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Predicting light leaf spot (*Pyrenopeziza brassicae*) risk on winter oilseed rape (*Brassica napus*) in England and Wales, using survey, weather and crop information

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Data from surveys of winter oilseed rape crops in England and Wales in growing seasons with harvests in 1987–99 were used to construct statistical models to predict, in autumn (October), the incidence of light leaf spot caused by *Pyrenopeziza brassicae* on winter oilseed rape crops the following spring (March/April), at both regional and individual crop scales. Regions (groups of counties) with similar seasonal patterns of incidence (percentage of plants affected) of light leaf spot were defined by using principal coordinates analysis on the survey data. At the regional scale, explanatory variables for the statistical models were regional weather (mean summer temperature and mean monthly winter rainfall) and survey data for regional light leaf spot incidence (percentage of plants with affected pods) in July of the previous season. At the crop scale, further explanatory variables were crop cultivar (light leaf spot resistance rating), sowing date (number of weeks before/after 1 September), autumn fungicide use and light leaf spot incidence in autumn. Risk of severe light leaf spot (> 25% plants affected) in a crop in spring was also predicted, and uncertainty in predictions was assessed. The models were validated using data from spring surveys of winter oilseed rape crops in England and Wales from 2000 to 2003, and reasons for uncertainty in predictions for individual crops are discussed.

Keywords: decision support systems, disease forecasting, disease risk analysis, interactive web-based forecasts, light leaf spot, model validation

Introduction

Light leaf spot (*Pyrenopeziza brassicae*) is a damaging disease of winter (autumn-sown) oilseed rape in the UK (Hardwick *et al*., 1991; Fitt *et al*., 1997), although control can be achieved by application of fungicides. Risk of severe epidemics differs between regions of the UK, with the most damaging epidemics in the north of England and in Scotland. Severity of light leaf spot-epidemics also differs between seasons and between crops within a region (Fitt *et al*., 1996). Accurate predictions of the risk of severe epidemics are therefore needed to guide decisions about fungicide applications. Su *et al*. (1998) demonstrated a relationship between incidence (percentage of plants affected) of light leaf spot at growth stage (GS) 3·3 (Sylvester-Bradley & Makepeace, 1985) in spring and percentage yield loss at harvest, with approximately 10% yield loss for each additional 30% plants affected by light leaf spot. However, incidence of disease in spring can be decreased by fungicide applications between November and February (Wale *et al*., 1990; Figueroa *et al*., 1994; Sansford *et al*., 1996) and predictions of the incidence of light leaf spot in spring can indicate the need for fungicide treatment in autumn/winter. Light leaf spot is a polycyclic disease, with epidemics initiated by wind-dispersed ascospores in autumn and maintained by secondary spread of rain-splashed conidia (Rawlinson *et al*., 1978; Gilles *et al*., 2000a; Evans *et al*., 2003). Leaf wetness is required for infection by ascospores or conidia, and the length of the latent period (from infection to production of new conidia) is temperature-dependent (Gilles *et al*., 2000b, 2001b; Karolewski *et al*., 2002). At a regional scale, disease incidence may be related to initial inoculum and weather conditions during the growing season, with variation within regions attributed to individual crop factors such as cultivar resistance and fungicide application. Experimental data from at least eight to 12 seasons are required to assess effects of climatic factors on progress of an epidemic (Coakley, 1988) to ensure that the dataset contains a sufficient range of environmental conditions. This paper describes the use of disease survey data from

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1987 to 1999 with meteorological data to construct models to predict light leaf spot incidence (percentage of plants affected) in spring at both regional and individual crop scales.

Materials and methods

The overall aim of this work was to develop region and crop scale predictive models of disease incidence. The regional model provided an assessment of relative risk of light leaf spot epidemics for different areas of the country, and the individual crop model provided a refined estimate of the risk specific to local conditions. All statistical analyses were done using the statistical package GenStat for Windows, 7th edition (Payne, 2000).

Winter oilseed rape disease survey (Defra)

The Defra (UK Department for Environment Food and Rural Affairs) winter oilseed rape disease survey (Turner *et al*., 2000; www.crop-disease-surveys.com/wosr.cfm) for England and Wales sampled approximately 100 crops per season since 1987 (minimum 93 in 1986/87, maximum 125 in 1993/94), with numbers of crops sampled proportional to oilseed rape area grown in each Defra region. Random samples of 25 plants per crop were taken in autumn/winter (late November to early February, GS 1·5–1·9), spring (late March to early April, GS 2·0–3·3) and summer (early July, GS 6·3–6·5). Disease assessments were done on leaves in autumn and spring and on stems and pods in summer and data stored in an Informix database, together with farm and crop details. The incidence of light leaf spot (percentage of plants affected) on all samples for harvest years 1987–99 was extracted from the database, together with records of sowing date (number of weeks before/after 1 September), autumn fungicide application, cultivar grown and farm location (county).

Table 1 Mean number of crops sampled per season in the Defra[a] survey of pests and diseases on winter oilseed rape for counties or groups of counties used in analysis to define light leaf spot (*Pyrenopeziza brassicae*) regions of England and Wales

Counties/groups of counties	Mean number of crops per season
Sampled in 1987–99[b]	
1 Bedfordshire	3·5
2 Buckinghamshire	2·1
3 Cambridgeshire	6·8
4 Derbyshire + South Yorkshire	2·1
5 Durham	2·3
6 Essex	7·2
7 Hampshire + Berkshire	3·8
8 Hereford & Worcester	2·5
9 Hertfordshire	2·2
10 Humberside	6·5
11 Leicestershire	5·0
12 Lincolnshire	12·9
13 Norfolk + Suffolk	7·7
14 Northamptonshire	4·8
15 Northumberland	2·9
16 North Yorkshire	6·9
17 Nottinghamshire	4·0
18 Oxfordshire	4·9
19 Staffordshire + Shropshire	2·3
20 Warwickshire	2·7
21 West Yorkshire	1·9
Sampled only in 1991–99	
22 South Glamorgan + Mid-Glamorgan + Gwent	2·0
23 East Sussex	1·0
24 Gloucestershire	3·1
25 Kent	4·9
26 Wiltshire	4·0

[a] UK Department for the Environment, Food and Rural Affairs.
[b] Winter oilseed rape growing seasons 1986/87 etc.

