HGCA

PROJECT REPORT No. 166

APPROPRIATE FUNGICIDE DOSES FOR WINTER WHEAT (EXPERIMENTS 1, 2 AND 3)

and

MATCHING CROP MANAGEMENT TO GROWTH AND YIELD POTENTIAL

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APPROPRIATE FUNGICIDE DOSES FOR WINTER WHEAT

MATCHING CROP MANAGEMENT TO GROWTH AND YIELD POTENTIAL

This is the report of two HGCA-funded projects. Project no. 0051/1/92 (**Appropriate fungicide doses for winter wheat, Experiments 1, 2 and 3**) started in October 1993, lasted for three years and was funded by a grant of £487,238.

Project no. 0051/1/93 (**Matching crop management to growth and yield potential**) started in January 1994, lasted for three years and six months and was funded by a grant of £222,485.

APPROPRIATE FUNGICIDE DOSES FOR WINTER WHEAT

EXPERIMENT 1:

Dose responses for conazole and morpholine fungicides

(pages 1-53)

by

N.D. Paveley[1] and M.J. Hims[2]

[1] ADAS High Mowthorpe, Duggleby, Malton, N. Yorks. YO17 8BP

[2] CSL, Sand Hutton, York. YO4 1LZ

Project leader: N.D. Paveley, ADAS High Mowthorpe

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1.0 INTRODUCTION

1.1 Background

There are almost as many opinions on the 'right' way to grow cereals as there are growers and consultants.

This diversity of opinion exists because of the large number of variable inputs that influence the unit cost of cereal production, the complexity of their interactions and the difficulty of quantifying the effect of changing any **one** of these variables, within the farm system.

One variable input that has a substantial effect on the economic efficiency of production, is the use of fungicides to control foliar diseases. Griffin (1994) reported that fungicides applied to the UK winter wheat crop in 1993, cost the industry in excess of £100m, but prevented losses estimated at £400m. More recent survey data suggest that potential losses fluctuate with season, but the fungicide spend remains substantial. Getting disease control 'right' is clearly important.

Growers and consultants use experience to make judgements about fungicide applications. This experience, often accumulated over many years, is a valuable commodity. Nevertheless, consistently good decisions seem more likely where experience is backed up by research information which quantifies responses to changes to individual components of the production system.

This report describes some of the principles behind the manipulation of fungicide dose to optimise the economic efficiency of disease control, and presents research information to support crop management decisions.

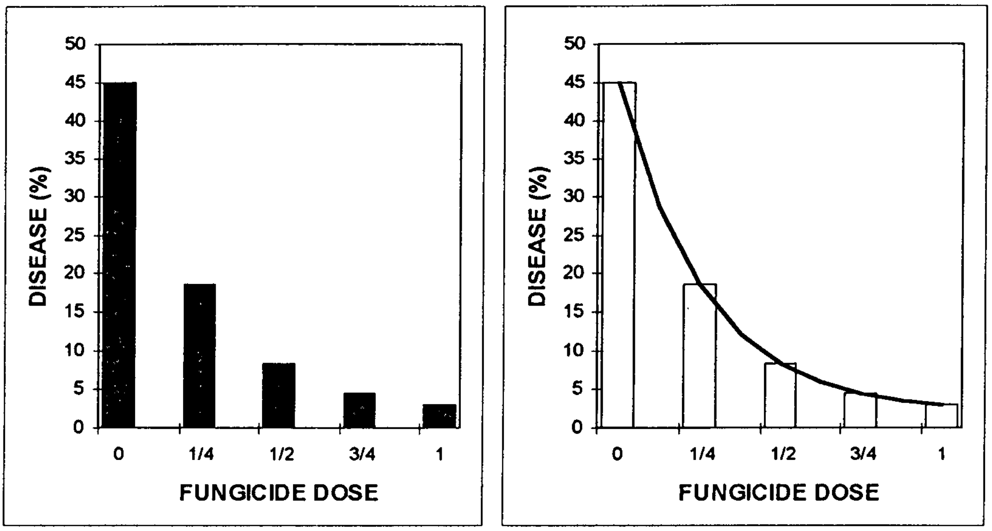
1.2 An introduction to appropriate fungicide doses

1.2.1 The dose-response curve

If the severity of foliar disease is measured in experimental plots which received fungicide treatment, at a range of doses, some time before, the results will typically look like those in Figure 1. Those plots which received no treatment will suffer a level of disease determined by the local 'disease pressure'. Fungicide treated plots will suffer less disease and the higher the dose, the lower the disease severity. However, a law of diminishing returns operates and each successive increase in dose causes a smaller additional effect.

The decrease in disease with increasing dose is commonly represented by a line, rather than bars, and is described as a 'dose-response curve'.

Figure 1. Disease severity following fungicide treatment at a range of doses and the dose-response curve



The maximum dose that can be used is specified on the label, as the recommended dose, and must not be exceeded. However, there is no legal limit to the minimum dose that should be applied, and the majority of crops now receive fungicides at doses substantially below those recommended (Paveley *et al.*, 1994). To understand why, it is helpful to consider how the recommended dose is set.

1.2.2 The recommended dose

The process of setting the recommended dose for a new product has been described by Finney (1993). He noted that 100% control is usually either technically unachievable in the field on a consistent basis, or is not cost effective. Furthermore, when the same fungicide is applied to control the same disease at a range of locations, the response to the applied chemical varies from place to place. The dose which gives 90% control in one field can be quite different to that which gives 90% control in another. To allow for this inherent variability and avoid product dissatisfaction, the label recommended dose is usually set at a level which consistently gives a high level of control across locations and seasons, typically 80-90% control 80-90% of the time.

It follows that on many, but not all, occasions the recommended dose is higher than that required to achieve satisfactory control.

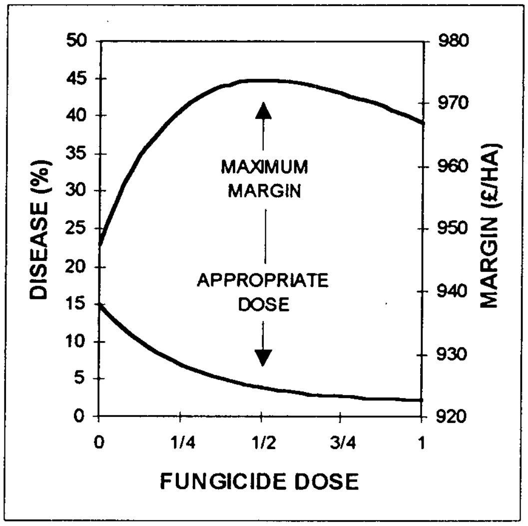
1.2.3 Reduced doses

During the late 1980's and early 1990's, growers recognised the safety margin built into the label recommended dose and, under pressure to reduce input costs, began to reduce the doses of fungicides applied to cereal crops. Survey data suggest that these reductions were (Paveley *et al.*, 1994) and still are (Stevens *et al.*, 1997) often made in an arbitrary manner.

1.2.4 Appropriate fungicide doses

Fungicide cost increases in direct proportion to the dose applied. As the loss of yield and grain quality is proportional to the level of disease, a point can be found on the dose-response curve, beyond which the cost of any further increase in dose would not be paid for by the resulting yield increase. At this point, profit is maximised (Figure 2) and unnecessary pesticide use minimised - by definition the **appropriate dose** to apply.

Figure 2. Dose-response curve, margin[1] over fungicide cost and appropriate dose



At doses below the appropriate dose, profit is reduced by ineffective disease control. At doses above the appropriate dose, profit is reduced by excessive fungicide cost.

It is important to note that the loss of profit is more severe if the dose is reduced below the appropriate dose than if increased above it. Hence, where there is uncertainty about the appropriate dose to apply, it is prudent to apply more, rather than less. The greater the uncertainty, the greater the safety margin required.

On what basis can a crop manager decide on the appropriate dose to apply - given that, as the shape of the dose-response curve varies from site to site and season to season, so must the appropriate dose ? And how can the uncertainty surrounding the choice of dose be minimised, to allow doses to be applied that are consistently close to the economic optimum, without suffering occasional severe losses due to under-application ?

The answers must come from taking account of the causes of the variation in disease control between sites and seasons; otherwise we are not *managing* crops, but merely playing the averages.

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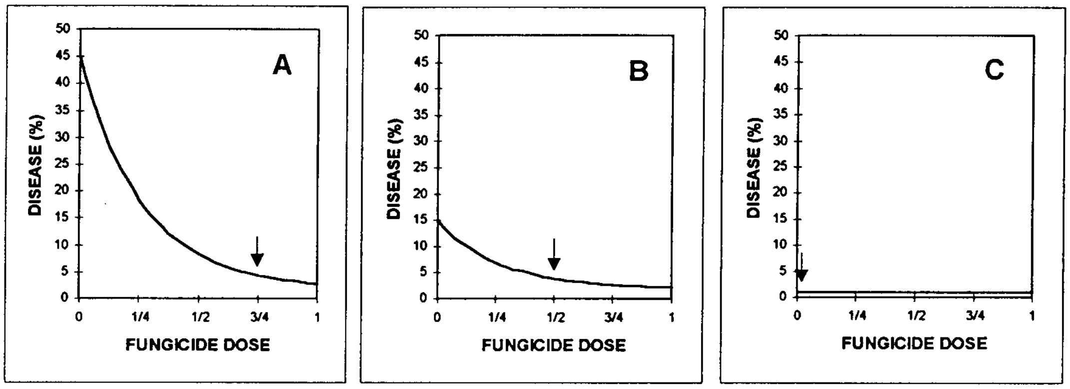
[1] Margin over fungicide cost: potential yield 10 tonnes/ha; grain value £100/tonne; yield loss 0.35% per 1% disease severity; fungicide cost £25/ha/dose. The effects of variation in grain price, fungicide cost and disease-yield loss relationships are dealt with later in the report.

1.2.5 Variation in dose-response curves

One of the main reasons for variation in disease control between sites and seasons is that, in the absence of treatment, disease severity varies between sites and seasons. Figure 3 shows the effect on the dose-response curve and the appropriate dose, of different levels of untreated disease. Curve (A) represents, for example, a crop of a disease susceptible variety, that experienced weather conditions favourable to disease development; curve (B) a more resistant variety or a susceptible variety under conditions less favourable to disease; and curve (C) a variety with complete immunity to that disease.

Figure 3. Effect of disease pressure on dose-response curve and appropriate dose (represented by an arrow)

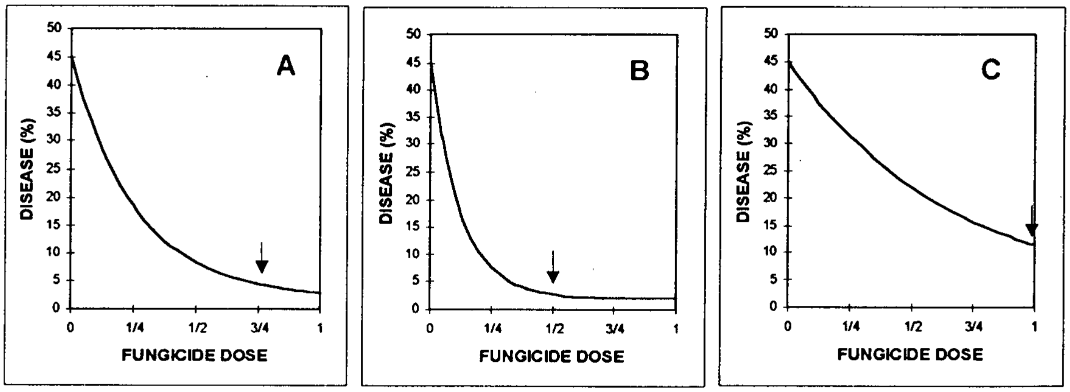


Clearly, higher disease pressure justifies higher inputs.

However, the appropriate dose also depends on efficiency of control. Figure 4 takes the high disease pressure case (A) and shows the effect of applying alternative products that are more (B), or less (C), effective.

All else being equal, more effective products have lower appropriate doses. However, efficacy is often reflected in price, so the best product/dose combination needs to be selected to do the job.

Figure 4. Effect of fungicide activity on dose-response curves and appropriate dose.



1.2.6 Input management for minimum unit cost

It can be seen, from the examples shown above, that the appropriate dose in a range of circumstances can vary between the recommended dose and zero.

A crop manager who is better able to quantify disease pressure and predict efficiency of control, will be able to apply doses that are consistently closer to the economic optimum - to the benefit of unit cost of production and the defensibility of pesticide use.

Experiment 1, reported in this Section, provides information to help predict the efficiency of control that might be expected from a range of widely used conazole and morpholine fungicides.

Experiment 2 measures the extent to which fungicide dose might be reduced by exploiting the reduction in disease pressure brought about by the genetic resistance of varieties.

Experiment 3 describes how individual fungicide applications can be most efficiently combined into spray programmes, and how treatments interact within programmes.

Matching Crop Management to Growth and Yield Potential (Project 0051/1/93), integrated within Experiment 3, investigates how responses to disease control (and hence dose optima) vary with the physiological state of the crop.

Research projects to improve the prediction of disease pressure, through understanding of: (i) weather-disease relationships, (ii) the role of within-crop inoculum on future epidemic progress, (iii) the effects of genetic resistance and disease escape, and (iv) variation in the relationship between disease and yield loss, are ongoing as part of the Integrated Disease Risk (IDR) programme (funded jointly by the Ministry of Agriculture, Fisheries and Food and the HGCA), and will be reported at the conclusion of the work in 1999.

2.0 OBJECTIVES - EXPERIMENT 1

To minimise fungicide costs, whilst maximising disease control, yield and grain quality, by:

- the production of dose-response curves for commonly used conazole and morpholine fungicides and chlorothalonil against the major pathogens of wheat;
- estimation of the effect of dose manipulation on the curative and protectant properties of the commonly used conazole and morpholine fungicides and chlorothalonil;
- the provision of data to improve the determination of Integrated Disease Risk (IDR).

3.0 MATERIALS AND METHODS

Complete protocols are presented in the Annual Report appendices. The following sections summarise the experimental sites, seasons, treatments, assessments and statistical analysis.

3.1 Sites, years and experiment numbers

Sites and varieties were selected to target specific diseases and the experiment was conducted for three harvest years.

Table 1. Sites, harvest years, experiment numbers and target diseases

Experiment number	Site and target disease/s	Harvest year
1	ADAS Rosemaund, Herefordshire	1994
2	(*Septoria tritici*)	1995
3		1996
4	Morley Research Centre, Norfolk	1994
5	(*Septoria tritici* and brown rust)	1995
6		1996
7	ADAS Terrington, Norfolk	1994
8	(Yellow rust)	1995
9		1996
10	SAC Aberdeen	1994
11	(Powdery mildew)	1995
12		1996

3.2 Site selection and drilling

Sites were selected according to Standard Operating Procedure (SOP) guidelines following at least a one year non-cereal break and soils were sampled pre-drilling for pH and nutrient status. Plots were drilled at a seed rate calculated from thousand grain weight and according to ADAS guidelines for the soil type and locality. Plot sizes were no smaller than 2m wide x 18m long and were drilled using an Øyjord plot drill or equivalent.

3.3 Experiment Design

Randomised complete block factorial design with three replicates. Guard plots of the variety Lynx or Pastiche were drilled alternating with the treated plots or where this was not possible plots were at least 3m wide.

3.4 Varieties

Varieties were selected for susceptibility to the target disease at each site:

ADAS Rosemaund - Riband
Morley Research Centre - Riband
ADAS Terrington - Slejpner
SAC Aberdeen - Apollo

3.5 Treatment products, doses, timing and application

Table 2. Treatment products, doses and numbers for 1994 harvest year

ADAS Rosemaund & Morley	SAC Aberdeen & ADAS Terrington
Trt. No. Commercial product (c.p.) and dose	Trt. No. Product and dose
1. Alto 100SL 0.8 litre c.p./ha (cyproconazole)	43. Alto 100SL 0.8 litre c.p./ha
2. Alto 100SL 0.6 litre c.p./ha	44. Alto 100SL 0.6 litre c.p./ha
3. Alto 100SL 0.4 litre c.p./ha	45. Alto 100SL 0.4 litre c.p./ha
4. Alto 100SL 0.2 litre c.p./ha	46. Alto 100SL 0.2 litre c.p./ha
5. Bayfidan 0.5 litre c.p./ha (triadimenol)	47. Bayfidan 0.5 litre c.p./ha
6. Bayfidan 0.375 litre c.p./ha	48. Bayfidan 0.375 litre c.p./ha
7. Bayfidan 0.25 litre c.p./ha	49. Bayfidan 0.25 litre c.p./ha
8. Bayfidan: 0.125 litre c.p./ha	50. Bayfidan: 0.125 litre c.p./ha
9. Bravo 2.0 litres c.p./ha (chlorothalonil)	51. Calixin 0.7 litre c.p./ha (tridemorph)
10. Bravo 1.5 litres c.p./ha	52. Calixin 0.525 litre c.p./ha
11. Bravo 1.0 litre c.p./ha	53. Calixin 0.35 litre c.p./ha
12. Bravo 0.5 litre c.p./ha	54. Calixin 0.175 litre c.p./ha
13. Corbel 1.0 litre c.p./ha (fenpropimorph)	55. Corbel 1.0 litre c.p./ha
14. Corbel 0.75 litre c.p./ha	56. Corbel 0.75 litre c.p./ha
15. Corbel 0.5 litre c.p./ha	57. Corbel 0.5 litre c.p./ha
16. Corbel 0.25 litre c.p./ha	58. Corbel 0.25 litre c.p./ha
17. Folicur 1.0 litre c.p./ha (tebuconazole)	59. Folicur 1.0 litre c.p./ha
18. Folicur 0.75 litre c.p./ha	60. Folicur 0.75 litre c.p./ha
19. Folicur 0.5 litre c.p./ha	61. Folicur 0.5 litre c.p./ha
20. Folicur 0.25 litre c.p./ha	62. Folicur 0.25 litre c.p./ha
21. Patrol 1.0 litre c.p./ha (fenpropidin)	63. Patrol 1.0 litre c.p./ha
22. Patrol 0.75 litre c.p./ha	64. Patrol 0.75 litre c.p./ha
23. Patrol 0.5 litre c.p./ha	65. Patrol 0.5 litre c.p./ha
24. Patrol 0.25 litre c.p./ha	66. Patrol 0.25 litre c.p./ha
25. Pointer 1.0 litre c.p./ha (flutriafol)	67. Pointer 1.0 litre c.p./ha
26. Pointer: 0.75 litre c.p./ha	68. Pointer: 0.75 litre c.p./ha
27. Pointer: 0.5 litre c.p./ha	69. Pointer: 0.5 litre c.p./ha
28. Pointer: 0.25 litre c.p./ha	70. Pointer: 0.25 litre c.p./ha
29. Sanction 0.5 litre c.p./ha (flusilazole)	71. Sanction 0.5 litre c.p./ha
30. Sanction 0.375 litre c.p./ha	72. Sanction 0.375 litre c.p./ha
31. Sanction 0.25 litre c.p./ha	73. Sanction 0.25 litre c.p./ha
32. Sanction 0.125 litre c.p./ha	74. Sanction 0.125 litre c.p./ha
33. Tilt 0.5 litre c.p./ha (propiconazole)	75. Tilt 0.5 litre c.p./ha
34. Tilt 0.375 litre c.p./ha	76. Tilt 0.375 litre c.p./ha
35. Tilt 0.25 litre c.p./ha	77. Tilt 0.25 litre c.p./ha
36. Tilt 0.125 litre c.p./ha	78. Tilt 0.125 litre c.p./ha
37. Bravo 1.5 litres + Pointer 1.0 litre c.p./ha	79. Folicur 1.0 litre + Patrol 0.70 litre c.p./ha
38. Bravo 1.125 litres + Pointer 0.75 litre c.p./ha	80. Folicur 0.75 litre + Patrol 0.525 litre c.p./ha
39. Bravo 0.75 litre + Pointer 0.5 litre c.p./ha	81. Folicur 0.5 litre + Patrol 0.35 litre c.p./ha
40. Bravo 0.375 litre + Pointer 0.25 litre c.p./ha	82. Folicur 0.25 litre + Patrol 0.175 litre c.p./ha
41. and 42. Untreated	83. and 84. Untreated

Table 3. Treatment products, doses and numbers for 1995 and 1996 harvest years

ADAS Rosemaund & Morley		SAC Aberdeen* & ADAS Terrington#	
Trt. No.	Product and dose	Trt. No.	Product and dose
1.	Alto 100SL 0.8 litre c.p./ha	43.	Alto 100SL 0.8 litre c.p./ha
2.	Alto 100SL 0.6 litre c.p./ha	44.	Alto 100SL 0.6 litre c.p./ha
3.	Alto 100SL 0.4 litre c.p./ha	45.	Alto 100SL 0.4 litre c.p./ha
4.	Alto 100SL 0.2 litre c.p./ha	46.	Alto 100SL 0.2 litre c.p./ha
5.	Opus 1.0 litre c.p./ha (epoxyconazole)	47.	Bayfidan# 0.5 or Match* 0.47 litre c.p./ha
6.	Opus 0.75 litre c.p./ha	48.	Bayfidan# 0.37 or Match* 0.352 litre c.p./ha
7.	Opus 0.5 litre c.p./ha	49.	Bayfidan# 0.25 or Match* 0.235 litre c.p./ha
8.	Opus: 0.25 litre c.p./ha	50.	Bayfidan#:0.12 or Match* 0.117 litre c.p./ha (difenzoquat)
9.	Bravo 2.0 litres c.p./ha	51.	Opus 1.0 litre c.p./ha
10.	Bravo 1.5 litres c.p./ha	52.	Opus 0.75 litre c.p./ha
11.	Bravo 1.0 litre c.p./ha	53.	Opus 0.5 litre c.p./ha
12.	Bravo 0.5 litre c.p./ha	54.	Opus 0.25 litre c.p./ha
13.	Corbel 1.0 litre c.p./ha	55.	Corbel 1.0 litre c.p./ha
14.	Corbel 0.75 litre c.p./ha	56.	Corbel 0.75 litre c.p./ha
15.	Corbel 0.5 litre c.p./ha	57.	Corbel 0.5 litre c.p./ha
16.	Corbel 0.25 litre c.p./ha	58.	Corbel 0.25 litre c.p./ha
17.	Folicur 1.0 litre c.p./ha	59.	Folicur 1.0 litre c.p./ha
18.	Folicur 0.75 litre c.p./ha	60.	Folicur 0.75 litre c.p./ha
19.	Folicur 0.5 litre c.p./ha	61.	Folicur 0.5 litre c.p./ha
20.	Folicur 0.25 litre c.p./ha	62.	Folicur 0.25 litre c.p./ha
21.	Patrol 1.0 litre c.p./ha	63.	Patrol 1.0 litre c.p./ha
22.	Patrol 0.75 litre c.p./ha	64.	Patrol 0.75 litre c.p./ha
23.	Patrol 0.5 litre c.p./ha	65.	Patrol 0.5 litre c.p./ha
24.	Patrol 0.25 litre c.p./ha	66.	Patrol 0.25 litre c.p./ha
25.	Pointer 1.0 litre c.p./ha	67.	Pointer 1.0 litre c.p./ha
26.	Pointer: 0.75 litre c.p./ha	68.	Pointer: 0.75 litre c.p./ha
27.	Pointer: 0.5 litre c.p./ha	69.	Pointer: 0.5 litre c.p./ha
28.	Pointer: 0.25 litre c.p./ha	70.	Pointer: 0.25 litre c.p./ha
29.	Sanction 0.5 litre c.p./ha	71.	Sanction 0.5 litre c.p./ha
30.	Sanction 0.375 litre c.p./ha	72.	Sanction 0.375 litre c.p./ha
31.	Sanction 0.25 litre c.p./ha	73.	Sanction 0.25 litre c.p./ha
32.	Sanction 0.125 litre c.p./ha	74.	Sanction 0.125 litre c.p./ha
33.	Tilt 0.5 litre c.p./ha	75.	Tilt 0.5 litre c.p./ha
34.	Tilt 0.375 litre c.p./ha	76.	Tilt 0.375 litre c.p./ha
35.	Tilt 0.25 litre c.p./ha	77.	Tilt 0.25 litre c.p./ha
36.	Tilt 0.125 litre c.p./ha	78.	Tilt 0.125 litre c.p./ha
37.	Bravo 1.5 + Pointer 1.0 litre c.p./ha	79.	Fol. 1.0 + Pat.# 0.70 litre or Unix* 1.0 kg c.p./ha
38.	Bravo 1.125 + Pointer 0.75 litre c.p./ha	80.	Fol. 0.75 + Pat.# 0.525 litre or Unix* 0.75 kg c.p./ha
39.	Bravo 0.75 + Pointer 0.5 litre c.p./ha	81.	Fol. 0.5 + Pat.# 0.35 litre or Unix* 0.5 kg c.p./ha
40.	Bravo 0.375 + Pointer 0.25 litre c.p./ha	82.	Fol. 0.25 + Pat.# 0.175 litre or Unix* 0.25 kg c.p./ha (cyprodinil)
41. and 42.	Untreated	83. and 84.	Untreated

Fungicide treatments were applied at GS 39 (1994) or GS 37 (1995 and 1996) using a hand-held pressurised sprayer of the OPS/MDM type and were applied in 200-250 litres of water per hectare, using low drift nozzles selected to produce a medium spray quality at 200-300 KPa pressure.

Other treatments (fertiliser, trace elements, herbicides, insecticides, growth regulators, molluscicides) followed standard farm practice.

3.6 Assessments and records

3.6.1 Agronomic details

Site, soil and crop details were recorded.

3.6.2 Meteorological data

Meteorological data from crop emergence to harvest were recorded using in-crop Delta-T data loggers.

3.6.3 Assessment of leaf diseases and green leaf area (GLA)

Pre-treatment disease and GLA assessments were made at GS37 (1995 and 1996) or GS39 (1994). 50 main tillers were randomly sampled across the whole of the 'test' variety plot area and the assessments described below recorded (on all leaf layers with an average of >25% GLA remaining).

