Project Report No. 357 Part 1 December 2004 Price: £12.50



Development of a decision support system for phoma and light leaf spot in winter oilseed rape ('PASSWORD' Project)

By

P Gladders¹, C Dyer¹, B D L Fitt², N Evans², F Vanden Bosch², J M Steed², A Baierl², J Turner³, K Walters³, P Northing³, K Sutherland⁴, S Campbell⁵, D Ellerton⁶, A Selley⁷, B Hall⁸, D Naylor⁹ and C Parker¹⁰

¹ADAS Boxworth, Battlegate Road, Boxworth, Cambridge CB3 8NN
 ²Rothamsted Research, Harpenden, Herts AL5 2 JQ
 ³Central Science Laboratory, Sand Hutton, York YO41 1LZ
 ⁴SAC Aberdeen, Ferguson Building, Craibstone Estate, Bucksburn, Aberdeen AB21
 ⁹YA
 ⁵HGCA, Caledonia House, 223 Pentonville Road, London N1 9HY
 ⁶ProCam Group Ltd, Saxon Way, Melbourn, Royston, Herts SG8 6DN
 ⁷ Du Pont (UK) Ltd, Wedgwood Way, Stevenage, Herts SG1 4QN
 ⁸ Syngenta Crop Protection UK Ltd, Whittlesford, Cambridge CB2 4QT
 ⁹The Perry Foundation, 31 Rossendale, Chelmsford, Essex CM1 2UA
 ¹⁰Computing Department, Glasgow Caledonian University, Glasgow G4 0BA

This is the final report of a five year project that started in October 2000. The work was funded under the SAPPIO LINK programme with a grant from Defra (project LK0917 - £179,568), and contracts from HGCA (Project 2155 - £148,546), DuPont (UK) Ltd (£30,000), Novartis Crop Protection UK Ltd (£30,000), Perry Foundation (£20,000) and ProCam Group Ltd (£30,000).

The Home-Grown Cereals Authority (HGCA) has provided funding for this project but has not conducted the research or written this report. While the authors have worked on the best information available to them, neither HGCA nor the authors shall in any event be liable for any loss, damage or injury howsoever suffered directly or indirectly in relation to the report or the research on which it is based.

Reference herein to trade names and proprietary products without stating that they are protected does not imply that they may be regarded as unprotected and thus free for general use. No endorsement of named products is intended nor is it any criticism implied of other alternative, but unnamed, products.

Contents

	Page no.
ABSTRACT	1
SUMMARY	2
TECHNICAL REPORT	11
Chapter 1 Introduction	11
Chapter 2 Development of a regional forecast for phoma stem canker	13
Chapter 3 A mechanistic model for describing dynamics of phoma stem	28
canker epidemics	
Chapter 4 Phoma progress models	40
Chapter 5 Light leaf spot forecast development and validation	46
Chapter 6 Benefits of crop-specific light leaf spot models to growers and	50
agronomists	
Chapter 7 Modelling fungicide effects against light leaf spot	54
Chapter 8 Evaluation of cultivar resistance and fungicide strategies	60
Chapter 9 User-centred design approach in PASSWORD	140
Chapter 10 PASSWORD Module Development	153
Chapter 11 Final discussion	163
Acknowledgements	165
References	166
Appendix I Experimental data	170
Appendix II Publications related to project	208

Abstract

Pests and diseases in winter oilseed rape cause serious loss of yield and quality. Losses, predominantly from diseases, are estimated to exceed £80 million/annum in some years. These losses have occurred despite an annual expenditure of about £3.5 million on insecticides and £9 million on fungicides. Decision-making is difficult because of complex spatial and temporal variation in pest and disease problems and improved guidance is required. The main objective of this project was to develop a decision support system for both pest and disease control in oilseed rape.

A new regional forecast for stem canker incidence pre-harvest was developed and is available on the Internet. Models for predicting the severity of phoma stem canker in July were also produced and could be operated where spore trap records, leaf surface wetness and temperature data are available. A regional light leaf spot forecast was produced annually and validation during the project showed that 86% of regional predictions were reliable. In addition to regional disease forecasts, crop-specific risk assessment methods were developed that predict the onset of phoma leaf spotting using post-harvest weather data and thermal time relationships for canker development and canker severity. Yield loss can then be calculated from canker severity and the economic impact of stem canker predicted.

Analysis of historic datasets and field experiments within the project indicate that considerable yield loss (up to 0.07 t/day) can occur if fungicide treatment is made after light leaf spot symptoms have appeared. For stem canker, only moderate and severe lesions cause loss of yield and these can be controlled using a two-spray programme applied when phoma leaf spots first appear and 4-6 weeks later. The most effective disease control was obtained using a combination of resistant cultivars and fungicides. In some years, responses to fungicides were not cost-effective and targeting their use to high risk situations is necessary to give the best margins over input costs.

Close contact was maintained during the project with potential users who influenced priorities and design features. A prototype decision support system was produced that provides guidance for managing invertebrate pests, phoma stem canker and light leaf spot. The system is compatible with ArableDS and is now undergoing a two year test phase to evaluate the new disease models.

Summary

Introduction

Pests and diseases in winter oilseed rape cause serious loss of yield and quality estimated to exceed £80 million/annum in some years, predominantly from diseases. These losses have occurred despite an annual expenditure of about £3.5 million for insecticides and £9 million on fungicides. Recent Defra-funded research has highlighted that timing of the first fungicide spray for disease control is absolutely critical. Many farmers apply fungicides too late and do not achieve satisfactory disease control. Decision-making is difficult because of complex spatial and temporal variation in pest and disease problems. Decisions on pest and disease control are frequently made in relation to calendar date or on a routine prophylactic basis. In much of England, phoma stem canker is the most important disease and guidance is needed to help the industry react to large seasonal variations in the onset of epidemics. Only a small proportion of winter oilseed rape crops suffer economic damage from pests. Insecticides are still used on 80% of crops, but most of this is unnecessary. Increased awareness of the benefits of monitoring pests and use of pest thresholds would substantially reduce insecticide use.

Recent and current Defra and HGCA-funded research has concentrated on understanding the factors that affect the occurrence and distribution of pests and diseases and on developing control strategies. The PASSWORD project will utilise this knowledge and develop new models for diseases and disease control for integration with an existing pest Decision Support System (DSS) known as DORIS. The use of DORIS provides a cost-effective means of extending DSS to diseases and disease control by combining pest and disease problems within a single system.

Objectives

The overall objective is to develop a decision support system for pests and the major diseases of oilseed rape. Specific objectives were to develop new models for light leaf spot and stem canker at regional and crop level to predict disease development and risk of yield loss.

Phoma regional forecast

Models for predicting both incidence and severity of phoma canker in July each year were derived through regression analyses of Defra winter oilseed rape disease survey data from the period 1991 to 2001 using possible explanatory variables. The parameters found to give the most accurate regional prediction of disease incidence (mean % plants affected) were region, incidence of stem canker in the previous season, total rainfall in September/October, total rainfall in February/March and temperature in February. Approximately 55% of the deviance within the data could be attributed to regional variation and the regional level variables

accounted for 76% of the regional variation. Crop level variables accounted for only 3% of the crop-withinregion level deviance. The parameters found to give the most accurate regional prediction of stem canker severity were region, rain days in August/September and the average daily temperature between November and January. These three terms within the model together accounted for 75.6% of the deviance. The stem canker severity model predictions underestimated severity for 2003. Refitting of the severity model incorporating 2003 data is still being investigated. The phoma forecast has been made available on the Internet since 2002. The home page of the phoma forecast (http://phoma.csl.gov.uk) indicates which forecast update is currently available and provides a brief description of the forecast itself.

A mechanistic model for describing dynamics of phoma stem canker epidemics

A mechanistic model was developed to describe the dynamics of phoma stem canker (*Leptosphaeria maculans*) epidemics in UK winter oilseed rape crops. The model includes the major stages in the life cycle of stem canker pathogen and the influence of environmental conditions on these stages. The model can be used to predict stem canker severity. The model inputs are the concentration of air-borne ascospores sampled with Burkard samplers, temperature and leaf wetness duration. Leaf wetness duration was calculated using a new leaf wetness model. Rate of infection of leaves was related to ascospore concentration, air temperature and wetness duration, using published data. Development of phoma leaf spots was related to temperature using published data. Rates of pathogen growth through the petiole and subsequent establishment of stem cankers were related to temperature. The model takes the form of a set of non-linear, delay differential equations.

Most of the model parameters could be estimated from published data, except for the probability that a spore establishes an infection on a leaf and leaf death rate. These parameters were variable and had to be estimated separately for each winter oilseed rape crop. This model was solved numerically to optimize unknown parameter values. The model was fitted to field experimental data collected at Rothamsted over three seasons. The model was fitted to the data on phoma leaf spot numbers in crops. On the basis of this fit and the optimized parameter values, the model was run to predict the proportion of plants developing stem canker. The fit of the model to the phoma leaf spot data was satisfactory. The model gave a good prediction for both the relationship between numbers of phoma leaf spots and incidence of stem canker and proportion of plants developing stem canker. The mechanistic model requires further validation as few data are currently available for ascospore concentrations.

Phoma progress model

A four-stage crop-specific phoma stem canker progress model was developed. Quantitative relationships were established for each of the four stages using historic datasets. The first stage model predicts the date when 10% of plants will have phoma leaf spotting (in autumn) using mean maximum temperature and total rainfall between 15 July and 26 September. Stage 2 is a thermal time (as degree-days) model predicting the

interval between the onset of phoma leaf spotting and first stem canker symptoms. Symptoms develop more slowly on canker resistant cultivars. The stage 3 model predicts in the increase in canker severity in thermal time. This increase is reduced in cultivars with canker resistance ratings >6. From the predicted canker severity at harvest, the stage 4 model can be used to estimate yield loss. Cultivar resistance did not influence the canker severity/yield loss relationship. These interlinked models can be used to predict yield loss when phoma leaf spot first appears and are updated during the growing season with actual weather data. The estimates of yield loss provide a framework for defining the number of fungicide applications that can be justified to optimise margins over fungicide costs.

Light leaf spot regional forecast

The forecast for light leaf spot was developed prior to the PASSWORD project using Defra-funded winter oilseed rape disease survey data from 1987-1999 and monthly weather data. The most important explanatory variables were mean summer temperature (July/August), mean monthly winter rainfall (December-February) and incidence of light leaf spot on pods in the previous season. The risk of severe light leaf spot (% crops with >25% plants affected in spring) was predicted in September and updated at the end of February to take account of winter rainfall.

Under PASSWORD, the light leaf spot forecast system underwent two main improvements: extension of the forecast delivery system to provide an interactive crop-specific forecast to the grower/advisor and extension of the forecast system to produce a prediction for Scottish growers/advisors. The use of Active Server Page (ASP) Internet-based technology allowed interactive input of cultivar resistance rating and sowing date, both of which were used to modify the regional forecast to produce a crop-specific forecast for the situation of a particular grower (see http://www3.res.bbsrc.ac.uk/leafspot/). As detailed previous season pod light leaf spot data was not available for Scotland (as Scotland was not included in the Defra Oilseed Rape Pest and Disease Survey), a Scottish forecast was produced by running the forecast done using north of England pod disease data with Scottish meteorological data. Validation of the forecast done using regional disease survey data for 2000-2003 showed that 86% of predictions were compatible with the model.

Potential benefits of crop-specific models for forecasting light leaf spot severity

Crop-specific elements were incorporated into the interactive web-based version of this forecasting scheme so that growers can input information about their own cultivars and sowing date to modify the forecasts. However, the effect of these factors is based on empirical models and they do not operate in real time. An alternative approach is to use mechanistic models to describe the development of light leaf spot using information on initial inoculum and local weather data. Models available for the effects of temperature on apothecial development, the effects of temperature and leaf surface wetness on light leaf spot development and the effects of temperature on the latent period were combined to predict the stages in the development of

light leaf spot. The mechanistic model provides continuous output and predicts disease progress. Both primary and secondary sporulation of light leaf spot developed close (0-14 days) to the predicted dates in inoculated experiments, indicating those infection events had been correctly identified. The mechanistic model still requires further testing and validation, as few suitable data are available. In future, the combined operation of both regional forecasts and mechanistic models would provide users with both strategic guidance and detailed output on disease progress to guide decision making.