Definition of light leaf spot regions

Survey results have been reported using the former Defra regions rather than counties, as too few samples per county were taken to give reliable estimates of disease incidence (Turner *et al*., 2000). However, since Defra administrative regions did not necessarily give optimal groupings of counties for light leaf spot prediction, the county-by-season light leaf spot incidence data were analysed to define groups of counties with similar patterns of light leaf spot incidence across years, as a basis for the regional models. Generally, only counties with at least two samples per season were included in the analysis. In some cases, adjacent counties could be combined to give a group of counties with at least two crops sampled per season. For South Wales, there were only two crops sampled per season across several counties. East Sussex (one crop per season) was also included to improve representation of the south-east of England. Since sampling had been intermittent in south-west England, Wales and Kent and Sussex before 1991, two sets of analyses were done: the first for all harvest years (1987–99) omitting these counties, and the second using data from all counties for harvest years 1991–99 (Table 1). Potential groupings of counties into light leaf spot regions were examined using principal coordinates analysis, hierarchical cluster analysis using complete linkage and nonhierarchical cluster analysis with five or eight groups. Principal coordinates analysis (PCO) was used in preference to principal components analysis (PCP) because the county × season data matrix contained many missing values. PCO requires a similarity matrix that can be constructed using all the data, whereas PCP would require the exclusion of counties with many missing values. For these data, Euclidean distances were used to form the similarity matrix. The criterion for defining a region was that all counties in the region had similar patterns of incidence of light leaf spot across seasons. In addition, it was desirable that regions formed a contiguous (and preferably compact) geographical grouping to make the regions easily recognized by the end user (farmers and their advisors). The new ‘light leaf spot’ regions were compared with former Defra regions or Meteorological

Office climatological regions (Anonymous, 1990) for their ability to describe region × season light leaf spot incidence patterns, using the Akaike Information Criteria (AIC, see, for example, Tong, 1990; section 5·4). AIC is a criterion used to compare (generalized) linear models with different explanatory variables, by taking the log-likelihood (deviance) of the model and penalizing this according to the number of parameters estimated.

Explanatory variables

A large set of potential explanatory variables that were expected to have relevance to light leaf spot disease progress was used to develop the models. Survey data for regional incidence of light leaf spot (percentage pods affected) was used to represent average regional disease risk from the previous season. Region effects were used to summarize the average climate within each region. Meteorological variables were used to represent seasonal variation in environmental conditions, but these were also only available at a regional scale, and were summarized as seasonal values, as described below. For individual crops, the explanatory variables available were as follows: the cultivar resistance rating for light leaf spot (1–9 scale; Anonymous, 1998); sowing date (number of weeks before/after 1 September); use of autumn fungicide (yes/no); and percentage of plants affected with light leaf spot in the survey autumn sample. Autumn survey results were available only for harvest years from 1990 onwards, so the mean autumn survey value was substituted prior to 1990 to allow harvest years 1987–89 to be included in the analysis.

Calculation of meteorological variables

Monthly regional values of mean temperature and total rainfall were calculated using the ARCMET daily database for a representative set of meteorological stations within each light leaf spot region. Corresponding 30-year (1961–90) regional means were calculated from a comparable set of meteorological station records from the ARCMET historical database. The two databases did not always have data from exactly the same set of meteorological stations, but they were matched as closely as possible. Data available on a daily basis (ARCMET daily database) were used for constructing the predictive model so that updates could be made, but these stations had not been operating for long enough to be used for long-term mean calculations. Deviations from the long-term means were calculated for each season × region combination. Both unadjusted weather variables and deviations from long-term regional means were tested as explanatory variables. Using deviations from long-term means allowed the model to estimate the effects of weather factors relative to regional means, rather than in absolute terms. Since there was a high correlation between successive monthly mean values of weather variables, autumn (September to November) and winter (December to February) means were calculated from monthly values to produce variables with lower correlation. Weather variables from the summer before the start of each winter oilseed rape growing season (e.g. July and August 1987 for 1987/88 growing season) were also calculated as summer weather might affect availability of inoculum in autumn.

Regional prediction (in autumn) of light leaf spot risk (in spring) from disease survey and weather data

To predict the regional mean incidence of light leaf spot in spring, weighted linear regression was used to relate the logit-transformed regional mean incidence in spring [i.e. logit ($p + 0{\cdot}1$), where p is the regional mean percentage of plants affected with light leaf spot] to regional effects, weather variables and the regional incidence of light leaf spot at the end of the previous season. The weights were proportional to the number of crops sampled in each season in each region, so that poorly sampled regions were given less weight in the analysis. Two models were fitted, using either deviations from regional long-term weather (model 1), or unadjusted weather variables (model 2). Forward stepwise regression was used to construct the models. The assumption of a linear response to explanatory variables was tested using smoothing spline terms, which fit a nonparametric smooth curve and can thus be used to detect nonlinearity in the relationship between variables.

Crop-specific prediction (in autumn) of light leaf spot risk (in spring) from disease survey, weather and crop factors

To predict light leaf spot risk for individual crops in spring, a generalized linear model with binomial errors and a logit link function was used to relate the number of plants affected with light leaf spot in each spring sample to the explanatory variables. All weather variables and incidence of light leaf spot on pods in July at the end of the previous season were calculated at a regional scale (i.e. taking the same value for all crops in a region), as values specific to each sample could not easily be obtained. To predict the risk of light leaf spot in spring (percentage of plants affected at early stem extension in March/April), two different models were considered, using either deviations from regional long-term weather (model 3) or unadjusted weather variables (model 4).

The crop-specific models were constructed in two stages. First, crop-specific variables were added into the model, then regional variables (region effects, weather, previous pod incidence) were added into the model using stepwise regression, with the significance of these regional variables assessed by comparing the change in deviance with the season × region mean deviance to take account of the hierarchical structure of the data. Selected interactions between the chosen variables were also examined. The assumption of a linear response to explanatory variables was tested using smoothing spline terms. The final models were compared with a generalized linear mixed model (Breslow & Clayton, 1993; using the PQL option in Genstat procedure GLMM). This analysis explicitly takes account of the hierarchical structure of the data (crops within regions), but uses an approximation to avoid the integration required to evaluate the full likelihood of the data, and hence is only an approximate method of analysis. Generalized linear mixed models were used to estimate the components of variance due to regions, seasons and the season × region interaction.

Crop-specific prediction (in autumn) of risk of severe light leaf spot epidemic (> 25% plants affected in spring) from disease survey, weather and crop factors

To predict the risk of severe epidemics for individual crops in spring (> 25% plants affected with light leaf spot in spring), the methods and sets of explanatory variables (i.e. using deviations in weather or actual weather) used to construct models were as given in the preceding section. In this case, the response was a binary variable with value 1 for crops with > 25% of plants affected in spring, and zero otherwise. The fitted models were labelled model 5 (using deviations in weather) and model 6 (using actual weather).

Model validation and assessment of uncertainty in model predictions

Data from surveys of winter oilseed rape in England and Wales, regional meteorological data and crop data from growing seasons with harvest in 2000–03 were available for model validation. There were 379 sample values of percentage of plants affected with light leaf spot in spring across the four years: 107 crops in 2000; 65 in 2001; 107 in 2002; and 100 in 2003. In the few cases that relevant crop data were missing (date of sowing in six cases, cultivar resistance rating in 32 cases), the long-term regional mean from 1987 to 1999 was substituted. The reduction in sampling in 2001 was due to restrictions caused by a foot and mouth disease epidemic.