At approximately 21 days and 35 days after treatment (for the yellow rust and mildew sites) or 28 and 42 days after treatment (at the *S. tritici* and brown rust sites) disease incidence, severity and % GLA were recorded on all green leaves on 10 main tillers per plot. The precise timing of these assessments was adjusted to optimise recording of treatment differences. The first assessment aimed to record treatment differences on leaves 3 and 4, before senescence and at the same time differences were becoming established on the upper leaves. The second assessment aimed at recording treatment effects on leaves 1 & 2.

Disease incidence was defined as the percentage of leaves sampled affected by disease;

Disease severity was defined as the percentage leaf area affected by disease, including chlorotic and necrotic areas attributable to disease;

3.6.4 Ear diseases

Diseases were assessed on 10 ears per plot at GS 85, if more than 5% ear area or more than five grain sites per ear were affected in the untreated controls.

3.6.5 Stem bases diseases

Stem-base diseases were assessed on 25 tillers from the trial area at GS 31.

At GS 75, stem-base diseases were assessed in all plots on 25 tillers per plot, if in untreated plots, >25% tillers were affected by moderate or severe lesions of any disease or if >10% tillers were affected by severe lesions of any disease.

3.6.6 Harvest

Whole plots were harvested. Grain yield was adjusted to 85% dry matter. Grain specific weight and thousand grain weight were adjusted to 85% dry matter.

3.7 SOP List

Work was conducted according to the following ADAS Standard Operating Procedures.

ADMIN/008	The production of R & D reports.
AGRON/004	The measurement of dry matter in grain, pulses and oilseeds using the Sinar Agritec meter.
AGRON/017G	Guidelines to practical site management.
AGRON/019G	Guidelines for the storage of pesticides
AGRON/023 G	Guidelines for the application of pesticides to plots.
CER/002	Diagnosis and assessment of stem-base diseases In winter cereals.
CER/007	Measurement of specific weight using a Corcoron/Nilema/Farmtec Chondrometer.
CER/008	Measurement of specific weight using the Sinar Datatec P25 or Tecator 6010 GP meters.
CER/014	Assessing growth stages in cereals.
CER/023	Assessment of green leaf area and foliar diseases in cereals.
CER/024	Assessment of ear diseases in cereals.
DATCL/001	Automatic collection from load cell/weighmeter equipment fitted to a plot combine harvester.
DATCL/013	Collating experimental data using MINITAB
DATCL/015	Manual recording of experimental data on proforma sheets.
DATCL/016	Recording experimental data on Hunter 16 using the "Plot-exe" software.
DATCL/017	Recording experimental data on Husky Hunter (CPM) using "Plot.hba" software.
DATCL/018 G	Guidelines for backup and archive of manually-recorded experimental data.
DATCL/019 G	Guidelines for backup and archive of experimental data held on computer.
DATCL/020 G	Guidelines for keeping manual file records of experiments.
DATCL/027 G	Guidelines for selecting suitable sites for land-based experiments.
MCP/015	Archiving of experiment data, reports and other records.

MECH/001	The calibration and use of the Øyjord tractor-mounted drill.
MECH/008 G	Harvesting of experimental plots, cereals and combineable crops.
SOILS/007	Soil sampling for pH and nutrient analysis.

3.8 Data handling

Disease, green leaf area and yield/grain quality measurements were collected either manually or directly on to portable computers and transferred onto MINITAB or EXCEL work files after collection.

3.9 Statistical analysis

Data were analysed using Genstat 5.

3.9.1 Individual Assessments

Each assessment (site, season, variate, date, leaf layer) was analysed by analysis of variance and the validity of the analysis was checked by examination of residuals. Normal plots, histograms and plots of residuals versus fitted values were used to assess the normality assumption and any requirement for transformation. Analysis of the *S. tritici* data suggested that, in some sites and seasons, a log transformation may have provided a more valid analysis. However, to maintain consistency over all sites and seasons, the data were left untransformed. A logit or probit transformation was also considered (Finney, 1971; Gisi, 1996), but proved inappropriate.

Outliers were identified from the above plots, and from graphs of residuals versus fungicide and residuals versus dose. A small number of extreme outliers were removed from the data after consultation as to the cause.

In some cases, plots of residuals versus plot number showed a linear trend in the residuals within some of the blocks. These trends were removed by using covariates on plot number within each block. Such covariates were often found to be required for harvest variates (yield, specific weight, thousand grain weight) at all sites except Terrington, for green leaf area at Rosemaund and Terrington, and for *S. tritici* at Rosemaund.

Variates which did not contribute useful information were excluded from further analysis. These were defined to be variates for which there were no significant treatment effects or interactions, disease variates for which there was less than an average of 5% disease on the untreated plots, and green leaf areas for which there was more than an average of 90% green leaf area on the untreated plots.

For disease variates which did contribute useful information, dose-response curves were plotted for each fungicide, using the treatment means (adjusted for covariates if appropriate). Exponential curves of the form $y = a+be^{kx}$, where y = % disease and x = proportion of recommended dose, were fitted. The three parameter exponential was the most parsimonious function, able to describe the variation in dose-response seen in the data. All of the parameters have biological meaning. Exponential curves were also fitted to green leaf areas and harvest variates. Since the untreated (dose=0) data point for each fungicide is the mean of the same six plot values, the curves were constrained to pass through this point. Note that, for simplicity of fitting, the curves were actually fitted in the equivalent form $y = a+br^x$ and the parameter k was then estimated as $k = \ln(r)$. An investigation of fitting k directly and estimating k as above showed that the difference in the two estimates of k was typically less than 0.01%.

3.9.2 Over-assessment means

For disease variates, assessments were split into those representing either eradicant or protectant activity of the fungicides. All assessments on a leaf layers were ascribed to the eradicant category if the leaf had been emerged suffícently long for infection to have become established, by the time treatments were applied. Assessments on leaf layers which were treated soon after emergence were ascribed to the protectant category. Exponential curves were fitted to means over all sites, seasons, dates and leaf layers for each fungicide and each type of activity, regardless of the closeness of the fit of the curves to the individual assessments. Inclusion of all the data was considered appropriate, as a lack of fit was often the result of poor disease control, and was thus a true reflection of the performance of the fungicide. The curves were again constrained to pass through the untreated (dose=0) point. Repeat assessments on the same leaf layer within a site/season are likely to be highly correlated. Hence, such assessments were averaged before the overall means were calculated.

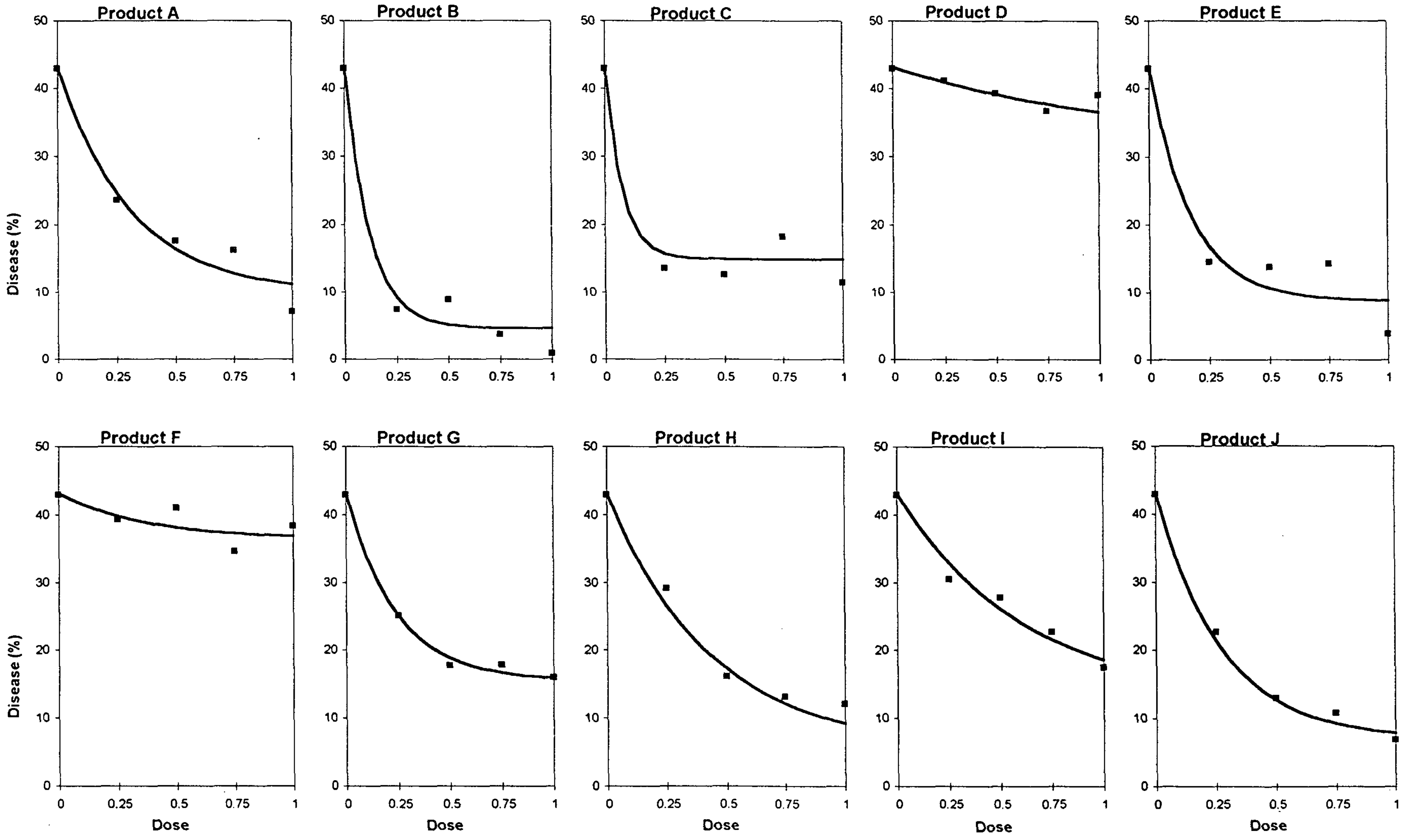
Green leaf area over-assessment means were calculated from the same site, season, date and leaf layer assessment combinations as the relevant disease means. Various combinations of site and season means were calculated for the harvest variables, for comparison with disease and green leaf area means. Exponential curves were fitted to green leaf area and harvest variates.

3.10 Interpretation of dose-response curves and parameter estimates

Biological data are subject to natural error variation, exacerbated in the case of disease data, by the subjective nature of visual disease assessments (Parker, 1992). Figure 5 shows typical percentage disease data points for untreated, quarter, half, three quarter and full doses of a range of fungicide products. The curves represent exponential functions fitted to the data. The extent to which data points depart from the fitted dose-response curves provides a measure of the error variation in the data. Where the scatter about the curve is small in proportion to the size of the treatment effect, the parameter estimates which describe the shape of the fitted dose-response curve can be compared with greater confidence.

Table 4 shows the parameter estimates for the example dose-response curves in Figure 5. The parameter a represents the level of disease that would have been recorded if an infinite dose of fungicide had been applied (the lower asymptote). In practice, with effective products, the level of disease at the recommended dose is close to a. Parameter b represents the difference between the lower asymptote and the untreated. Hence $a + b$ = the level of untreated disease. The parameter k represents the curvature of the response curve, with low (more negative) values being associated with greater

Figure 5. Example dose-response curves for a range of fungicides, fitted to percentage disease data



curvature. Where dose=1, disease = $a+be^k$; providing a value for the lowest level of disease that could be obtained with a recommended dose of that product.

Table 4. Example parameter estimates for fitted product dose response curves

Product	Parameter estimates				
	a	b	k	a + b	$a+be^k$
A	10.0	33.2	-3.26	43.2	11.2
B	4.6	38.6	-8.52	43.2	4.6
C	14.9	28.3	-14.23	43.2	14.9
D	31.7	11.5	-0.86	43.2	36.6
E	8.7	34.5	-5.78	43.2	8.8
F	36.5	6.7	-2.77	43.2	36.9
G	15.6	27.7	-4.26	43.2	15.9
H	5.7	37.5	-2.34	43.2	9.3
I	12.8	30.4	-1.64	43.2	18.7
J	7.0	36.2	-3.70	43.2	7.9

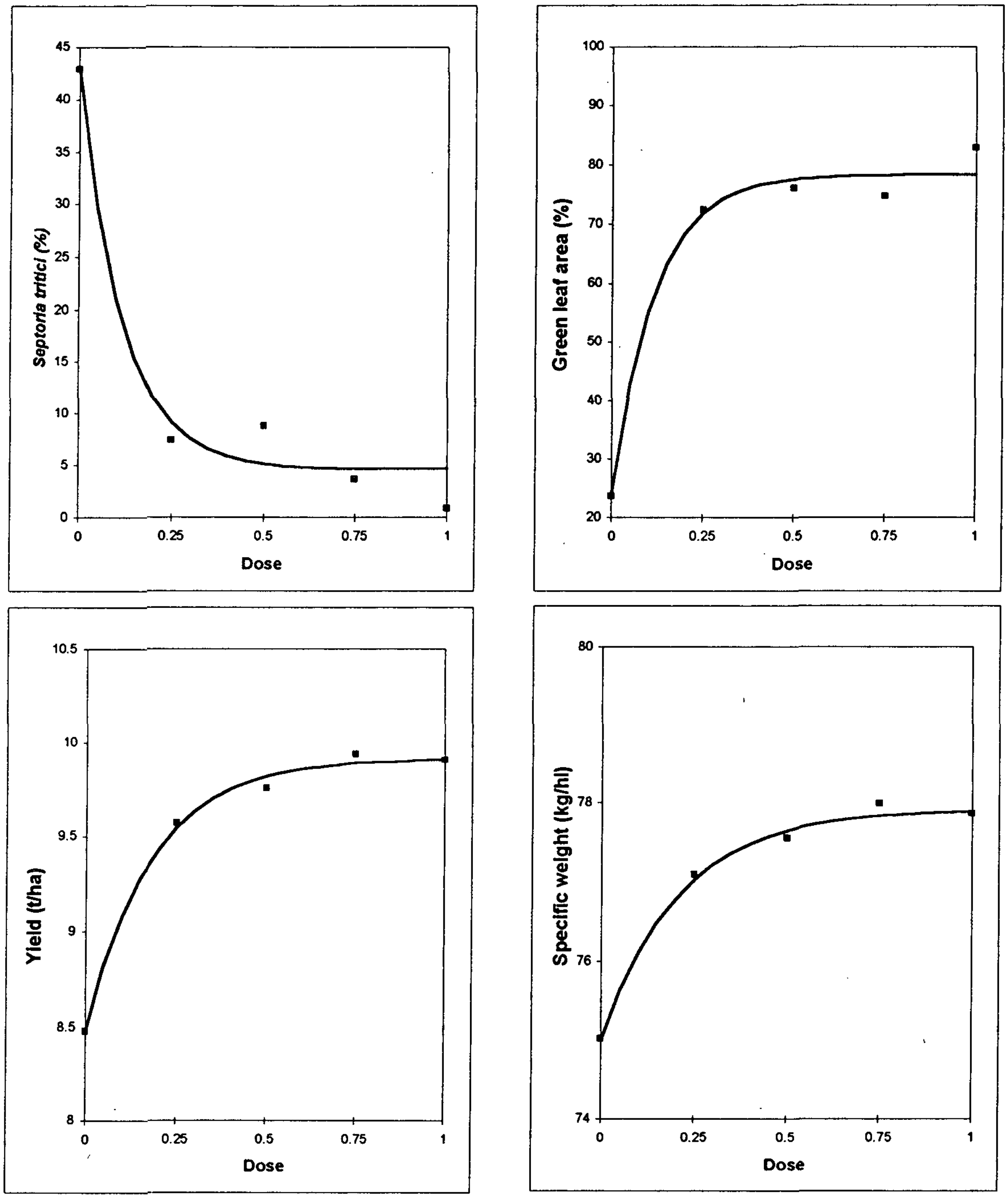
Clearly, the products in the example vary substantially in their efficacy, with a full dose of product B reducing 43 % disease (a+b) to less than 5% ($a+be^k$), whereas product F was largely ineffective. The high k value for product B, suggests that disease control at low doses was almost as effective as at high doses.

Taking product B as an example, dose-response curves for disease severity are reflected in the shapes (Figure 6) and parameter estimates (Table 5) of the fitted curves for green leaf area, grain yield and specific weight.

Table 5. Example parameter estimates for fitted product dose-response curves for percentage disease, green leaf area, yield and specific weight, for product B

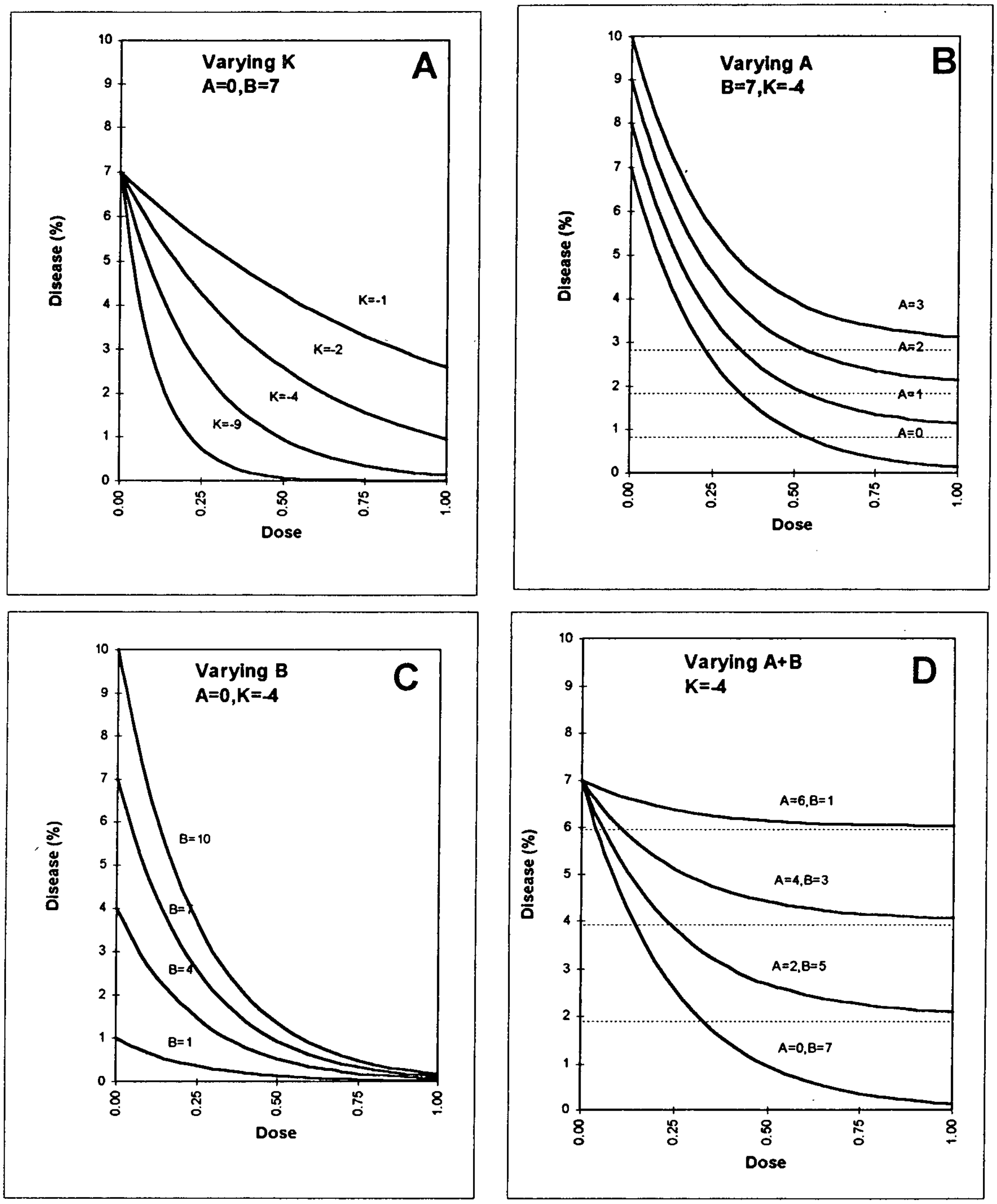
	Parameter estimates				
	a	b	k	a + b	$a+be^k$
Disease	4.6	38.6	-8.52	43.2	4.6
Green leaf area	78.2	-54.6	-8.62	23.5	78.2
Yield	9.9	-1.4	-5.48	8.5	9.9
Specific weight	77.9	-2.9	-4.72	75.0	77.9

Figure 6. Example disease, green leaf area, yield and specific weight dose-response curves, for product B.



The hypothetical dose-response curves shown in Figure 7 illustrate, more fully, the relationship between curve shape and parameter estimates - in this case for percentage disease. In example A, parameters a and b were held constant and varying curvature produced a range of values for k. In example B, b and k were constant and varying the lower asymptote (a) shifted the whole curve. In example C, a and k were constant, so varying the untreated amount of disease produced a range of b values. And in example D, the untreated value (a+b) was held constant and the lower asymptote and potential degree of control (b) varied in opposition.

Figure 7. Hypothetical dose-response curves to illustrate relationships between curve shape and parameter estimates



In the data from experiment 1, a+b (untreated) values were constant across fungicides (as in examples A and D), but varied across sites, seasons, leaf layers and assessment date. In experiment 2, a+b varied with variety (as in example C).

4.0 RESULTS

4.1 *Septoria tritici* experiments

4.1.1 Disease control

Dose-response curves describing the eradicant activity of fungicides against *S. tritici*, derived from over-assessment means, are shown in Figure 8. Parameter estimates (Table 6) describe the curves quantitatively and the R^2 values suggest that a high proportion of the variance in the data was accounted for by the fitted exponential function.

The data represent a range of situations, from treatments which were applied shortly after infection, to those applied to well established infections, at the limit of eradicant activity. These provide a realistic representation of the activity which might be expected in commercial use, where spray timing is often compromised by adverse weather and logistical considerations.

As expected, the morpholine materials Corbel (fenpropimorph) and Patrol (fenpropidin), provided little control, although where these materials are added to a spray mixture for the control of powdery mildew or rusts, there may be some small benefit to the control of *S. tritici*. Similarly, Bravo (chlorothalonil) provided poor control where infection was already established, reflecting its non-systemic action.

Alto (cyproconazole), Folicur (tebuconazole), Pointer (flutriafol), Sanction (flusilazole) Tilt and Bravo + Pointer, provided intermediate control. The performance of the mixture appearing additive in relation to its components. Good control was obtained with Opus (epoxyconazole). The mean data suggest that, across the range of circumstances experienced in the experiments, a three-quarter dose was required for consistent control. The parameter estimates for individual assessments (Section 6.0) show that where spray timing was good, a half dose was highly effective. Care is needed when comparing Opus against the other products, as the material was not included in the first year of the experiment. However, disease pressure across the experiments in which Opus was included, was similar to those in which it was not, and assessments within experiments where direct comparisons were possible, support the observations reported above.

In the protectant situation (Figure 9; Table 7) relative product performance was similar, with the clear exception of Bravo and Bravo + Pointer. Where infections were not established at the time of treatment application, Bravo provided control as effective as the best conazole materials. The chlorothalonil + conazole mixture was particularly effective.