Effects of fungicides against light leaf spot

Data from two series of experiments (HGCA Project report numbers OS17 and OS63) were examined to produce information on the effect of fungicide on disease and yield levels. The series of 14 experiments with programmes of fungicide starting or finishing each month from October to June (OS17 'wave' design) (1991-1994) were found to be the most productive because of the larger number of fungicide sprays applied. For early outbreaks of disease, fungicides nearly always gave 90% control even at high levels of disease on untreated control plots. For the later disease epidemics, there was normally no apparent disease on plots that had been sprayed up to 12 weeks before symptoms were detected.

A relationship was calculated between potential yield loss and maximum severity, fitting an exponential curve, which indicated a maximum potential yield loss of 1.68 t/ha from light leaf spot. Lines were calculated showing the relationship between potential yield loss and the number of days between first disease and spraying. This showed that the potential yield loss doubled if severity was >10%. The potential yield benefit was calculated and estimated on average as 0.55 t/ha when spraying in the autumn and 0.50 t/ha with a spring spray.

Fungicide timing experiments

At Rothamsted during 2000/01, 2001/02 and 2002/03, field experiments were done using the fungicide flusilazole + carbendazim (Punch C) at three different timings during the autumn to find the optimum time for controlling phoma stem canker (*Leptosphaeria maculans*) epidemics on winter oilseed rape (cv. Apex). Plots were regularly sampled to assess the effect of fungicide timing on both the phoma leaf spot and stem canker phases of the disease. In addition, ten plants in each of three untreated plots in these experiments were marked soon after emergence. Development and loss of individual leaves and the number of phoma leaf spot lesions occurring on each leaf was monitored throughout the season on these marked plants so that relationships between plant development (leaf production and loss), pathogen progress (phoma leaf spotting and stem canker) and fungicide timing could be studied. In 2002/03 30 small and 30 large plants were marked and monitored in this way. Up to 70 days after sowing, leaf production was rapid with little leaf loss and the number leaves/plant therefore increased. From 70 to 170 days after sowing, rates of leaf production and loss were similar and therefore number of leaves/plant remained fairly constant.

The phoma leaf spot epidemic was early and severe in 2000/01, early and moderate in 2001/02 and late and severe in 2002/03. The resultant stem canker was severe in 2000/01 and 2001/02, but slight in 2002/03, suggesting that the time of the phoma leaf spot epidemic is more important than its severity. The severe stem canker epidemics in the first two seasons caused yield reductions of approximately 1 t/ha. In 2002/03, large plants were more heavily infected with phoma leaf spot than small plants because of their larger leaf area. Despite this, stem canker severity was greater on small plants at harvest. This was probably because infected leaves were present for longer on small plants than large plants in the autumn, giving the pathogen longer to reach the crown. Early application of fluzilazole + carbendazim, before GS 1,10, reduced early phoma leaf spotting, but was less effective than later applications in reducing stem canker severity. This suggests that flusilazole + carbendazim has a significant curative effect and can prevent or slow the growth of the pathogen from leaf lesions to the crown of the plant.

Fungicide x cultivar experiments

Three experiments to investigate the most effective management strategies for control of phoma stem canker in relation to cultivar resistance were investigated using three cultivars (Pronto, Apex and Escort) at ADAS Boxworth, Cambs during 2001-2003. Similar experiments for light leaf spot using cvs Synergy, Apex and Escort were done at SAC Aberdeen, Scotland. Three fungicide regimes with alternating flusilazole + carbendazim and difenoconazole + carbendazim at Boxworth and flusilazole + carbendazim followed by tebuconazole at Aberdeen were evaluated in relation to an untreated control. The fungicide treatments were a 'Full programme' of three sprays initiated at onset of phoma leaf spotting or early November for light leaf spot, an 'Autumn programme' of two sprays and a 'Managed programme' of two sprays initiated at first symptoms of disease and followed by a mid-stem extension application. Phoma leaf spot was well controlled by autumn and winter fungicide treatments. Stem canker control was related to the number of fungicide sprays applied in autumn and winter. The mean untreated pre-harvest index (0-100 scale) was reduced from 49 to 10, 18 and 33 in Full, Autumn and Managed programmes respectively. Cultivar resistance had smaller effect than best fungicide treatments and mean canker indices for each cultivar were Pronto 35, Apex 24 and Escort 23. The three fungicide treatments gave similar yields of 3.43, 3.34 and 3.41 t/ha for Full, Autumn and Managed programmes respectively, all significantly higher than the untreated control (2.91 t/ha). There were no significant yield responses in 2001 at Boxworth. The corresponding yields at Aberdeen were 3.95, 3.81 and 3.62 t/ha for Full, Autumn and Managed programmes respectively and 3.50 t/ha untreated. The Managed programme initiated when light leaf spot symptoms appeared gave no significant yield response. There were no yield responses on cv. Synergy. Control of light leaf spot was poor during the winter as weather conditions sometimes delayed the second spray application until spring. In spring, the Full programme gave 75% control of light leaf spot by late April/early May. The best margins over fungicide costs were given by the Managed programme at Boxworth and the Full programme at Aberdeen.

User-centred design approach in PASSWORD

The PASSWORD project adopted a style of development known as 'user-centred'; this means that the endusers are consulted at every stage of the design from initial concept to final product. Four focus groups with farmers and consultants were used to prioritise factors used in the decision making process and other issues. This activity was supported by a postal survey of 25 potential users and demonstration of the User Interface at the Cereals 2002 and Sprays and Sprayers events. The project benefited from the views expressed by potential users in determining design features and priorities. Additional areas for development that were outside the scope of this project were identified. The prototype DSS will be demonstrated to potential users during the next development phase of the project. Individual users have a range of preferences for obtaining information. Some will use DSS, whilst others will prefer simple warnings and guidance to be delivered by their advisers. These issues will need to be considered further during discussions about commercialisation of the system.

PASSWORD module development

The development and design of the Decision Support System utilised experiences from ArableDS and DORIS (Decision support for Oilseed Rape Invertebrate pestS) systems in addition to user consultations. It was an essential requirement to supply useful and accurate information in an easily understandable format and in a timely and cost-effective manner. ArableDS was designed as a PC-based system made up of a decision support system (DSS) shell into which multiple DSS's can be plugged databases for weather and pesticide data and a fully functional farm management system. The PASSWORD entity was developed as an ArableDS compliant module; building upon the structure of DORIS using the toolkit ensures that PASSWORD both conforms to the ArableDS requirements and, on release, will be familiar to the users of the DORIS module.

The development process of the PASSWORD module began by considering the current position of the DORIS module, the associated user consultation results and the likely type of data and models that would be available for the two main fungal diseases in winter oilseed rape, phoma stem canker (*Leptosphaeria maculans*) and light leaf spot (*Pyrenopeziza brassicae*). Initial amendments to the DORIS module had to include a change to the way in which the disease considerations were dealt with. DORIS asked the question 'are you going to tank mix?' and this affected the financial implications of treatment against the pest under review. In PASSWORD, the system provides information on whether and when to treat against diseases, so the pest models have to access this information in order to change the financial aspect of the models. The disease models incorporated into PASSWORD are the strategic regional forecasts for light leaf spot and phoma stem canker that are currently available via the Internet and crop based models for phoma and light leaf spot. The new phoma progress model predicts the date at which 10% of plants showed symptoms, the date of the onset of stem canker, the final stem canker severity and the associated yield loss. These predicted dates are highlighted in the display area alongside the output from a second model that indicates when

conditions have been favourable for leaf infection. For light leaf spot, a model indicating the occurrence of infection events and subsequent symptom expression is also available. This enables the user to identify key times when they could go out into the crop to look for symptoms.

Economic appraisal of model output is displayed as a range on the User Interface, but more detailed display of yield loss and financial return is available by clicking on the cost-benefit analysis button. Various alternative scenarios may be run with differing weather or disease development. Examples with differing disease levels are included within the encyclopaedic section for users to explore alternative fungicide strategies and their economic consequences. Regional default values have been prepared for yield losses for both light leaf spot and phoma stem canker, using historic survey and experimental data and these may be used when users are unable to define likely yield loss. Pesticide information is provided by the LIAISON database. When treatments have been applied the display provides a graded indicator to show how activity diminishes with time.

PASSWORD was designed to be compatible with existing farm recording systems and requires minimal additional information about the crop. It is recognised that users have different requirements; some will operate the DSS themselves, whilst others prefer to receive pest and disease warnings derived from the DSS. This system therefore has the potential to be a major contributor to an increase in the sustainability of arable farming in the UK. The integration of detailed disease control strategies with DORIS in a new module (PASSWORD) should, following a similarly successful validation stage, improve the usefulness and scope of oilseed rape DSS's and provide the basis for a rational decision making policy for both pests and diseases in this important arable crop.

Key results

Regional disease forecasts are now available on the Internet for both phoma stem canker and light leaf spot and may be used interactively by users.

The light leaf spot forecast was validated and predictions during 2000-2003 were reliable in 86% of cases.

New crop-specific forecasts were produced that allow early estimation of yield loss from stem canker. These predictions require a further phase of testing and this is now in progress.

The combined use of spore trapping and weekly crop monitoring identified progress of phoma leaf spot reliably and provides 2-3 weeks warning of disease onset.

Control of light leaf spot continues to cause concern in Scotland. In high risk situations, it is important to apply fungicides before symptoms of light leaf spot appear. Delaying the first spray until after the first appearance of light leaf spot may result in a yield loss of 0.07t per day at high disease sites.

Good control of light leaf spot on leaves was obtained in spring during 2001-2003, particularly on the resistant cultivar Escort. Poor control of light leaf spot was apparent in winter when ground and weather conditions prevented fungicide applications.

Light leaf spot control required multiple fungicide applications at Aberdeen and these were cost-effective except where treatments were applied only after the appearance of symptoms of the disease. There were no yield responses in 2001 or on cv. Synergy and margins could be improved by identifying non-responsive situations in future.

Early phoma leaf spotting developing in late September and October is most likely to cause yield loss. Fungicides have provided more effective control of stem canker than cultivar resistance. An integrated approach with use of late August sowing, cultivars with good stem canker resistance and autumn fungicides provides a robust strategy for stem canker management.

Phoma leaf spot and stem canker were well-controlled using autumn sprays, but additional canker control from a winter treatment gave no economic benefit. There was no yield response to fungicides at Boxworth in 2001 when stem canker severity was low. Carefully targeted fungicides used in a two-spray programme may produce margins of £60/ha in crops with a high incidence of phoma canker.

There is strong interest in the development of a decision support system for pest and disease control in oilseed rape. Potential users identified key areas of decision-making where support through PASSWORD was a priority. Some would prefer warnings by email or fax rather than have to use the system itself.

The PASSWORD decision support system has a user interface with pest and disease activity indicated on a daily basis in relation to weather conditions. The economic impact is indicated on the same screen with further options to calculate cost-benefits of decisions to run various alternative scenarios using historic data. PASSWORD is compatible with ArableDS.

A prototype PASSWORD module is now available and, subject to satisfactory testing in 2004 and 2005, should be available for use in autumn 2006.

Conclusions and implications for levy payers

There are large differences between regions and large year-to-year variations in disease risk. Decision making and use of crop protection is complex and early assessment of yield loss is required to improve targeting of treatments.

The regional forecasts for light leaf spot and stem canker provide a strategic view on changes in risk from year to year. Crop specific risk can now be quantified using local weather data, sowing date and cultivar resistance, supplemented with disease records as the season progresses.

Winter oilseed rape crops should be established in late autumn so that plants have reached at least the 6-leaf stage before the phoma leaf spot epidemics become severe. Larger plants and resistant cultivars contribute to stem canker control, but fungicides are still required where phoma leaf spot incidence is usually high. The risk of yield loss is low where phoma leaf spot develops late (December onwards) on large plants (10 or more leaves).

Infection periods for phoma leaf spot and light leaf spot can be identified using weather data and the PASSWORD system also indicates when new symptoms are likely to appear. This provides new guidance on when to inspect crops.

Control of light leaf spot requires use of both resistant cultivars and fungicides in high-risk situations. The use of resistant cultivars is becoming increasingly important as triazole resistant strains of light leaf spot fungus have been found in Scotland and fungicide efficacy may decline. In Scotland, northern England and other high-risk situations, the first fungicide spray should be applied in late autumn prior to the appearance of first symptoms. Always use at least half rate of triazole fungicide in autumn.

The use of fungicides where disease pressure is low is not cost-effective and new predictive models should be used to improve the targeting of fungicides, thereby improving margins over fungicide costs.