The regional models (models 1 and 2) were used to generate region-scale predictions for all regions in each year during 2000–03. The crop-specific models (models 3 and 4) were used to generate crop-scale predictions for each farm in the survey in each year during 2000–03. The crop-specific models were also used to generate region-scale predictions using the relevant long-term regional means in place of individual crop data. A weighted mean square error of prediction (MSEP) was used to quantify the predictive ability of the crop-specific and regional models at both the crop and region scales. At the crop scale, the MSEP value for a model was calculated as

$$\mathrm{MSEP} = \frac{1}{379}\sum_{c=1}^{379}\frac{(y_c - n\hat{p}_c)^2}{n\hat{p}_c(1-\hat{p}_c)}$$

where c indexes the 379 survey crops used in validation, y_c is the number of plants affected with light leaf spot in sample c, W_c is the predicted proportion of plants affected in sample c, and $n = 25$ is the sample size in all cases. The weighting used in the mean square error calculation is the binomial variance corresponding to the predicted proportion of plants affected. At the regional scale, the MSEP value for a model was calculated as

$$\mathrm{MSEP} = \frac{1}{28}\sum_{i=2000}^{2003}\sum_{r=1}^{7} n_{ir}(y_{ir} - \hat{y}_{ir})^2$$

where i indexes the validation years 2000–03 and r indexes the seven light leaf spot regions, y_{ir} is the logit-transformed percentage of plants affected in region r in year i, X_{ir} is the corresponding prediction from the model, and n_{ir} is the number of crops used to form the regional mean. In this case, the weighting used reflects the relative accuracy of the regional means.

The MSEP values can be used to quantify and compare the predictions of models for the validation dataset. At the crop scale, MSEP values were calculated for predictions from the crop-specific models (models 3 and 4) using actual crop data, for predictions from the crop-specific models using long-term regional mean values of crop factors, and for predictions from the regional models (models 1 and 2) applied to individual crops. At the regional scale, MSEP values were calculated for predictions from the regional models (models 1 and 2) and for regional means of predictions from the crop-specific models (models 3 and 4), using either actual crop data or long-term regional mean values of crop factors.

For prediction of the risk of severe light leaf spot epidemics (> 25% plants affected) in spring (models 5 and 6), regional predictions of risk were obtained from the crop-specific models as the average risk over crops in each region for each year during 2000–03. The predicted risk W_{ir}, for region r in year i, is then interpreted as the probability of a crop in the region having > 25% plants affected with light leaf spot in spring. Assuming independence between crops, the number of crops in each region with > 25% of plants affected with light leaf spot should behave as a binomial random variable. Accordingly, the number of crops in each region with > 25% of plants affected at the spring survey in each year during 2000–03 was assessed for its likelihood under a binomial distribution with success probability W_{ir} and number of trials n_{ir}.

To investigate the uncertainty in model predictions, the empirical distribution of the data was examined. For a given predicted value p, the actual incidence of light leaf spot in crops with predicted values for disease incidence within ± 5 percentile points of p was plotted. The crops chosen could be taken from the whole dataset (1254 values) or restricted to crops from the same region as the predictions (100–369 values, depending on region), to give an indication of typical distributions of observed incidence of disease, given the prediction p.

Results

Definition of light leaf spot regions

Hierarchical and nonhierarchical cluster analysis of the 22 counties/county groups with data for harvest years 1987–99 consistently placed several sets of counties in the

Table 2 Definition of light leaf spot (*Pyrenopeziza brassicae*) regions for England and Wales derived from analysis of survey data for light leaf spot incidence (percentage of plants affected) in March/April. The allocation of counties to eight groups by non-hierarchical cluster analysis of data from 1991 to 1999 is indicated by the superscript numbers 1–8. Counties in italics were not included in the original analysis but have been allocated to regions according to their location

Region	Counties
South (S)	Berkshire^{5}, Buckinghamshire^{5}, Hampshire^{5}, Oxfordshire^{5}, *Surrey*, *West Sussex*
East Anglia (EA)	Bedfordshire^{1}, Cambridgeshire^{1}, Hertfordshire^{1}, Norfolk^{1}, Northamptonshire^{1}, Suffolk^{1}
South-east (SE)	East Sussex^{2}, Essex^{2}, Kent^{2}
East (E)	Humberside^{4}, Leicestershire^{4}, Lincolnshire^{1}, Nottinghamshire^{4}
North (N)	*Cleveland*, *Cumbria*, Durham^{6}, *Lancashire*, Northumberland^{8}, North Yorkshire^{8}, *Tyne & Wear*, West Yorkshire^{7}
South-west (SW)	*Cornwall*, *Devon*, *Dorset*, Gloucestershire^{8}, *Somerset*, Wiltshire^{8}, South Wales^{3}
West (W)	*Cheshire*, Derbyshire^{4}, Hereford & Worcester^{3}, Shropshire^{8}, South Yorkshire^{4}, Staffordshire^{8}, Warwickshire^{4}, *West Midlands*, *Mid- and North Wales*

same groups. For these data, the first and second principal coordinate axes accounted for 57 and 13% of the variance, respectively. The same analysis with the 28 counties/county groups with data for harvest years from 1991 to 1999 identified similar sets of counties that were consistently placed together (Table 2). The first and second principal coordinates then accounted for 57 and 15% of the variance, respectively. The position of the counties/county groups with respect to the first two principal coordinate axes is shown in Fig. 1, and largely reflected the groups found by cluster analysis. Considered together, these analyses suggested several light leaf spot regions: south (Hampshire, Berkshire, Buckinghamshire, Oxfordshire), East Anglia (Norfolk, Suffolk, Cambridgeshire, Hertfordshire, Northamptonshire, Bedfordshire), south-east (Kent, Essex, East Sussex), north (North and West Yorkshire, Durham, Northumberland) and the Midlands (Humberside, Lincolnshire, Leicestershire, Nottinghamshire, Warwickshire, Derbyshire, South Yorkshire). There were several counties which did not have any clear associations with the regional groups [Gloucestershire, Wiltshire, South Wales (Glamorgan and Gwent), Staffordshire, Shropshire, Hereford and Worcester, West Sussex]. Gloucestershire and Wiltshire are physical neighbours and take the same value on the first principal coordinates axis, although they are separated in the second (less influential) dimension. The rest of these counties had only very small numbers of samples (maximum 2·4) and so could not be placed with any accuracy.

To achieve compact regional county groupings with similar weather patterns, the Midlands group was split into eastern and western counties. For practical reasons, Wales was split into southern counties, allocated to the 'south-west' region, and the remaining Welsh counties, allocated to the 'west' region. The final allocation of the counties to light leaf spot regions is given in Table 2. Fitting region × season means within a generalized linear model (with binomial errors and logit link) to all individual crop data (1987–99) gave AIC values of 10964 for the new light leaf spot regions, 12180 for Defra regions and 13597 for UK Meteorological Office climatic regions, indicating that the new light leaf spot regions gave an improved grouping in relation to seasonal patterns of light leaf spot incidence.