Figure 8. Eradicant dose-response curves for *Septoria tritici* - overall means

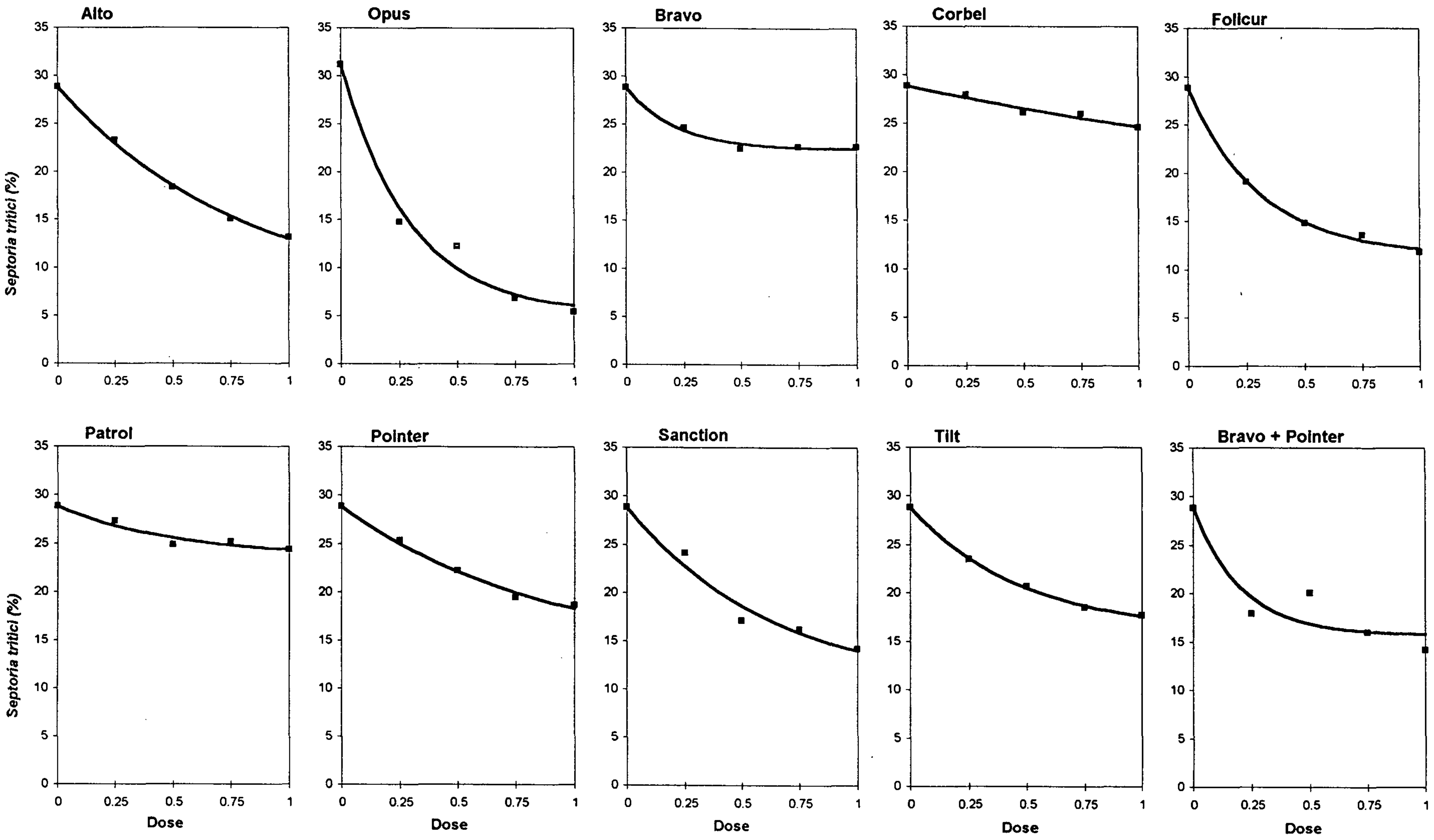


Figure 9. Protectant dose-response curves for *Septoria tritici* - overall means

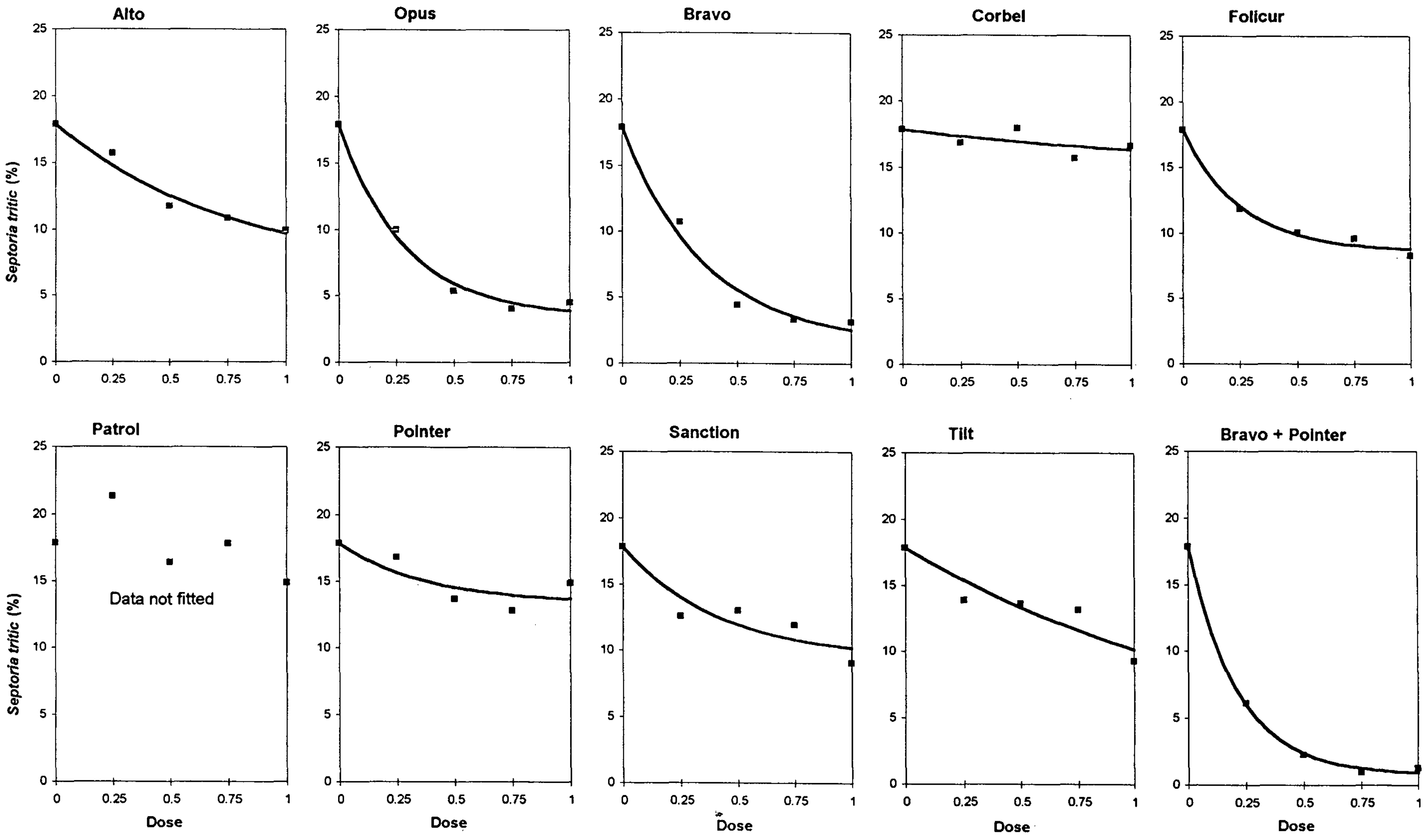


Table 6. Cross-site parameter estimates for fitted product dose response curves - eradicant

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	6.4	22.5	-1.22	28.8	13.0	99.8
Opus	5.3	25.9	-3.43	31.2	6.1	97.5
Bravo	22.4	6.4	-4.80	28.8	22.5	98.2
Corbel	14.7	14.1	-0.35	28.8	24.7	94.2
Folicur	11.6	17.3	-3.28	28.8	12.2	99.7
Patrol	23.7	5.1	-1.99	28.8	24.4	91.8
Pointer	13.2	15.6	-1.12	28.8	18.3	99.1
Sanction	10.0	18.8	-1.56	28.8	14.0	96.2
Tilt	16.1	12.7	-2.13	28.8	17.6	99.9
Bravo + Pointer	15.7	13.1	-4.88	28.8	15.8	83.9

Table 7. Cross-site parameter estimates for fitted product dose response curves - protectant

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	6.5	11.4	-1.26	17.87	9.7	95.6
Opus	3.5	14.4	-3.51	17.87	3.9	98.8
Bravo	1.6	16.3	-2.80	17.87	2.6	97.7
Corbel	15.2	2.6	-.086	17.87	16.4	16.2
Folicur	8.6	9.2	-3.97	17.87	8.8	98.7
Patrol	Data not fitted					
Pointer	13.4	4.4	-2.76	17.87	13.7	64.0
Sanction	9.5	8.4	-2.47	17.87	10.2	81.0
Tilt	2.7	15.2	-0.71	17.87	10.2	79.8
Bravo + Pointer	0.8	17.1	-4.74	17.87	0.9	99.8

4.1.2 Green leaf area

In both the eradicant (Figure 10; Table 8) and protectant (Figure 11, Table 9) cases, green leaf area dose-response curves completely mirrored the disease assessment response curves presented above. Those products which were most effective in controlling disease were also those most effective in prolonging green leaf area. There was no evidence that higher doses were required to maintain green area than were required to control disease. The non-systemic material, Bravo, was as effective at maintaining green leaf area, in protectant situations, as the systemic fungicides. The fitted exponential function accounted for a high proportion of the variance in the data, with the exception of the less effective morpholine materials.

Figure 10. Eradicant dose-response curves for green leaf area in *Septoria tritici* experiments - overall means

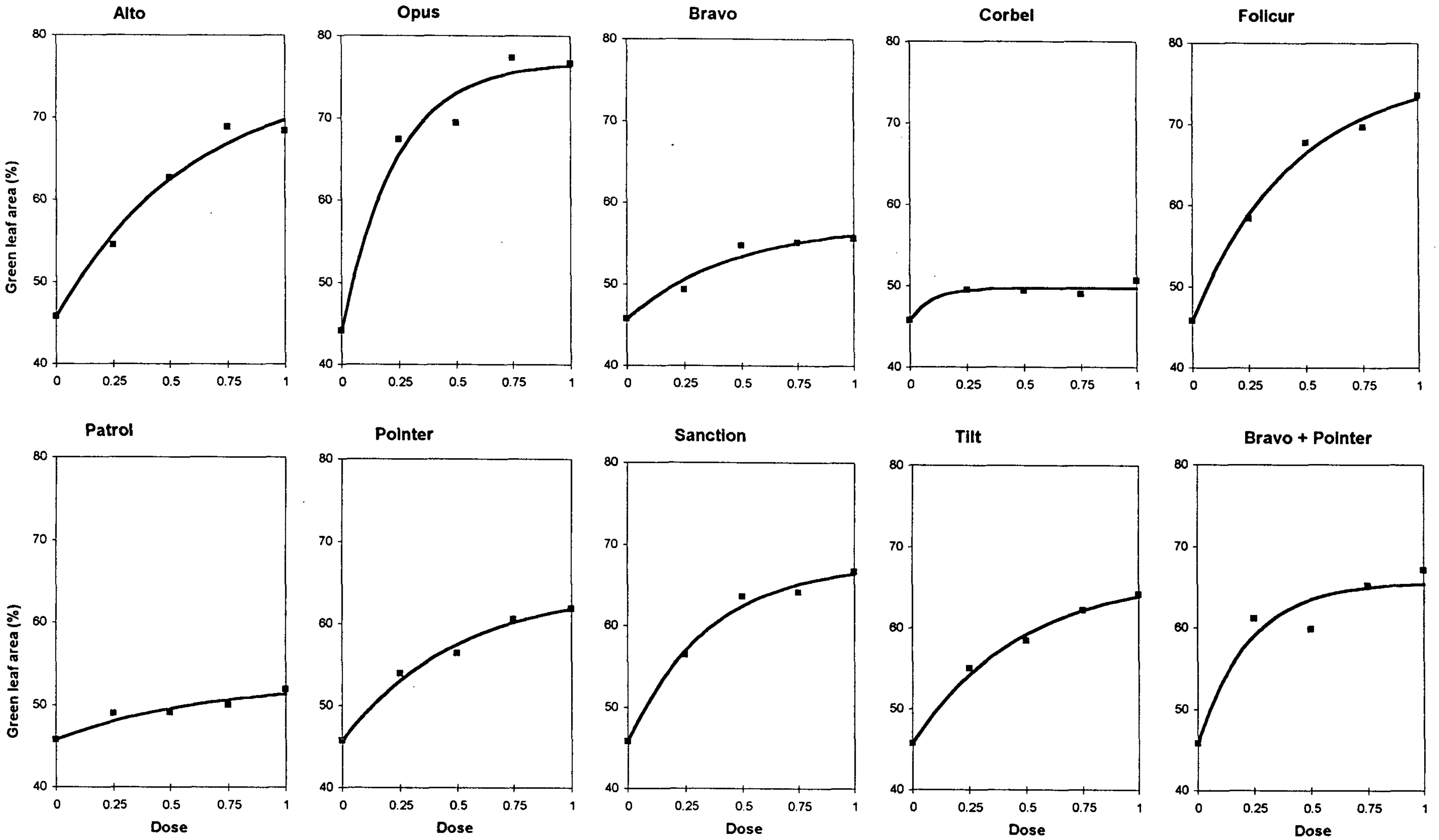


Figure 11. Protectant dose-response curves for green leaf area in *Septoria tritici* experiments - overall means

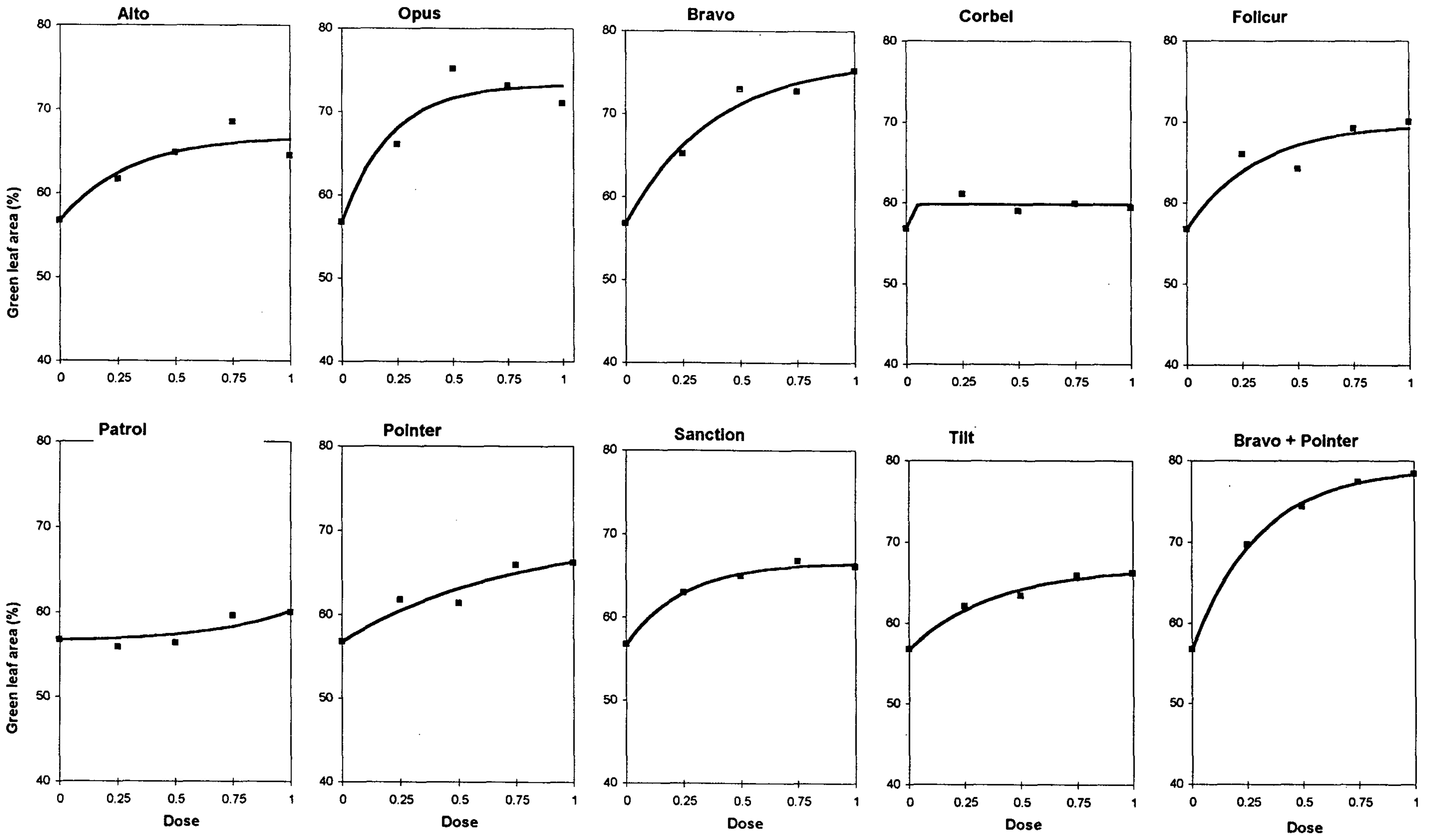


Table 8. Cross-site parameter estimates for fitted product dose response curves - green leaf area, eradicant

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	75.3	-29.6	-1.67	45.8	69.7	97.4
Opus	76.9	-32.8	-4.26	44.1	76.4	96.4
Bravo	57.5	-11.7	-2.11	45.8	56.1	93.8
Corbel	49.7	-4.0	-0.60	45.8	49.7	85.7
Folicur	76.4	-30.7	-10.25	45.8	73.2	99.1
Patrol	52.7	-7.0	-1.59	45.8	51.3	87.2
Pointer	64.2	-18.4	-2.02	45.8	61.8	98.4
Sanction	67.6	-21.9	-2.86	45.8	66.4	98.8
Tilt	66.4	-20.7	-2.10	45.8	63.9	99.2
Bravo + Pointer	65.7	-19.9	-4.41	45.8	65.4	90.2

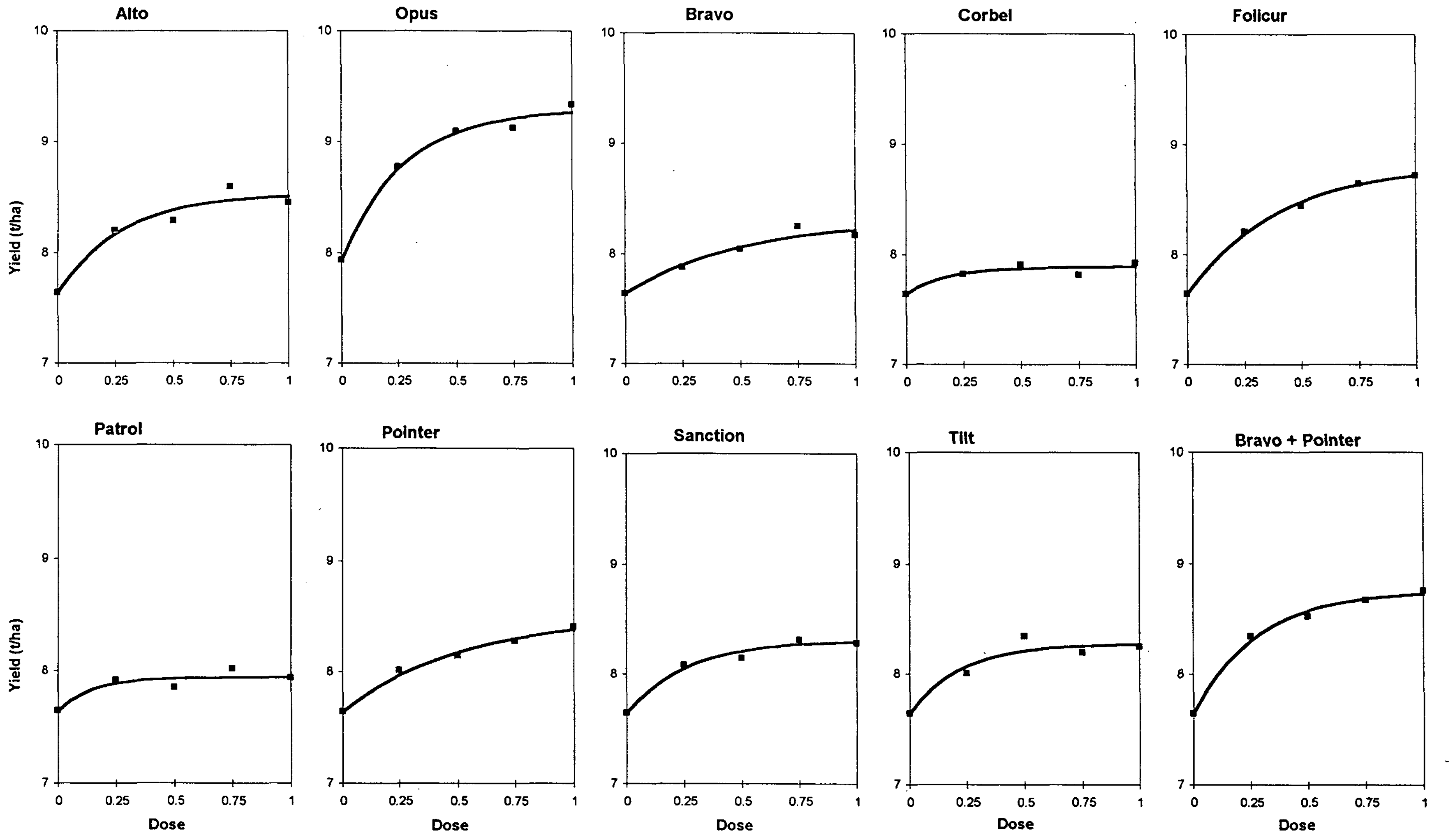
Table 9. Cross-site parameter estimates for fitted product dose response curves - green leaf area, protectant

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	66.8	-10.0	-3.30	56.8	66.4	81.3
Opus	73.3	-16.6	-4.60	56.8	73.1	87.2
Bravo	76.5	-19.8	-2.62	56.8	75.1	96.9
Corbel	59.8	-3.1	-62.45	56.8	59.8	67.7
Folicur	69.8	-13.1	-3.19	56.8	69.3	83.4
Patrol	56.5	0.2	2.86	56.8	60.3	64.8
Pointer	69.5	-12.7	-1.40	56.8	66.4	87.7
Sanction	66.7	-10.0	-3.91	56.8	66.5	98.6
Tilt	67.0	-10.3	-2.58	56.8	66.2	97.9
Bravo + Pointer	79.2	-22.4	-3.31	56.8	78.3	99.8

4.1.3 Grain yield

The grain yield data (Figure 12; Table 10) reflect a combination of eradicant and protectant activity, on different leaf layers within the crop canopy. In most experiments, the flag leaf was treated before infection, but at some sites, rainfall both caused infection and delayed treatment. At such sites, yield responses related only to eradicant activity. Full yield potential for a disease susceptible and responsive variety such as Riband, was unlikely to be realised with a single spray treatment. Nevertheless, the full dose treatments gave fitted yields in the range, 7.9 to 9.3 t/ha. Overall, the yield dose-response curves reflected the disease and green area curves, with the morpholines providing small responses and the more effective conazoles, and the conazole + chlorothalonil mixture, providing substantial returns. The mean yield response to Bravo was limited by the inclusion of data from purely eradicant sites.

Figure 12. Dose-response curves for grain yield in *Septoria tritici* experiments - overall means



It is important to note that the yield of the Opus treatment is exaggerated in Figure 12, by its inclusion in experiments with, on average, a higher yield potential. Comparison of the untreated (a+b) and full dose ($a+be^k$) values in Table 10, gives yield response values of 1.4 t/ha for Opus, compared to 1.1 t/ha for Folicur and the Bravo + Pointer mixture, 0.7 to 0.9 t/ha for the other conazoles, and 0.3 t/ha for the morpholines. Consideration of the parameter estimates in Section 6.0, for experiments where direct comparisons can be made, suggest that these relative yields are realistic, but may be biased slightly in favour of Opus.

For the more effective products, estimates of the a parameter were close to, or the same as (subject to rounding), estimates for $a+be^k$, suggesting that yield had plateaued by the full dose, and was approaching the plateau by three-quarters of a dose (Table 10). The fitted exponential function explained a high proportion of the variation in the data. There was no evidence of higher doses being required to improve yield, than were required to control disease or prolong green leaf area.

Table 10. Cross-site parameter estimates for fitted product dose response curves - yield

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	8.5	-0.9	-3.62	7.6	8.5	92.8
Opus	9.3	-1.4	-3.66	7.9	9.3	98.6
Bravo	8.3	-0.7	-1.93	7.6	8.2	93.5
Corbel	7.9	-0.2	-5.62	7.6	7.9	80.2
Folicur	8.8	-1.1	-2.53	7.6	8.7	99.7
Patrol	7.9	-0.3	-6.96	7.6	7.9	76.8
Pointer	8.5	-0.9	-1.90	7.6	8.4	98.5
Sanction	8.3	-0.7	-3.77	7.6	8.3	97.0
Tilt	8.3	-0.6	-4.48	7.6	8.3	88.7
Bravo + Pointer	8.8	-1.1	-3.58	7.6	8.7	99.2

4.1.4 Grain quality

Dose-response curves for both specific weight (Figure 13; Table11) and thousand grain weight (Figure 14; Table 12) mirrored yield; with those treatments and doses most effective at yield improvement, giving most benefit to grain quality.

The majority of the yield benefit from the treatments can be explained by increases in thousand grain weight. For example, a full dose of Opus gave a fitted yield response ($(a+be^k)-(a+b)$) of 17% (Table 10) and a thousand grain weight response of 10% (Table 12). As fertile shoots survival was largely determined by the time septoria was expressed on the upper leaves (and the treatments had expressed their effect on the epidemic), the remainder of the response was probably due to an increase in fertile grains per ear or a reduction in shrivelled grains lost during combining.