Phoma stem canker was effectively controlled with a two-spray programme applied at the onset of phoma leaf spotting and 4-6 weeks later. Only moderate or severe canker lesions should be controlled, as slight lesions (i.e. those affecting less than 50% stem circumference) do not affect yield. Fungicide treatments for stem canker control should be completed prior to stem extension.

Where both pest and disease risks are identified PASSWORD will indicate the optimum date for combining treatments. The economic consequences of delaying a treatment can be estimated, thus guiding decisions on whether a sub-optimal timing is worthwhile.

The new disease models will be tested in 2004 and 2005, prior to dissemination of the PASSWORD decision support system. The PASSWORD module will extend the technical support provided by ArableDS and provide guidance for pest and disease management in a single system.

Technical report

Chapter 1

Introduction

Pests and diseases in oilseed rape cause serious loss of yield and quality, estimated to exceed £80 million/annum, predominantly from diseases, in years such as 1995 and 1996 (Fitt *et al.*, 1997). Annual expenditure is about £3.5 million for insecticides and £9 million on fungicides. Recent Defra-funded research has highlighted that timing of the first fungicide spray for disease control is absolutely critical. Many farmers have been spraying too late and not achieving satisfactory disease control (Gladders *et al.*, 1998). In much of England, stem canker caused by *Leptosphaeria maculans* is the most important disease and guidance is needed for the industry to be able react to large seasonal variations in the onset of epidemics. Disease epidemics can develop very rapidly and timely spraying may not be possible without early warning of disease risk, if there are adverse weather conditions. In addition, there is complex spatial and temporal variation in pest and disease problems and different decisions may be required for individual crops on the same farm. Because of the uncertainties about the risk of yield loss, decisions on disease control are frequently made in relation to calendar date or on a routine prophylactic basis.

Only a small proportion of winter oilseed rape crops suffer economic damage from pests, yet insecticides are still used on 80% of crops, but most of this usage is unnecessary. Increased awareness of the benefits of monitoring pests and use of pest thresholds would substantially reduce insecticide use. Recent Defra and HGCA-funded research has concentrated on understanding the factors that affect the occurrence and distribution of pests and diseases and developing control strategies. This project builds on this knowledge and develops models for diseases and disease control and integrates them with an existing pest Decision Support System (DSS) known as DORIS developed by the Central Science Laboratory.

The use of DORIS provides a cost-effective means of extending DSS to diseases and disease control by combining pest and disease problems within a single system. To achieve a DSS, it is essential to incorporate new disease forecasts and risk assessments for the major diseases of winter oilseed rape. It is also necessary to develop a systematic appraisal of the effects of fungicides in relation epidemic development. Scientific challenges are faced by dealing with contrasting monocyclic (canker) and polycyclic (light leaf spot) pathosystems during the winter and spring and their interactions with weather factors. This project brings together disparate field and laboratory projects on the major diseases of oilseed rape, providing a synthesis of existing data and predictive models. Recent research contributes substantially to the project, providing datasets for the onset of disease development, cultivar resistance, infection conditions, the relationship between leaf and stem canker development and the relationship between yield loss and disease severity.

A DSS enables existing research to be more fully exploited, capitalising on recent progress on understanding disease control requirements. The DSS integrates decisions on pest control with those diseases for the first time. Emphasis on pests and diseases in oilseed rape complements other areas of ongoing research in the crop, namely:

- 1. Establishment of oilseed rape
- 2. Canopy management
- 3. Pod shatter

This project addresses a crucial missing element on agrochemical usage with the aim of helping producers trim production costs so that oilseed rape remains a profitable crop.

Improved management and higher yields of oilseed rape are considered essential for the survival of the crop under Agenda 2000. Improved decision making could contribute up to 0.5 t/ha of yield from improved disease control. This project addresses fundamental scientific issues relating to prediction and management of epidemics whilst raising outputs and improving crop production margins. The sustainability of oilseed rape will be enhanced by the project through improved targeting of appropriate agrochemical doses. Improved disease control and more effective use of fungicides using guidance from the DSS has potential to increase average yields by up to 0.5 t/ha (equivalent to £50/ha or £20 million/annum). Insecticides are a low cost input and environmental benefits could be achieved by reducing unnecessary applications by up to 160,000 spray ha (cost savings of £0.6 million/annum). Closer attention to detail during crop monitoring (outside the scope of this project) is also expected to improve overall management of the crop, notably the optimising the crop canopy in the spring, with further yield improvements of up to 0.5 t/ha. Direct benefits in reduced pesticide costs and improved yield from the DSS are estimated to be £32 million/annum.

Objective

The overall objective of this project is to develop a decision support system for pests and the major diseases of oilseed rape. Specific objectives are to develop new models for light leaf spot and stem canker at regional and crop level to predict disease development and risk of yield loss.

Chapter 2

Development of a regional forecast for phoma stem canker

2.1 Introduction

Data from the Defra winter oilseed rape disease surveys of England and Wales show that phoma stem canker caused by *Leptosphaeria maculans* is now the most important disease of oilseed rape, affecting a mean of over 40% of plants nationally each year since 1999 (Turner *et al.* 2002). Mapping of the data also indicates that although disease levels fluctuate from season to season and between regions, crops in the south and east of England are consistently at most risk of infection. Phoma incidence and severity is affected by key weather conditions, being most favoured by rainfall in the autumn (Gladders & Symonds, 1995). Data from the Defra survey were used to develop empirical models to predict the incidence and severity of phoma canker in commercially managed oilseed rape (i.e. mainly fungicide treated) crops in England and Wales.

2.2 Methods

Defra winter oilseed rape disease survey data for the years 1987–2001 were analysed to examine patterns in incidence of phoma canker and to identify discrete 'phoma regions'. Counties with at least two samples per season were included in the analysis to define regions (phoma risk region) to use in the forecast. Principle co-ordinates analysis and hierarchical clustering and non-hierarchical clustering were carried out to determine the most appropriate groups. A UK map was drawn of the county boundaries and the location of all the meteorological stations highlighted. These were then allocated to the correct phoma risk region for use in forecasting regional disease risk.

Models for predicting both incidence and severity of phoma canker in July each year were derived through regression analyses of data from the period 1991 to 2001, using possible explanatory variables.

2.3 Results and Discussion

2.3.1 Regional risk

Six regions were identified in which the survey data indicated that incidence of phoma canker followed a similar pattern (Table 1).

Phoma risk region	Counties grouped together by analysis	
South-central	Hampshire, Berkshire, Oxfordshire,	
	Buckinghamshire, Surrey & West Sussex	
North	Cleveland, Cumbria, Gr. Manchester,	
	Northumberland, N. Yorkshire, W. Yorkshire,	
	Durham, Humberside, Lancashire, Merseyside and	
	Tyne & Wear	
East/South-east	Norfolk, Suffolk, Northamptonshire,	
	Cambridgeshire, Essex, Hertfordshire, Bedfordshire,	
	Kent & E. Sussex.	
Lincolnshire	Lincolnshire	
Midlands and west	Cheshire, Clwyd, Derbyshire, Dyfed, Gwynedd,	
	Hereford & Worcestershire, Leicestershire,	
N & W Wales	Nottinghamshire, Powys, Shropshire, S. Yorkshire,	
	Staffordshire & Warwickshire.	
S West & S Wales	Avon, Cornwall, Devon, Dorset, Somerset, West	
	Midlands, Gloucestershire, Wiltshire, S. Glamorgan,	
	W. Glamorgan, Mid Glamorgan & Gwent.	

Table 1. Phoma risk regions

2.3.2 Prediction of disease incidence

All analyses were carried out on data from 1991-1999 inclusive and then using the equations developed to validate predictions with the survey results for the year 2000.

The parameters found to give the most accurate regional prediction of disease incidence (mean % plants affected) were region, incidence of stem canker in the previous season, total rainfall in September/October, total rainfall in February/March and temperature in February.

Three models were developed:

Model 1 - 10 parameters – including region (6) and weather variables (4) as above.

Model 2 - 12 parameters – model 1 plus HGCA Recommended List disease resistance rating and autumn spray factors.

Model 3 – 13 parameters – model 2 incorporating a factor from results of autumn disease assessments.

Models were fitted using generalised linear regression with binomial errors and a logit link function. Weather variables and previous summer incidence were fitted at the regional level and were assessed by comparing changes in disease to the year x region mean deviance. The % plants affected with phoma leaf spot in the autumn was fitted at the individual crop level. Variables were chosen for inclusion in a model by forward stepwise selection, and the assumption of linear responses to explanatory variables was checked by using smoothing spline terms.

The most important variables in order of importance (see also Fig. 1) were: Rainfall in September and October Rainfall in February and March Incidence of phoma canker in previous summer Incidence of phoma leaf spot in autumn (December) Number of rain days in August and September Mean temperature in November, December and January

Approximately 55% of the deviance within the data could be attributed to regional variation and the regional level variables accounted for 76% of the regional variation. Crop level variables accounted for only 3% of the crop-within-region level deviance.

Regional predictions (model 1)

First predictions of canker levels in 2002 were made at the beginning September 2001 by running the models on previous summer disease incidence and using the ten-year mean for each individual region for the four weather variables. Regional disease data generated from assessments carried out as part of the 2002 survey were used for validation of the models. This involved comparison of the observed percentage of plants affected by phoma canker in each region against the predicted percentage of affected plants for that region as shown in Figure 1. The model was updated during the season as data for the key weather factors became available.

Revised models were used in predictions made in autumn 2002 for canker levels in summer 2003. Canker incidence in 2003 was the second highest on record and the models correctly predicted a high risk of infection. Accuracy of prediction improved during the season as actual weather variables were incorporated, with the most accurate predictions being made in February. Predictions of disease incidence were within tolerance for all regions except the Midlands and west.



Figure 1. Percentage plants affected by phoma canker predicted using model 1 in September, February and May against actual percentage plants affected from Defra Winter Oilseed Rape Pest and Disease Survey data for July 2002. See Table 1 for details of the 6 regions.

Comparison of observed against predicted regional phoma disease levels showed that predictions for Lincolnshire, the north and the southwest were significantly lower than the final disease levels recorded. Further examination of the residual for each region against terms in the models showed that the slope in the relationship between incidence and February temperature should have been larger in the Lincolnshire and northern regions than that for other regions, as February temperatures tend to be lower in these two areas. The models were refitted to generate three new models (1a to 3a), which incorporated these factors and the accuracy of prediction was improved for all regions except the southwest (Figure 2). The underestimate of disease levels in the southwest could not be explained at this stage but was most likely due to the small sample size from this region (9 samples).



Figure 2. Comparison of models 1 and 1a for prediction of percentage plants affected by phoma canker using data from the Defra Winter Oilseed Rape Pest and Disease Survey for 2002.



Figure 3. Predicted percentage plants affected by phoma canker using model 1a against actual percentage plants affected from Defra Winter Oilseed Rape Pest and Disease Survey data for 2003.

The models were run again in autumn 2003 to make regional predictions for 2004 and these are detailed in Table 2 below.

	Predicted percentage plants affected by phoma canker (summer 2004)					
Prediction date	September	November				
North	55.2	21.3				
M & W	42.7	12.8				
South east	71.8	34.6				
Lincolnshire	46.7	17.4				
South central	58.9	19.5				
South west	44.8	11.1				

Table 2. Predictions for regional incidence of phoma canker 2004.

Predictions of disease incidence issued in November were significantly lower than those made in September due to the exceptionally low rainfall in some areas during September and October.

2.3.3 Crop level predictions (Models 2a and 3a)

Variables that were found to significantly affect phoma incidence at the crop level were cultivar disease resistance and use of an autumn spray. Historical data were used to predict disease incidence on crops on the basis of three levels of resistance (low (1-3), medium (4-6) and high (7-9)) in sprayed and unsprayed crops. These analyses quantified the influence of these crop variables on regional disease incidence (Figure 4) and these have been incorporated into the interactive prediction system on the website. Analyses illustrate the benefit of using resistant cultivars and an autumn spray for minimising stem canker incidence.





2.3.4 Prediction of disease severity

Analyses were carried out on data from the period 1991-2002 with the aim of using the models developed to make and validate predictions for 2003. Models were fitted using generalised linear regression with binomial errors and a logit link function. The parameters found to give the most accurate regional prediction of disease severity were region, raindays in August/September and the average daily temperature between November and January. These three terms within the model together accounted for 75.6% of the deviance.

