 a	48.6 b
Sugar beet	33.7 a	42.7 a	24.1 ab	33.5 a
Fallow	71.0 c	45.8 a	34.7 b	50.5 b

Percentage values were arcsin-transformed before statistical analysis. In the Table, untransformed data are reported. Means in the same column followed by different letters were significantly different according the LSD test at $P < 0.01$. Crop rotation and crop rotation x year interaction were significant at $P < 0.01$.

Eyespot. Wheat plants affected by eyespot were found in all treatments. Mean disease incidence independent of tillage technique and crop rotation was: 8.1% in 1999, 2.9% in 2000, and 12.1% in 2001. Eyespot development was favoured by non-inversion of soil (MT), whereas ploughing treatments (T25 and T50) drastically reduced incidence over the whole period of observation (Table 4). In ploughed plots incidence was very low in all crop rotations (T25: W=0.5%; W/B=0.5%, W/F=0.3%, and W/S=0.1%; T50: W=0.4%; W/B=0.2%, W/F=0%, and W/S=0.6%), whereas in minimum tilled plots the effect of previous crop on eyespot incidence was different (W=49.6%; W/B=25.6%, W/F=12.8%, and W/S=1.7%). Crop rotation with fallow (W/F) and sugar-beet (W/S) significantly decreased incidence compared with

Table 4. Effect of tillage technique on eyespot disease of wheat expressed as percentage of diseased plants.

Tillage technique	1999	2000	2001	Means
MT	23.1	8.7	35.5	22.4 b
T25	0.5	0.2	0.3	0.3 a
T50	0.4	0.1	0.4	0.3 a

MT = minimum tillage; T25 = ploughing to 25 cm depth; T50 = ploughing to 50 cm depth. Percentage values were arcsin-transformed before statistical analysis. In the Table untransformed data are reported. Means in the same column followed by different letters were significantly different according the LSD test at $P < 0.01$. Tillage technique was significant at $P < 0.01$, tillage x year interaction was not significant.

continuous wheat (Table 5). Crop rotation with barley was more favourable to the disease than rotation with a non-host crop and less favourable than continuous wheat. Averaged over the three years, the same results were observed.

Table 5. Effect of crop rotation on eyespot disease of wheat expressed as percentage of diseased plants.

Previous crop	1999	2000	2001	Means
Wheat	17.2	7.4	25.8	16.8 c
Barley	8.7	3.5	14.0	8.7 b
Sugar beet	0.9	0.1	1.4	0.7 a
Fallow	5.2	0.8	7.1	4.4 ab

Percentage values were arcsin-transformed before statistical analysis. In the Table untransformed data are reported. Means in the same column followed by different letters are significantly different according the LSD test at $P < 0.01$. Crop rotation was significant at $P < 0.01$, tillage x year interaction was not significant.

Sharp eyespot. No significant effect of tillage techniques on sharp eyespot development was observed over the whole period of observation (Table 6). Wheat/sugar-beet was significantly more favourable to disease than other crops in 1999, 2000 and 2001 (Table 7). The effect of tillage technique as well as crop rotation was not year-dependent.

Table 6. Effect of tillage technique on sharp eyespot disease of wheat expressed as percentage of diseased plants.

Tillage technique	1999	2000	2001	Means
MT	7.9	1.6	6.9	5.5
T25	16.7	6.1	5.6	9.5
T50	18.8	4.5	10.7	11.3

MT = minimum tillage; T25 = ploughing to 25 cm depth; T50 = ploughing to 50 cm depth. Percentage values were arcsin-transformed before statistical analysis. In the Table untransformed data are reported. No statistical differences were found.

Table 7. Effect of crop rotation on sharp eyespot disease of wheat expressed as percentage of diseased plants.

Previous crop	1999	2000	2001	Means
Wheat	5.0	2.0	2.2	3.1 a
Barley	0.7	1.3	2.2	1.4 a
Sugar beet	44.1	9.6	22.4	25.4 b
Fallow	8.0	3.4	4.2	5.2 a

Percentage values were arcsin-transformed before statistical analysis. In the Table untransformed data are reported. Means in the same column followed by different letters are significantly different according the LSD test at $P < 0.01$. Crop rotation was significant at $P < 0.01$; crop rotation x year interaction was not significant.

Table 8. Mean percentages of fungi associated with brown foot rot disease of durum wheat plants collected under different treatments at two growth stages in 2000.