Figure 13. Dose-response curves for specific weight in *Septoria tritici* experiments - overall means

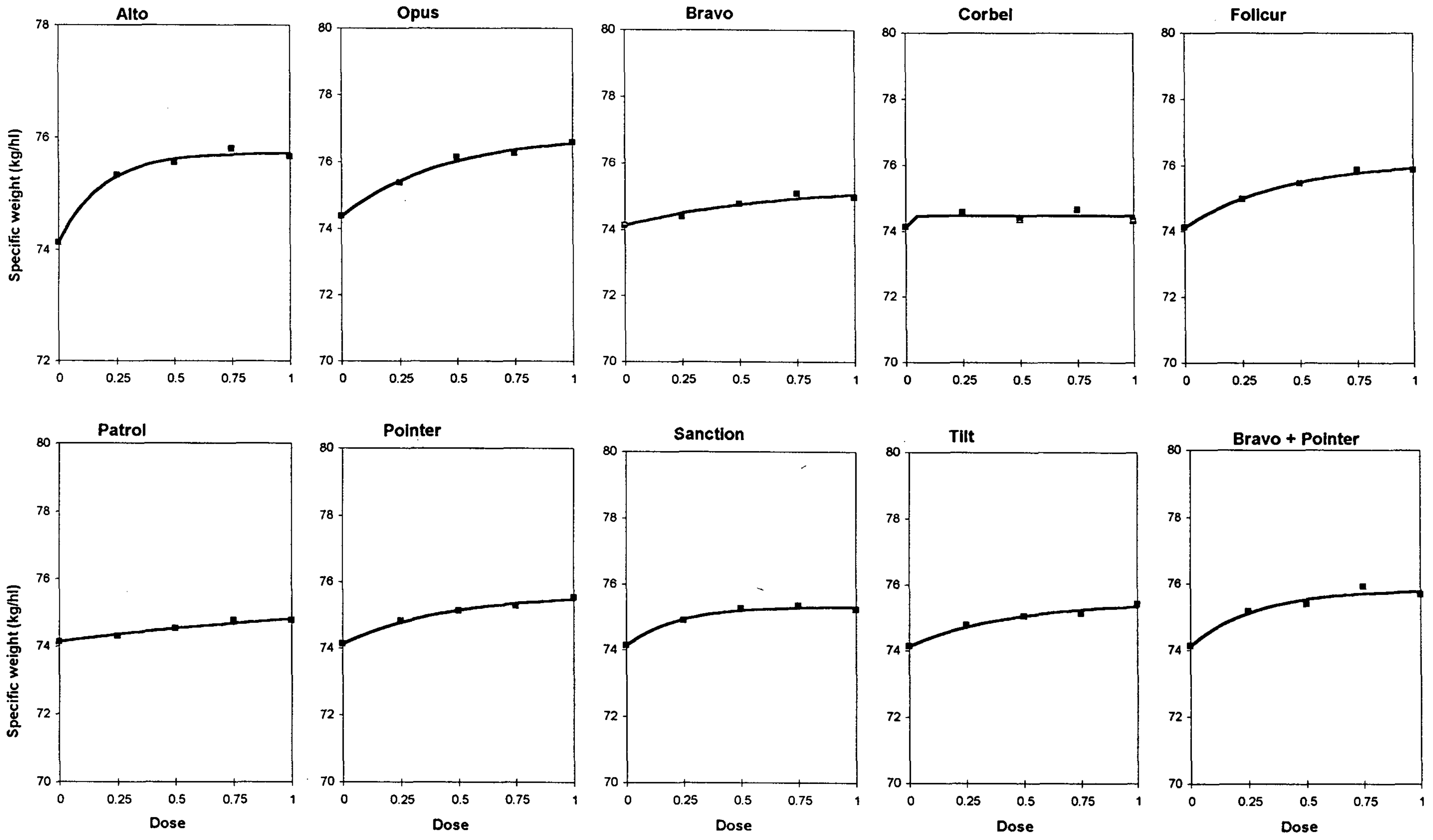


Figure 14. Dose-response curves for thousand grain weight in *Septoria tritici* experiments - overall means

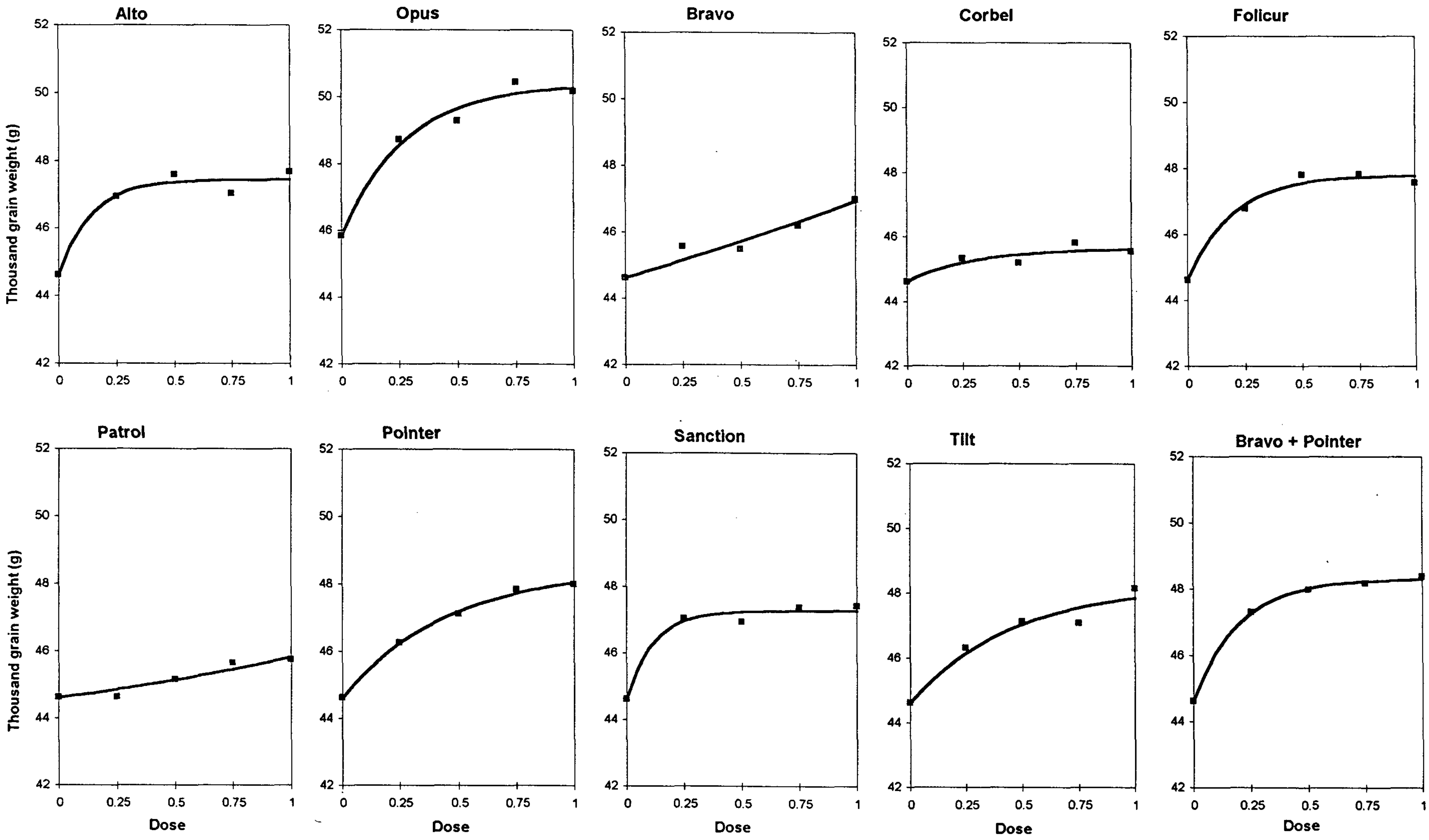


Table 11. Cross-site parameter estimates for fitted product dose response curves - specific weight

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	75.7	-1.6	-5.35	74.1	75.7	98.6
Opus	76.8	-2.4	-2.28	74.4	76.6	98.7
Bravo	75.4	-1.2	-1.43	74.1	75.1	91.3
Corbel	75.5	-0.4	-62.45	74.1	74.5	36.5
Folicur	76.1	-2.0	-2.28	74.1	75.9	99.0
Patrol	75.4	-1.3	-0.76	74.1	74.8	95.9
Pointer	75.6	-1.5	-2.28	74.1	75.5	98.6
Sanction	75.3	-1.2	-4.52	74.1	75.3	97.9
Tilt	75.5	-1.4	-2.27	74.1	75.3	97.1
Bravo + Pointer	75.8	-1.7	-3.50	74.1	75.8	94.9

Table 12. Cross-site parameter estimates for fitted product dose response curves - thousand grain weight

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	47.4	-2.8	-7.12	44.6	47.4	94.2
Opus	50.4	-4.6	-3.62	45.8	50.3	97.2
Bravo	35.5	9.1	0.23	44.6	46.9	90.3
Corbel	45.6	-1.0	-3.34	44.6	45.6	75.9
Folicur	47.8	-3.2	-5.11	44.6	47.8	97.5
Patrol	42.7	1.9	0.49	44.6	45.8	89.2
Pointer	48.5	-3.9	-2.18	44.6	48.1	99.6
Sanction	47.3	-2.7	-8.66	44.6	47.3	96.8
Tilt	48.3	-3.7	-2.17	44.6	47.8	93.3
Bravo + Pointer	48.3	-3.7	-5.01	44.6	48.3	99.8

4.2 Yellow rust experiments

4.2.1 Disease control

Overall mean, eradicant, dose-response curves for yellow rust are shown in Figure 15, with parameter estimates in Table 13. The scatter of points about the fitted curve is greater than for the *S. tritici* data, primarily because the focal nature of the disease increases the error variation in the assessments, unless sampling is made prohibitively intense. Nevertheless, R^2 values indicate that a high proportion of the variation in the data was accounted for by the fitted exponential functions.

The patterns of response are substantially different to those for *S. tritici*. The majority of the control was obtained with the first quarter dose, and thereafter, increasing dose provided only a small, or zero, additional benefit. These highly curved responses are described by high k values (Table 13). In the eradicant situation, there seems little justification for doses above half, when applications are aimed purely at yellow rust control. However, eradicant treatment of yellow rust must be considered as a 'fire brigade' measure. The short latent period between infection and symptom expression means that if applications are delayed even a few days beyond the optimum timing, many infections have already been expressed, or are so near to expression, that systemic fungicides are unable to prevent symptom development. The high lower asymptotes in Figure 15, represented by the a parameters (Table 13), quantify such infections.

Few differences between products were seen, although the morpholine materials, used alone, may have been marginally less effective than some of the conazole products. Overall, mean comparisons against Opus were confounded by lower disease pressure in the experiments in which Opus was included. Comparisons of parameter estimates (Section 6.0) within those experiments, suggest that Opus was as effective, or marginally more effective than the other conazole products.

Table 13. Parameter estimates for fitted product dose response curves - eradicant

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	10.0	33.7	-7.28	43.7	10.0	99.1
Opus	0.2	24.9	-16.81	25.0	0.2	100.0
Corbel	16.1	27.6	-10.11	43.7	16.1	96.7
Folicur	11.1	32.6	-6.26	43.7	11.1	99.2
Patrol	19.3	24.3	-62.45	43.7	19.3	92.5
Pointer	14.7	28.9	-6.54	43.7	14.8	98.5
Sanction	15.7	27.9	-9.09	43.7	15.7	91.8
Tilt	14.9	28.8	-62.45	43.7	14.9	94.2
Bayfidan	12.6	31.1	-7.78	43.7	12.6	99.3
Folicur + Patrol	10.8	32.9	-7.49	43.7	10.8	98.1

The protectant data (Figure 16; Table 14) show that if treatments are applied as soon as a leaf is fully emerged, i.e. prior to, or immediately after, infection has occurred, excellent control of yellow rust can be obtained. The most effective treatments, Opus, Folicur and Folicur + Patrol, all suppressed disease to negligible levels with all doses greater than quarter. Alto was slightly less effective, and Pointer, Sanction, Tilt and Bayfidan, noticeably less active - generally requiring higher doses to obtain comparable control. These results contrast with data collected in the early 1990s, when propiconazole was shown to perform exceptionally well, even at quarter dose. The shapes of the dose-response curves for the 'older' conazoles, may suggest a shift in pathogen sensitivity, which would be detected first at low doses.

The morpholine materials provided useful control, but need to be used in combination with conazoles, for reliable control, due to their short persistence.

Figure 15. Eradicant dose-response curves for yellow rust - overall means

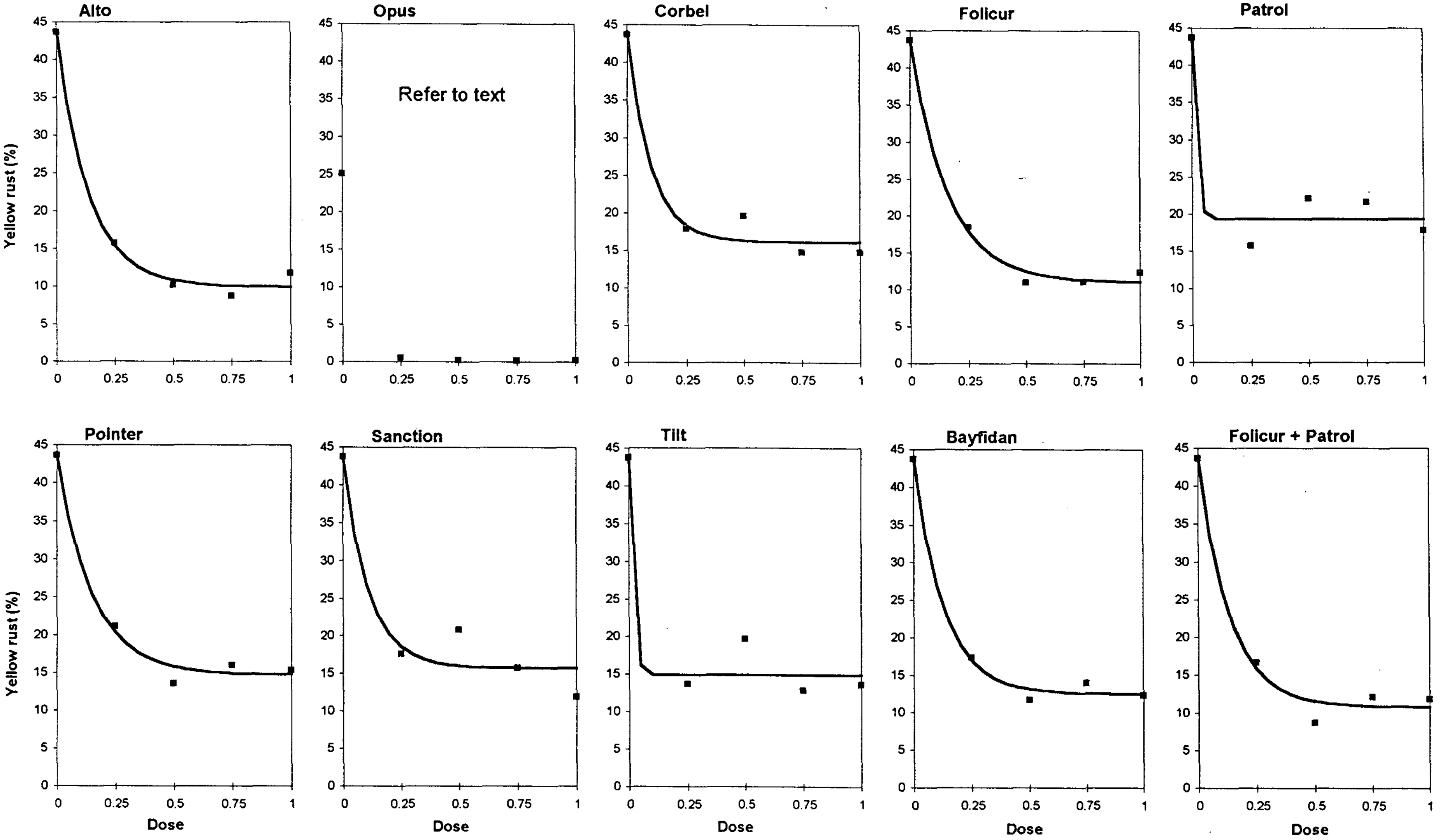


Figure 16. Protectant dose-response curves for yellow rust - overall means

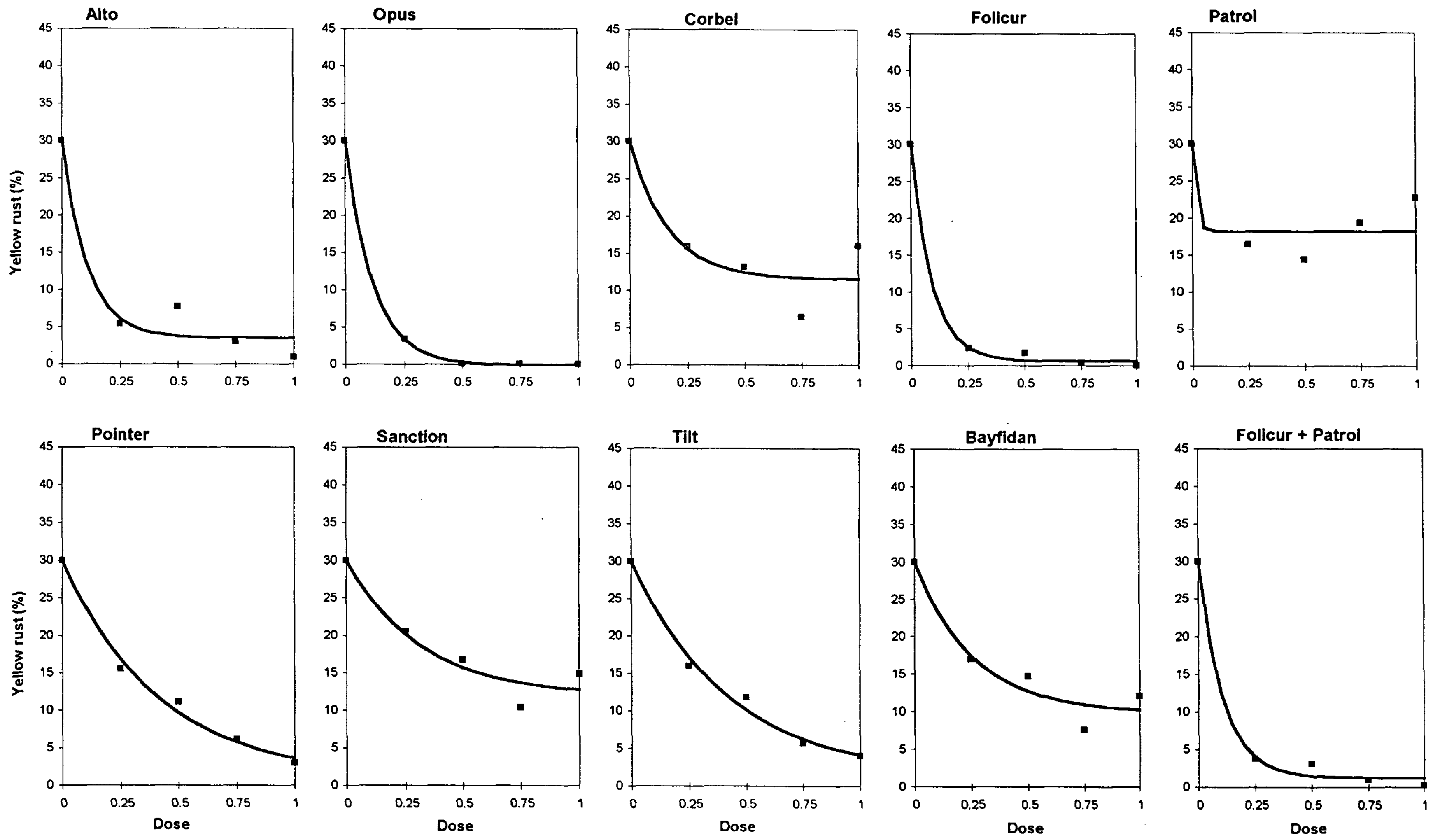


Table 14. Parameter estimates for fitted product dose response curves - protectant

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	3.5	26.5	-9.27	30.0	3.5	94.4
Opus	-0.1	30.1	-8.72	30.0	-0.1	100.0
Corbel	11.6	18.4	-6.07	30.0	11.6	78.3
Folicur	0.6	29.4	-11.11	30.0	-0.6	99.8
Patrol	18.2	11.9	-62.45	30.0	18.2	65.0
Pointer	1.1	28.9	-2.42	30.0	3.6	98.7
Sanction	12.0	18.0	-3.16	30.0	12.8	90.1
Tilt	1.6	28.4	-2.40	30.0	4.2	98.7
Bayfidan	9.9	20.1	-3.93	30.0	10.3	91.1
Folicur + Patrol	1.2	28.8	-9.32	30.0	1.2	99.2

4.2.2 Green leaf area

Eradicant (Figure 17) and protectant (Figure 18) dose-response curves for green leaf area were precise mirror images of the disease dose-responses (Figures 15 and 16). Those products providing more effective disease control, also provided the greatest benefits to green leaf area retention. There was no evidence that higher doses were required to obtain green area benefits than were required to control disease.

R^2 values (Tables 15 and 16) show that a high proportion of the variation in the data was accounted for by the fitted exponential functions.

Table 15. Parameter estimates for fitted product dose response curves - green leaf area, eradicant

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	84.9	-43.5	-7.72	41.4	84.9	99.2
Opus	95.3	-43.9	-9.65	51.4	95.3	100.0
Corbel	77.3	-35.9	-12.85	41.4	77.3	98.0
Folicur	83.9	-42.5	-6.08	41.4	83.8	99.7
Patrol	73.5	-32.1	-62.45	41.4	73.5	95.2
Pointer	78.8	-37.4	-7.13	41.4	78.8	99.3
Sanction	78.2	-36.8	-7.76	41.4	78.2	96.3
Tilt	79.3	-37.9	-62.45	41.4	79.3	97.2
Bayfidan	79.1	-37.7	-9.53	41.4	79.1	100.0
Folicur + Patrol	84.5	-43.1	-62.45	41.4	84.5	99.7

Figure 17. Eradicant dose-response curves for green leaf area in yellow rust experiments - overall means

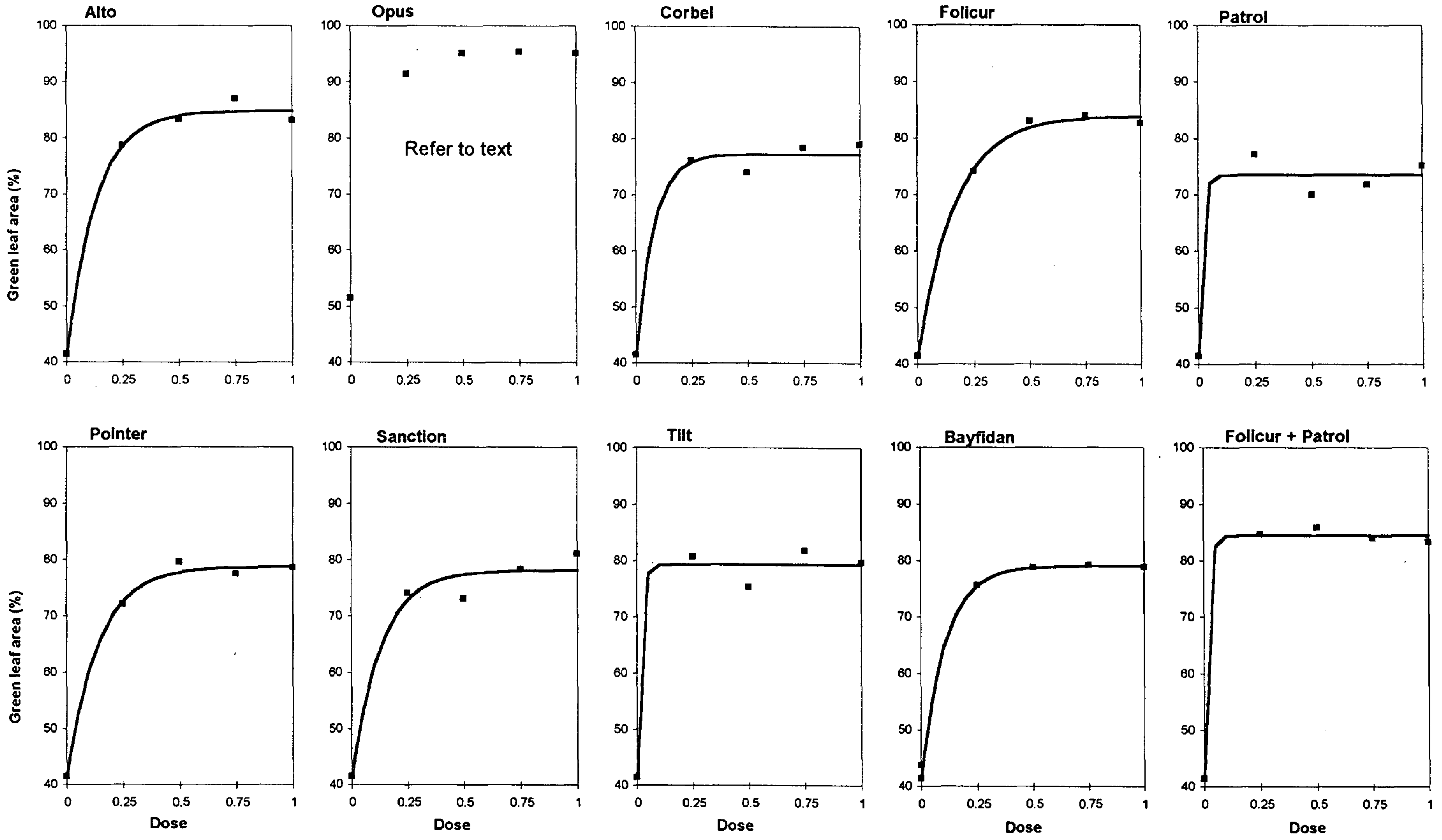


Figure 18. Protectant dose-response curves for green leaf area in yellow rust experiments - overall means

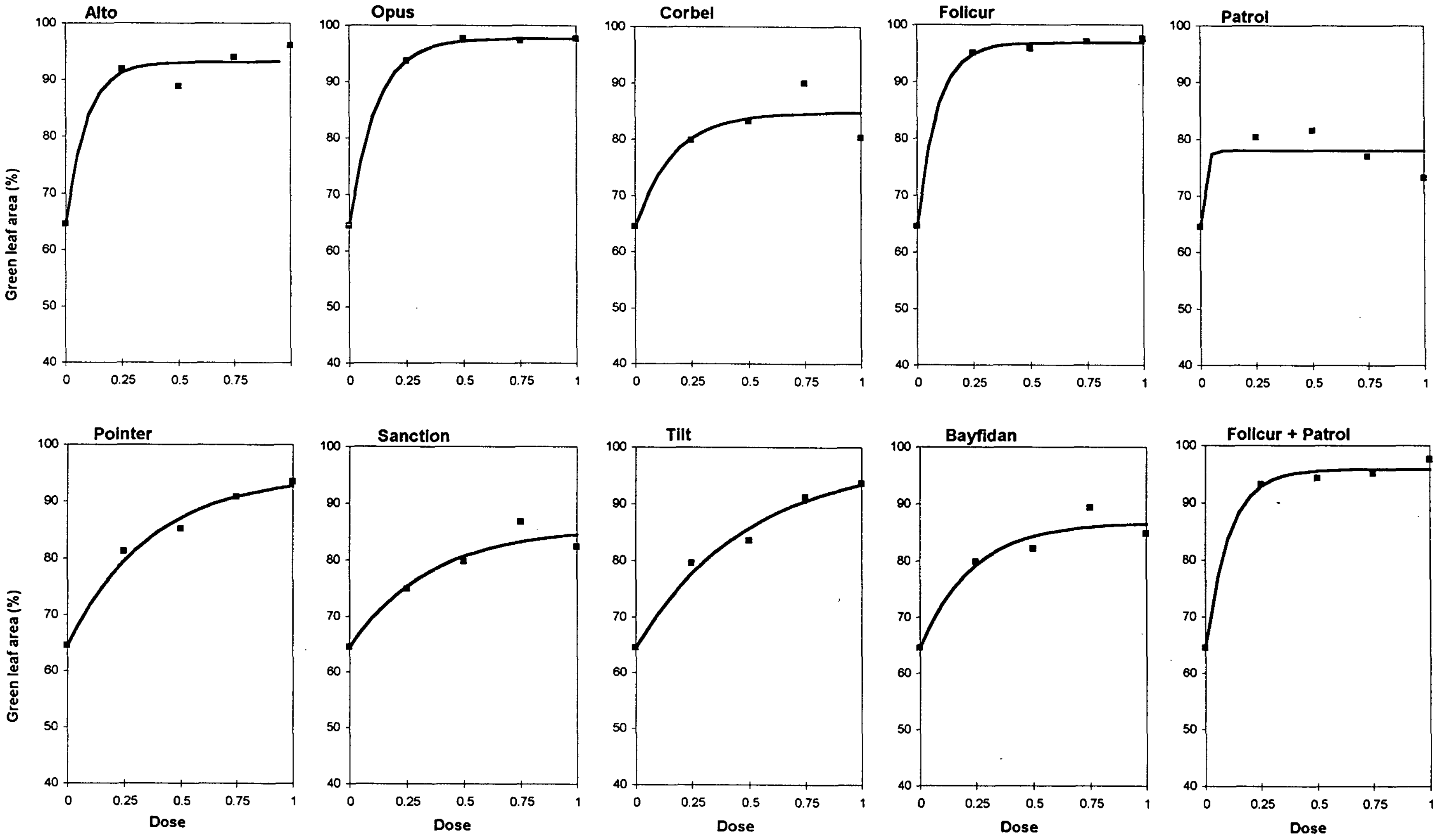


Table 16. Parameter estimates for fitted product dose response curves - green leaf area, protectant

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	93.2	-28.7	-10.94	64.5	93.2	94.6
Opus	97.7	-33.2	-8.52	64.5	97.7	100.0
Corbel	84.9	-20.4	-5.88	64.5	84.8	81.1
Folicur	96.8	-32.4	-11.21	64.5	96.8	99.8
Patrol	78.0	-13.5	-62.45	64.5	78.0	70.2
Pointer	94.7	-30.2	-2.77	64.5	92.8	98.2
Sanction	85.7	-21.2	-2.86	64.5	84.5	91.8
Tilt	97.8	-33.3	-2.03	64.5	93.4	97.9
Bayfidan	86.9	-22.4	-4.33	64.5	86.6	92.9
Folicur + Patrol	95.9	-31.4	-9.41	64.5	95.9	99.1

4.2.3 Grain yield

Yields at the experimental sites were good, with the better products providing mean yields in the region of 9.5 t/ha, with a single fungicide application. A high proportion of the variation in yield (R^2) was accounted for by the fitted exponential functions (Table 17).