Severity of phoma canker in oilseed rape is assessed using a disease index on a 0-4 scale where:

- 0 no disease
- 1 less than half the stem circumference affected
- 2 more than half the stem circumference affected
- 3 whole stem girdled by the lesion
- 4 plant dead due to canker

Crops with a mean stem canker disease index of >1.5 were identified as likely to suffer economic loss of yield. This parameter was built into the model as a threshold and a prediction made of the percentage crops in each region, which would be above this threshold in 2003. First predictions of canker severity levels in 2003 were made at the beginning September 2002 by running the regional models and using the ten-year mean for each individual region for the two weather variables. These predictions were updated in October and February as data for the key weather factors became available.

Regional disease data generated from disease assessments carried out as part of the 2003 survey were used for validation of the models. This involved comparison of the observed percentage of crops with a mean stem canker disease index of >1.5 against the predicted percentage of crops affected for that region as shown in Figure 5.



Figure 5. Predicted percentage crops with a mean stem disease index of >1.5 for phoma canker (using model 1) against actual percentage crops affected from Defra Winter Oilseed Rape Pest and Disease Survey data for 2003.

Predicted canker severity levels for summer 2003 were a significant underestimate compared to the actual severity levels recorded in the survey. Examination of the historical dataset (Table 3) showed that disease severity levels have been steadily increasing over the last five years, and that in 2003 unprecedented levels were recorded in the North, Midlands and Lincolnshire. The model may have underestimated levels for 2003 because the historical dataset used in its development was dominated by years where severity levels were low and cultivar resistance ratings were higher.

The original model has been run to make predictions for stem canker severity in 2004 in order that further validation of the model can be carried out. The update in October showed a decreased risk of disease as a result of the very dry autumn. Re-examination of the explanatory variables, particularly previous disease severity, and refitting of the model incorporating data from 2003 is being investigated to improve predictions.

Year	North	M & W	South east	Lincs	South	South west
					central	
1991	0	0	2.3	0	0	0
1992	0	0	11.1	0	0	0
1993	44.0	5.0	40.5	7.1	16.7	0
1994	4.2	0	11.9	0	53.3	11.1
1995	0	0	55.6	0	43.8	18.2
1996	0	0	14.7	0	6.7	0
1997	0	0	5.7	0	6.7	0
1998	0	0	3.2	0	0	7.7
1999	0	0	6.5	0	0	15.4
2000	10.5	6.3	39.4	27.3	0	0
2001	21.1	0	18.9	33.3	8.3	0
2002	37.5	5.3	19.4	33.3	23.1	0
2003	57.1	11.7	21.2	40.0	20.0	10.0

Table 3. Percentage crops with a mean phoma stem canker index of >1.5 (1991-2002).

Table 4. Predictions for regional severity of phoma stem canker 2004.

	Predicted percentage crops with mean stem index >1.5 (summer 2004)				
Prediction date	September	October			
North	7.33	1.48			
M & W	0.75	0.13			
South east	15.03	3.07			
Lincolnshire	4.56	0.78			
South central	10.64	1.50			
South west	2.98	0.38			

2.4 Conclusions

Models for prediction of canker disease incidence have been successful in identifying ongoing high risk of infection since the model was first used in autumn 2001 and have clearly predicted the differences in degree of risk between regions. Extension of the model to include crop variables has also been effective in predicting lower levels of risk in treated crops with high levels of disease resistance. This model has been taken forward for incorporation into the phoma forecasting website. Models for prediction of disease severity need modification and further validation, as the original historical data set used did not contain enough data from years with high disease severity to accurately predict current levels.

2.4.1 Incorporation of phoma risk models into a web-enabling phoma forecast

Following the completion of the construction of models to forecast regional incidence and severity of phoma stem canker in winter oilseed rape, the decision was taken to release the models for public use. The earlier development and successful use of the web-enabled light leaf spot forecasting system provided initial guidance as to how the newly developed forecast could be released into the public domain as soon as possible.

Alongside a web-enabled system for public release it was also important to ensure that those who will use the ArableDS-compliant module should have opportunity to access to the forecast without having to continually go online to use it. To facilitate this, the web application was developed in a way that ensured its efficient transfer into the encyclopaedic element of the ArableDS system.

2.4.2 System development

For a web-based application of any kind to be successful, in terms of its use and re-use by the target audience, it must be designed in a way that makes every effort to ensure the user understands what is going on at each stage and is able to reach the required targeted information in a minimum of steps. Predevelopment planning of the phoma forecast application included thorough consideration of the functionality and design of the light leaf spot forecast in association with recommendations from Northing *et al.* (in press) on the development of web-based decision support systems.

The model parameters include regional factors, environmental data and previous incidence of the disease. These data are stored on a Microsoft SQL Server relational database (Figure 6) alongside data (e.g. name and e-mail address) of those individuals who have signed up for the e-mail notification service. The use of a relational database to store the parameters and data required to generate the forecast for all of the regions allows the system to be set up in a way that minimises the length of time required to update the system. Forecast updates take place three times over the course of the season: Forecast 1 is issued in September and based on average weather variables, this is updated in November to Forecast 2, which includes actual autumn weather variables, and finally this is updated in March to Forecast 3 to include actual spring weather variables.



Figure 6: Relational database schema for Phoma Forecast web application

The web application has been developed using Dynamic HTML (a combination of HTML, JavaScript and Cascading Style Sheets) and Macromedia ColdFusionTM. This technology contains tools for efficient data summary and retrieval from the database and provides these results to the web application for manipulation and output.

2.5 System description

2.5.1 Home Page

The home page of the phoma forecast (http://phoma.csl.gov.uk) indicates which forecast update is currently available and provides a brief description of what these forecasts are based on (Figure 7). The banner at the top of the page and the menu down the left hand side are in the same position on every page of the site. This uniformity of design promotes familiarity and ease of use for the visitors to the site. The design of this website took place in conjunction with a redesign of the light leaf spot forecast website, so that the uniformity of design and associated familiarity goes across both sites as if they were one thus enhancing the user experience. A link to the light leaf spot forecast was also provided (www3.res.bbsrc.ac.uk/leafspot).



Figure 7: Home page of the Phoma forecast



Figure 8. Display of the regional phoma forecast for 2004.

2.5.2 Risk Forecast

In the initial development of the application, the risk forecast showed two colour-coded maps (Figure 8) providing the forecasts of the incidence and severity of phoma stem canker. The purpose of this mapping system is to enable the user to view at a glance the relative risk across the whole country. The system uses model 1 to generate the predictions for the regional 'at a glance' forecast. The user is then encouraged to click on the region in which they are interested for a more detailed forecast. A pop-up window asks them to choose the cultivar for which they require an assessment. Once this choice has been made, further calculations are undertaken to provide a risk assessment based on model 3, thus incorporating cultivar resistance, autumn fungicide application and previous regional disease incidence. The final output provides an assessment for both sprayed and unsprayed crops (Figure 9).



Figure 9. Adjusted 'crop-specific' forecast provided on the web site.

2.5.3 Further Information

Alongside the risk assessments, the site provides information on the epidemiology of phoma stem canker, a breakdown of how the risk assessment models were developed and some historical data on both the long-term distribution of the disease and the performance of the model.

2.5.4 E-Mail Notification

As the forecast is updated three times a year the application allows users to sign up to an e-mail notification service which will automatically e-mail all those on the database when the forecast has been updated. There are currently 17 individuals signed up to this system. The intention in the future is to merge the e-mail notification database for both the phoma and light leaf spot forecasting systems, but due to Data Protection Act requirements we will need to contact all the individuals in advance of this change to ensure that they are all agree to the proposed merger.

2.5.5 Website launch and use

The prototype website was launched in November 2002 at the 'IT in Practice' evening session of the British Crop Protection Council Conference: Pests and Diseases 2002. Following this launch, there has been a steady increase in the number of visits to the website (Figure 10). We intend to reinforce this increase in

interest by releasing a number of targeted press releases and links from other pertinent websites such as the Defra Crop Monitoring website (http://www.cropmonitor.co.uk). While the validation stage of the forecast continues, the severity element of the forecast will be removed from the website until further evaluation of the model parameters is completed.



Figure 10: Number of visits per month to the Phoma Forecasting website in 2003

Chapter 3

A mechanistic model for describing dynamics of phoma stem canker epidemics

3.1 Introduction

A mechanistic model was developed to estimate the proportion of plants in a winter oilseed crop that will develop phoma stem canker (*L. maculans*). The model consists of a series of differential and delay-differential equations. Using data for temperature, wetness duration and concentrations of *L. maculans* ascospores, it predicts changes in phoma leaf spot lesion area with time. The rate of infection of leaves by ascospores was dependent on temperature and wetness duration. The growth of the fungus through the petiole to the stem was dependent on temperature. The probability that the stem became infected changed with time for each oilseed rape plant. The model can thus predict the start of phoma leaf spot development and how the corresponding leaf area affected changes with time. This is important as it has been reported that a high incidence of phoma leaf spots cannot always be related to high numbers of ascospores, and leaf spot incidence cannot always be directly related to stem canker incidence (West *et al.*, 1999). However, this model predicts the probability of stem canker development as a function of the average phoma lesion area per plant, using inoculum and weather data as inputs. It provided a good estimate of the incidence of stem canker observed in winter oilseed rape experiments over three seasons at Rothamsted. It provides a description of the *L. maculans* life cycle and it is possible to assess the relative importance of weather conditions and ascospore concentrations in relation to occurrence of severe phoma stem canker epidemics.

3.2 Materials and methods

3.2.1 Field data

The development of phoma leaf spot and phoma stem canker in relation to winter oilseed rape leaf production and death was studied at Rothamsted Research during three consecutive seasons: 2000/01, 2001/02 and 2002/03. The precise experimental procedures are outlined in Chapter 8. Numbers of phoma leaf spots were assessed on each leaf of thirty marked plants in untreated plots at regular intervals during the autumn/winter. From experimental data (Biddulph *et al.*, 1999), it was estimated that three phoma leaf spots covered 1 cm², and numbers of leaf spots were converted to areas of phoma leaf spotting. Severity of stem canker was assessed on these plants at intervals during the spring/summer.

Estimation of leaf areas: An experiment was done in the glasshouse with 15 winter oilseed rape plants, cv. Apex, to study the growth of the petioles of leaves. The experiment was set up with an average daily temperature of 10 °C. Measurements of the petiole lengths, from the tip of the leaf to the point of attachment

to the stem, were taken at roughly weekly intervals. Curves were fitted to data for all leaf layers. The equation used was:

Petiole length_i(t) = $M_i \{1 - \exp[-k(Thermal time(t) - (a + b i))]\}$

where M_i is the maximum petiole length for leaf layer *i*, *Thermal time(t)*, the accumulated temperature >0°C between sowing and time *t*, *k* the growth rate, *a* the minimum thermal time required before the petiole of leaves in layer 1 started growing and *b* the increase, per leaf layer, in thermal time above *a*. Oilseed rape plants were collected from the field. The lengths of the petioles were measured and the corresponding leaf areas were measured using a planimeter. The relationship between leaf area and petiole length was a quadratic polynomial:

$$y = -6.76 + 2.12 x + 0.03 x^{2}$$

where y is the estimated leaf area for a leaf with a petiole length of x. The combination of the function to estimate petiole length from thermal time separately for each leaf layer and the quadratic function to estimate a corresponding leaf area for a given petiole length provided a chain rule for estimating, for each leaf layer, changes in leaf areas with thermal time or ordinary time.

3.2.2 Meteorological data

For all three seasons, hourly meteorological data for net radiation, dry-bulb temperature, wind speed, rainfall and relative humidity were obtained from ECN (Environmental Change Network) to run the model.

3.2.3 Ascospore concentrations

A Burkard volumetric spore sampler (Burkard Manufacturing Co; Rickmansworth UK) was used to collect air-borne ascospores of *L. maculans*. Stem bases of plants with stem canker were collected from winter oilseed rape crops after harvest in each season and spread on the ground surface around a Burkard spore sampler, which was operated from early September until the end of March to estimate the daily concentration of air-borne *L. maculans* ascospores throughout the season.