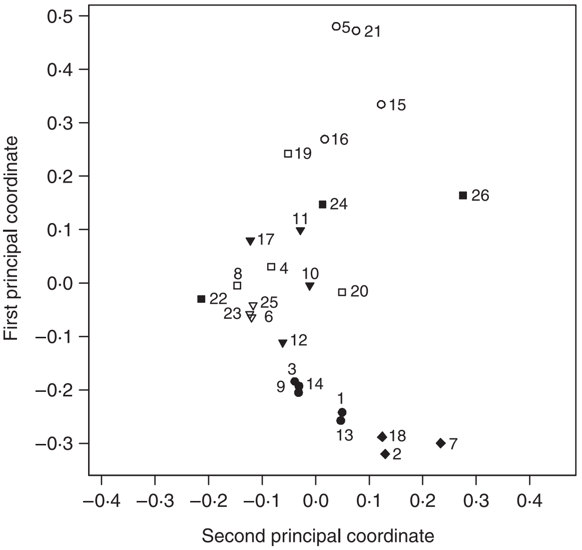

Figure 1 Scores from principal coordinates analysis of seasonal patterns in incidence (percentage of plants affected) of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in March/April for harvest years from 1991 to 1997, for each county/county group in Table 1 (i.e. 26 points). Symbols indicate allocation of counties to light leaf spot regions: south (◆), East Anglia (•), south-east (▽), east (▼), north (○), south-west (■), west (□).

For these light leaf spot regions, the regional values of percentage of plants affected with light leaf spot in March/April showed substantial variation between both seasons and regions (Fig. 2). The seasonal pattern changed relatively smoothly, with highest incidences of light leaf spot for seasons with harvest years from 1988 to 1990 and 1993 to 1995. The incidence of light leaf spot in March/April was generally higher in the 'north' and 'west' regions but the regions changed in ranking for severity with season, indicating a season × region interaction.

Quantifying differences between light leaf spot regions in terms of weather variables

To quantify the difference between light leaf spot regions in terms of climate, weighted linear regression was used on the seven logit-transformed regional means (mean percentage of plants affected with light leaf spot in March/April, 1987–99). Weights were proportional to the number of samples per region used to calculate each mean and explanatory variables were regional long-term mean

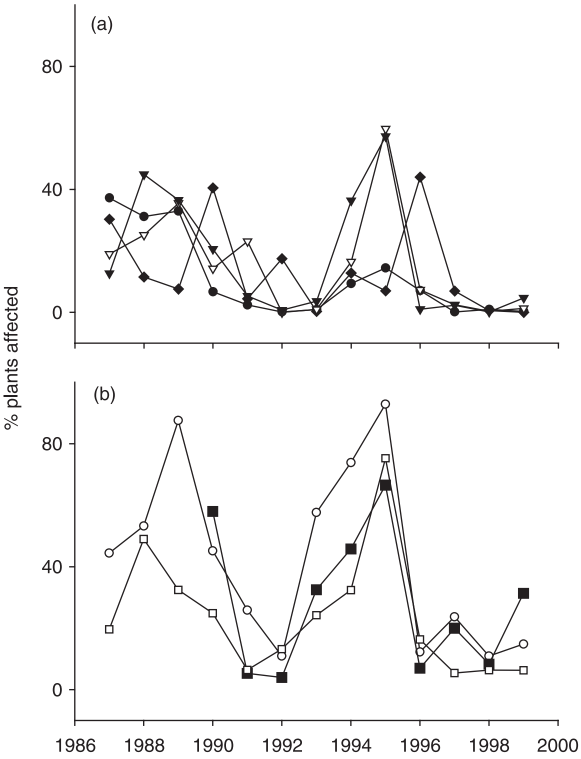

Figure 2 Regional mean incidence (percentage of plants affected) of light leaf spot (*Pyrenopeziza brassicae*) in March/April for light leaf spot regions for seasons with harvest years from 1987 to1999. (a) south (◆), East Anglia (●), south-east (▽), east (▼); (b) north (○), south-west (■) and west (□).

summer temperature (July/August) and monthly winter rainfall (December–February; Table 3). Mean regional light leaf spot incidence (logit transformed) in March/April was linearly related to mean summer temperature and winter rainfall (76% variance accounted for):

$$\text{Logit}\ (p) = 5\cdot0(3\cdot92) - 0\cdot49(0\cdot225)T_s + 0\cdot022(0\cdot010)R_w$$

where p was regional mean incidence of light leaf spot (percentage of plants affected) in spring, T_s was regional mean summer temperature (July/August) and R_w regional mean monthly winter rainfall (December to February). Standard errors are shown in brackets after parameter values and predicted values are shown in Table 3. There was reasonable agreement between the regional means and model predicted values except for the 'south-west' region, where the regional mean was underestimated.

Regional prediction (in autumn) of light leaf spot risk (in spring) from disease survey and regional weather

The final regional model based on deviations in weather (model 1) included regional effects, the regional mean percentage of plants affected with light leaf spot (on pods) the previous season (July survey sample), deviations from regional mean summer temperature (July/August) and deviations from regional mean monthly winter rainfall (December to February inclusive). These variables together accounted for 53·4% of the variation in the regional data. The fitted model (model 1) was as follows (with parameter estimates followed by standard errors):

$$\text{Logit}(p + 0\cdot1) = c_r + 0\cdot035(0\cdot009)s + 0\cdot030(0\cdot007)r_w - 0\cdot43(0\cdot14)t_s$$

where p is the regional mean percentage of plants affected with light leaf spot in the spring survey, s is the regional mean percentage of plants with pods affected by light leaf spot in the previous summer survey, r_w is the deviation in mean monthly winter rainfall about the long-term regional mean (mm), t_s is the deviation in summer temperature about the regional mean (°C) and c_r is the effect for each region: south, $c_S = -2\cdot93$ (SE 0·48); East Anglia, $c_{EA} = -3\cdot59$ (SE 0·38); south-east, $c_{SE} = -3\cdot39$ (SE 0·51); east, $c_E = -2\cdot57$ (SE 0·35); north, $c_N = -0\cdot98$ (SE 0·50); south-west, $c_{SW} = -2\cdot21$ (SE 0·65); west and Wales, $c_W = -1\cdot72$ (SE 0·50).

The final regional model based on unadjusted weather variables (model 2) included the regional mean percentage of plants affected with light leaf spot (on pods) the previous

Table 3 Mean incidence (percentage of plants affected) of light leaf spot (*Pyrenopeziza brassicae*) in March/April for different light leaf spot regions, estimated from survey data, in relation to long-term regional mean summer temperature (July–August) and monthly winter rainfall (December–February) obtained from the ARCMET historical meteorological database, and predicted regional mean light leaf spot incidence in March/April

Region[a]	% of plants with light leaf spot in March/April (1987–1999)[b]	Number of samples in each region (1987–1999)[c]	Summer temperature (°C) (1961–1990)	Monthly winter rainfall (mm) (1961–1990)	Predicted regional mean % of plants with light leaf spot
S	14.1	156	16.6	65.3	15.6
EA	11.1	325	16.2	48.8	13.7
SE	15.8	156	16.6	50.8	11.8
E	17.4	369	15.8	49.2	15.9
N	42.6	199	14.6	78.7	39.0
SW	31.5	100	16.1	84.0	25.8
W	24.0	149	15.4	79.8	31.8

[a] See Table 2 for details of counties in each region.

[b] Winter oilseed rape growing season, specified by harvest year.