Substantial yield responses were recorded to the control of yellow rust (Figure 19). Relative yield responses to different products were in proportion to the efficacy of disease control and maintenance of green leaf area; with responses ((a+be^k)-(a+b)) (Table 17) of approximately 4.0 t/ha to Folicur and Folicur + Patrol, 3.6 t/ha to Alto, and 2.5 - 2.8 t/ha to Pointer, Sanction, Tilt and Bayfidan. Corbel and Patrol gave responses of 2.2 and 1.8 t/ha respectively.

Yield response curves for the most effective products were approaching a plateau by half dose. Similar yields could not be obtained with the less effective products, even at full dose.

There was no evidence that higher doses were required to improve yield than were required to provide effective disease control.

The Opus yield values shown in Figure 19 and Table 17, should be treated with reserve, for the reasons described above. Comparisons of parameter estimates within experiments in which Opus was represented (Section 6.0) show that Opus provided a yield approximately 0.3 t/ha higher than Folicur + Patrol.

Figure 19. Dose-response curves for yield in yellow rust experiments - overall means

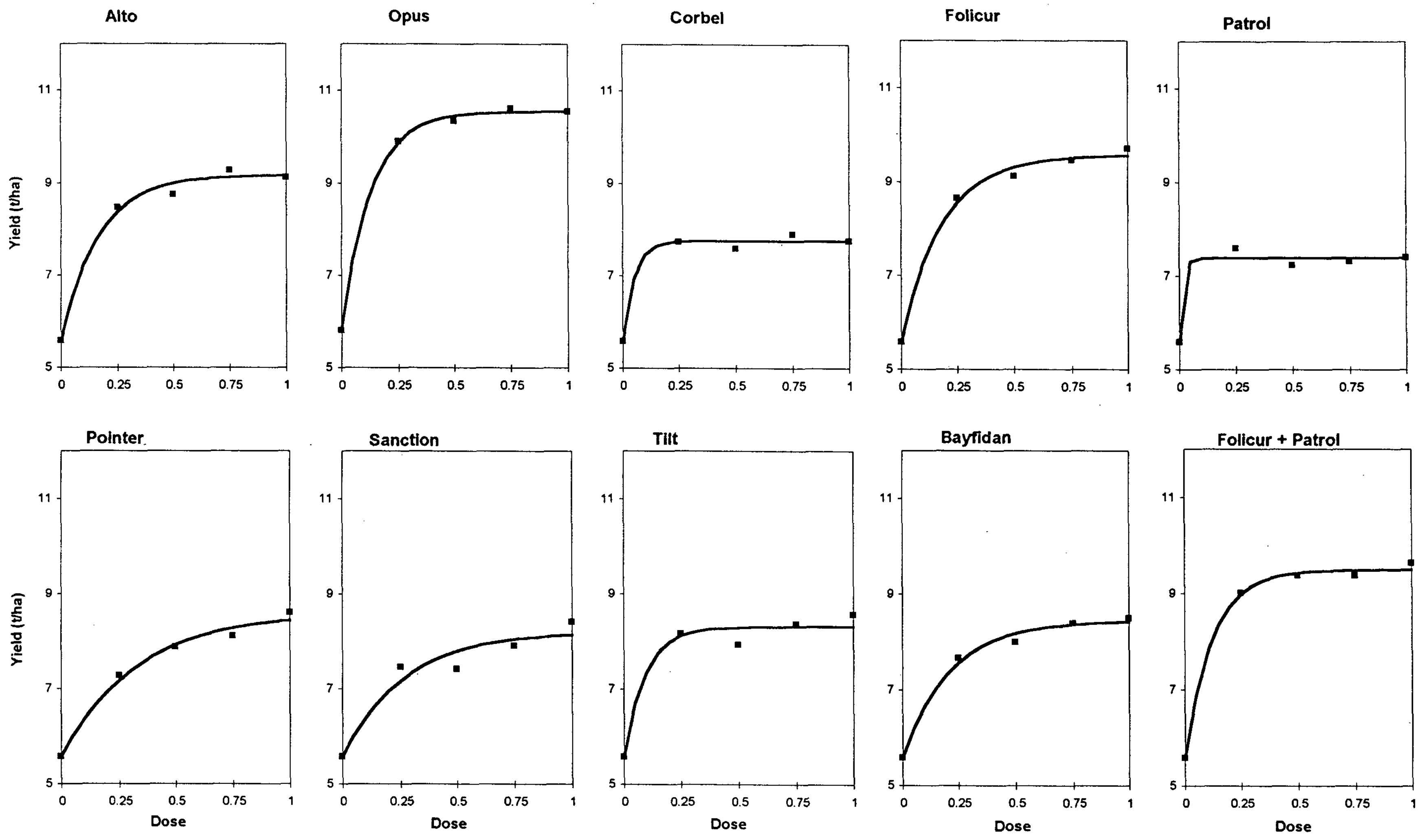


Table 17. Parameter estimates for fitted product dose response curves - yield

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	9.2	-3.6	-6.07	5.58	9.2	98.7
Opus	10.6	-4.7	-7.86	5.81	10.5	99.8
Corbel	7.8	-2.2	-19.86	5.58	7.8	98.3
Folicur	9.6	-4.0	-5.46	5.58	9.6	99.2
Patrol	7.4	-1.8	-62.45	5.58	7.4	96.4
Pointer	8.6	-3.0	-3.02	5.58	8.4	98.3
Sanction	8.2	-2.6	-3.73	5.58	8.1	90.8
Tilt	8.3	-2.7	-10.61	5.58	8.3	95.4
Bayfidan	8.4	-2.9	-4.71	5.58	8.4	98.9
Folicur + Patrol	9.5	-3.9	-8.15	5.58	9.5	99.6

4.2.4 Grain quality

Grain quality dose-response curves for specific weight (Figure 20) and thousand grain weight (Figure 21) mirrored those for yield (Figure 19). Those treatments and doses which most effectively improved yield were also most effective at increasing grain quality. Thousand grain weight responses explained a smaller proportion of the yield response than for the *S. tritici* experiments. This may be a reflection of the earlier and more severe yellow rust epidemic, having a greater impact on fertile grains per ear or the number of shrivelled grains lost during combining.

Table 18. Parameter estimates for fitted product dose response curves - specific weight

Product	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Alto	75.2	-5.5	-11.51	69.8	75.2	96.8
Opus	76.8	-9.7	-9.27	67.2	76.8	100.0
Corbel	73.7	-3.9	-6.62	69.8	73.7	95.0
Folicur	76.0	-6.2	-8.30	69.8	76.0	94.9
Patrol	73.1	-3.3	-62.45	69.8	73.1	84.6
Pointer	77.2	-7.4	-1.75	69.8	75.9	93.4
Sanction	73.4	-3.6	-6.93	69.8	73.4	95.4
Tilt	74.7	-5.0	-5.78	69.8	74.7	99.4
Bayfidan	74.1	-4.4	-62.45	69.8	74.1	94.5
Folicur + Patrol	76.2	-6.4	-11.38	69.8	76.2	97.4

Figure 20. Dose-response curves for specific weight in yellow rust experiments - overall means

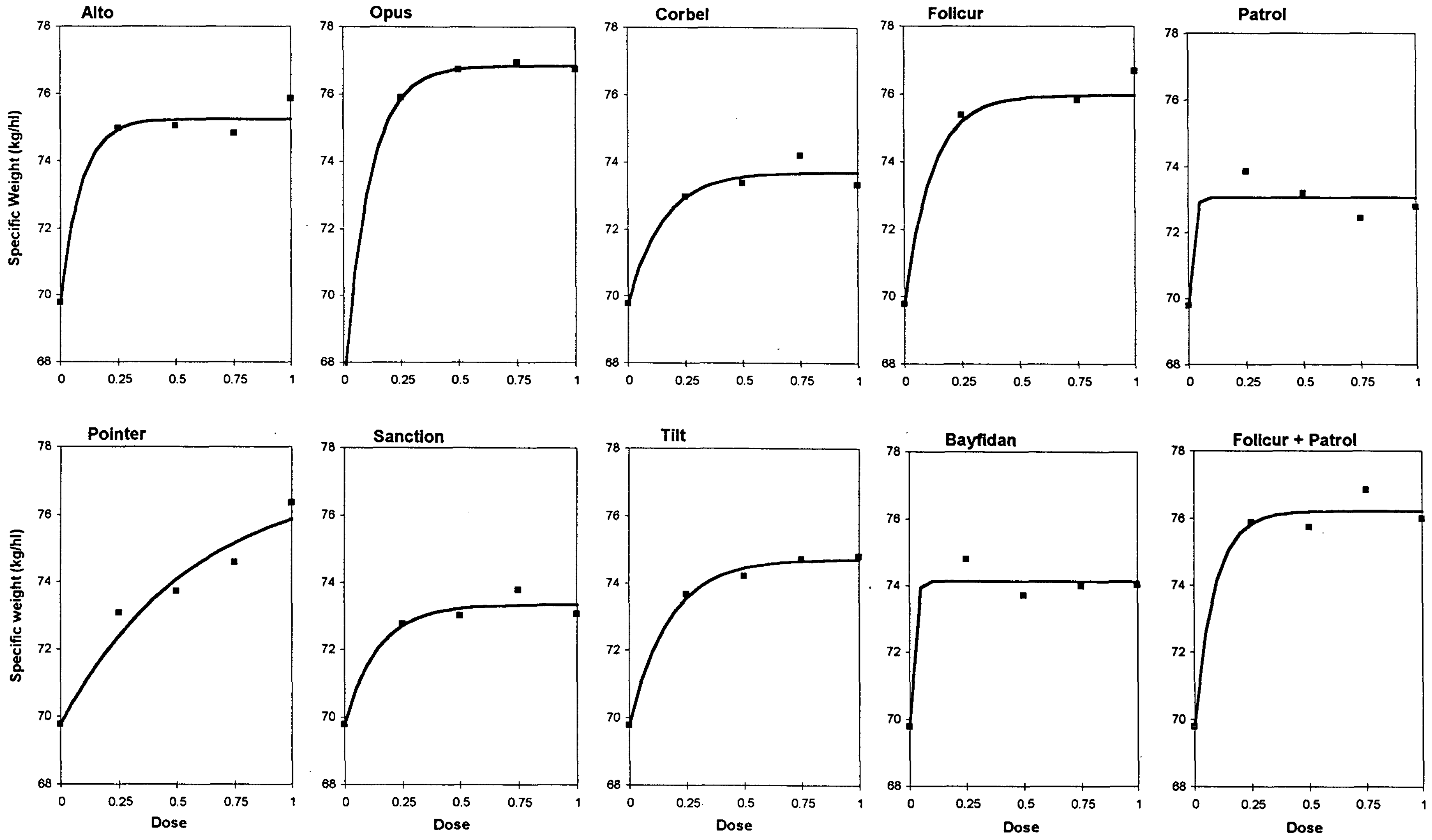


Figure 21. Dose-response curves for thousand grain weight in yellow rust experiments - overall means

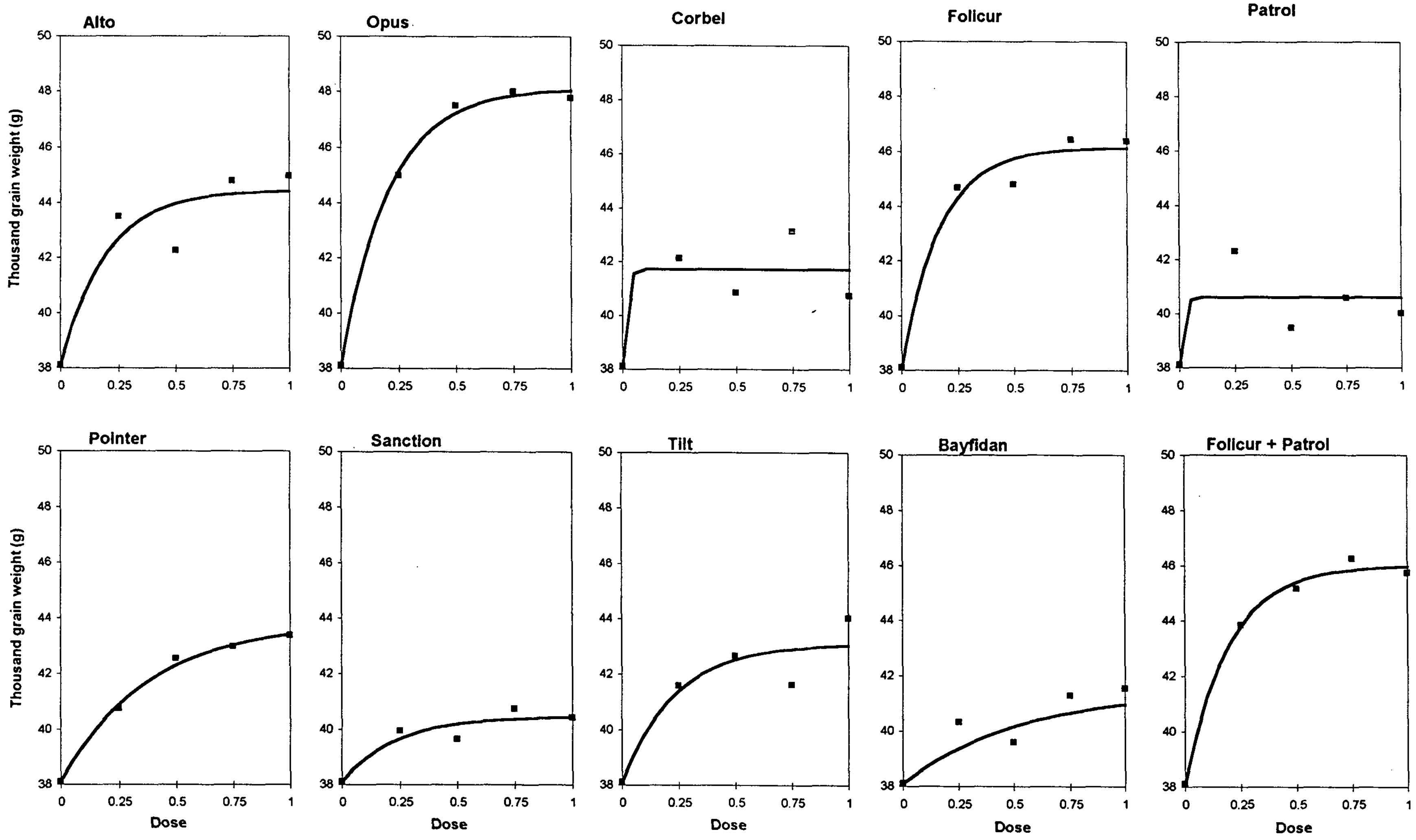


Table 19. Parameter estimates for fitted product dose response curves - thousand grain weight

Product	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Alto	44.5	-6.4	-5.15	38.1	44.4	82.8
Opus	48.1	-10.0	-4.86	38.1	48.0	99.6
Corbel	41.7	-3.6	-62.45	38.1	41.7	63.8
Folicur	46.2	-8.0	-5.96	38.1	46.1	96.6
Patrol	40.6	-2.5	-62.45	38.1	40.6	37.6
Pointer	43.8	-5.7	-2.70	38.1	43.4	99.4
Sanction	40.5	-2.4	-4.36	38.1	40.4	83.9
Tilt	43.1	-5.0	-4.31	38.1	43.0	81.6
Bayfidan	41.5	-3.4	-1.89	38.1	41.4	75.6
Folicur + Patrol	46.0	-7.9	-5.10	38.1	46.0	99.1

4.3 Responses at low disease severity

The Aberdeen site in 1996 provided the best opportunity to quantify the effects of treatment at very low disease severity. *S. tritici* affected 8% of leaf 4 on Julian day 192 and powdery mildew 4% of leaf 3 on day 205. Other leaf layers were affected by only trace of low levels of disease.

4.3.1 Green leaf area

Small improvements, of between 5 - 10% ((a+be^k)-(a+b)), were seen in green leaf area retention, following treatment with some products (Table 20). A small benefit was also seen with Corbel, but a logical dose-response function could not be fitted.

Table 20. Parameter estimates for fitted product dose response curves - green leaf area

	Parameter estimates				
Product	a	b	k	a + b	a+be^k
Alto	85.7	-6.24	-2.27	79.5	85.1
Opus	88.2	-8.74	-4.27	79.5	88.1
Folicur	73.4	6.08	1.00	79.5	90.0
Sanction	86.2	-6.66	-4.57	79.5	86.1
Unix	86.9	-7.39	-2.45	79.5	87.0

4.3.2 Grain yield

Fitted yield responses in the range 0.3 - 0.9 t/ha were recorded for a full dose (Table 21) at this high yield site. Yield response curves were shallow and inconsistent, making judgement of optimum doses uncertain.

Table 21. Parameter estimates for fitted product dose response curves - yield

Product	Parameter estimates				
	a	b	k	a + b	$a+be^k$
Alto	9.9	-0.3	-3.00	9.6	9.9
Opus	10.5	-0.9	-2.60	9.6	10.5
Corbel	10.0	-0.4	-2.17	9.6	10.0
Folicur	10.9	-1.3	-0.94	9.6	10.4
Sanction	21.0	-11.4	-0.05	9.6	10.2
Unix	10.4	-0.7	*	9.6	10.4

5.0 CONCLUSIONS

5.1 Overview

- Robust, comparative, dose-response data sets have been gathered for the most widely used conazole and morpholine active ingredients, against *Septoria tritici* and yellow rust. Experiments are in place to gather comparable data for powdery mildew and brown rust, and to assess strobilurin materials.

- The experiments were successful in separating eradicant and protectant action, whilst using a single spray timing. This technique makes efficient use of research resource.

- The natural error in biological data, makes interpretation of dose-responses from raw data, highly subjective. There is a conflict between the need to quantitatively describe the wide range of variation seen in dose-responses, and the need for simplicity and biological meaning in the mathematical functions used for that description. Not least because any increase in the number of parameters, requires an increase in the measurements (and hence experimental cost) required to support their estimation.

- The exponential function: $y=a+be^{k\ \mathrm{dose}}$, proved both parsimonious and able to describe the range of dose-response variation experienced across a wide range of circumstances. The a, b and k parameters all have clear biological meanings.

- Fitted exponential dose-response curves describing the effect of fungicides on disease, green leaf area, grain yield and grain quality, typically explained a high proportion (over 90%) of the variance in the data. Low R^2 values were generally only found where treatment effects were small.

- Comparative disease control, or yield response, per unit input cost, can be calculated for any product:dose combination, by multiplying dose by fungicide cost in the dose-response functions for each product.

- Dose equivalents, for any combination of products, can be calculated from the fitted exponential functions, for any given level of disease control, yield or grain quality.

- Dose-response curves reflect the fungicide sensitivity distribution of the pathogen population at the test site. The low dose end of the curve is particularly responsive to sensitivity shifts. Dose-response analysis may provide a method of assessing changes in sensitivity, that can be readily related to their impact on farm practice.

- The conclusions below relate to a single treatment applied under high disease pressure, on a disease susceptible variety. Where more resistant cultivars are grown, disease pressure is lower, or the treatment forms part of a two- or three-spray programme, the appropriate dose will be reduced (see Final Reports for Experiments 2 and 3).

- Overall, there were very substantial differences in dose-response curves between fungicide products. Substantial economic benefits would accrue from accounting for these differences when selecting products for particular circumstances and deciding on the appropriate dose to apply.

5.2 *Septoria tritici*

- The mean data from *S. tritici* experiments represented a range of situations, from treatments which were applied shortly after infection, to those applied to well established infections, at the limit of eradicant activity. They provide a realistic representation of the activity which might be expected in commercial use, where spray timing is often compromised by adverse weather and logistical considerations.

- Opus provided the most effective and consistent control of *S. tritici*. Alto, Folicur, Pointer, Sanction, Tilt and Bravo, provided intermediate control.

- Under high disease pressure, on a highly susceptible variety, and across a range of spray timings, a three-quarter dose of Opus was required for consistent control. Where spray timings were optimal, very good control could be obtained with a half dose.

- A half dose of Opus was generally more effective than a full dose of another product.

- The clear distinction, seen in previous experiments, between the control obtained by Folicur and that obtained by other triazoles, appears to have been eroded.

- Where morpholine materials are added to a spray mixture for the control of powdery mildew or rusts, there may be some small benefit to the control of *S.tritici*.

- Bravo and the Bravo + Pointer mixture, provided economical protectant control of *S. tritici*, as effective as the best conazole materials. Eradicant control with Bravo was poor, reflecting its non-systemic action.

5.3 Yellow rust

- The scatter of data points about the fitted dose-response curves, was higher for yellow rust than *S. tritici*: primarily because the focal nature of the disease increases the sampling error in the assessments, unless sampling is made prohibitively intense. Nevertheless, a high proportion of the variance in the data was accounted for by the fitted exponential dose-response functions.

- The short latent period of yellow rust means that treatments to unprotected crops, need to be applied as soon as a newly emerged leaf is exposed to infection. A few days delay can lead to poor control.

- Patterns of dose-response were substantially different to those for *S. tritici*. The majority of the control of yellow rust being obtained with the first quarter dose.

- Provided spray timing is accurate, highly effective and consistent control can be obtained with a half dose of the most effective products (Opus, Folicur or a conazole + morpholine mixture).

- Poor spray timing cannot be compensated for, by increasing dose.

- Evidence from Experiment 3 in this project, suggests that a two- or three-spray programme at low doses provides robust control, and makes the timing of individual treatments somewhat less critical.

- There was some evidence that disease control obtained from low doses of the older conazoles had deteriorated since dose-response studies carried out in the early 1990s; possibly due to shifts in the sensitivity of the *Puccinia striiformis* population.

5.4 Green leaf area effects

- Green leaf area dose-response curves completely mirrored the disease response curves. Those products which were most effective in controlling disease were also most effective in prolonging green leaf area.

- The non-systemic material Bravo, was as effective in prolonging green leaf, in protectant situations against *S. tritici*, as the systemic fungicides.

- There was no evidence that higher doses were required to enhance green area retention, than were required to control disease.

5.5 Grain yield

- The full yield potential of a disease susceptible and responsive variety, such as Riband, will not be achieved with a single treatment (see Experiment 3 Final Report). Nevertheless, substantial responses to the control of *S. tritici* were obtained. Calculations of full and untreated fitted yields, gave responses of 1.4 t/ha for Opus, compared to 1.1 t/ha for Folicur and the Bravo + Pointer mixture, and 0.7 to 0.9 t/ha for the other conazoles. The estimates may be biased slightly in favour of Opus (see text).

- Even under high *S. tritici* pressure, on a susceptible variety, yield responses with the more effective products were approaching a plateau by three-quarters dose.

- Substantial yield responses were recorded to the control of yellow rust: with responses of approximately 4.0 t/ha to Folicur and Folicur + Patrol, and 3.6 t/ha to Alto. Opus yields were approximately 0.3 t/ha higher than those for Folicur + Patrol.

- Yield dose-response curves for the more effective products were approaching a plateau by half dose, where yellow rust was the main disease. Similar yields could not be obtained with the less effective products, even at full dose.

- There was no evidence that higher doses were required to enhance yield, than were required to provide effective control of disease.

5.6 Grain quality

- The majority of the yield response to disease control could be accounted for by increases in thousand grain weight.

- Dose-response curves for specific weight and thousand grain weight, mirrored the yield response curves. If doses are optimised for yield, grain quality will also be optimised.

5.7 Responses at low disease severity

- In the presence of low levels of disease, small benefits to green leaf area retention were obtained from some treatments. A single spray at GS 37-39 provided a small but economic yield benefit.