3.2.4 Model structure and formulation

The leaf area compartments of the model are susceptible S(t), infected without visible symptoms I(t), latent Z(t), and leaf area (affected with) phoma F(t). The model allows for production of new leaf area, growth of existing leaf area and senescence of leaf area in all compartments. There is a single type of inoculum, the airborne ascospores A(t), produced on crop debris from the previous season. Newly infected leaf area moves into the compartment I(t), and previously infected leaf area that has survived for the minimum length of the incubation period (period between infection and appearance of phoma lesions), $\tau_1(t)$, moves into the compartment Z(t). New area with phoma leaf spots appears at a constant rate and moves into the

compartment F(t). The probability that a stem does not get infected by *L. maculans* depends on the rate of appearance of new area with phoma at time $[t-\tau_2(t)]$, the probability of survival of the plant tissue during the interval $\tau_2(t)$ and the probability that the stem is not already infected. The interval $\tau_2(t)$ is the time between the appearance of new phoma spots on the leaf and the infection of the stem. The probability of survival of the leaf tissue during either of the periods $\tau_1(t)$ and $\tau_2(t)$ depends on the constant death rate, μ , and the minimum equivalent of $\tau_1(t)$ and $\tau_2(t)$ in thermal time. The model is the series of delay-differential equations:

$$\frac{dS(t)}{dt} = Net \ Leaf \ Area \ Change \ - \ New \ Infections$$

- $\frac{dI(t)}{dt} = New Infections Surviving Infections from (t \tau_1(t)) Death$
- $\frac{dZ(t)}{dt} = Surviving Infections from (t \tau_1(t)) New Phoma Appearance Death$

$$\frac{dF(t)}{dt} = New Phoma Appearance - Death$$

$$\frac{d\tau_1(t)}{dt} = f[T(t), T[t - \tau_1(t)]]$$

$$\frac{d\tau_2(t)}{dt} = f[T(t), T[t - \tau_2(t)]]$$

 $\frac{dPni(t)}{dt} = -(New Phoma Appearance at [t-\tau_2(t)]) (Survival and Stem Not Infected)$

All variables and parameters are summarised in Table 5.

Table 5. Description of the variables and parameters, with their units, used in the phoma stem canker model.

variable t A	Description [units] time [day] mean daily concentration of ascospores [number m ⁻³]
S I Z F τ_1 τ_2 Pni T W TT $g[T, W]$	healthy susceptible leaf area $[cm^2]$ infected leaf area with no phoma leaf spotting $[cm^2]$ Infected leaf area that has survived for τ_I days $[cm^2]$ phoma leaf spot area $[cm^2]$ incubation period [days] time period between phoma leaf spot appearance and stem infection [days] probability of the stem not getting infected [-] mean daily temperature ¹ [°C] daily rain duration ¹ [hours] thermal time since sowing [°C-days] infection criterion dependent on daily mean temperature and leaf wetness duration [-]
$parameter$ a b TT_0 σ μ p ζ	Description [units] maximum leaf area achieved $[cm^2]$ rate of growth in leaf area $[cm^2 (^{o}C-day)^{-1}]$ thermal time since sowing when maximum leaf area achieved $[^{o}C- days]$ probability of successful infection by an ascospore [-] probability per degree-day of leaf death due to disease or natural senescence $[^{o}C-day]^{-1}$ probability of leaf area death due to pigeon damage [-] rate of phoma leaf spot appearance $[day^{-1}]$

3.2.5 Leaf area production and death

The model includes production and growth of healthy leaf area and death of leaf area from all the leaf area compartments. The model allows for leaf area to be removed from each of its compartments due to senescence. The death rate is assumed to be linearly dependent on temperature for temperatures >0.

3.2.6 New infections

New infections occur when there is ascospore inoculum present and the temperature and wetness conditions are favorable for *L. maculans* to infect. A Heaviside step function is used to describe this infection criterion:

$$g[T(t), W(t)] = \begin{cases} 1, T(t) > 0 \text{ °C and } W(t) > 4 \text{ h} \\ 0, \text{ otherwise} \end{cases}$$

The infection rate per unit time is:

 $g[T(t), W(t)] \sigma A(t) S(t)$

3.2.7 Leaf area infected

The rate of increase in leaf area which is infected but symptomless is:

$$g[T(t-\tau_{1}(t)), W(t-\tau_{1}(t)]\sigma A[t-\tau_{1}(t)]S[t-\tau_{1}(t)]P\tau_{1}(t)\left[1-\frac{d\tau_{1}(t)}{dt}\right]$$

where the first four terms represent the newly infected area at time $[t - \tau_I(t)]$. $P \tau_I(t)$ is the probability that infected leaf area did not die during the incubation period, $\tau_I(t)$, and is equal to $\exp(-\mu TT_{min})$ where TT_{min} is the thermal time equivalent to the minimum incubation period. The term $[1-(d\tau_I(t)/dt)]$ is a correction factor to determine the exact infected leaf area reaching the end of the minimum incubation period in a fluctuating environment.

3.2.8 Leaf area with phoma leaf spots

The rate of appearance of area with phoma leaf spots is proportional to the infected leaf area, Z(t), and linearly dependent on temperature, T(t): [New phoma area] = $\zeta T(t) Z(t)$

where ζ is the probability that infections develop into phoma leaf spots.

$$f[T_i(t), W_i(t)] = M_i \{ 1 - \exp\{-\zeta [TT(t) - \beta] \} \}$$

where $f[T_i(t), W_i(t)]$ is the number of new phoma lesions for the temperature and wetness duration regime *i*.

3.2.9 Survival probabilities

The probability of survival of the leaf tissue during either $\tau_1(t)$ or $\tau_2(t)$ is assumed to be constant and equal to:

$$P\tau_1(t) = \exp(-\mu TT_{\min})$$
 and $P\tau_2(t) = \exp(-\mu TT_{2,\min})$

 TT_{min} has been taken from Biddulph et al. (2000), where a range of [90, 200] degree-days is given for the incubation period and. TT_{min} has been assumed equal to 145 degree-days (the average of the interval). $TT_{2,min}$ was estimated by using information provided by DuPont: when the mean daily temperature is 15 °C, then *L*. *maculans* grows down the petiole at a rate of 1cm per day until it reaches the stem.

3.2.10 Probability of stem infection

The probability that the stem will not have become infected $\tau_2(t)$ days after new phoma leaf spots appeared is negatively proportional to the new phoma at time $[t - \tau_2(t)]$, the probability that the leaf tissue remains alive during time $\tau_2(t)$ and the probability that the stem is not already infected. The probability that the stem becomes infected is simply calculated as [1-Pni(t)].

3.2.11 Model equations

Substituting all terms we find:

$$\begin{split} \frac{dS(t)}{dt} &= -\alpha \exp\left\{-0.5 \left[\ln\left(TT/TT_{0}\right)/b\right]^{2}\right\} \left[\ln\left(TT/TT_{0}\right)/b^{2} TT\right] T(t) - g[T(t),W(t)] \sigma A(t) S(t) \\ \frac{dI(t)}{dt} &= g[T(t),W(t)] \sigma A(t) S(t) - g[T(t-\tau_{1}(t)),W(t-\tau_{1}(t))] \sigma A(t-\tau_{1}(t)) S(t-\tau_{1}(t)) P\tau_{1}(t) \left[1 - d\tau_{1}(t)/dt\right] - \mu T(t) I(t) \\ \frac{dZ(t)}{dt} &= g[T(t-\tau_{1}(t)),W(t-\tau_{1}(t))] \sigma A(t-\tau_{1}(t)) S(t-\tau_{1}(t)) P\tau_{1}(t) \left[1 - d\tau_{1}(t)/dt\right] - (\mu + \zeta) T(t) Z(t) \\ \frac{dF(t)}{dt} &= T(t) \left[\zeta Z(t) - \mu F(t)\right] \\ \frac{d\tau_{1}(t)}{dt} &= 1 - \left[T(t)/T(t-\tau_{1}(t))\right] \\ \frac{d\tau_{1}(t)}{dt} &= 1 - \left[T(t)/T(t-\tau_{2}(t))\right] \\ \frac{dPni(t)}{dt} &= -\zeta T(t-\tau_{2}(t)) Z(t-\tau_{2}(t)) P\tau_{2}(t) Pni(t) \end{split}$$

3.2.12 Model fitting: optimized parameters

The model equations were implemented using ModelMaker software (Anonymous, 1997) and Runge-Kutta integration was used to solve differential equations numerically. The final estimated model parameters were found by fitting the model to mean phoma lesion area per plant with time. The Marquardt optimization algorithm was used to minimize the weighted residual sum of squares, using the standard error of each mean (per plant) phoma lesion area as the weight of each datum (each mean).

3.3 Results

3.3.1 Meteorological data and ascospore concentrations

The temperature and leaf wetness duration for the three seasons, calculated using the model from the previous chapter, and spore concentrations as measured using the Burkard spore sampler are given in Figure 11.



Figure 11. Daily ascospore concentrations and fitted spline with 20 degrees of freedom, mean daily temperature (—) and estimated daily leaf wetness duration (---) for the seasons 2000/01 (a), 2001/02 (b) and 2002/03 (c) at Rothamsted.

3.3.2 Phoma leaf spot progress: observed data and model fitting

Figure 12 shows the changes with time in average phoma lesion area per plant on winter oilseed rape at Rothamsted for the seasons 2000/01, 2001/02 and 2002/03 (\bullet), estimated from the data for numbers of leaf spots per leaf. It also shows the line fitted by the model estimating the phoma lesion area developing on an average winter oilseed rape plant during the rosette stage (—) and the 1st and 3rd quartile values of the phoma lesion area of all plants (----).



Figure 12. Average estimated phoma lesion area assessed in winter oilseed rape at Rothamsted during: 2000/01 (a), 2001/02 (b); 2002/03-small plants (c) and 2002/03-large plants (d) with the corresponding 1^{st} and 3^{rd} quartiles (— —). The solid (——) line represents the phoma leaf area for a single oilseed rape plant as estimated by the stem canker model.

3.3.3 Model fitting: probability of stem infection

Figure 13 shows the predictions of the model about occurrence and development of stem canker. In Fig. 13 the thick solid lines represent the model estimation of the probability of the stem becoming infected. The other lines show the proportion of the plants in the field that, at consecutive assessment dates, had a stem

canker severity score of at least 1, 2, 3, 4 or 5; the last assessment was destructive and immediately after harvest. Table 6 summarizes the maximum phoma leaf spot area and the final proportion of plants that developed stem canker, for each season.



Figure 13. Proportion of winter oilseed rape plants with stem canker severity scores >=1 (--), >=2 (---), >=3 (---), >=4 (---) or =5 (....), observed in the field during three seasons at Rothamsted: 2000/01 (a), 2001/02 (b), 2002/03-small plants (c) and 2002/03-large plants (d). The model estimate of the probability that the stem became infected by *L. maculans* is represented by the thick solid line (--).

Table 6. Summary of results derived from the stem canker model for the seasons 2000/01, 2001/02 and 2002/03 at Rothamsted.

Season	Average phoma lesion area/plant (cm ²)	% stem canker infection
2000/01	up to 6	85%
2001/02	up to 1.2	100% (extra mortality)
2002/03	up to 3	90% (large plants)
2002/03	up to 1.5	50% (small plants)

3.3.4 Model fitting: optimized parameters

The parameters σ and μ for the 2000/01, 2002/03 and 2001/02 seasons were optimized concurrently. In each case, the initial values were chosen so that the model output provided a good representation of the data. The

parameter σ is the most uncertain as it is a complex parameter with little information about its components (described above). The parameters with their optimized values are shown in Table 7.

Season	Parameter			
-	М	σ		
2000/01	0.01 (0.0002)	0.000013 (0.0000006)		
2001/02	0.002 (0.001)	0.000006 (0.000001)		
2002/03 (large plants)	0.0007 (0.00024)	0.000003 (0.0000002)		
2002/03 (small plants)	0.002 (0.0006)	0.000002 (0.0000002)		

Table 7. Estimated optimal values for the parameters used in the stem canker model. The model was fitted to data for average (per plant) phoma lesion area obtained from field experiments in 2000/01, 2001/02 and 2002/03 seasons at Rothamsted. The estimated standard errors are given in parentheses.