[c] Total number of crops sampled in each region over this period.

season (July survey sample), the regional mean summer temperature (July/August) and regional mean monthly winter rainfall (December to February inclusive) and accounted for 53·9% of the variation in the data. The fitted model (model 2) was:

$$\mathrm{Logit}(p + 0{\cdot}1) = 4{\cdot}29(2{\cdot}11) + 0{\cdot}034(0{\cdot}008)s + 0{\cdot}031(0{\cdot}006)R_w - 0{\cdot}55(0{\cdot}12)T_s$$

where R_w is the regional mean monthly winter rainfall (mm) and T_s is the regional summer mean temperature (°C) and parameter estimates are followed by their standard errors.

Crop-specific prediction (in autumn) of light leaf spot risk (in spring) from disease survey, weather and crop factors

Fitted models 3 and 4 both included all the crop-specific variables, accounting for the effects of autumn fungicide use, cultivar light leaf spot resistance rating, sowing date (number of weeks before/after 1 September) and the light leaf spot incidence observed in the autumn survey. There was a significant interaction between autumn fungicide use and region, which suggested that fungicide use was effective in reducing light leaf spot risk only in the four regions with higher risk (E, N, SW, W). A new variable was defined, which took the value 1 for regions E, N, SW, W when autumn fungicide was used and 0 otherwise. For model 3, the regional variables selected for the final model were the regional mean percentage of plants affected with light leaf spot (on pods) the previous season (July survey sample), deviations from regional mean summer temperature (July/August) and deviations from mean monthly winter rainfall (December to February inclusive). Fitting variables as spline terms showed the response of all the variables to be approximately linear. For model 4, the regional variables selected for the final model were the regional percentage pods affected with light leaf spot the previous season and regional mean summer temperature and monthly winter rainfall. Fitted smoothing spline terms for this model indicated that the response to all variables except summer temperature was approximately linear, and that the response to summer temperature was approximately quadratic. For both models, GLMM analysis confirmed this selection of variables and suggested that standard errors for the estimated coefficients of regional incidence of light leaf spot on pods in the previous season, summer temperature and winter rainfall were underestimated by a factor of three. Parameter estimates from the fitted models, with standard errors, are shown in Table 4. The percentage deviance accounted for by regional factors alone was 30·2% for model 3 and 30·8% for model 4, indicating that addition of the crop-specific variables to the models improved the fit, although there was still much variation unaccounted for.

Assessment of sources of variability

GLMM analysis for both final models, plus models excluding the regional scale variables and including random terms for region, season and region × season gave similar levels of variation (estimated variance components) between seasons and between regions (Table 5). The season × region interaction was larger, indicating substantial variation between seasons that differed between regions. However, these estimates were small compared with the dispersion parameter, which indicated very large variation within regions that was not explained by the model. This was reflected in the relatively small percentage deviance accounted for and correlation between fitted values and observed data (Table 4). The change in variance component estimates provided an indication of the variation explained by the regional scale variables at each level. By definition, all of the regional variation was accounted for in model 3, which included a fixed regional effect. However, model 4, which used unadjusted weather variables without explicit regional effects, still accounted for most of the regional variation, because regional differences were largely accounted for by differences in mean summer temperature and winter rainfall, as described earlier. A large proportion of variation between seasons was accounted for by the regional scale variables, but the region × season interaction was largely unaccounted for.

Crop-specific prediction (in autumn) of risk of severe light leaf spot epidemic (> 25% of plants affected in spring) from disease survey, weather and crop factors

For the binary response variable, > 25% of plants affected with light leaf spot in March/April, the variables which gave the best predictions of the probability of severe light leaf spot epidemics (> 25% of plants affected) in fitted models 5 and 6 were the same variables used for models 3 and 4, respectively. These models could thus be used alongside models 3 or 4 to estimate the probability of a severe epidemic. Parameter estimates from the fitted models, with standard errors, are shown in Table 4.

Model validation and assessment of uncertainty in model predictions

Table 6 shows the MSEP values calculated with respect to the validation data set at crop and regional scales for predictions from the crop-specific model using actual crop values and long-term regional means for crop factors, and from the regional model. At the crop scale, the MSEP values were smallest for the crop-specific model using actual crop data. There was an increase of 13–21% in MSEP in predicting from the crop-specific model with long-term regional mean values for the crop factors, and a 56–64% increase in MSEP in predicting from the regional model. These results indicate that a substantial improvement in prediction was achieved by using crop factors in the model. At the regional scale, there was little difference between MSEP values for either the crop-specific or regional models. However, at both scales the MSEP values were consistently smaller for the models based on deviations in weather from the regional mean (models 1 and 3) than for models based on actual weather (models 2 and 4). Figure 3 shows

Table 4 Summary statistics and parameter estimates for predicting, in October, percentage of winter oilseed rape plants affected with light leaf spot (*Pyrenopeziza brassicae*) or the risk of a severe epidemic (> 25% of plants affected with light leaf spot) in March/April at the individual crop scale, in terms of regional light leaf spot incidence from the previous July, regional weather parameters and individual crop factors. Standard errors are shown in brackets after parameter estimates

	Parameter estimates from GLM analysis to predict:			
	% of plants affected		Risk of severe epidemic	
Term in model	Deviations in weather (model 3)	Unadjusted weather (model 4)	Deviations in weather (model 5)	Unadjusted weather (model 6)
Constant	–	60.0 (7.0)	–	92.5 (10.6)
Effect for region S	−0.27 (0.34)	–	0.76 (0.48)	–
Effect for region EA	−0.95 (0.33)	–	−0.37 (0.47)	–
Effect for region SE	−0.56 (0.34)	–	0.53 (0.47)	–
Effect for region E	0.30 (0.31)	–	1.29 (0.45)	–
Effect for region N	1.17 (0.33)	–	2.13 (0.47)	–
Effect for region SW	0.05 (0.38)	–	0.88 (0.47)	–
Effect for region W	0.46 (0.33)	–	1.36 (0.47)	–
Regional % of plants with light leaf spot in previous July	0.026 (0.007)[a]	0.026 (0.010)[a]	0.031 (0.004)	0.032 (0.004)
Regional summer temperature (linear term)	−0.33 (0.17)[a]	−7.03 (2.5)[a]	−0.31 (0.07)	−10.80 (1.27)
Regional summer temperature (quadratic term)	–	0.20 (0.08)[a]	–	0.31 (0.04)
Regional winter rainfall	0.017 (0.007)[a]	0.015 (0.007)[a]	0.017 (0.003)	0.014 (0.003)
Autumn fungicide use in E, N, SW or W region (0/1)	−1.13 (0.20)	−0.86 (0.20)	−1.51 (0.30)	−1.19 (0.30)
Crop cultivar light leaf spot resistance rating	−0.32 (0.05)	−0.29 (0.05)	−0.40 (0.07)	−0.37 (0.07)
Crop sowing date (number of weeks before/after 1 September)	−0.12 (0.04)	−0.16 (0.04)	−0.13 (0.05)	−0.18 (0.05)
% of plants with light leaf spot in crop, autumn sample	0.046 (0.016)	0.046 (0.016)	0.042 (0.026)	0.042 (0.026)
% deviance accounted for[b]	35.7	35.7	24.6	25.4
Correlation *r* of fitted values and observed data (logit scale)	0.63	0.62	0.54	0.53
Deviance accounted for by model	6630	6613	358	370
Residual deviance	11 925	11 942	1100	1088
Residual d.f.	1240	1245	1240	1245
Dispersion estimate	9.6	9.6	n/a	n/a
AIC	11 953	11 960	1128	1106
Number of observations	1254	1254	1254	1254

[a] Standard errors from the GLM have been multiplied by 3 to give a better indication of uncertainty as indicated by GLMM analysis.