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6.0 APPENDIX - PARAMETER ESTIMATE SUMMARY TABLES

6.1 *Septoria tritici* experiments - dose-response parameter estimates

6.1.1 *Septoria tritici*

Experiment	Leaf	Date	Product	a	b	k	a+b	$a+be^k$
1	2	188	Alto	2.3	9.5	-9.2	11.8	2.3
			Bravo	2.3	9.4	-7.3	11.8	2.3
			Folicur	0.1	11.7	-3.0	11.8	0.7
			Pointer	0.3	11.5	-1.0	11.8	4.7
			Tilt	1.6	10.2	-5.2	11.8	1.7
			Opus	*	*	*	11.8	*
			Corbel	2.0	9.7	-2.1	11.8	3.3
			Patrol	*	*	*	11.8	*
			Sanction	2.2	9.6	-6.1	11.8	2.2
			Bravo+Pointer	1.5	10.3	*	11.8	1.5
1	3	175	Alto	2.9	12.4	-2.1	15.3	4.5
			Bravo	7.9	7.5	-2.3	15.3	8.6
			Folicur	4.7	10.6	-3.1	15.3	5.2
			Pointer	6.6	8.7	-1.4	15.3	8.9
			Tilt	5.1	10.3	-3.6	15.3	5.4
			Opus	*	*	*	15.3	*
			Corbel	8.6	6.7	-1.4	15.3	10.2
			Patrol	11.0	4.4	-6.6	15.3	11.0
			Sanction	0.4	15.0	-1.9	15.3	2.6
			Bravo+Pointer	7.3	8.1	*	15.3	7.3
2	1	193	Alto	*	*	*	15.9	*
			Bravo	0.6	15.3	-1.9	15.9	2.9
			Folicur	15.4	0.5	-14.6	15.9	15.4
			Pointer	*	*	*	15.9	*
			Tilt	*	*	*	15.9	*
			Opus	7.5	8.4	-2.1	15.9	8.5
			Corbel	*	*	*	15.9	*
			Patrol	*	*	*	15.9	*
			Sanction	*	*	*	15.9	*
			Bravo+Pointer	-1.2	17.0	-1.6	15.9	2.2
2	1	178	Alto	9.9	0.7	*	10.6	9.9
			Bravo	0.7	9.9	-2.7	10.6	1.3
			Folicur	*	*	*	10.6	*
			Pointer	9.5	1.1	-0.9	10.6	9.9
			Tilt	*	*	*	10.6	*
			Opus	5.9	4.7	-4.1	10.6	5.9
			Corbel	*	*	*	10.6	*
			Patrol	*	*	*	10.6	*
			Sanction	*	*	*	10.6	*
			Bravo+Pointer	0.9	9.7	-3.4	10.6	1.2
2	2	193	Alto	*	*	*	30.8	*
			Bravo	-12.9	43.8	-1.1	30.8	2.2
			Folicur	*	*	*	30.8	*
			Pointer	*	*	*	30.8	*
			Tilt	*	*	*	30.8	*

			Opus	*	*	*	30.8	*
			Corbel	*	*	*	30.8	*
			Patrol	*	*	*	30.8	*
			Sanction	*	*	*	30.8	*
			Bravo+Pointer	0.0	30.8	-3.1	30.8	1.4
2	2	178	Alto	3.7	15.2	-1.5	18.9	7.0
			Bravo	0.9	18.0	-4.8	18.9	1.1
			Folicur	4.2	14.7	-3.0	18.9	4.9
			Pointer	11.2	7.7	-1.6	18.9	12.7
			Tilt	-5.0	23.8	-0.7	18.9	7.4
			Opus	0.7	18.2	-8.1	18.9	0.7
			Corbel	14.3	4.5	*	18.9	14.3
			Patrol	14.5	4.3	-4.6	18.9	14.6
			Sanction	7.1	11.8	-4.2	18.9	7.3
			Bravo+Pointer	0.2	18.6	-5.4	18.9	0.3
2	3	178	Alto	9.9	25.8	-2.4	35.7	12.2
			Bravo	9.8	26.0	-3.5	35.7	10.6
			Folicur	-6.9	42.6	-1.0	35.7	9.6
			Pointer	21.1	14.6	-1.3	35.7	25.0
			Tilt	*	*	*	35.7	*
			Opus	0.9	34.8	-4.1	35.7	1.5
			Corbel	*	*	*	35.7	*
			Patrol	26.7	9.0	*	35.7	26.7
			Sanction	*	*	*	35.7	*
			Bravo+Pointer	7.6	28.1	-9.9	35.7	7.6
2	4	159	Alto	*	*	*	22.9	*
			Bravo	19.7	3.2	-4.3	22.9	19.7
			Folicur	14.4	8.5	-3.1	22.9	14.8
			Pointer	*	*	*	22.9	*
			Tilt	20.0	2.9	*	22.9	20.0
			Opus	2.2	20.7	-2.0	22.9	5.0
			Corbel	*	*	*	22.9	*
			Patrol	*	*	*	22.9	*
			Sanction	13.1	9.8	-4.5	22.9	13.2
			Bravo+Pointer	17.6	5.3	-6.4	22.9	17.6
2	5	159	Alto	*	*	*	40.8	*
			Bravo	33.5	7.3	*	40.8	33.5
			Folicur	31.2	9.7	*	40.8	31.2
			Pointer	*	*	*	40.8	*
			Tilt	*	*	*	40.8	*
			Opus	13.8	27.0	-3.3	40.8	14.8
			Corbel	19.3	21.6	-1.4	40.8	24.4
			Patrol	*	*	*	40.8	*
			Sanction	*	*	*	40.8	*
			Bravo+Pointer	*	*	*	40.8	*
3	1	197	Alto	6.3	18.0	-3.4	24.3	6.9
			Bravo	3.9	20.4	-3.0	24.3	4.9
			Folicur	6.3	17.9	-4.2	24.3	6.6
			Pointer	6.4	17.9	-3.3	24.3	7.0
			Tilt	7.4	16.9	*	24.3	7.4
			Opus	6.0	18.3	-7.6	24.3	6.0
			Corbel	14.4	9.9	-2.4	24.3	15.3

			Patrol	*	*	*	24.3	*
			Sanction	9.6	14.7	-6.9	24.3	9.6
			Bravo+Pointer	0.2	24.0	-6.6	24.3	0.3
3	2	176	Alto	4.0	30.4	-2.3	34.4	7.1
			Bravo	25.9	8.5	-2.2	34.4	26.9
			Folicur	5.0	29.4	-4.6	34.4	5.3
			Pointer	7.5	26.9	-1.4	34.4	14.3
			Tilt	15.7	18.8	-8.4	34.4	15.7
			Opus	4.9	29.6	-6.3	34.4	4.9
			Corbel	*	*	*	34.4	*
			Patrol	17.1	17.3	-0.9	34.4	24.2
			Sanction	9.2	25.2	-2.3	34.4	11.7
			Bravo+Pointer	15.0	19.5	-9.1	34.4	15.0
3	3	176	Alto	####	299.3	-0.1	54.3	21.6
			Bravo	*	*	*	54.3	*
			Folicur	*	*	*	54.3	*
			Pointer	*	*	*	54.3	*
			Tilt	40.2	14.2	-1.5	54.3	43.2
			Opus	-5.1	59.4	-1.4	54.3	10.3
			Corbel	*	*	*	54.3	*
			Patrol	47.6	6.7	-7.3	54.3	47.6
			Sanction	*	*	*	54.3	*
			Bravo+Pointer	*	*	*	54.3	*
4	2	176	Alto	4.7	12.5	-4.0	17.3	4.9
			Bravo	*	*	*	17.3	*
			Folicur	0.9	16.4	-5.8	17.3	0.9
			Pointer	6.8	10.5	-4.9	17.3	6.9
			Tilt	-2.2	19.5	-1.3	17.3	2.9
			Opus	*	*	*	17.3	*
			Corbel	*	*	*	17.3	*
			Patrol	13.5	3.8	-5.9	17.3	13.5
			Sanction	-0.7	18.0	-1.9	17.3	1.9
			Bravo+Pointer	4.8	12.5	-5.1	17.3	4.9
4	3	189	Alto	28.8	22.4	-2.1	51.2	31.6
			Bravo	*	*	*	51.2	*
			Folicur	13.0	38.2	-2.2	51.2	17.1
			Pointer	34.0	17.2	-1.3	51.2	38.8
			Tilt	5.1	46.1	-0.4	51.2	35.2
			Opus	*	*	*	51.2	*
			Corbel	*	*	*	51.2	*
			Patrol	45.1	6.1	-8.8	51.2	45.1
			Sanction	31.3	19.9	-3.5	51.2	31.9
			Bravo+Pointer	31.2	20.0	-4.6	51.2	31.4
4	3	171	Alto	11.3	9.9	*	21.2	11.3
			Bravo	20.3	0.9	*	21.2	20.3
			Folicur	7.2	14.1	-3.3	21.2	7.6
			Pointer	12.2	9.0	-1.7	21.2	13.8
			Tilt	-3.7	24.9	-0.5	21.2	11.8
			Opus	*	*	*	21.2	*
			Corbel	*	*	*	21.2	*
			Patrol	*	*	*	21.2	*
			Sanction	10.6	10.6	-3.7	21.2	10.9

			Bravo+Pointer	15.5	5.7	*	21.2	15.5
4	4	171	Alto	8.8	29.3	-0.8	38.1	22.2
			Bravo	36.4	1.7	-3.7	38.1	36.5
			Folicur	10.0	28.1	-1.2	38.1	18.8
			Pointer	30.6	7.5	*	38.1	30.6
			Tilt	23.4	14.7	-1.8	38.1	25.8
			Opus	*	*	*	38.1	*
			Corbel	36.2	1.9	*	38.1	36.2
			Patrol	*	*	*	38.1	*
			Sanction	23.7	14.4	-3.7	38.1	24.1
			Bravo+Pointer	29.3	8.8	*	38.1	29.3
5	1	185	Alto	1.5	7.6	*	9.1	1.5
			Bravo	1.7	7.4	*	9.1	1.7
			Folicur	0.5	8.6	-11.2	9.1	0.6
			Pointer	1.3	7.8	-3.7	9.1	1.5
			Tilt	0.7	8.4	-8.7	9.1	0.7
			Opus	0.2	8.9	-13.1	9.1	0.2
			Corbel	6.6	2.5	*	9.1	6.6
			Patrol	4.1	5.0	-4.6	9.1	4.2
			Sanction	0.9	8.2	-5.3	9.1	0.9
			Bravo+Pointer	0.6	8.5	-12.0	9.1	0.6
5	2	185	Alto	2.4	10.5	-6.9	12.9	2.4
			Bravo	2.6	10.3	*	12.9	2.6
			Folicur	1.0	11.9	-10.2	12.9	1.0
			Pointer	2.5	10.4	-2.6	12.9	3.2
			Tilt	0.7	12.2	-3.8	12.9	1.0
			Opus	0.3	12.6	-15.3	12.9	0.3
			Corbel	9.2	3.7	*	12.9	9.2
			Patrol	7.1	5.8	-10.4	12.9	7.1
			Sanction	1.7	11.2	-4.5	12.9	1.9
			Bravo+Pointer	1.6	11.4	-8.6	12.9	1.6
5	3	185	Alto	10.0	33.2	-3.3	43.2	11.2
			Bravo	14.9	28.3	-14.2	43.2	14.9
			Folicur	8.7	34.5	-5.8	43.2	8.8
			Pointer	15.6	27.7	-4.3	43.2	15.9
			Tilt	12.8	30.4	-1.6	43.2	18.7
			Opus	4.6	38.6	-8.5	43.2	4.6
			Corbel	31.7	11.5	-0.9	43.2	36.6
			Patrol	36.5	6.7	-2.8	43.2	36.9
			Sanction	5.7	37.5	-2.3	43.2	9.3
			Bravo+Pointer	7.0	36.2	-3.7	43.2	7.9
5	3	172	Alto	2.7	10.4	-7.1	13.1	2.7
			Bravo	5.0	8.1	*	13.1	5.0
			Folicur	2.6	10.4	-5.5	13.1	2.7
			Pointer	2.8	10.2	-4.7	13.1	2.9
			Tilt	4.4	8.6	*	13.1	4.4
			Opus	1.8	11.3	*	13.1	1.8
			Corbel	6.5	6.5	*	13.1	6.5
			Patrol	7.8	5.3	*	13.1	7.8
			Sanction	2.3	10.8	-5.4	13.1	2.3
			Bravo+Pointer	3.2	9.9	-7.2	13.1	3.2
5	4	172	Alto	24.2	29.4	-1.0	53.6	35.0

			Bravo	48.6	5.0	*	53.6	48.6
			Folicur	38.2	15.4	-2.2	53.6	39.8
			Pointer	-4.1	57.7	-0.3	53.6	37.7
			Tilt	*	*	*	53.6	*
			Opus	10.2	43.4	-1.6	53.6	18.5
			Corbel	*	*	*	53.6	*
			Patrol	*	*	*	53.6	*
			Sanction	*	*	*	53.6	*
			Bravo+Pointer	2.1	51.5	-0.4	53.6	35.0
6	2	190	Alto	1.2	6.0	-2.3	7.2	1.8
			Bravo	-46.4	53.6	0.0	7.2	4.9
			Folicur	1.6	5.6	-10.5	7.2	1.6
			Pointer	0.9	6.3	-0.8	7.2	3.8
			Tilt	0.6	6.6	-1.9	7.2	1.6
			Opus	0.2	7.0	-6.2	7.2	0.2
			Corbel	*	*	*	7.2	*
			Patrol	5.7	1.4	*	7.2	5.7
			Sanction	-5.2	12.4	-0.5	7.2	2.0
			Bravo+Pointer	4.2	3.0	*	7.2	4.2
6	3	190	Alto	-18.6	51.3	-0.5	32.7	13.6
			Bravo	15.2	17.5	-1.1	32.7	21.1
			Folicur	9.8	22.9	-2.6	32.7	11.5
			Pointer	25.5	7.2	*	32.7	25.5
			Tilt	18.2	14.5	-2.7	32.7	19.1
			Opus	4.2	28.5	-5.8	32.7	4.3
			Corbel	30.7	2.0	*	32.7	30.7
			Patrol	23.7	9.0	-0.6	32.7	28.7
			Sanction	17.1	15.6	-2.2	32.7	18.9
			Bravo+Pointer	*	*	*	32.7	*
6	3	179	Alto	-3.6	17.5	-1.1	13.9	2.2
			Bravo	*	*	*	13.9	*
			Folicur	3.2	10.7	-6.0	13.9	3.3
			Pointer	4.8	9.1	-1.9	13.9	6.1
			Tilt	6.2	7.7	-4.1	13.9	6.4
			Opus	1.0	12.8	-4.3	13.9	1.2
			Corbel	11.3	2.6	-6.5	13.9	11.3
			Patrol	*	*	*	13.9	*
			Sanction	3.5	10.3	-2.7	13.9	4.2
			Bravo+Pointer	-6.9	20.8	-0.5	13.9	5.7
6	4	179	Alto	*	*	*	29.4	*
			Bravo	*	*	*	29.4	*
			Folicur	10.3	19.1	-3.8	29.4	10.8
			Pointer	16.6	12.9	-1.7	29.4	19.0
			Tilt	-4.9	34.3	-0.4	29.4	18.1
			Opus	3.5	25.9	-2.9	29.4	4.9
			Corbel	*	*	*	29.4	*
			Patrol	*	*	*	29.4	*
			Sanction	14.3	15.2	-2.2	29.4	16.0
			Bravo+Pointer	-31.9	61.3	-0.2	29.4	20.5

6.1.2 Green leaf area

Experiment	Leaf	Date	Product	a	b	k	a+b	$a+be^k$
1	2	188	Alto	91.7	-15.1	-7.8	76.7	91.7
			Bravo	89.0	-12.3	-5.2	76.7	88.9
			Folicur	100.7	-24.0	-1.6	76.7	95.7
			Pointer	88.8	-12.2	-2.3	76.7	87.6
			Tilt	90.3	-13.6	-5.8	76.7	90.2
			Opus	*	*	*	76.7	*
			Corbel	90.8	-14.1	-2.1	76.7	89.0
			Patrol	*	*	*	76.7	*
			Sanction	89.0	-12.3	-8.0	76.7	89.0
			Bravo+Pointer	92.6	-15.9	-10.1	76.7	92.5
1	3	175	Alto	*	*	*	70.5	*
			Bravo	246.2	-175.7	-0.1	70.5	79.0
			Folicur	95.8	-25.4	-1.9	70.5	92.1
			Pointer	111.2	-40.8	-0.5	70.5	85.3
			Tilt	90.5	-20.1	-3.1	70.5	89.6
			Opus	*	*	*	70.5	*
			Corbel	*	*	*	70.5	*
			Patrol	79.3	-8.8	-4.2	70.5	79.2
			Sanction	92.9	-22.5	-3.9	70.5	92.5
			Bravo+Pointer	89.5	-19.0	-14.7	70.5	89.4
2	1	178	Alto	84.5	-2.4	*	82.1	84.5
			Bravo	88.2	-6.1	-9.7	82.1	88.2
			Folicur	83.0	-1.0	*	82.1	83.0
			Pointer	82.4	-0.3	*	82.1	82.4
			Tilt	*	*	*	82.1	*
			Opus	87.6	-5.5	-2.3	82.1	87.0
			Corbel	*	*	*	82.1	*
			Patrol	*	*	*	82.1	*
			Sanction	*	*	*	82.1	*
			Bravo+Pointer	96.6	-14.5	-1.0	82.1	91.0
2	1	193	Alto	*	*	*	31.4	*
			Bravo	66.2	-34.8	-1.4	31.4	57.9
			Folicur	*	*	*	31.4	*
			Pointer	*	*	*	31.4	*
			Tilt	*	*	*	31.4	*
			Opus	40.6	-9.2	-3.2	31.4	40.2
			Corbel	*	*	*	31.4	*
			Patrol	*	*	*	31.4	*
			Sanction	*	*	*	31.4	*
			Bravo+Pointer	2946.2	-2914.8	0.0	31.4	65.1
2	2	178	Alto	85.4	-21.1	-3.5	64.3	84.7
			Bravo	85.4	-21.1	-11.8	64.3	85.4
			Folicur	83.3	-19.0	-15.5	64.3	83.3
			Pointer	76.0	-11.7	-2.5	64.3	75.0
			Tilt	96.1	-31.8	-1.1	64.3	85.7
			Opus	90.1	-25.9	-5.4	64.3	90.0
			Corbel	73.0	-8.7	*	64.3	73.0
			Patrol	78.9	-14.6	-0.9	64.3	73.0
			Sanction	80.3	-16.1	-7.6	64.3	80.3

			Bravo+Pointer	88.4	-24.1	-6.0	64.3	88.3
2	2	gl193	Alto	3.2	-2.7	-2.5	0.4	2.9
			Bravo	54.0	-53.6	-1.9	0.4	46.2
			Folicur	*	*	*	0.4	*
			Pointer	2.8	-2.4	*	0.4	2.8
			Tilt	*	*	*	0.4	*
			Opus	32.3	-31.9	-3.5	0.4	31.4
			Corbel	3.4	-3.0	*	0.4	3.4
			Patrol	*	*	*	0.4	*
			Sanction	*	*	*	0.4	*
			Bravo+Pointer	50.6	-50.2	-2.1	0.4	44.2
2	3	178	Alto	85.8	-64.8	-1.3	21.0	67.6
			Bravo	73.0	-52.0	-3.7	21.0	71.7
			Folicur	81.2	-60.2	-1.6	21.0	68.7
			Pointer	*	*	*	21.0	*
			Tilt	134.1	-113.1	-0.4	21.0	55.9
			Opus	79.4	-58.4	-4.8	21.0	78.9
			Corbel	32.6	-11.6	*	21.0	32.7
			Patrol	*	*	*	21.0	*
			Sanction	52.3	-31.3	-2.8	21.0	50.5
			Bravo+Pointer	69.1	-48.1	-8.6	21.0	69.1
2	4	157	Alto	*	*	*	69.1	*
			Bravo	71.6	-2.5	-2.2	69.1	71.4
			Folicur	86.1	-17.0	-0.8	69.1	78.6
			Pointer	*	*	*	69.1	*
			Tilt	74.4	-5.3	*	69.1	74.4
			Opus	95.1	-26.0	-1.4	69.1	89.0
			Corbel	69.1	0.0	*	69.1	69.1
			Patrol	*	*	*	69.1	*
			Sanction	78.1	-9.0	*	69.1	78.1
			Bravo+Pointer	78.9	-9.8	*	69.1	79.0
2	5	157	Alto	26.3	-17.4	-0.4	8.8	14.1
			Bravo	*	*	*	8.8	*
			Folicur	40.8	-31.9	-0.6	8.8	23.2
			Pointer	14.2	-5.3	*	8.8	14.2
			Tilt	11.0	-2.1	*	8.8	11.0
			Opus	34.0	-25.2	-3.7	8.8	33.4
			Corbel	11.0	-2.1	*	8.8	11.0
			Patrol	*	*	*	8.8	*
			Sanction	19.1	-10.3	-6.6	8.8	19.1
			Bravo+Pointer	345.9	-337.1	0.0	8.8	23.1
3	1	197	Alto	87.9	-18.2	-3.6	69.7	87.4
			Bravo	90.1	-20.4	-1.8	69.7	86.8
			Folicur	89.1	-19.4	-2.9	69.7	88.0
			Pointer	89.4	-19.7	-2.5	69.7	87.7
			Tilt	84.8	-15.2	*	69.7	84.8
			Opus	88.8	-19.2	-7.0	69.7	88.8
			Corbel	75.7	-6.0	-4.1	69.7	75.6
			Patrol	*	*	*	69.7	*
			Sanction	83.7	-14.0	-4.4	69.7	83.5
			Bravo+Pointer	92.4	-22.7	-6.6	69.7	92.3
3	2	176	Alto	95.8	-31.7	-2.3	64.1	92.7

			Bravo	74.3	-10.2	-1.3	64.1	71.7
			Folicur	94.6	-30.4	-4.3	64.1	94.2
			Pointer	92.1	-28.0	-1.3	64.1	84.5
			Tilt	82.4	-18.2	-9.3	64.1	82.4
			Opus	93.9	-29.7	-6.0	64.1	93.8
			Corbel	*	*	*	64.1	*
			Patrol	85.6	-21.5	-0.8	64.1	76.0
			Sanction	87.6	-23.5	-3.0	64.1	86.4
			Bravo+Pointer	84.2	-20.1	-8.0	64.1	84.3
3	3	176	Alto	230.5	-208.2	-0.3	22.3	72.7
			Bravo	*	*	*	22.3	*
			Folicur	242.8	-220.5	-0.3	22.3	80.8
			Pointer	63.1	-40.8	-1.2	22.3	50.9
			Tilt	39.5	-17.2	-2.9	22.3	38.6
			Opus	105.9	-83.6	-1.6	22.3	88.2
			Corbel	*	*	*	22.3	*
			Patrol	26.1	-3.8	*	22.3	26.1
			Sanction	83.7	-61.4	-0.6	22.3	51.3
			Bravo+Pointer	*	*	*	22.3	*
4	2	189	Alto	75.7	-29.4	-6.5	46.3	75.7
			Bravo	*	*	*	46.3	*
			Folicur	85.4	-39.1	-8.6	46.3	85.4
			Pointer	74.8	-28.5	-6.1	46.3	74.7
			Tilt	87.9	-41.6	-2.6	46.3	84.8
			Opus	*	*	*	46.3	*
			Corbel	47.7	-1.4	*	46.3	47.7
			Patrol	69.1	-22.9	-1.2	46.3	62.1
			Sanction	86.0	-39.7	-3.7	46.3	85.0
			Bravo+Pointer	80.9	-34.6	-5.6	46.3	80.8
4	3	171	Alto	103.2	-38.3	-0.7	65.0	85.0
			Bravo	67.7	-2.7	*	65.0	67.7
			Folicur	88.1	-23.1	-4.6	65.0	87.9
			Pointer	77.3	-12.3	*	65.0	77.3
			Tilt	*	*	*	65.0	*
			Opus	*	*	*	65.0	*
			Corbel	*	*	*	65.0	*
			Patrol	68.4	-3.4	*	65.0	68.4
			Sanction	81.1	-16.2	-5.0	65.0	81.0
			Bravo+Pointer	77.0	-12.0	-11.0	65.0	76.9
4	3	189	Alto	18.6	-12.6	-2.5	6.0	17.6
			Bravo	*	*	*	6.0	*
			Folicur	44.3	-38.3	-2.5	6.0	41.1
			Pointer	*	*	*	6.0	*
			Tilt	34.1	-28.1	-0.7	6.0	19.6
			Opus	*	*	*	6.0	*
			Corbel	*	*	*	6.0	*
			Patrol	*	*	*	6.0	*
			Sanction	25.7	-19.7	-3.1	6.0	24.8
			Bravo+Pointer	20.4	-14.4	*	6.0	20.4
4	4	171	Alto	53.3	-35.0	-2.2	18.3	49.5
			Bravo	24.1	-5.8	*	18.3	24.1
			Folicur	86.6	-68.3	-1.0	18.3	60.2