The 2000/01 season appears to be the most different in terms of optimized parameter results, as the optimized values differ by an order of magnitude from the optimized results derived for the other seasons. The death parameter for 2001/02 and the small plants from 2002/03 is the same and just over double that estimated for the large plants from 2002/03, which might imply that the large plants were more vigorous than the small ones in the same season or plants in 2001/02 that were attacked by pigeons. The σ parameter is on the other hand roughly the same for large and small plants in 2002/03 and one third of that estimated for 2001/02. Since the average leaf lesion area during 2001/02 was very similar to that for the small plants in 2002/03 but the stem infection probability was double, the higher estimate for σ reflects the fact that during 2001/02 there might have been infections that did not produce leaf spots before the infected leaves were damaged by pigeons. It is difficult to associate leaf lesion area and final probability of stem infection. For example, during 2000/01 the final stem infection probability is not very different from that for 2001/02 or the large plants in 2002/03, even though the leaf lesion area was at least twice as great. Since both μ and σ were also higher for this season, the explanation might be that despite higher occurrence of infection and leaf spots, the higher leaf senescence rate functioned as trade-off and therefore no differences in stem infection were observed.

3.4 Discussion

3.4.1 Phoma leaf spot progress

From Figure 12 we see that, on average, the highest phoma lesion area per plant was observed in 2000/01. During this season, the average phoma lesion area increased to reach a maximum of about 6 cm² (equivalent to 18 lesions) on 1 December 2000 and then started to decrease. During 2001/02, the largest phoma lesion area observed on average per plant was around 1 cm² (equivalent to 3 lesions). A small plant during 2002/03 reached a maximum of 1.2 cm² (equivalent to about 4 lesions) towards the end of January 2003. The large

plants, however, reached a higher maximum of about 3 cm² (equivalent to 9 lesions) between the end of January 2003 and beginning of February 2003. The crops were sown on very similar dates in 2000/01 and 2002/03 (23 August 2000 and 20 August 2002, respectively). However, the leaf phoma lesions started appearing about a month later in 2002/03. At around the time the phoma lesion area had started declining in 2000/01, it was still increasing during 2002/03. In terms of the general progress pattern, the most different season appears to be 2001/02 as it does not exhibit a very definite hump shape (partly because of the absence of phoma incidence records when incidence was low). It is very likely that this season would be different if such extensive pigeon damage had not occurred.

3.4.2 Meteorological data

Mean daily temperatures were used in the stem canker model in association with the estimated leaf wetness duration to provide an infection criterion for *L. maculans* ascospores. The mean daily temperature is also an important factor overall as it influences the net production of leaf area, the senescence of leaf area irrespective of its state (healthy, infected without phoma lesions, latent phoma leaf area or phoma lesion area), the rate of appearance of phoma lesions, the incubation period and the period from phoma leaf spot appearance to stem infection, the survival of leaf/plant tissue and the probability of the stem becoming infected. The overall pattern of the mean daily temperature in any season was similar in the sense of showing a decreasing trend through autumn and early winter. The overall mean daily temperature between sowing date and last assessment date was 8.5°C, 9.5°C and 8.3°C for 2000/01, 2001/02 and 2002/03, respectively. In 2000/01, the mean daily temperature was at a maximum of about 20°C around 1 September. Around the same time, the mean daily temperature was at a maximum of 22.3°C during 2001/02 and 18.3°C during 2002/03 (Fig. 6). After this, there was a trend for decreasing temperature in all seasons, but during 2001/02 the mean daily temperature started to increase at the beginning of February and during 2002/03, the overall decrease slowed down after mid December (Fig. 6).

3.4.3 Ascospore concentration

Ascospore concentrations per m³ varied between 0 and 3346, 0 and 2015 and 0 and 265 during 2000/01, 2001/02 and 2002/03, respectively (Fig. 11). During 2000/01, there was only a single observation that was much higher than the rest (3346 ascospores per m³) but apart from this, the highest ascospore concentrations were similar to the highest values observed during 2001/02 (around 2000 ascospores/m³). The release of ascospores started earlier in the autumn of 2000/01 than in the autumn of 2001/02 or 2002/03. The overall shape of the ascospore release pattern was similar in all seasons even though the maximum ascospore release was earlier and higher in 2000/01 than in the other two seasons. A cubic spline was fitted to the ascospore concentration data (Fig. 11). A range of degrees of freedom were tested while fitting the splines and 20 degrees of freedom produced a satisfactory representation of the trend of the spore release pattern with sufficient variability present in the fitted values.

3.4.4 Model fitting: phoma lesion area and probability of stem infection

The model predicted the progress of the average phoma lesion area per plant satisfactorily as the model estimates follows the observed pattern of lesion areas well. Fig. 8 shows that the model has generally predicted stem canker occurrence well. The time the probability estimated by the stem canker model starts increasing above 0 agrees with the time in winter oilseed rape that stems first showed symptoms of severity score 2 (2000/01 and 2001/02, Fig. 13a and 13b, respectively) or of severity score 1 (2002/03 small and large plants, Fig. 13c and 13d, respectively). The highest value of the estimated probability at the end of each model run agrees best in value with the proportion of plants (stems) with a severity score of at least 4 (2000/01, Fig. 13a), at least 1 or 2 (2001/02, Fig. 13b), 0 (2002/03, small plants, Fig. 13c) and at least 1 (2002/03, large plants, Fig. 13d). The estimation of the time when stem infections first start produced stem cankers is important as a later start was expected in 2002/03 as the phoma leaf spotting also started much later than the first two seasons. Combining the increase in phoma lesion area on leaves and the probability of stem infection estimated by the model, a conclusion can be made about the proportion of plants developing infected stems in relation to their size (small or large) and the maximum phoma lesion area observed per plant (Table 6).

3.4.5 Model fitting: optimized parameters

Table 7 shows that the 2000/01 season appears the most different in terms of optimized parameter results, as the optimized values differ by an order of magnitude from the optimized values derived for the other seasons. The death parameter for 2001/02 and the small plants in 2002/03 is the same and just over double that estimated for the large plants in 2002/03, which might imply that the large plants were more vigorous than the small ones in the same season and than those in 2001/02 that were attacked by pigeons. The σ parameter is on the other hand roughly the same for the plants of both sizes in 2002/03 and one third of that estimated for 2001/02. Since the average leaf lesion area during 2001/02 was very similar to that for the small plants in 2002/03 but the stem infection probability was double, the higher estimate for σ reflects the fact that during 2001/02 there was pigeon damage. It is difficult to associate leaf lesion area and final probability of stem infection. For example, during 2000/01 the final stem infection probability is not very different from that for 2001/02 or the large plants in 2002/03, even though the leaf lesion area was at least double in size. Since both μ and σ were also higher for this season, despite higher occurrence of infections and leaf spots, perhaps the greater leaf senescence functioned as trade-off so that no differences were observed in stem infection.

Chapter 4

Phoma progress models

4.1 Introduction

Seasonal yield losses caused by phoma stem canker (Leptosphaeria maculans) have been estimated to reach £40M/annum in the UK (Fitt et al., 1997) and it continues to cause problems as susceptible culitivars are widely grown (Defra winter oilseed rape disease suveys; <u>www.csl.gov.uk</u>). This makes phoma stem canker one of the two most important diseases on winter oilseed rape. It remains a more consistent cause of yield loss than light leaf spot in England. However, the severity of phoma stem canker epidemics differs between seasons, between different regions of the UK and between individual crops within a region (West et al., 2002). Poor timing of fungicide sprays is thought to be mainly responsible for poor control of phoma stem canker in commercial crops (Gladders et al., 1998). To achieve cost-effective control of phoma, reliable guidance on the timing of epidemics and their effect on yield are required to guide decisions.

L. maculans, the fungal pathogen that causes phoma stem canker, reproduces on oilseed rape crop residues that remain after harvest (mid July). It produces air-borne spores in autumn and winter that cause phoma leaf spots in new crops. The first symptoms of phoma leaf spotting are usually observed between early October and late November. Once phoma leaf spots have appeared, the fungus then grows down the petiole of the infected leaf into the stem and produces stem canker that increases in severity until harvest.

Phoma leaf spot incidence can increase very rapidly in autumn over a period of 7-14 days and early warning of disease onset would be beneficial for planning applications. Fungicides must be applied before the canker fungus has reached the stem to be effective and treatments are required before the phoma leaf spot stage is well-established. Decisions on the number of applications and the fungicide dose for each crop should take into consideration the expected yield loss and the economic benefit from spraying. Generally, early phoma leaf spot epidemics are most damaging as they lead to the development of severe stem canker lesions by harvest.

An empirical system for forecasting stem canker (see Chapter 2 "Phoma forecast") exists that predicts canker incidence before harvest on a regional level using monthly temperature, rainfall and the previous pre-harvest disease incidence as input. The aim of this part of the project was to develop a crop-specific phoma stem canker progress model that uses information at a local scale and where observations and assessments during the season can be used to update the prediction.

The epidemic progress was divided into 4 stages over the season

- 1. prediction of the start of phoma leaf spotting (in autumn)
- 2. time between start of phoma leaf spotting and onset of stem canker

- 3. increase in stem canker severity until harvest
- 4. relationship between stem canker severity and yield loss

4.2 Materials and methods

Historic datasets from projects that focused on different aspects of the phoma stem canker epidemic were assembled and subsets of experiments were used to model each of the four stages.

4.2.1 Stage 1: prediction of the start of phoma leaf spotting

Experiments with frequent phoma leaf spot assessments in autumn were needed to provide an accurate estimation of the start of the epidemic. 28 Experiments between 1997 and 2001 at 7 different sites were available. Some experiments included more than one cultivar (see Table 8).

The following information was available for each of the datasets

- location
- sowing date (between end of August and mid September)
- disease assessments: mean incidence and severity of phoma leaf spotting was recorded weekly between end of September and mid December and monthly until March (random sample of 25 plants per assessment).
- daily maximum and minimum temperature and rainfall data from local weather stations
- proximity to oilseed rape fields from the previous season

Table 8. Datasets on development of phoma leaf spotting on winter oilseed rape at different locations in England, used to develop a model for predicting the start of phoma leaf spotting.

Location	Year crop was sown/cultivar(s)					
	1996	1997	1998	1999	2000	2001
ADAS Boxworth	Rocket	Alpine	Apex	Apex	Apex	Apex Recital Royal
Rothamsted		Capitol Lipton	Apex	Apex	Apex Pronto	Apex
ADAS Rosemaund		Apex	Apex	Apex	Apex	Apex Recital Royal
ADAS Bridgets				Apex	Apex	
ADAS Mamhead						Apex Recital Royal
ADAS Terrington			Apex	Apex	Apex	Apex Recital Royal
ADAS High Mowthorpe		Apex	Apex	Apex	Apex	Apex Recital Royal

4.2.2 Stage 2: time between start of phoma leaf spotting and onset of stem canker

To produce good estimates of the time span between onset of phoma leaf spotting and onset of stem canker, regular assessments of phoma leaf spotting in autumn and stem canker in early spring were required. Data was restricted to assessments from untreated plots. 18 experiments from the following locations and seasons were available (numbers of datasets are in brackets): Rothamsted: 1992/93(1), 1993/94(1), 1996/97(2), 1997/98(4), 1998/99(4), 1999/2000(3)

ADAS Boxworth: 1997/98(1), 1998/99(1), 1999/2000(1)

4.2.3 Stage 3: increase in stem canker severity until harvest

Suitable datasets had to include regular stem canker assessments from early spring until harvest from untreated plots. A total of 31 experiments were available for the following locations and seasons:

Rothamsted: 1992/93(1), 1993/94(1), 1996/97(2), 1997/98(4), 1998/99(5), 1999/2000(3) ADAS Boxworth: 1997/98(2), 1998/99(1), 1999/2000(3), 2000/01(3), 2001/02(6)

The following information could be obtained for all datasets: pre-harvest stem canker incidence and severity (0-4 scale), location, local daily maximum and minimum temperature, cultivar and corresponding UK resistance rating (Anonymous, 1997).

4.2.4 Stage 4: relationship between stem canker severity and yield loss

Disease and yield data for fungicide treated and untreated plots and information about sowing date, cultivar and location were available for experiments across England. Data were restricted to experiments with significant stem canker (mean stem canker severity score ≤ 1 before harvest) and negligible light leaf spot to eliminate the effect of the light leaf spot.

The following 28 datasets were used in the analysis: ADAS Boxworth: 1994/95(2), 1995/96(1), 1996/97(1), 1997/98(3), 1998/99(2), 1999/2000(4), 2000/01(6), 2001/02(7), ADAS High Mowthorpe: 1996/97(1)

Rothamsted: 1999/2000(1)

4.2.5 Statistical analysis

Random effects models were applied to predict the start of phoma leaf spotting. The effect of UK resistance rating on the thermal time span between phoma leaf spotting and onset of stem canker was estimated by analysis of variance. Increase in stem canker severity with thermal time (degree-days) was analysed with random coefficient models to account for repeated assessments on the same crop. Finally, the relationship between yield and stem canker severity was investigated using linear regression. All data analysis was carried out with the statistical software package GenStat 6 (Payne *et al.*, 1993).