[b] Percentage deviance accounted for calculated as $100 \times (1 - D_m/D_c)$, where D_m is the residual deviance for the model and D_c is the residual deviance for a model with an intercept only. Note this does not adjust for degrees of freedom used.

Table 5 Estimated variance components from a GLMM analysis, modelling percentage of plants affected with light leaf spot (*Pyrenopeziza brassicae*) in March/April for individual winter oilseed rape crops in terms of regional and crop factors, estimating variation due to seasons[a], regions and season × region interactions

	Estimated variance components		
Model term	Deviations in weather (model 3)	Unadjusted weather (model 4)	Crop scale variables only
Region	–	0.03	0.74
Season	0.29	0.24	0.94
Season × region	0.66	0.70	0.75
Dispersion	8.08	8.00	8.00

[a] Winter oilseed rape growing season, specified by harvest year.

the observed regional mean percentage of plants affected with light leaf spot for seasons with harvest years 2000–03, with regional means calculated from individual crop predictions from model 3.

For predicting risk of a severe epidemic, comparison of model predictions with the observed number of crops per region with > 25% plants affected in spring 2000–03 was performed using a binomial distribution with average regional success probability estimated from model 5 or 6 based on either actual crop values or regional long-term means for crop factors. For models 5 and 6 based on individual crop values, there were four and seven observations, respectively, not compatible with the predictions ($P \leq 0{\cdot}05$, two-sided test). For models 5 and 6 using regional means for crop values, there were six and nine observations, respectively, not compatible with the predictions ($P \leq 0{\cdot}05$). If the models described the risk of severe epidemics well, this number of incompatible observations would be unlikely ($P = 0{\cdot}05$ for four or more incompatible observations). However, these results again indicate that predictions from a model based on deviations in weather (model 5) performed better than the model using actual weather (model 6) and that predictions were improved by using individual crop data. For model 5, three of the four observations incompatible with the data occurred in spring 2002 (regions N, E and EA) and all underestimated

Table 6 Mean square error of prediction (MSEP) calculated at crop and regional scale for percentage of plants affected with light leaf spot (*Pyrenopeziza brassicae*) in March/April recorded in the winter oilseed rape survey during 2000–2003 using crop-specific models (models 3 and 4) and regional models (models 1 and 2). The relative value of the MSEP as a percentage of the smallest crop/regional scale MSEP is shown in brackets after the MSEP value

	Scale of predictions	
Model/weather variables	Crop scale	Regional scale
Crop-specific model using actual crop data		
Deviations in weather (model 3)	11.71 (100)	21.30 (103)
Actual weather (model 4)	13.48 (115)	22.15 (107)
Crop-specific model using long-term regional mean values for crop factors		
Deviations in weather (model 3)	13.27 (113)	20.62 (100)
Actual weather (model 4)	16.31 (139)	22.19 (108)
Regional model		
Deviations in weather (model 1)	19.25 (164)	20.88 (101)
Actual weather (model 2)	20.98 (179)	22.15 (107)

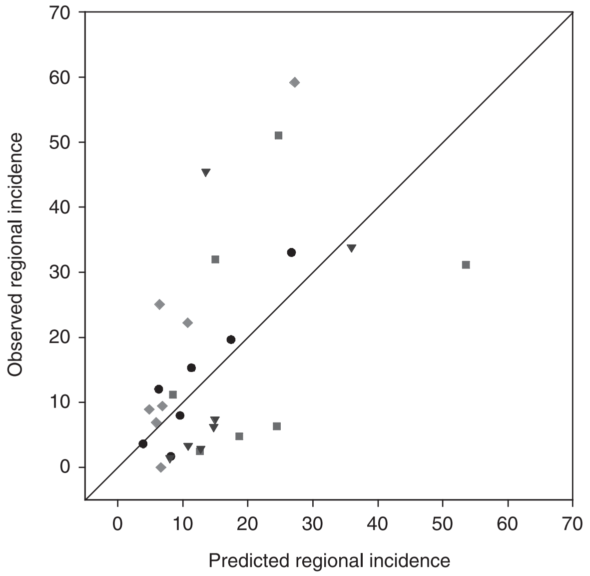

Figure 3 Observed and predicted regional mean incidence (percentage of plants affected) of light leaf spot (*Pyrenopeziza brassicae*) in March/April for light leaf spot regions for seasons with harvest years 2000 (•), 2001 (■), 2002 (◆) and 2003 (▼). Predicted values were calculated as regional means of individual crop predictions from the crop-specific model 3. The 1:1 line representing perfect prediction is also shown.

the risk of a severe epidemic. Although there was little light leaf spot incidence on pods in summer 2001, there were relatively high levels of stem infection which could also lead to ascospore production but were unaccounted for by the model and could explain the under-prediction for spring 2002.

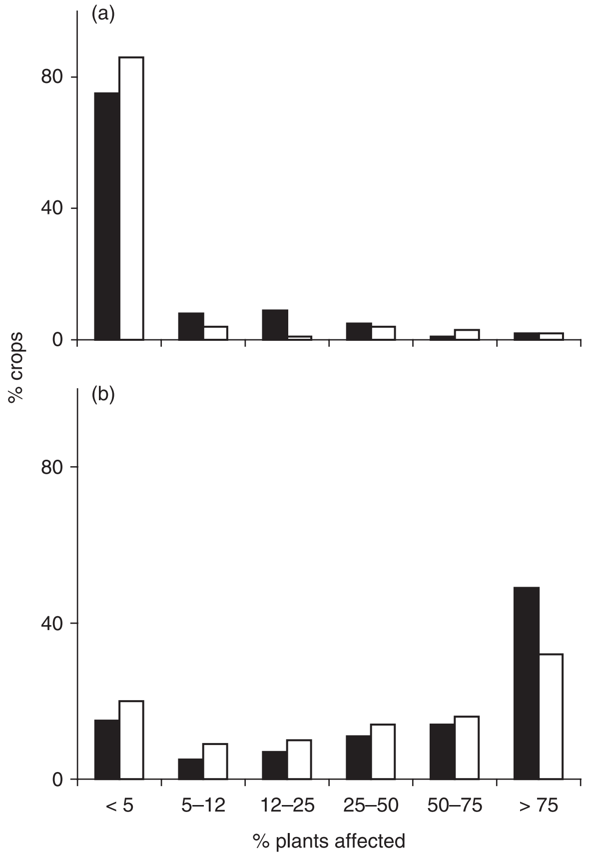

Figure 4 Frequency distribution of individual crop values during 1987–99 for percentage of plants affected with light leaf spot (*Pyrenopeziza brassicae*) in March/April with fitted values within ± 5 percentile points of values predicted by model 1 for: (a) East Anglia light leaf spot (*P. brassicae*) region without fungicide (shaded bar, predicted value 8·3% plants affected) and with an autumn fungicide application targeted at light leaf spot (white bar, predicted value 3·0% plants affected); and (b) north region without fungicide (shaded bar, predicted value 69% plants affected) and with an autumn fungicide application targeted at light leaf spot (white bar, predicted value 43% plants affected).