			Pointer	37.6	-19.3	*	18.3	37.6
			Tilt	*	*	*	18.3	*
			Opus	*	*	*	18.3	*
			Corbel	26.0	-7.6	-2.8	18.3	25.5
			Patrol	*	*	*	18.3	*
			Sanction	44.5	-26.2	-4.0	18.3	44.0
			Bravo+Pointer	38.5	-20.2	*	18.3	38.6
5	1	185	Alto	76.4	-8.1	-8.1	68.3	76.4
			Bravo	74.1	-5.8	*	68.3	74.1
			Folicur	80.5	-12.3	-7.7	68.3	80.5
			Pointer	*	*	*	68.3	*
			Tilt	80.0	-11.7	-2.3	68.3	78.8
			Opus	78.4	-10.1	*	68.3	78.4
			Corbel	70.9	-2.6	*	68.3	70.9
			Patrol	72.1	-3.9	-3.1	68.3	72.0
			Sanction	77.9	-9.7	*	68.3	77.9
			Bravo+Pointer	78.6	-10.3	-7.5	68.3	78.5
5	2	185	Alto	83.4	-13.0	*	70.4	83.4
			Bravo	82.5	-12.1	*	70.4	82.5
			Folicur	85.8	-15.4	-9.1	70.4	85.8
			Pointer	83.3	-12.9	-3.8	70.4	83.0
			Tilt	89.1	-18.7	-2.7	70.4	87.8
			Opus	85.7	-15.3	*	70.4	85.7
			Corbel	75.7	-5.3	*	70.4	75.7
			Patrol	78.0	-7.6	-5.8	70.4	78.0
			Sanction	86.7	-16.3	-3.4	70.4	86.1
			Bravo+Pointer	85.2	-14.8	-4.7	70.4	85.0
5	3	172	Alto	92.6	-12.2	-5.8	80.4	92.5
			Bravo	90.0	-9.6	*	80.4	90.0
			Folicur	92.8	-12.4	-6.4	80.4	92.8
			Pointer	92.4	-12.0	-4.4	80.4	92.2
			Tilt	93.4	-13.0	-2.8	80.4	92.6
			Opus	94.3	-13.9	*	80.4	94.3
			Corbel	91.2	-10.8	-1.6	80.4	89.1
			Patrol	88.6	-8.2	-1.6	80.4	86.9
			Sanction	93.5	-13.1	-4.7	80.4	93.4
			Bravo+Pointer	91.9	-11.5	-11.2	80.4	91.9
5	3	185	Alto	69.4	-45.8	-4.3	23.5	68.8
			Bravo	66.0	-42.5	-8.9	23.5	66.0
			Folicur	74.0	-50.5	-4.3	23.5	73.3
			Pointer	65.1	-41.6	-5.0	23.5	64.8
			Tilt	61.3	-37.8	-3.6	23.5	60.2
			Opus	78.2	-54.7	-8.6	23.5	78.2
			Corbel	26.9	-3.3	*	23.5	26.9
			Patrol	32.5	-8.9	-3.1	23.5	32.1
			Sanction	80.8	-57.3	-1.9	23.5	72.6
			Bravo+Pointer	72.4	-48.9	-3.6	23.5	71.1
5	4	172	Alto	60.1	-31.1	-1.2	29.0	50.3
			Bravo	35.3	-6.4	*	29.0	35.3
			Folicur	45.6	-16.6	-2.0	29.0	43.3
			Pointer	69.3	-40.4	-0.5	29.0	45.7
			Tilt	*	*	*	29.0	*

			Opus	90.5	-61.5	-1.2	29.0	71.1
			Corbel	*	*	*	29.0	*
			Patrol	*	*	*	29.0	*
			Sanction	*	*	*	29.0	*
			Bravo+Pointer	68.8	-39.8	-0.8	29.0	50.5
6	2	190	Alto	85.2	-7.3	-5.8	77.8	85.2
			Bravo	83.0	-5.2	-1.6	77.8	82.0
			Folicur	87.7	-9.8	-11.4	77.8	87.7
			Pointer	85.4	-7.5	-1.4	77.8	83.6
			Tilt	88.3	-10.5	-3.3	77.8	87.9
			Opus	90.6	-12.8	-6.0	77.8	90.6
			Corbel	80.7	-2.8	-15.5	77.8	80.7
			Patrol	81.9	-4.0	*	77.8	81.9
			Sanction	91.3	-13.5	-1.2	77.8	87.2
			Bravo+Pointer	83.1	-5.3	-8.9	77.8	83.1
6	3	179	Alto	92.4	-22.4	-1.7	70.0	88.3
			Bravo	*	*	*	70.0	*
			Folicur	89.9	-19.9	-2.2	70.0	87.7
			Pointer	85.4	-15.4	-1.2	70.0	81.0
			Tilt	166.5	-96.5	-0.2	70.0	84.3
			Opus	89.8	-19.8	-5.8	70.0	89.8
			Corbel	*	*	*	70.0	*
			Patrol	74.7	-4.7	*	70.0	74.7
			Sanction	84.1	-14.1	-2.1	70.0	82.4
			Bravo+Pointer	80.4	-10.4	-3.1	70.0	80.0
6	3	190	Alto	75.0	-39.6	-1.2	35.4	62.8
			Bravo	47.8	-12.4	-3.1	35.4	47.2
			Folicur	75.3	-39.9	-2.1	35.4	70.3
			Pointer	46.9	-11.5	*	35.4	46.9
			Tilt	59.8	-24.4	-2.8	35.4	58.3
			Opus	77.9	-42.5	-7.6	35.4	77.9
			Corbel	42.2	-6.8	*	35.4	42.2
			Patrol	43.3	-7.9	-4.0	35.4	43.1
			Sanction	57.2	-21.8	-2.2	35.4	54.7
			Bravo+Pointer	730.8	-695.4	0.0	35.4	58.9
6	4	179	Alto	147.4	-129.9	-0.3	17.5	51.6
			Bravo	*	*	*	17.5	*
			Folicur	144.5	-127.0	-0.4	17.5	55.0
			Pointer	31.4	-13.9	-1.3	17.5	27.7
			Tilt	*	*	*	17.5	*
			Opus	47.4	-29.9	*	17.5	47.4
			Corbel	19.4	-1.9	*	17.5	19.4
			Patrol	24.7	-7.2	*	17.5	24.7
			Sanction	35.5	-18.0	*	17.5	35.5
			Bravo+Pointer	*	*	*	17.5	*

6.2 Yellow rust experiments - dose-response parameter estimates

6.2.1 Yellow rust

Experiment	Leaf	Date	Product	a	b	k	a+b	a+be^{k}
7	1	181	Alto	12.6	40.2	-7.3	52.8	12.7
			Bayfidan	12.5	40.3	-7.7	52.8	12.6
			Corbel	12.0	40.8	-2.8	52.8	14.6
			Folicur + Patrol	14.6	38.2	*	52.8	14.6
			Folicur	14.9	38.0	-6.4	52.8	14.9
			Opus	*	*	*	52.8	*
			Patrol	20.6	32.3	*	52.8	20.6
			Pointer	16.1	36.7	-8.4	52.8	16.1
			Sanction	18.0	34.8	-14.9	52.8	18.0
			Tilt	14.1	38.8	*	52.8	14.1
7	1	191	Alto	10.0	55.0	-6.7	65.1	10.1
			Bayfidan	10.3	54.7	-6.5	65.1	10.4
			Corbel	18.2	46.9	-7.2	65.1	18.2
			Folicur + Patrol	12.6	52.5	-13.5	65.1	12.6
			Folicur	10.4	54.7	-5.8	65.1	10.6
			Opus	*	*	*	65.1	*
			Patrol	21.4	43.6	*	65.1	21.4
			Pointer	21.3	43.7	-5.5	65.1	21.5
			Sanction	14.7	50.4	-7.9	65.1	14.7
			Tilt	12.3	52.7	*	65.1	12.3
7	2	181	Bayfidan	33.3	32.4	-7.5	65.7	33.3
			Corbel	38.9	26.8	*	65.7	38.9
			Folicur + Patrol	26.2	39.5	-3.1	65.7	28.0
			Folicur	29.5	36.2	-3.3	65.7	30.8
			Patrol	41.9	23.8	*	65.7	41.9
			Pointer	38.0	27.7	-5.4	65.7	38.1
			Sanction	36.5	29.2	*	65.7	36.5
			Tilt	41.4	24.3	*	65.7	41.4
8	1	163	Alto	0.1	9.1	-13.0	9.2	0.1
			Bayfidan	0.9	8.2	*	9.2	0.9
			Corbel	0.7	8.5	-5.7	9.2	0.7
			Folicur + Patrol	0.1	9.1	*	9.2	0.1
			Folicur	0.0	9.1	*	9.2	0.0
			Opus	0.0	9.1	*	9.2	0.0
			Patrol	1.3	7.9	*	9.2	1.3
			Pointer	-1.5	10.6	-2.3	9.2	-0.4
			Sanction	1.0	8.1	-5.3	9.2	1.1
			Tilt	0.1	9.1	-9.1	9.2	0.1
8	1	184	Alto	6.8	44.0	-8.4	50.8	6.8
			Bayfidan	17.6	33.3	-3.0	50.8	19.3
			Corbel	22.4	28.4	-6.2	50.8	22.5
			Folicur + Patrol	2.3	48.5	-8.6	50.8	2.3
			Folicur	1.2	49.6	-10.3	50.8	1.2
			Opus	-0.2	51.1	-8.1	50.8	-0.2
			Patrol	35.2	15.7	*	50.8	35.2
			Pointer	3.7	47.2	-2.4	50.8	7.7
			Sanction	23.1	27.8	-2.9	50.8	24.7

			Tilt	-2.3	53.1	-1.7	50.8	7.7
8	2	163	Alto	0.7	21.6	-12.9	22.3	0.7
			Bayfidan	1.8	20.5	-8.5	22.3	1.8
			Corbel	1.6	20.8	-8.8	22.3	1.6
			Folicur + Patrol	0.5	21.8	*	22.3	0.5
			Folicur	0.4	21.9	*	22.3	0.5
			Opus	0.4	21.9	*	22.3	0.4
			Patrol	3.0	19.3	*	22.3	3.0
			Pointer	1.1	21.3	-10.6	22.3	1.0
			Sanction	2.3	20.1	-7.2	22.3	2.3
			Tilt	1.0	21.4	-13.4	22.3	1.0
8	2	181	Alto	27.0	38.7	-4.9	65.7	27.3
			Opus	*	*	*	65.7	*
8	2	184	Alto	1.4	40.4	*	41.8	1.4
			Bayfidan	7.5	34.4	-9.2	41.8	7.5
			Corbel	7.7	34.2	-7.5	41.8	7.7
			Folicur + Patrol	0.5	41.4	*	41.8	0.5
			Folicur	0.2	41.6	*	41.8	0.2
			Opus	0.1	41.7	*	41.8	0.1
			Patrol	19.0	22.9	*	41.8	19.0
			Pointer	2.0	39.9	-5.2	41.8	2.2
			Sanction	11.3	30.5	-3.4	41.8	12.3
			Tilt	4.7	37.1	-8.1	41.8	4.7
8	3	163	Alto	0.4	6.4	*	6.8	0.4
			Bayfidan	0.9	5.9	-6.6	6.8	0.9
			Corbel	1.1	5.8	-6.4	6.8	1.1
			Folicur + Patrol	0.3	6.5	-10.3	6.8	0.3
			Folicur	0.2	6.6	*	6.8	0.2
			Opus	0.1	6.7	-10.1	6.8	0.1
			Patrol	1.8	5.0	*	6.8	1.8
			Pointer	0.2	6.7	-4.3	6.8	0.3
			Sanction	1.7	5.1	-14.7	6.8	1.7
			Tilt	1.1	5.7	-7.6	6.8	1.2
8	3	184	Alto	0.1	29.0	*	29.1	0.1
			Bayfidan	0.7	28.4	-10.0	29.1	0.7
			Corbel	0.6	28.6	-10.2	29.1	0.6
			Folicur + Patrol	-0.1	29.2	*	29.1	-0.1
			Folicur	0.2	29.0	*	29.1	0.2
			Opus	0.0	29.1	-14.4	29.1	0.0
			Patrol	5.0	24.1	*	29.1	5.0
			Pointer	0.5	28.6	*	29.1	0.5
			Sanction	2.5	26.6	*	29.1	2.5
			Tilt	1.1	28.1	-12.1	29.1	1.1

6.2.2 Green leaf area

Experiment	Leaf	Date	Product	a	b	k	a+b	a+be^k
7	1	181	Alto	82.8	-40.8	-7.4	42.0	82.8
			Bayfidan	83.2	-41.2	-7.4	42.0	83.1
			Corbel	81.1	-39.1	-3.3	42.0	79.7
			Folicur	81.4	-39.4	-5.7	42.0	81.3

			Folicur+Patrol	82.3	-40.3	-15.1	42.0	82.3
			Opus	*	*	*	42.0	*
			Patrol	73.2	-31.2	*	42.0	73.2
			Pointer	78.1	-36.1	-9.1	42.0	78.1
			Sanction	77.1	-35.1	-14.1	42.0	77.1
			Tilt	80.3	-38.3	*	42.0	80.3
7	1	191	Alto	86.7	-57.5	-7.0	29.2	86.6
			Bayfidan	86.0	-56.9	-6.2	29.2	85.9
			Corbel	78.5	-49.3	-7.3	29.2	78.5
			Folicur	86.3	-57.1	-6.0	29.2	86.2
			Folicur+Patrol	84.5	-55.3	-12.9	29.2	84.5
			Opus	*	*	*	29.2	*
			Patrol	75.1	-45.9	*	29.2	75.1
			Pointer	75.4	-46.3	-5.6	29.2	75.3
			Sanction	81.3	-52.1	-8.7	29.2	81.3
			Tilt	83.9	-54.7	*	29.2	83.9
7	2	181	Alto	66.8	-39.7	-4.3	27.2	66.3
			Bayfidan	59.9	-32.8	-6.9	27.2	59.9
			Corbel	55.3	-28.1	*	27.2	55.3
			Folicur	65.2	-38.0	-2.8	27.2	62.9
			Folicur+Patrol	65.5	-38.4	*	27.2	65.5
			Opus	*	*	*	27.2	*
			Patrol	50.3	-23.1	*	27.2	50.3
			Pointer	53.3	-26.1	-5.5	27.2	53.2
			Sanction	58.7	-31.6	-7.5	27.2	58.7
			Tilt	51.5	-24.3	*	27.2	51.5
8	1	163	Alto	97.4	-9.4	-12.4	88.0	97.4
			Bayfidan	96.6	-8.6	-14.7	88.0	96.6
			Corbel	96.7	-8.7	-7.0	88.0	96.7
			Folicur	97.8	-9.8	*	88.0	97.8
			Folicur+Patrol	97.8	-9.8	-12.0	88.0	97.8
			Opus	98.0	-10.0	*	88.0	98.0
			Patrol	95.9	-7.9	*	88.0	95.9
			Pointer	99.8	-11.8	-1.9	88.0	98.1
			Sanction	96.4	-8.4	-5.1	88.0	96.3
			Tilt	97.7	-9.7	-13.4	88.0	97.7
8	1	184	Alto	88.9	-47.9	-10.5	41.0	88.9
			Bayfidan	77.9	-36.9	-3.5	41.0	76.8
			Corbel	73.0	-32.0	-5.7	41.0	72.9
			Folicur	96.0	-55.0	-10.2	41.0	96.0
			Folicur+Patrol	94.0	-53.0	-9.0	41.0	94.0
			Opus	97.5	-56.5	-7.9	41.0	97.4
			Patrol	60.1	-19.1	*	41.0	60.1
			Pointer	89.3	-48.3	-3.1	41.0	87.2
			Sanction	75.0	-34.0	-2.6	41.0	72.5
			Tilt	109.4	-68.4	-1.3	41.0	89.9
8	2	163	Alto	96.2	-21.6	-14.8	74.7	96.2
			Bayfidan	95.1	-20.5	-8.8	74.7	95.1
			Corbel	95.3	-20.7	-8.8	74.7	95.3
			Folicur	96.4	-21.8	*	74.7	96.4
			Folicur+Patrol	95.9	-21.2	*	74.7	95.9
			Opus	96.8	-22.1	*	74.7	96.8

			Patrol	94.0	-19.3	*	74.7	94.0
			Pointer	95.1	-20.4	*	74.7	95.1
			Sanction	94.3	-19.6	-8.7	74.7	94.3
			Tilt	96.2	-21.6	*	74.7	96.2
8	2	184	Alto	95.0	-84.2	*	10.8	95.0
			Bayfidan	85.4	-74.6	*	10.8	85.4
			Corbel	87.1	-76.3	-11.8	10.8	87.1
			Folicur	96.1	-85.3	*	10.8	96.1
			Folicur+Patrol	96.1	-85.3	*	10.8	96.1
			Opus	96.4	-85.6	*	10.8	96.4
			Patrol	74.5	-63.7	*	10.8	74.5
			Pointer	93.8	-82.9	-7.6	10.8	93.7
			Sanction	80.8	-69.9	-7.6	10.8	80.7
			Tilt	91.9	-81.1	-10.2	10.8	91.9
8	3	163	Alto	96.1	-7.6	*	88.5	96.1
			Bayfidan	95.8	-7.3	-4.6	88.5	95.8
			Corbel	94.8	-6.3	-4.3	88.5	94.7
			Folicur	95.9	-7.4	-11.3	88.5	95.9
			Folicur+Patrol	96.2	-7.7	-6.7	88.5	96.2
			Opus	96.5	-8.0	-9.1	88.5	96.5
			Patrol	94.5	-6.0	*	88.5	94.5
			Pointer	96.3	-7.8	-3.9	88.5	96.1
			Sanction	94.9	-6.4	*	88.5	94.9
			Tilt	94.7	-6.2	*	88.5	94.7
8	3	184	Alto	89.6	-57.9	*	31.7	89.6
			Bayfidan	70.2	-38.5	*	31.7	70.2
			Corbel	80.0	-48.3	-15.1	31.7	80.0
			Folicur	89.7	-58.0	-6.8	31.7	89.6
			Folicur+Patrol	92.1	-60.4	-12.8	31.7	92.1
			Opus	92.3	-60.7	-5.6	31.7	92.1
			Patrol	77.5	-45.8	-9.9	31.7	77.5
			Pointer	85.2	-53.6	-11.9	31.7	85.2
			Sanction	79.2	-47.5	-6.0	31.7	79.1
			Tilt	87.5	-55.9	-10.4	31.7	87.5

6.3 Yield - dose-response parameter estimates

Experiment	Product	a	b	k	a+b	$a+be^{K}$
1	Alto	7.56	-0.67	*	6.89	7.56
	Bravo	*	*	*	6.89	*
	Bravo+Pointer	7.65	-0.76	-6.496	6.89	7.65
	Corbel	7.10	-0.20	*	6.89	7.10
	Folicur	8.22	-1.33	-1.608	6.89	7.95
	Opus	*	*	*	6.89	*
	Patrol	7.45	-0.56	-1.864	6.89	7.36
	Pointer	7.60	-0.71	-2.912	6.89	7.56
	Sanction	7.51	-0.61	-4.713	6.89	7.50
	Tilt	7.49	-0.60	-3.201	6.89	7.47
2	Alto	8.80	-0.74	-1.452	8.06	8.63
	Bravo	8.91	-0.85	-4.980	8.06	8.90
	Bravo+Pointer	9.59	-1.53	-2.057	8.06	9.39

	Corbel	*	*	*	8.06	*
	Folicur	9.90	-1.84	-0.569	8.06	8.86
	Opus	8.92	-0.86	-4.820	8.06	8.91
	Patrol	8.34	-0.28	-6.129	8.06	8.34
	Pointer	8.48	-0.42	*	8.06	8.48
	Sanction	8.48	-0.42	-5.289	8.06	8.48
	Tilt	8.50	-0.44	-1.619	8.06	8.42
3	Alto	7.86	-1.97	-1.678	5.89	7.49
	Bravo	8.51	-2.62	-0.417	5.89	6.78
	Bravo+Pointer	7.43	-1.54	-5.424	5.89	7.42
	Corbel	6.48	-0.59	-1.434	5.89	6.34
	Folicur	7.52	-1.64	-2.537	5.89	7.40
	Opus	8.48	-2.59	-1.953	5.89	8.11
	Patrol	6.45	-0.56	-1.929	5.89	6.37
	Pointer	*	*	*	5.89	*
	Sanction	6.94	-1.05	-1.885	5.89	6.78
	Tilt	6.86	-0.97	-7.096	5.89	6.86
4	Alto	8.22	-1.00	-6.265	7.22	8.22
	Bravo	9.02	-1.79	-0.440	7.22	7.86
	Bravo+Pointer	8.39	-1.16	-3.778	7.22	8.36
	Corbel	7.55	-0.32	*	7.22	7.55
	Folicur	8.33	-1.11	-12.332	7.22	8.33
	Opus	*	*	*	7.22	*
	Patrol	7.47	-0.24	*	7.22	7.47
	Pointer	8.06	-0.84	-3.770	7.22	8.04
	Sanction	8.10	-0.88	-9.446	7.22	8.10
	Tilt	8.01	-0.78	-5.221	7.22	8.00
5	Alto	9.50	-1.02	-3.690	8.48	9.47
	Bravo	*	*	*	8.48	*
	Bravo+Pointer	9.77	-1.29	-2.882	8.48	9.69
	Corbel	8.84	-0.36	-2.109	8.48	8.79
	Folicur	9.56	-1.08	-4.901	8.48	9.55
	Opus	9.91	-1.44	-5.478	8.48	9.91
	Patrol	8.73	-0.26	*	8.48	8.73
	Pointer	9.43	-0.95	-2.948	8.48	9.38
	Sanction	9.30	-0.82	-3.687	8.48	9.28
	Tilt	9.26	-0.78	-3.970	8.48	9.25
6	Alto	9.81	-0.50	-2.876	9.30	9.78
	Bravo	9.41	-0.10	*	9.30	9.41
	Bravo+Pointer	10.45	-1.14	-0.826	9.30	9.95
	Corbel	*	*	*	9.30	*
	Folicur	*	*	*	9.30	*
	Opus	10.28	-0.98	-3.347	9.30	10.25
	Patrol	9.55	-0.24	*	9.30	9.55
	Pointer	9.84	-0.54	-0.913	9.30	9.62
	Sanction	9.61	-0.30	-2.684	9.30	9.59
	Tilt	9.68	-0.37	-3.718	9.30	9.67
7	Alto	8.88	-3.53	-5.300	5.35	8.87
	Bayfidan	8.29	-2.93	-2.974	5.35	8.14
	Bravo	*	*	*	5.35	*
	Corbel	7.21	-1.86	-5.332	5.35	7.20
	Folicur	8.98	-3.63	-3.534	5.35	8.88

	Folicur+Patrol	8.73	-3.38	-9.561	5.35	8.73
	Opus	*	*	*	5.35	*
	Patrol	7.30	-1.94	-3.557	5.35	7.24
	Pointer	7.60	-2.25	-2.990	5.35	7.49
	Sanction	7.93	-2.58	-4.329	5.35	7.90
	Tilt	7.69	-2.33	*	5.35	7.69
8	Alto	9.46	-3.65	-7.401	5.81	9.46
	Bayfidan	8.74	-2.93	-7.972	5.81	8.74
	Bravo	*	*	*	5.81	*
	Corbel	8.45	-2.65	*	5.81	8.45
	Folicur	10.25	-4.45	-8.669	5.81	10.25
	Folicur+Patrol	10.28	-4.47	-7.212	5.81	10.27
	Opus	10.55	-4.74	-7.860	5.81	10.55
	Patrol	7.78	-1.98	*	5.81	7.78
	Pointer	9.59	-3.78	-3.043	5.81	9.41
	Sanction	8.44	-2.63	-3.391	5.81	8.35
	Tilt	8.91	-3.11	-9.309	5.81	8.91
12	Alto	9.94	-0.31	*	9.63	9.94
	Corbel	10.01	-0.38	-2.169	9.63	9.96
	Folicur	10.89	-1.26	-0.935	9.63	10.40
	Opus	10.55	-0.92	-2.602	9.63	10.48
	Sanction	21.04	-11.41	-0.048	9.63	10.16
	Unix	10.38	-0.75	*	9.63	10.38

6.4 Specific weight - dose-reponse parameter estimates

Experiment	Product	a	b	k	a+b	$a+be^{K}$
1	Alto	76.6	-1.4	-5.7	75.2	76.5
	Bravo	75.8	-0.6	*	75.2	75.8
	Bravo+Pointer	77.2	-2.0	-1.6	75.2	76.8
	Corbel	75.3	-0.1	*	75.2	75.3
	Folicur	76.8	-1.6	-1.5	75.2	76.4
	Opus	*	*	*	75.2	*
	Patrol	*	*	*	75.2	*
	Pointer	77.1	-1.9	-1.1	75.2	76.5
	Sanction	76.4	-1.2	-1.4	75.2	76.1
	Tilt	*	*	*	75.2	*
2	Alto	77.3	-1.6	-1.3	75.7	76.8
	Bravo	77.0	-1.3	-2.9	75.7	77.0
	Bravo+Pointer	77.1	-1.4	-5.4	75.7	77.1
	Corbel	76.0	-0.3	*	75.7	76.0
	Folicur	76.7	-1.0	*	75.7	76.7
	Opus	76.7	-1.0	-6.4	75.7	76.7
	Patrol	76.4	-0.7	*	75.7	76.4
	Pointer	76.6	-0.9	-8.8	75.7	76.6
	Sanction	76.8	-1.1	-4.6	75.7	76.8
	Tilt	76.3	-0.6	-2.2	75.7	76.2
3	Alto	71.0	-2.4	*	68.6	71.0
	Bravo	70.2	-1.7	-1.4	68.6	69.8
	Bravo+Pointer	72.0	-3.4	-1.8	68.6	71.4
	Corbel	69.1	-0.5	-4.8	68.6	69.1