4.3 Analyses

4.3.1 Stage 1: prediction of the start of phoma leaf spotting

The Julian day when 10 percent of plants showed symptoms (Y) was defined as the start of the phoma leaf spotting epidemic. Linear interpolation between the two weekly assessment dates with incidences that were closest above and below the 10 percent incidence was used to estimate the date. The following aggregates of temperature and rainfall produced the best prediction of the start of the phoma leaf spotting epidemic: mean maximum daily temperature [*temp_max*] and sum of rainfall [*rain_sum*] between 15 July (approximate harvest date) and 26 September of each year. Mean maximum daily temperature discriminated well between different locations and sum of rainfall discriminated between different growing seasons.

Linear relationships for *temp_max* and *rain_sum* were estimated. Sowing year and location were included as random effects to take into account the hierarchy in the data. The model equation was: Y = 421 - 0.24 rain sum - 4.6 temp max

Y - is the Julian day when 10% plants will have phoma leaf spot.

Standard errors of estimates are 26.4, 0.044 and 1.18 respectively for the three factors in the equation and show that both explanatory variables were significant (P < 0.001).

The derived variables appear biologically meaningful, according to previous work (Biddulph *et al.*, 1999) that showed that temperature and rainfall influence the time that pseudothecia take to mature. Local temperature and rainfall data can usually be obtained and a prediction of the start of phoma leaf spotting can be made by the end of September. This would usually be before the spray decision has to be taken (e.g. in dry areas of the south-east of England the predicted start of phoma leaf spotting was later than average in both 2002 and 2003).

Sowing date, stem canker resistance rating and proximity to previous oilseed rape crops were included in the model but they did not improve the model prediction significantly after temperature and rainfall were taken

into account. No evidence for a non-linear relationship between explanatory and dependent variables was found.

4.3.2 Stage 2: time between start of phoma leaf spotting and onset of stem canker

Previous work by Sun *et al.*, (2001) found a cultivar-specific thermal time span between the start of phoma leaf spotting and onset of stem canker that was constant between seasons. To make the model applicable to new cultivars, the corresponding stem canker resistance ratings were substituted for cultivars. Mean degree-days between start of phoma leaf spotting and onset of stem canker for cultivars with stem canker resistance ratings ≤ 5 were compared with those for cultivars with ratings ≥ 6 . Differences were significant (P=0.005) with 1102 degree-days for cultivars with resistance ratings ≤ 5 and an average of 1409 degree-days for cultivars with ratings ≥ 6 . The standard error of the difference (16 df) was 87.6.

4.3.3 Stage 3: increase in stem canker severity in spring/summer before harvest

Stem canker severity on infected plants (mean canker severity divided by stem canker incidence) was defined as the dependent variable. Mean severity on all plants can be derived by multiplying the predicted stem canker incidence from section "Phoma forecast" by the stem canker severity on infected plants. It was assumed that stem canker severity increased linearly with thermal time (Sun *et al.*, 2001). To account for repeated assessments on the same crop, "Experiment" was included as a random coefficient in the model.

A significant (P=0.005) difference in the rate of increase in severity between cultivars with different resistance ratings was detected. Two separate slopes, one for cultivars with stem canker resistance rating ≤ 5 (0.0011) and one for cultivars with stem canker resistance rating ≥ 6 (0.0006) were estimated, with a standard error of the difference of 0.00019.

4.3.4 Stage 4: relationship between phoma stem canker severity and yield loss

The relationship between stem canker severity and yield loss was calculated by taking the difference in yield between untreated and treated (mostly 2-spray programmes) plots. A linear relationship was found between yield difference and mean stem canker severity (*stem_canker*) on untreated plots (assessed before harvest) :

Yield(treated) – Yield(untreated) = -0.19 + 0.31 stem_canker

Inclusion of sowing date, cultivar and location did not improve the model significantly (see discussion).

4.4 Discussion

A disease progress model for phoma stem canker was established (Figure 14) within this part of the PASSWORD project. By end of September, a prediction of the timing of phoma leaf spotting can be made, based on local temperature and rainfall data in summer. At this stage, scenarios for the further progress of the disease can be run using expected values for daily temperature in winter and spring and information about the cultivar sown. The predicted disease progress can be updated with observed records, as new information becomes available during the season. This applies both to temperature data and to disease assessments. If symptoms of phoma leaf spot or stem canker are observed earlier than predicted, the prediction can be adjusted ("shifted to the left").



Figure 14. Schematic summary of the phoma stem canker progress model. Numbers in brackets indicate stages 1 to 4.

Investigating cultivar specific differences for stages 2 and 3 in more detail would certainly improve the model. Another useful extension would be the comparison of data from plots with single spray programmes, multiple spray programmes and untreated plots. At the moment, stages 2 and 3 are based on untreated crops only.

Stage 4, the relationship between stem canker severity and yield loss, can be used as a guideline to predict the economic loss due to stem canker. The model is certainly not exhaustive and its applicability is restricted to crops were stem canker was the dominant disease. Inclusion of cultivar, size of plants at phoma leaf spotting stage and location did not improve the model significantly, but they are important factors to investigate.

Chapter 5

Light leaf spot forecast development and validation

5.1 Introduction

The light leaf spot (*Pyrenopeziza brassicae*) forecast was developed under HGCA project 1531. The original regional forecast used empirical models to forecast, in autumn, the incidence (% plants affected) and severity (% of crops with >25% plants affected) of light leaf spot which could be expected to develop by the following spring for specific "light leaf spot regions" of England and Wales (Souter *et al.*, 1999; Welham *et al.*, 1999).

5.2 Development of the forecast system

Under PASSWORD, the forecast system underwent two main improvements: extension of the forecast delivery system to provide an interactive crop-specific forecast to the grower/advisor and extension of the forecast system to produce a prediction for Scottish growers/advisors. The use of Active Server Page (ASP) Internet-based technology allowed interactive input of cultivar resistance rating and sowing date, both of which were used to modify the regional forecast to produce a crop-specific forecast for the situation of a particular grower (Figs. 15 and 16 http://www3.res.bbsrc.ac.uk/leafspot/)(Evans et al. 2002). As detailed previous season pod light leaf spot data was not available for Scotland (as Scotland was not included in the Defra Oilseed Rape Pest and Disease Survey), a Scottish forecast was produced by running the forecast model using north of England pod disease data with Scottish meteorological data. Validation of the Scottish forecast should be possible in the future as collection of pod light leaf spot incidence data commenced as part of the PASSWORD project.

The light leaf spot forecast website has undergone a number of changes since its inception in 1997. The first major update in the winter of 2000 coincided with the introduction of the interactive forecast system (Evans *et al.*, 2002). Recent improvements (spring 2003) provided a new look to the website with the introduction of a menu bar allowing easy navigation around the site. The style of the website was developed in collaboration with colleagues at CSL so that the light leaf spot and phoma forecast websites would have the same format, providing a common identity within the project (Figs 17 and 18).



Figure 15. Input page for the light leaf spot interactive forecast. Growers/advisors are asked to choose a specific cultivar from the drop down list and to adjust the week of sowing to the date when the crop was sown. After clicking on the "Submit Query" button, the forecast system produced a crop-specific output page (Figure 16).



Figure 16. Crop-specific output page from the light leaf spot forecast website showing an incidence and severity prediction for light leaf spot for a farm in the North of England growing Apex (resistance rating 5) sown on 1 September (week 0).



© Rothamsted Research 2003

Figure 17. Front page of the light leaf spot forecast website following changes to user interface made in Spring 2003. The light leaf spot forecast and phoma stem canker forecast (hosted at CSL website, York) now utilise the same style and navigable menu system



Figure 18. Detail of the risk forecast page of the light leaf spot forecast website showing the present season and previous season regional risk forecasts for the UK.

5.3 Validation of the forecast

Validation of the light leaf spot forecast was done by comparing the observed percentage of affected plants for a region (using data from the spring survey) against the predicted percentage of affected plants for that region each season (Fig. 19). Validation of the forecast for the 2000/2001 season was not possible, as much of the survey data was not collected due to the outbreak of foot and mouth disease in the UK that year.



Figure 19. Graph of predicted percentage plants affected for individual regions in spring against actual percentage plants affected for 1997-2003 seasons. (Data from spring Defra Winter Oilseed Rape Pest and Disease Survey were used to validate the light leaf spot forecast). Symbols below the line indicate over-prediction in comparison to actual values whilst symbols above the line indicate the model underestimated the amount of disease.

A further validation of the light leaf spot forecast has recently been completed on survey data from 2000-2003 by Welham *et al.* (paper submitted for publication) using forecast models based on 1987-1999 disease survey data. Only 4 out of 28 regional predictions (14%) during 2000-2003 were incompatible with the model. Three out of these four cases occurred in spring 2002 and were underestimates, almost certainly because inoculum from stems affected by light leaf spot did not decline to the same extent as inoculum from affected pods in the previous season. Models based on pod disease generally account for more the variability in the data than those based on stem disease and have therefore been adopted to produce new forecasts.

Chapter 6

Benefits of crop-specific light leaf spot models to growers and agronomists

6.1 Introduction

Seasonal yield losses caused by light leaf spot (Pyrenopeziza brassicae) were estimated to range from £13M to £40M in the UK over harvest years 1987 to 2001 (Fitt et al., 1997; CSL, www.csl.gov.uk), making light leaf spot one of the two major diseases on winter oilseed rape. However, the severity of light leaf spot differs between seasons, between different regions of the UK and between individual crops within a region (Gilles et al., 2000a). For effective control of light leaf spot, fungicides need to be applied in the autumn (Figueroa et al., 1994). An empirical forecasting system for light leaf spot (see chapter "Light leaf spot forecast") exists that predicts light leaf spot incidence in spring on a regional basis, using monthly temperature, rainfall and incidence of light leaf spot in the previous season as inputs (see http://www3.res.bbsrc.ac.uk/leafspot/). Crop-specific elements have been incorporated into the interactive web-based version of this forecasting scheme so that growers can input information about their own cultivars and sowing date to modify the forecasts (Evans et al., 2003). Furthermore, the initial forecasts made in September/October are updated at the end of February by including observed (as opposed to predicted) winter weather (Evans et al., 2003). However, these forecasts cannot be operated in 'real time' because they are based on empirical rather than mechanistic models (Welham et al., 2000). Various relationships were investigated recently (Papastamati et al., 2000; Gilles et al., 2000b, 2001c) that describe the progress of light leaf spot at a crop-specific level. Input data for these models includes detailed local weather data, information on initial inoculum (ascospore) sources and concentrations and leaf wetness observations. The aim of this part of the project was to describe recently developed crop-specific models, evaluate them for their applicability and show their potential benefits to growers and agronomists.

6.2 Material and Methods

The effects of temperature and wetness duration on development of light leaf spot on inoculated plants (Gilles *et al.*, 2000b), the role of ascospores and conidia of *Pyrenopeziza brassicae* in light leaf spot epidemics (Gilles *et al.*, 2001a) and the effects of temperature on the development of apothecia of *Pyrenopeziza brassicae* (Gilles *et al.*, 2001a) have been investigated. The progress of light leaf spot in relation to initial ascospore concentrations and weather factors was modelled by Papastamati *et al.* (2000). The spatial spread of light leaf spot was investigated using detailed assessments on micro-plots by Evans *et al.* (2003).

6.3 Results

Models for the development of apothecia require a defined starting point for the maturation process, which, under experimental conditions, is provided by the date sources of inoculum are put out on the crop field. For a "commercial" crop, this date is not obvious. One possibility would be to use the harvest date of the previous crop, but because of crop rotation and differences in harvest dates between crops, this cannot be applied straight forwardly.

The light leaf spot progress model of Papastamati *et al.* (2000) requires inoculum concentrations as input. This requires regular ascospore counts in autumn. There are considerable local differences in inoculum sources, so measurements made at regional centres (e.g. ADAS sites) are unlikely to provide accurate information about inoculum on a specific crop.