Because there was some evidence that the models might not produce accurate predictions, it was important to indicate the likely variation of observations about the predicted regional value. For a given predicted value p, this was done by examining the empirical distribution of individual crop values from the same region with similar predicted values. For example, predictions could be made in autumn 2000, of percentage of plants affected with light leaf spot in spring 2001 for crops in the north (N) or East Anglian (EA) regions sown on 1 September with cv. Apex (light leaf spot resistance rating 5). Using model 3, the predicted percentages of plants affected were 8·3% (EA, no autumn fungicide treatment for light leaf spot), 3·0% (EA, with fungicide), 69·2% (N, no fungicide) and 43·4% (N, with fungicide). Figure 4 shows the empirical distribution of subsets of survey data from 1987 to 1999 that had predictions falling within ± 5 percentile points of these values. In all cases, observed light leaf spot incidence in March/April ranged across the categories from < 5% to 50–75%. Thus, even when the predicted regional incidence was 3% (EA, with fungicide), a small number of crops with severe epidemics would be expected. The wide distribution in data values for these predictions illustrates the unexplained variation in the data. Publication of these histograms with model predictions serves to alert the user to the uncertainty in the forecast.

Discussion

These results show that it is possible to predict, in autumn, the average regional incidence of light leaf spot in spring using survey data and weather data. The factors found to be important can be interpreted in terms of their influence on components of epidemics. The incidence of light leaf spot at the end of the previous season in July presumably influences the amount of primary inoculum available to initiate epidemics at the start of the next season. The amount of ascospore inoculum available is known to influence the severity of light leaf spot epidemics greatly (Gilles *et al*., 2000a; Papastamati *et al*., 2001, 2002). The effect of increasing summer temperature on decreasing light leaf spot incidence the following spring probably also relates to primary inoculum, as fewer ascospores mature at higher temperatures (> 20°C) (Gilles *et al*., 2001a; Evans *et al*., 2003). The effect of increasing winter rainfall on increasing light leaf spot incidence can be explained because secondary spread occurs by splash dispersal of conidia (Evans *et al*., 1999a; Gilles *et al*., 2000a). Thus, these empirical models can be used to guide growers about the regional risk of severe light leaf spot epidemics in any given season through press releases, the internet (Sutherland *et al*., 2002) and as part of decision support systems (e.g. PASSWORD, http://password.csl.gov.uk/).

The regional predictions can be made more crop-specific by inclusion of cultivar (resistance), sowing date, autumn fungicide use and autumn survey information. Crop-specific information has been used to develop an interactive web-based forecast, which allows growers to input their own information (www3.res.bbsrc.ac.uk/leafspot). This interactive forecast can be used to help guide choice of cultivar and sowing date (before the start of the growing season) and autumn fungicide use. The forecasts could be improved by including local weather data instead of regional data since local weather variation can be adjusted for in either of models 3 or 4. In this context, model 4 (unadjusted weather) may be more user-friendly, and also avoid problems at regional boundaries, although model 3 (deviations in weather from regional mean) performed better on the validation data. Whilst the forecasts indicate predicted effects of autumn fungicide use on epidemic severity, differences in fungicide timing may influence effectiveness of autumn fungicide treatments (Steed *et al*., 1999). It is probable that autumn fungicide use in S, EA and SE regions, which showed no effect of autumn fungicide application, was mainly targeted at phoma leaf spot (*Leptosphaeria maculans*) and therefore suboptimal for light leaf spot control. Fungicide effects should be included in predictions in S, EA or SE regions only where autumn fungicide use is targeted at light leaf spot control.

Table 7 Number and percentage of winter oilseed rape crops where light leaf spot (*Pyrenopeziza brassicae*) has been recorded in the autumn winter oilseed rape survey in each of seven light leaf spot regions, 1987–1999[a]

Region[b]	Total number of crops with autumn samples (1987–1999)	Number of autumn samples where light leaf spot incidence > 0	% crops affected in autumn
S	117	3	2.6
EA	230	0	0
SE	126	5	4.0
E	248	5	2.0
N	146	11	7.5
SW	88	8	9.1
W	110	5	4.5

[a] Winter oilseed rape seasons, specified by harvest years (i.e. for 1987, the sample was in autumn 1986).

[b] See Table 2 for details of counties in each region.

Occurrence of light leaf spot on crops in the autumn, as assessed by the autumn sample, is possibly the best indicator of local inoculum levels, which can greatly affect light leaf spot incidence later in the season (Evans *et al*., 1999a,b, 2003). In the autumn survey, few crops were affected with light leaf spot (Table 7), although only a single visit was made to each crop in the autumn. Growers could overcome this problem for individual crops by monthly autumn sampling, which would improve detection of disease and hence prediction of risk (Fitt *et al*., 1998). This would, however, introduce a considerable, and probably unrealistic, overhead of sampling time into the management practices for this disease.

The model did not account for the season × region interaction, i.e. changes in relative disease incidence between regions across seasons. Investigations on interactions between regions, survey and weather data suggested that summer temperature was more important in north/east regions, incidence of light leaf spot on pods in the previous season was more important in the east region and winter rainfall was important in all regions (Welham *et al*., 1999). These models, however, were based on a small number of data points (nine to 13) selected from a large number of potential explanatory variables. In comparison, the current regional scale models are based on regression with 88 season × region combinations. With further data, more reliable within-region models could be developed to account for season × region variation.

These results demonstrate how long-term survey and weather data can be used to construct empirical models, which can help to provide growers with tactical guidance of the risks of severe light leaf spot epidemics in their crops. There is scope for improving these empirical models by combining them with process-based simulation models that predict epidemic progress within crops over time (Papastamati *et al*., 2001, 2002). This type of model can account for the interaction between the plant, pathogen and weather conditions (Welham *et al*., 2000), but such an approach requires detailed quantitative knowledge of factors influencing the epidemic to give realistic predictions. Papastamati *et al*. (2001, 2002) found that the input of ascospore numbers was essential for predicting the onset of the epidemic. It may ultimately be possible to use weather-based models (Gilles *et al*., 2001a) or direct measurements with novel spore samplers (Calderon *et al*., 2002) to obtain this information.

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References

Anonymous, 1990. *Monthly Weather Report 106, Issue 1–12*. Bracknell, UK: UK Meteorological Office.

Anonymous, 1998. *Oilseeds Variety Handbook*. Cambridge, UK: National Institute of Agricultural Botany.

Breslow NE, Clayton DG, 1993. Approximate inference in generalized linear mixed models. *Journal of the American Statistical Association* **88**, 9–25.

Calderon C, Ward E, Freeman J, Foster SJ, McCartney HA, 2002. Detection of airborne inoculum of *Leptosphaeria maculans* and *Pyrenopeziza brassicae* in oilseed rape crops by polymerase chain (PCR) assays. *Plant Pathology* **51**, 303–10.