Pathogen	Stem elongation plant growth stage	Late milk early-dough plant growth
<i>Bipolaris sorokiniana</i>	22.3 b	41.9 b
<i>Fusarium avenaceum</i>	3.3 a	0.9 a
<i>Fusarium culmorum</i>	44.1 c	51.9 c
<i>Fusarium graminearum</i>	3.5 a	4.9 a
<i>Microdochium nivale</i>	26.8 bc	0.5 a

The pathogen factor was significant at both plant growth stages at $P < 0.01$.

Different letters on the same column show significant differences according the LSD test.

Take-all. Take-all incidence was very low over the whole period of observation. The mean incidence independent of tillage technique and crop rotation was: 5.0% in 1999, 0.2% in 2000, and 5.7% in 2001. No significant effect of tillage techniques on disease incidence was observed. In 1999 wheat/barley (10.7%) was significantly more favourable to take-all than continuous wheat (6.1%), wheat/ fallow (0.6%), and wheat/sugar-beet (2.5%). The same was observed in 2001 (W/B=14.4%, W=5.5%, W/F=2.9%, and W/S=0.1%). In 2000 the disease was observed sporadically in all treatments. Both tillage technique and crop rotation effects were year-dependent.

Effect of agronomic treatments on fungi associated with brown foot rot. The percentages of fungal pathogens associated with BFR are reported in Table 8. *Fusarium culmorum* (Smith) Sacc. was the most important component followed by *B. sorokiniana* at both plant growth stages. *Microdochium nivale* (Ces. ex Berl. & Vogl.) Sammuels & Hallett was also frequently isolated at the stem elongation stage, whereas it was only sporadically present at the late milk early-dough plant growth stage. At stem elongation crop rotation significantly ($P < 0.05$) affected the presence of *B. sorokiniana*. Continuous wheat was more favourable (34.8%) to this pathogen than W/F (9.9%), no influence by previous crop was observed on other fungi associated with BFR; no effect was shown by tillage technique. At late milk early-dough stage, tillage technique significantly ($P < 0.01$) influenced the presence of *B. sorokiniana* and *F. culmorum*. MT was more favourable to *F. culmorum* (82.8%) than to *B. sorokiniana* (11.7%); the opposite was observed under ploughing (21.0% for *F. culmorum*, and 72.1% for *B. sorokiniana*); no influence was observed on other fungi associated with BFR. Crop rotation did not influence the percentages of BFR pathogens.

Correlation between brown foot rot disease and its causal organisms. A positive correlation was found be-

tween BFR incidence and the sum of the percentages of the causal organisms *F. culmorum*, *B. sorokiniana*, *F. avenaceum* (Corda ex Fr.) Sacc., *F. graminearum* Schwabe, and *M. nivale* at the two growth stages. No correlation was found between BFR incidence and incidence of individual pathogens. During stem elongation, the function that best described the relationship is: $y = 2.70x^{0.42}$ (where x = sum of the percentages of BFR pathogens, and y = BFR incidence) with a coefficient of correlation = 0.69 ($P < 0.05$). During the late milk - early dough development stage the function that best described the relationship is: $y = 0.29x^{0.78}$ (where x = sum of the percentages of BFR pathogens, and y = BFR incidence) with a coefficient of correlation = 0.56 ($P = 0.06$).

Correlation between yield and disease. A significant negative correlation was found between crop yield and the sum of BFR and eyespot incidence values. The function that best described this relationship is: $y = 5.6 - 0.19 \sqrt{x}$ (where y = yield, and x = sum of the incidence of BFR and eyespot) with a coefficient of correlation = - 0.43 ($P < 0.05$). No correlation was found between individual diseases (BFR or eyespot) and yield. Also, no correlation was found between sharp eyespot and take-all incidence separately or combined with yield.

DISCUSSION

Brown foot rot was the major component of the foot and root disease complex of Creso durum wheat over the period 1999-2001, as it was for durum wheat in other areas in northern and southern Italy (Corazza *et al.*, 1987; Rossi *et al.*, 1994, 1995; Balmas *et al.*, 2000). In the present study, a significant reduction in BFR development after mouldboard ploughing (T25 and T50) compared with minimum tillage (chiselling; MT) was observed in 1999, when the incidence of the disease was the highest (mean disease incidence 59.5%). There was no tillage effect in 2000 and 2001 when the incidence was lower (46.5 and 24.4% of plants affected respectively). Analysis of the associated fungal organisms showed that *F. culmorum* and *B. sorokiniana* were the main causal organisms of the disease, the former more abundant under minimum tillage and the latter under ploughing. Bailey *et al.* (2000; 2001) also observed in Saskatchewan (Canada) that reduced and zero tillage increased *Fusarium* spp. and decreased *B. sorokiniana*.