However, the relationship between light leaf spot development and weather factors can be evaluated on most fields as local weather stations are usually available. Ideally, hourly readings of temperature, rainfall and leaf wetness (through a wetness sensor) are required. This enables the evaluation of the equation to predict percentage leaf area with *P. brassicae* sporulation (*c*)(Gilles *et al.*, 2001c), which depends on temperature (*T*) and daily hours of leaf wetness (*W*) at the time of infection:

 $c(T,W) = (3.65 + 7.02T - 0.3T^2)\exp(-\exp(-0.15(W - (55.47 - 6.08T + 0.21T^2)))) \text{ for } W \ge 6$ [1]

c(T, W) = 0 for W < 6

and the equation to estimate the time from initial infection to the production of spores (conidia) (latent period) described as a function of temperature:

 $l(T) = 48.0 - 3.87T + 0.11T^2$

[2]

In Figure 20, daily maximum values for percentage leaf area with sporulation are plotted for the 1998/99 growing season. Figure 21 shows for each day the number of potential infection events (predicted percentage leaf area with sporulation greater than 10) that are not yet visible (e.g. that occurred within one latent period before that day).



Figu

Figure 20. Predicted percentage leaf area with *Pyrenopeziza brassicae* sporulation which results from temperature/wetness conditions on each day, calculated using equation (2) for each day between October 1998 and mid February 1999 at Rothamsted.



Figure 21. Number of potential infection events (predicted percentage leaf area with sporulation greater than 10%) that occurred within one latent period before the corresponding Julian day.

The location of the inoculum source and corresponding wind conditions greatly influence the amount of initial infection (Evans *et al.* (2003), Figure 22). The individual field situation can be assessed using past records and experience of the grower. Secondly, secondary spread of light leaf spot through splash dispersion of conidia causes significant aggregation of the disease (Evans *et al.*, 2003). This has a consequence for the protocol for sampling crops to estimate disease incidence (Hughes & Madden, 1992, 1995, Madden & Hughes, 1999). To estimate disease incidence with the same accuracy as for a randomly distributed disease, larger numbers of small samples are required.



Figure 22. Impact of the location of the inoculum source and corresponding wind conditions on the amount of initial infection from ascospores of *Pyrenopeziza brassicae* (light leaf spot) on winter oilseed rape (schematic representation).

6.4 Discussion

Applying results from light leaf spot progress models improves the interpretation of field assessments. The amount of latent disease that does not show symptoms at the time of assessing can be estimated by evaluating equations 1 and 2 using local weather and leaf wetness readings. Furthermore, timing and severity of potential infection events can be indicated as shown in Figure 20. The indication of infection events and the corresponding latent periods is implemented in DESSAC (see Chapter 10 "Development of DSS"). Default values for temperature and leaf wetness are available from the nearest experimental station.

Chapter 7

Modelling fungicide effects against light leaf spot

7.1 Introduction

The severity of light leaf spot varies considerably between different regions and seasons, and the aim of this work is to define the factors affecting disease development and yield loss and thereby improve control strategies. To do this data were obtained from two series of field experiments (HGCA Report Numbers OS17 and OS63) at several sites in England and Scotland.

7.2 Materials and Methods

The two sets of data used were

 A series of HGCA experiments forecasting light leaf spot on winter oilseed rape (HGCA Report Number OS63) carried out at Boxworth, Rothamsted and SAC over three years (August 1996- July 1999).

Typically the treatments were: -

Cultivars - Bristol (a cultivar with low resistance to light leaf spot) and Capitol (a cultivar with high resistance to light leaf spot)

Fungicides- Tebuconazole (as Folicur) was applied at different times in the growing season at either full (1.0 l/ha product) or half rate (0.5 l/ha product) as single sprays or programmes. Timings were generally: Untreated

Unitedicu

Routine (monthly October - April) at full rate

October at full rate

November at full rate

December at full rate

October and March at half rates

November and March at half rates

December and March at half rates

March at full rate

Flowering at full rate

2. Wave experiments

This series of experiments (HGCA Report Number OS17) was done at 14 sites throughout England and Scotland between 1991 and 1994. They were specifically planned to allow the differential development of a series of epidemics to occur by the sequential application of monthly sprays of a broad-spectrum fungicide mixture (iprodione + thiophanate methyl and prochloraz) to cv. Envol. The first series of sprays all began in

autumn and finished progressively later, continuing until harvest. The second series all finished at harvest and started progressively earlier. Typical timings of fungicide applications are shown in Table 9.

Treat	2.10	29.10	26.11	30.12	2.2	24.2	17.3	16.4	8.5	5.6	25.6
1	-	-	-	-	-	-	-	-	-	-	-
2	Х	-	-	-	-	-	-	-	-	-	-
3	Х	Х	-	-	-	-	-	-	-	-	-
4	Х	Х	Х	-	-	-	-	-	-	-	-
5	Х	Х	Х	Х	-	-	-	-	-	-	-
6	Х	Х	Х	Х	Х	-	-	-	-	-	-
7	Х	Х	Х	Х	Х	Х	-	-	-	-	-
8	Х	Х	Х	Х	Х	Х	Х	-	-	-	-
9	Х	Х	Х	Х	Х	Х	Х	Х	-	-	-
10	Х	Х	Х	Х	Х	Х	Х	Х	Х	-	-
11	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	-
12	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х
13	-	-	-	-	-	-	-	-	-	-	Х
14	-	-	-	-	-	-	-	-	-	Х	Х
15	-	-	-	-	-	-	-	-	Х	Х	Х
16	-	-	-	-	-	-	-	Х	Х	Х	Х
17	-	-	-	-	-	-	Х	Х	Х	Х	Х
18	-	-	-	-	-	Х	Х	Х	Х	Х	Х
19	-	-	-	-	Х	Х	Х	Х	Х	Х	Х
20	-	-	-	Х	Х	Х	Х	Х	Х	Х	Х
21	-	-	Х	Х	Х	Х	X	X	Х	X	Х
22	-	Х	Х	Х	Х	X	X	X	Х	X	Х
				•		•					

Table 9. Typical fungicide application dates in 'wave' experiments 1991-1994.

7.3 Results and Discussion

Fungicide can act on light leaf spot in two ways, firstly as an eradicant, killing off infection present and secondly as a protectant reducing new infection. To try to identify the duration of the fungicide effect, the data from the HGCA series OS41 were examined using Genstat. The disease progress at the Rothamsted

1999 site for both cultivars showed good control with the routine programme, but more limited control with single and two spray treatments (Table 10). The duration of the fungicide effect in days varied from 21 to 101 days depending on fungicide timing and cultivar (Table 11).

Treatment	Date assessed				
Cultivar	6.1.99	12.2.99	19.3.99	21.4.99	
Bristol	Ι	Light leaf spot (% leaf area affe	cted)	
Untreated	6.1	20.1	18.5	11.6	
Routine	1.3	3.3	2.5	5.0	
Oct	0.8	11.1	10.4	11.7	
Nov	2.9	12.9	16.6	11.7	
Dec	6.3	11.3	18.9	11.6	
Oct+Mar	1.2	16.3	11.8	9.3	
Nov+Mar	1.1	20.3	12.7	8.6	
Dec+Mar	4.6	10.0	15.1	7.7	
Capitol					
Untreated	3.0	13.9	10.2	4.2	
Routine	0.03	0.5	1.4	1.2	
Oct	0.7	4.9	10.1	5.1	
Nov	0.6	9.9	10.7	4.3	
Dec	0.8	4.2	6.9	4.5	
Oct+Mar	1.3	8.3	7.5	4.0	
Nov+Mar	0.02	8.4	7.4	3.7	
Dec+Mar	2.3	7.4	6.3	3.3	

Table 10. Effect of spray timing on light leaf severity (% leaf area affected), Rothamsted 1998-99.

Light leaf spot was starting to develop on cv. Bristol at about the time that the December spray was applied and because of this, the effect of this spray was limited compared to the earlier timings (Table 10). The December spray was more effective on cv. Capitol, the more resistant cultivar. By mid–April, the amount of disease in plots with the single dose treatments were similar to those in the untreated control, indicating that there were no longer any effects of previous treatments.

Fungicide spray (month)	Duration of fungicide effect (days)			
Cultivar	Full dose	Half dose		
Bristol				
Oct	78	72		
Nov	58	79		
Dec	21	24		
<u>Capitol</u>				
Oct	101	82		
Nov	67	71		
Dec	68	40		

 Table 11.
 Duration of fungicide effect against light leaf spot.

Tebuconazole (as Folicur) showed more prolonged activity when applied early (October) particularly on the resistant cultivar Capitol (Table 11). The difference between the effects of full and half doses was not very large.

Averaged across the sites, the benefit in yield achieved by applying a full autumn spray was around 0.3 t/ha for both Bristol and Capitol. For the split dose (2 x half dose), autumn + spring programme, the improvement was 0.50 t/ha for cv. Bristol and 0.45 t/ha for cv. Capitol. Applying the Full rate in spring also increased the yield by about 0.4 t/ha compared to the untreated control for both Bristol and Capitol. The results from this set of data were not consistent across sites and years and variable disease development and the relatively few spray application timings made it difficult to estimate the fungicide effects. In consequence, analyses were done mainly on data from the series of 14 wave experiments that contained many more spray application dates.

Light leaf spot developed at 9 of the 14 sites in the wave experiments. First symptoms of light leaf spot were seen at Rothamsted (1992/93) during November, at two Scottish sites (Foveran and Pettymuick) during December, at three sites (Boxworth, Thurloxton and Udny Station) in January and at Rosemaund, Tarrant Hinton and Rothamsted (1993/94) in February. To establish the duration of fungicide effect, the sites were put into three groups according to time of first symptoms and the disease data were examined to establish the effect of fungicide 4, 8 or 12 weeks after application. For the three sites with the earliest disease, there was always at least 95% control of light leaf spot 4 weeks after treatment, even at the highest disease levels. After 8 weeks, light leaf spot control was always above 90%, except at one site (Pettymuick) where severity reached 20% and percentage control was 82%. Even after 12 weeks, the percentage control was generally around 90%, only decreasing to 76% at Pettymuick.

At sites where first light leaf spot symptoms occurred in January, there was almost always complete control for up to 8 weeks after application. At one site (Thurloxton), fungicide effect had declined slightly 12 weeks after treatment but % control still about 80%. Where disease symptoms did not appear on control plots until February, no disease was apparent on any plots that had been sprayed up to 12 weeks prior to the appearance of symptoms.

To establish a relationship between potential yield loss and maximum light leaf spot severity, an exponential curve constrained to go through the origin (i.e. no yield loss when no disease) was the best fit. Using data from all 9 wave sites with light leaf spot, the fitted curve was calculated as

 $Y = A(1 - R^x)$

where A=1.68, R=0.892,

Y = Potential yield loss (t ha⁻¹)

X = Maximum severity (% leaf area affected)

This equation showed that the maximum estimated yield loss was 1.68t/ha.

The effects of delaying fungicide applications for light leaf spot control on yield were quantified using datasets from the same wave experiments. The data were divided into two groups depending on whether the light leaf spot severity was greater or less than 10% leaf area affected. A straight line through the origin was fitted in each case. The two lines were:

1. Crops with light leaf spot severity >10% leaf area affected Y = 0.068X

2. Crops with light leaf spot severity <10% leaf area affected Y = 0.031X

Where Y = potential yield loss (t ha⁻¹) X = Number of days between first observed disease and spraying.

Finally, the potential yield benefit from spraying was calculated, averaging the results across the 9 sites. The benefit from an autumn spray was estimated as 0.55 t/ha and from a late spray 0.50 t/ha

These analyses clearly demonstrate the need for a programmed approach to light leaf spot control. Under high disease pressure, both autumn and winter/early spring treatments can produce yield responses of more than 0.5 t/ha and would be highly cost-effective. Delaying the first spray until first symptoms of light leaf spot are present is likely to result in considerable loss of yield, at least in Scotland. For each day's delay in applying a fungicide after symptoms are found, yield loss is estimated at 0.068 t/day. Even at sites with moderate light leaf spot infection, yield loss may be up to 0.031 t/day. The maximum yield loss from light

leaf spot within the analysed dataset was calculated to be 1.68 t/ha. Rather greater yield losses have been noted in some other experiments where plant losses during the winter have been high. A combination of good cultivar resistance and fungicides is required to achieve satisfactory control of light leaf spot. The first treatment should be applied in late autumn prior to symptom expression and whilst ground and weather conditions allow ground application. In future, improved methods of crop risk assessment should be developed so that ingress of external inoculum and symptomless disease development can be quantified.