Coakley SM, 1988. Variation in climate and prediction of disease in plants. *Annual Review of Phytopathology* **26**, 163–81.

Evans N, Baierl A, Brain P, Welham SJ, Fitt BDL, 2003. Spatial aspects of light leaf spot (*Pyrenopeziza brassicae*) epidemic development on winter oilseed rape (*Brassica napus*) in the UK. *Phytopathology* **93**, 657–65.

Evans N, Fitt BDL, McCartney HA, Welham SJ, McRoberts N, 1999a. Investigating the horizontal spread of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in the UK. *Aspects of Applied Biology* **55**, 31–6.

Evans N, Fitt BDL, McCartney HA, Welham SJ, McRoberts N, 1999b. Sampling winter oilseed rape crops to assess incidence of light leaf spot (*Pyrenopeziza brassicae*) in the UK. *Aspects of Applied Biology* **56**, 123–8.

Figueroa L, Shaw MW, Fitt BDL, McCartney HA, Welham SJ, 1994. Effects of previous cropping and fungicide timing on the development of light leaf spot (*Pyrenopeziza brassicae*), seed yield and quality of winter oilseed rape (*Brassica napus*). *Annals of Applied Biology* **124**, 221–39.

Fitt BDL, Doughty KJ, Gilles T, Gladders P, Steed JM, Su H, Sutherland KG, 1998. Methods for assessment of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape (*Brassica napus*) in the UK. *Annals of Applied Biology* **133**, 329–41.

Fitt BDL, Gladders PG, Turner JA, Sutherland KG, Welham SJ, 1996. Predicting risk of severe light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in the UK. *Proceedings of the Brighton Crop Protection Conference 1996 – Pests and Diseases*. Farnham, UK: BCPC, 239–44.

Fitt BDL, Gladders P, Turner JA, Sutherland KG, Welham SJ, Davies JML, 1997. Prospects for developing a forecasting scheme to optimise use of fungicides for disease control on winter oilseed rape in the UK. *Aspects of Applied Biology* **48**, 135–42.

Gilles T, Evans N, Fitt BDL, Jeger MJ, 2000a. Epidemiology in relation to methods for forecasting light leaf spot (*Pyrenopeziza brassicae*) severity on winter oilseed rape (*Brassica napus*) in the UK. *European Journal of Plant Pathology* **106**, 593–605.

Gilles T, Fitt BDL, Jeger MJ, 2001a. Effects of environmental factors on development of *Pyrenopeziza brassicae* (light leaf spot) apothecia on oilseed rape debris. *Phytopathology* **91**, 392–8.

Gilles T, Fitt BDL, Kennedy R, Welham SJ, Jeger MJ, 2000b. Effects of temperature and wetness duration on conidial infection, latent period and asexual sporulation of *Pyrenopeziza brassicae* on leaves of oilseed rape. *Plant Pathology* **49**, 498–508.

Gilles T, Fitt BDL, McCartney HA, Papastamati K, Steed JM, 2001b. The roles of ascospores and conidia of *Pyrenopeziza brassicae* in light leaf spot epidemics on winter oilseed rape (*Brassica napus*) in the UK. *Annals of Applied Biology* **138**, 141–52.

Hardwick NV, Fitt BDL, Wale SJ, Sweet JB, 1991. *Oilseed Rape Diseases*. London, UK: H-GCA. (Home-Grown Cereals Authority Oilseeds Research Review OS4.)

Karolewski Z, Evans N, Fitt BDL, Todd AD, Baierl A, 2002. Sporulation of *Pyrenopeziza brassicae* (light leaf spot) on oilseed rape (*Brassica napus*) leaves inoculated with ascospores or conidia at different temperatures and wetness durations. *Plant Pathology* **51**, 654–65.

Papastamati K, van den Bosch F, Welham J, Fitt BDL, Evans N, Steed JM, 2002. Modelling the daily progress of light leaf spot epidemics on winter oilseed rape (*Brassica napus*), in relation to *Pyrenopeziza brassicae* inoculum concentrations and weather factors. *Ecological Modelling* **148**, 169–89.

Papastamati K, Welham SJ, Fitt BDL, Gladders P, 2001. Modelling the progress of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape (*Brassica napus*) in relation to leaf wetness and temperature. *Plant Pathology* **50**, 154–64.

Payne RW, ed., 2000. *The Guide to Genstat, Part 2: Statistics*. Oxford, UK: VSN International Ltd.

Rawlinson CJ, Sutton BC, Muthyalu G, 1978. Taxonomy and biology of *Pyrenopeziza brassicae* sp. nov. (*Cylindrosporium concentricum*) a pathogen of winter oilseed rape (*Brassica napus* ssp. *oleifera*). *Transactions of the British Mycological Society* **71**, 425–39.

Sansford CE, Fitt BDL, Gladders PG, Lockley KD, Sutherland KG, 1996. *Oilseed Rape: Disease Development, Forecasting and Yield Loss Relationships*. Home Grown Cereals Authority Project Report OS17. London, UK: H-GCA.

Steed JM, Fitt BDL, Gladders P, Sutherland KG, 1999. Optimising fungicide timing for control of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in the UK. *Aspects of Applied Biology* **56**, 117–22.

Su H, Fitt BDL, Welham SJ, Sansford CE, Sutherland KG, 1998. Effects of light leaf spot (*Pyrenopeziza brassicae*) on yield of winter oilseed rape (*Brassica napus*). *Annals of Applied Biology* **132**, 371–86.

Sutherland KG, Evans N, Fitt BDL, Gladders P, Morgan D, Northing P, Turner JA, Walters KFA, Parker C, 2002. Development of a DSS for diseases and pests in winter oilseed rape. In: *Proceedings, Crop Protection in Northern Britain 2002*. Farnham, UK: BCPC, 163–8.

Sylvester-Bradley R, Makepeace RJ, 1985. Revision of a code for stages of development in oilseed rape (*Brassica napus* L.). *Aspects of Applied Biology* **10**, 395–400.

Tong H, 1990. *Non-linear Times Series: A Dynamical Systems Approach*. Oxford, UK: Clarendon Press.

Turner JA, Gladders P, Elcock SJ, Walters KFA, Wright DM, 2000. *Winter Oilseed Rape: Survey of Pests and Diseases 1998/9*. York, UK: ADAS/CSL Research and Development.

Wale SJ, Brokenshire T, Oxley S, Sutherland K, Munro JM, 1990. Fungicide control of light leaf spot (*Pyrenopeziza brassicae*) on oilseed rape in Scotland. In: *Proceedings, Crop Protection in Northern Britain, 1990*. Farnham, UK: BCPC, 289–94.

Welham SJ, Fitt BDL, Turner JA, Gladders P, Sutherland K, 1999. Relationships between regional weather and incidience of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in England and Wales. *Aspects of Applied Biology* **56**, 51–9.

Welham SJ, Papastamai K, Fitt BDL, Turner JA, Gladders P, 2000. A comparison of modelling methods for forecasting light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape in the UK. *Proceedings of the Brighton Crop Protection Conference 2000 – Pests and Diseases*. Farnham, UK: BCPC, 801–8.