A reduction of *Fusarium* under tillage compared with minimum or no-tillage, has been reported by other authors in different areas (Herman, 1990; Bateman *et al.*, 1998; Bailey *et al.*, 2001; Maecka *et al.*, 2002; Steinkellner and Langer, 2004). In these studies, the controlling effect of tillage on *Fusarium* disease was attributed to less inoculum in tilled plots, to more favourable environmental conditions in untilled plots, and to a direct

effect of soil disturbance caused by tillage. In contrast, lower levels of *Fusarium* infection in wheat crops under reduced tillage than under conventional tillage were observed by Brautigam and Tebrugge (1994) and this effect was related to higher soil microbial activity in reduced-till plots. Further work is needed to confirm these data and to determine why, under climatic conditions in the Po Valley, chiselling was more favourable to *Fusarium* disease than soil inversion and why the opposite was observed for *B. sorokiniana*. Other pathogens such as *M. nivale*, *F. graminearum*, and *F. avenaceum* appeared to be involved in BFR as shown by the positive correlation between the sum of the percentages of BFR pathogens and disease incidence.

One-year barley and fallow increased BFR incidence on the following wheat crop compared with continuous wheat. Perhaps this occurred because barley is more susceptible to the disease than wheat, as observed in previous work carried out in the same area (Innocenti *et al.*, 2000b). Fallow may have enhanced the disease due to the presence of *Avena fatua* during the set-aside period; this host is a well-known amplifier of *Fusarium* (Cook and Reis, 1981; Balmas and Corazza, 1992). Sugar-beet rotation effectively reduced the disease in 1999, when disease incidence was the highest.

Our data show that BFR fluctuates greatly from year to year. The year effect is caused mainly by weather differences, which influence disease on the assessed crop, and also determine the amount of primary inoculum available for infecting the next wheat crop. The 1999 weather characterised by a relatively warm and wet spring was more favourable to BFR development than that of 2000 and 2001. The 2000 spring was too dry and that of 2001 too wet for BFR pathogens.

The results of this study confirm that eyespot is an important component of foot and root rot disease complex of winter cereal in Italy, as observed in previous work (Innocenti *et al.*, 2000b). In particular, the disease was favoured by the wetter and colder spring of 2001. The important role of eyespot together with BFR pathogens is confirmed by the negative correlation between the sum of incidence of BFR and eyespot diseases and yield production. Minimum tillage was highly favourable to eyespot development, whereas ploughing significantly reduced its incidence.

Under our environmental conditions soil inversion seems to drastically decrease pathogen inoculum. Our findings are in contrast to those of Prew *et al.* (1995), Jenkyn *et al.* (1995) and Anken *et al.* (2004); these authors showed that eyespot was more severe after soil inversion than after non-inversion in experiments carried out under moist, cool conditions. The mechanism assumed to be responsible for this effect is that non-inversion is more favourable to antagonistic micro-organisms than ploughing. The weather in Italy during the inter-crop period is probably too dry for antagonistic biota to

flourish on crop debris and thus to control eyespot. Sugar-beet, as a non-host of the pathogens responsible for the disease, was significantly less favourable to eyespot than fallow or cereal rotation. Sharp-eyespot was detected only where the other components of the foot and root disease complex, and particularly eyespot, were scarce or absent. This supports the concept that competition for infection sites occurs between *Oculimacula* and *R. cerealis*, as observed by other authors (Colbach and Heut, 1995).

Take-all was infrequent over the whole period considered, and the effects of tillage technique and crop rotation on the disease are not sufficiently evident.

Clearly the effects of tillage technique and crop sequence on wheat diseases caused by soil-borne fungi are complex. The present study seems to indicate that the relationship between foot and root rot disease incidence and agronomic treatments depends on the pathogen responsible for the disease and on the environmental conditions, and so the effects of tillage and crop succession are often unpredictable. However, the data, averaged over the three-year trial, suggest that no effect of the tillage techniques tested was observed against brown foot rot, whereas sugar-beet was less favourable to BFR than the other crops. Both agronomic treatments significantly influenced the incidence of eyespot.

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Received 19 September 2005

Accepted 4 April 2006