	Folicur	73.3	-4.7	-1.1	68.6	71.7
	Opus	*	*	*	68.6	*
	Patrol	*	*	*	68.6	*
	Pointer	*	*	*	68.6	*
	Sanction	70.3	-1.7	-4.5	68.6	70.2
	Tilt	70.2	-1.7	-3.2	68.6	70.1
4	Alto	73.5	-1.4	-12.6	72.0	73.5
	Bravo	*	*	*	72.0	*
	Bravo+Pointer	73.4	-1.4	*	72.0	73.4
	Corbel	72.5	-0.5	*	72.0	72.5
	Folicur	74.1	-2.0	-3.5	72.0	74.0
	Opus	*	*	*	72.0	*
	Patrol	*	*	*	72.0	*
	Pointer	73.9	-1.8	-3.0	72.0	73.8
	Sanction	73.4	-1.3	-7.5	72.0	73.4
	Tilt	73.5	-1.4	-4.5	72.0	73.5
5	Alto	77.6	-2.5	-5.5	75.0	77.5
	Bravo	83.0	-7.9	-0.3	75.0	77.0
	Bravo+Pointer	77.5	-2.5	-3.4	75.0	77.5
	Corbel	76.2	-1.2	-1.4	75.0	75.9
	Folicur	77.9	-2.9	-2.9	75.0	77.8
	Opus	77.9	-2.9	-4.7	75.0	77.9
	Patrol	75.9	-0.8	-3.2	75.0	75.8
	Pointer	77.4	-2.4	-2.8	75.0	77.2
	Sanction	77.0	-2.0	-5.3	75.0	77.0
	Tilt	77.4	-2.3	-3.0	75.0	77.2
6	Alto	79.4	-1.1	-1.3	78.3	79.1
	Bravo	*	*	*	78.3	*
	Bravo+Pointer	*	*	*	78.3	*
	Corbel	78.3	-0.1	*	78.3	78.4
	Folicur	78.9	-0.6	-3.7	78.3	78.9
	Opus	79.2	-0.9	-1.4	78.3	79.0
	Patrol	*	*	*	78.3	*
	Pointer	78.9	-0.7	-1.3	78.3	78.7
	Sanction	*	*	*	78.3	*
	Tilt	*	*	*	78.3	*
7	Alto	75.7	-3.3	-10.5	72.4	75.7
	Bayfidan	74.7	-2.3	*	72.4	74.7
	Bravo	*	*	*	72.4	*
	Corbel	79.6	-7.2	-0.4	72.4	74.9
	Folicur	76.2	-3.8	-4.9	72.4	76.2
	Folicur+Patrol	76.5	-4.1	*	72.4	76.5
	Opus	*	*	*	72.4	*
	Patrol	74.1	-1.7	*	72.4	74.1
	Pointer	*	*	*	72.4	*
	Sanction	74.7	-2.2	-5.1	72.4	74.6
	Tilt	76.4	-4.0	-1.4	72.4	75.4
8	Alto	74.8	-7.6	-12.7	67.2	74.8
	Bayfidan	73.5	-6.4	*	67.2	73.5
	Bravo	*	*	*	67.2	*
	Corbel	72.9	-5.7	*	67.2	72.9
	Folicur	75.8	-8.7	-10.3	67.2	75.9

	Folicur+Patrol	76.2	-9.0	-7.2	67.2	76.2
	Opus	76.8	-9.7	-9.3	67.2	76.8
	Patrol	72.0	-4.8	*	67.2	72.0
	Pointer	75.7	-8.6	-3.4	67.2	75.4
	Sanction	72.1	-4.9	-7.9	67.2	72.1
	Tilt	74.2	-7.0	-16.1	67.2	74.2

6.5 Thousand grain weight - dose-response parameter estimates

Experiment	Product	a	b	k	a+b	$a+be^{K}$
1	Alto	47.3	-2.5	*	44.7	47.3
	Bravo	47.7	-2.9	-1.9	44.7	47.2
	Bravo+Pointer	49.3	-4.5	-2.5	44.7	48.9
	Corbel	45.1	-0.4	*	44.7	45.1
	Folicur	47.2	-2.5	-10.2	44.7	47.2
	Opus	*	*	*	44.7	*
	Patrol	*	*	*	44.7	*
	Pointer	*	*	*	44.7	*
	Sanction	48.6	-3.9	-1.8	44.7	48.0
	Tilt	48.0	-3.3	-2.1	44.7	47.6
4	Alto	44.2	-2.2	*	42.0	44.2
	Bravo	*	*	*	42.0	*
	Bravo+Pointer	45.9	-3.8	-8.4	42.0	45.9
	Corbel	43.8	-1.8	-1.7	42.0	43.5
	Folicur	45.7	-3.7	-5.5	42.0	45.7
	Opus	*	*	*	42.0	*
	Patrol	*	*	*	42.0	*
	Pointer	45.4	-3.4	-3.8	42.0	45.3
	Sanction	45.4	-3.3	*	42.0	45.4
	Tilt	47.7	-5.7	-1.3	42.0	46.1
5	Alto	50.9	-5.8	-3.0	45.0	50.6
	Bravo	*	*	*	45.0	*
	Bravo+Pointer	49.8	-4.7	-14.1	45.0	49.8
	Corbel	*	*	*	45.0	*
	Folicur	51.8	-6.7	-2.0	45.0	50.9
	Opus	50.7	-5.6	-6.7	45.0	50.7
	Patrol	46.2	-1.2	*	45.0	46.2
	Pointer	50.2	-5.1	-2.5	45.0	49.7
	Sanction	48.1	-3.1	-13.1	45.0	48.1
	Tilt	50.3	-5.2	-2.0	45.0	49.6
6	Alto	48.6	-2.0	-2.6	46.6	48.5
	Bravo	*	*	*	46.6	*
	Bravo+Pointer	50.6	-4.0	-1.0	46.6	49.1
	Corbel	47.6	-0.9	-6.2	46.6	47.6
	Folicur	48.0	-1.4	-5.7	46.6	48.0
	Opus	52.0	-5.3	-1.0	46.6	50.0
	Patrol	*	*	*	46.6	*
	Pointer	48.8	-2.2	-3.4	46.6	48.8
	Sanction	48.5	-1.9	-2.5	46.6	48.4
	Tilt	48.1	-1.5	*	46.6	48.1
8	Alto	44.5	-6.4	-5.1	38.1	44.4

	Bayfidan	42.0	-3.9	-1.9	38.1	41.4
	Bravo	*	*	*	38.1	*
	Corbel	41.7	-3.6	*	38.1	41.7
	Folic+Pl	46.0	-7.9	-5.1	38.1	46.0
	Folicur	46.2	-8.1	-6.0	38.1	46.1
	Opus	48.1	-10.0	-4.9	38.1	48.1
	Patrol	40.6	-2.5	*	38.1	40.6
	Pointer	43.8	-5.7	-2.7	38.1	43.4
	Sanction	40.5	-2.4	-4.4	38.1	40.4
	Tilt	43.1	-5.0	-4.3	38.1	43.0

APPROPRIATE FUNGICIDE DOSES FOR WINTER WHEAT

EXPERIMENT 2:

Variety/dose interactions

(Pages 2-33)

by

N.D. Paveley[1] and D.B. Stevens[2]

[1] ADAS High Mowthorpe, Duggleby, Malton, N. Yorks. YO17 8BP

[2] CSL, Sand Hutton, York. YO4 1LZ

Project leader: N.D. Paveley, ADAS High Mowthorpe

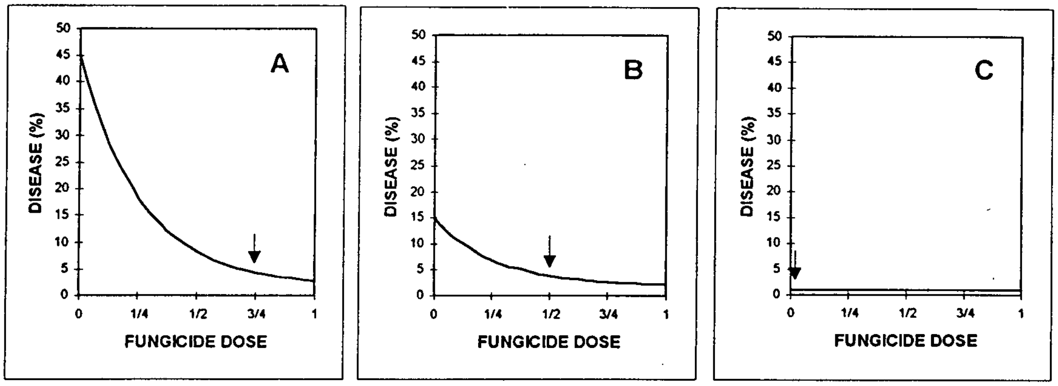
CONTENTS

1.0 INTRODUCTION TO EXPERIMENT 2

Winter wheat varieties are known to vary in their genetic resistance to disease (Anon., 1998). Resistance against biotrophs (the rusts and powdery mildew) can sometimes provide immunity, but more usually resistance is quantitative and is expressed through a delay in disease onset, a reduction in epidemic rate or a lower maximum level of disease (Vanderplank, 1984; Gilligan, 1990).

As the untreated point of a dose-response curve represents the level of disease reached in the absence of treatment at the time of the assessment, it is clear that under a given environment, resistant varieties will have flatter dose-response curves than susceptible varieties. This effect is illustrated, using hypothetical data, in Figure 1. Curve (A) represents a variety susceptible to a given disease; curve (B) a more resistant variety; and curve (C) a variety with complete immunity. If the relationship between disease and yield loss were the same on each variety, the appropriate dose (and hence fungicide requirement) would decrease with increasing resistance.

Figure 1. Effect of genetic resistance on the dose-response curve and appropriate dose (represented by an arrow)



The yield dose-response curve of a variety results from the combination of the disease dose-response curves for the diseases present at a given site, and the relationship between disease and yield loss for that variety. The latter has long been thought to vary and varieties showing lower levels of loss per unit disease are referred to as being 'tolerant' (Cobb, 1892).

Winter wheat varieties are chosen by growers largely for their yield potential, marketability and a range of agronomic characteristics. Individual choice results in a wide range of varieties being grown in the UK. This experiment was designed to provide information to help crop managers adjust fungicide inputs according to the requirements of varieties, to reduce the unit cost of production through exploitation of varietal resistance and tolerance

2.0 OBJECTIVES - EXPERIMENT 2

To minimise fungicide costs, whilst maximising disease control, yield and grain quality, by:

- quantifying the effect of variety on fungicide dose-response curves and economic optima.
- the provision of data to improve the determination of Integrated Disease Risk (IDR).

3.0 MATERIALS AND METHODS

Complete protocols are presented in the Annual Report appendices. The following sections summarise the experimental sites, seasons, treatments, assessments and statistical analysis.

3.1 Sites, years and experiment numbers

Sites and varieties were selected to target specific diseases and the experiment was conducted for three harvest years.

Table 1. Sites, harvest years, experiment numbers and target diseases

Experiment number	Site and target disease/s	Harvest year
1	ADAS Rosemaund, Herefordshire	1994
2	(*Septoria tritici*)	1995
3		1996
4	Morley Research Centre, Norfolk	1994
5	(*Septoria tritici* and brown rust)	1995
6		1996
7	ADAS Terrington, Norfolk	1994
8	(Yellow rust)	1995
9		1996
10	SAC Aberdeen	1994
11	(Powdery mildew)	1995
12		1996

3.2 Site selection and drilling

Sites were selected according to Standard Operating Procedure (SOP) guidelines following at least a one year non-cereal break and soils were sampled pre-drilling for pH and nutrient status. Plots were drilled at a seed rate calculated from thousand grain weight and according to ADAS guidelines for the soil type and locality. Plot sizes were no smaller than 2m wide x 18m long and were drilled using an Øyjord plot drill or equivalent.

3.3 Experiment Design

Randomised complete block factorial design with three replicates. Guard plots of the variety Lynx or Pastiche were drilled alternating with the treated plots or where this was not possible plots were at least 3m wide.

3.4 Varieties

The varieties shown in Table 2 were selected to provide a range of levels of resistance to the target disease and, as far a possible, minimise interference by non-target diseases.

Table 2. Winter wheat varieties selected for each site

	Variety	Rosemaund and MRC	SAC	Terrington
1	Admiral			✓
2	Apollo		✓	
3	Brigadier	✓		
4	Genesis		✓	✓
5	Haven	✓		✓
6	Hereward		✓	✓
7	Hunter	✓	✓	
8	Hussar	✓	✓	✓
9	Mercia		✓	
10	Riband	✓		
11	Rialto	✓		
12	Slejpner			✓

3.5 Treatment products and doses

Tebuconazole (as c.p. Folicur, Bayer UK) was chosen as the 'industry standard' broad-spectrum fungicide at the start of the experiment. At the the mildew and yellow rust target sites, fenpropidin (as c.p. Patrol, Zeneca) was added as a tank mixture (Table 3).

Table 3. Fungicide products and doses applied at each site

Trt. No.	Rosemaund and MRC	SAC and Terrington*
1	Untreated	Untreated
2	Folicur 1.0 litre c.p./ha	Folicur 1.0 litre + Patrol 0.7 litre c.p./ha
3	Folicur 0.75 litre c.p./ha	Folicur 0.75 litre + Patrol 0.525 litre c.p./ha
4	Folicur 0.5 litre c.p./ha	Folicur 0.5 litre + Patrol 0.35 litre c.p./ha
5	Folicur 0.25 litre c.p./ha	Folicur 0.25 + Patrol 0.175 litre c.p./ha

* The doses specified above were halved at the Terrington site in the 1996 harvest year, in order to increase the number of data points in the region of greatest dose-response curvature.

Fungicide treatments were applied at GS 39 (1994) or GS 37 (1995 and 1996) using a hand-held pressurised sprayer of the OPS/MDM type and were applied in 200-250 litres of water per hectare, using nozzles selected to produce a medium spray quality at 200-300 KPa pressure.

Other treatments (fertiliser, trace elements, herbicides, insecticides, growth regulators, molluscicides) followed standard farm practice.

3.6 Assessments and records

3.6.1 Agronomic details

Site, soil and crop details were recorded.

3.6.2 Meteorological data

Meteorological data from crop emergence to harvest were recorded using in-crop Delta-T data loggers.

3.6.3 Assessment of leaf diseases and green leaf area (GLA)

Pre-treatment disease and GLA assessments were made at GS37 (1995 and 1996) or GS39 (1994). 50 main tillers were randomly sampled across the whole of the variety plot area and the assessments described below recorded (on all leaf layers with an average of >25% GLA remaining).

At approximately 21 days and 35 days after treatment (for the yellow rust and mildew sites) or 28 and 42 days after treatment (at the *S. tritici* and brown rust sites) disease incidence, severity and % GLA were recorded on all green leaves on 10 main tillers per plot. The precise timing of these assessments was adjusted to optimise recording of treatment differences. The first assessment aimed to record treatment differences on leaves 3 and 4, before senescence and at the same time differences were becoming established on the upper leaves. The second assessment aimed at recording treatment effects on leaves 1 & 2.

Disease incidence was defined as the percentage of leaves sampled affected by disease;

Disease severity was defined as the percentage leaf area affected by disease, including chlorotic and necrotic areas attributable to disease;

3.6.4 Ear diseases

Diseases were assessed on 10 ears per plot at GS 85, if more than 5% ear area or more than five grain sites per ear were affected in the untreated controls.

3.6.5 Stem bases diseases

Stem-base diseases were assessed on 25 tillers from the trial area at GS 31.

At GS 75, stem-base diseases were assessed in all plots on 25 tillers per plot, if in untreated plots, >25% tillers were affected by moderate or severe lesions of any disease or if >10% tillers were affected by severe lesions of any disease.

3.6.6 Harvest

Whole plots were harvested. Grain yield was adjusted to 85% dry matter. Grain specific weight and thousand grain weight were adjusted to 85% dry matter.

3.7 SOP List

Work was conducted according to the following ADAS Standard Operating Procedures.

ADMIN/008	The production of R & D reports.
AGRON/004	The measurement of dry matter in grain, pulses and oilseeds using the Sinar Agritec meter.
AGRON/017G	Guidelines to practical site management.
AGRON/019G	Guidelines for the storage of pesticides
AGRON/023 G	Guidelines for the application of pesticides to plots.
CER/002	Diagnosis and assessment of stem-base diseases In winter cereals.
CER/007	Measurement of specific weight using a Corcoron/Nilema/Farmtec Chondrometer.
CER/008	Measurement of specific weight using the Sinar Datatec P25 or Tecator 6010 GP meters.
CER/014	Assessing growth stages in cereals.
CER/023	Assessment of green leaf area and foliar diseases in cereals.
CER/024	Assessment of ear diseases in cereals.
DATCL/001	Automatic collection from load cell/weighmeter equipment fitted to a plot combine harvester.
DATCL/013	Collating experimental data using MINITAB
DATCL/015	Manual recording of experimental data on proforma sheets.
DATCL/016	Recording experimental data on Hunter 16 using the "Plot-exe" software.
DATCL/017	Recording experimental data on Husky Hunter (CPM) using "Plot.hba" software.
DATCL/018 G	Guidelines for backup and archive of manually-recorded experimental data.
DATCL/019 G	Guidelines for backup and archive of experimental data held on computer.
DATCL/020 G	Guidelines for keeping manual file records of experiments.
DATCL/027 G	Guidelines for selecting suitable sites for land-based experiments.
MCP/015	Archiving of experiment data, reports and other records.
MECH/001	The calibration and use of the Øyjord tractor-mounted drill.
MECH/008 G	Harvesting of experimental plots, cereals and combineable crops.
SOILS/007	Soil sampling for pH and nutrient analysis.

3.8 Data handling

Disease, green leaf area and grain yield/quality measurements were collected either manually or directly on to portable computers and transferred onto MINITAB or EXCEL work files after collection.

3.9 Statistical analysis

Data were analysed using Genstat 5.

3.9.1 Individual Assessments

Each assessment (site, season, variate, date, leaf layer) was analysed by analysis of variance and the validity of the analysis was checked by examination of residuals. Normal plots, histograms and plots of residuals v fitted values were used to assess the normality assumption and any requirement for transformation. Analysis of the *septoria tritici* data suggested that, in some sites and seasons, a log transformation may have provided a more vaild analysis. However, to maintain consistency over all sites and seasons, the data were left untransformed.

Outliers were identified from the above plots, and from graphs of residuals versus variety and residuals versus dose. A small number of extreme outliers were removed from the data after consultation as to the cause.

In some cases, plots of residuals v plot number showed a linear trend in the residuals within some of the blocks. These trends were removed by using covariates on plot number within each block. Such covariates were often found to be required for harvest variates (yield, specific weight, thousand grain weight) at Rosemaund and Aberdeen, for green leaf area at Rosemaund and occasionally for *S. tritici* at Rosemaund, Morley and Aberdeen.

Variates which did not contribute useful information were excluded from further analysis. These were defined to be variates for which there were no significant treatment effects or interactions, disease variates for which there was less than an average of 5% disease on the untreated plots, and green leaf areas for which there was more than an average of 90% green leaf area on the untreated plots.

For disease variates which did contribute useful information, dose-response curves were plotted for each variety using the treatment means (adjusted for covariates if appropriate). Exponential curves of the form $y = a+be^{kx}$, where y = % disease and x = proportion of recommended dose were fitted. The three parameter exponential was the most parsimonious function able to describe the variation in dose-response seen in the data. All of the parameters have biological meaning. Examination of the data suggested that a model which allowed the a and b parameters to vary for each variety, but used a common k across all the varieties, provided a reasonable description of the data in most cases. This model was used to fit exponential curves to all individual assessments.

Exponential curves were also fitted to green leaf areas and harvest variates.

3.9.2 Over-assessment means

For disease variates, assessments were split into eradicant and protectant categories, as described for Experiment 1. Exponential curves were fitted to means over all sites (containing the same varieties), seasons, dates and leaf layers for each variety and each type of activity, regardless of the closeness of the fit of the curves to the individual assessments. Repeat assessments on the same leaf layer within a site/season are likely to be highly correlated. Hence, such assessments were averaged before the overall means were calculated.

Green leaf area over assessment means were calculated from the same site, season, date and leaf layer assessment combinations as the relevant disease means. Various combinations of site and season means were calculated for the harvest variables, for comparison with disease and green leaf area means. Exponential curves were fitted to green leaf area and harvest variates.

Observation of the fitted response curves did not suggest the presence of variety by eradicant/protectant category interactions for disease or green leaf area variates. The absence of interactions was confirmed by regression analysis on a sub-set of the data; allowing response curve fitting to combined eradicant and protectant data.

In order to identify the way in which the exponential curve parameters were varying across the varieties, an analysis of parallelism was carried out for over-assessment means for Aberdeen and for Rosemaund and Morley combined. Such an analysis fits a sequence of models, of increasing complexity, until allowing extra parameters does not markedly improve the fit of the model. The sequence of models fitted was:

a) common curve for all varieties:

$$y=a+be^{kx}$$

b) separate b parameters (difference between the asymptote and the untreated value) for each variety:

$$y=a+b_ie^{kx}$$

c) separate a (lower asymptote) and b parameters for each variety:

$$y=a_i+b_ie^{kx}$$

d) separate a, b and k (curvature) parameters for each variety:

$$y=a_i+b_ie^{k_ix}$$

For all disease and green leaf area means, curves with a common k and separate a and b parameters was found to be appropriate. For the harvest variates models b), c) and d) above were all identified for at least one set of means.

Where 'data not fitted' appears in the results section, either the model could not be fitted to the data, or an R^2 value less than 50% was obtained, despite the data showing a substantial dose effect.

4.0 RESULTS

4.1 *Septoria tritici* experiments

4.1.1 Disease control

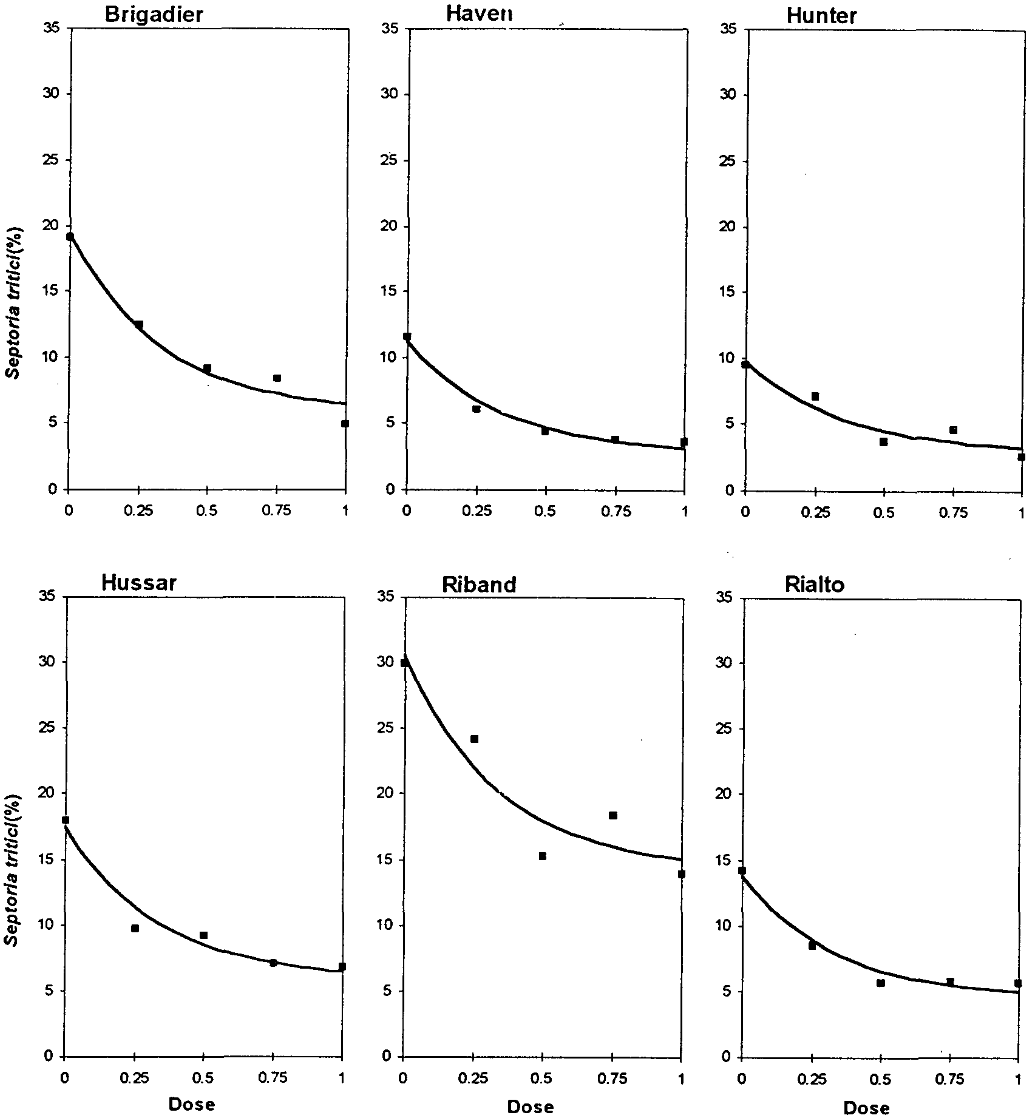
One hypothesis being tested by this experiment was that the dose-response curves on contrasting varieties would fall between two extremes. The first, where the *amount* of disease reduction for a given dose was constant, regardless of the untreated disease level (i.e. common k and b across varieties). The second where the *proportion* of untreated severity controlled by a given dose was constant (i.e. common k and a across varieties).

There was no evidence of a variety by eradicant/protectant category interaction; thus allowing dose-response curves to be fitted to means of combined eradicant and protectant data sets (Figure 2). The fitted functions described between 78% and 95% of the variation in the data. Untreated disease severity (a + b) varied from 30% for the susceptible variety Riband, to 10% for the partially resistant Hunter (Table 4), providing a good test of the hypothesis described above. Parallel curve analysis confirmed that the data from all varieties could be described with a single k value, but both the a and b parameters varied. Hence, a given dose did not simply control a given proportion of the untreated level of disease. Neither, at the other extreme, was the amount of control for a given dose, constant.

Table 4. Cross-site parameter estimates for fitted *Septoria tritici* dose response curves

Variety	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Brigadier	5.7	13.6	-2.96	19.4	6.4	93.0
Haven	2.7	8.6	-2.96	11.2	3.1	95.5
Hunter	2.9	6.9	-2.96	9.8	3.2	82.9
Hussar	5.9	11.5	-2.96	17.4	6.5	91.2
Riband	14.2	16.3	-2.96	30.5	15.1	78.7
Rialto	4.5	9.3	-2.96	13.8	5.0	93.5

Figure 2. Fitted cross-site *Septoria tritici* dose-response curves



4.1.2 Green leaf area

Functions fitted following parallel curve analysis (Figure 3) explained 81% to 94% of the variation in the green leaf area data and mirrored the *Septoria tritici* dose-response curves. Estimated values for k were comparable. The highest levels of untreated green area were seen on varieties least affected by disease, and the greatest increases in green area with treatment, on varieties most affected by disease. Increases in green area with treatment, as quantified by the b parameter, were greater than the reduction in disease (Table 5 cf. Table 4).

Figure 3. Fitted cross-site green leaf area dose-response curves

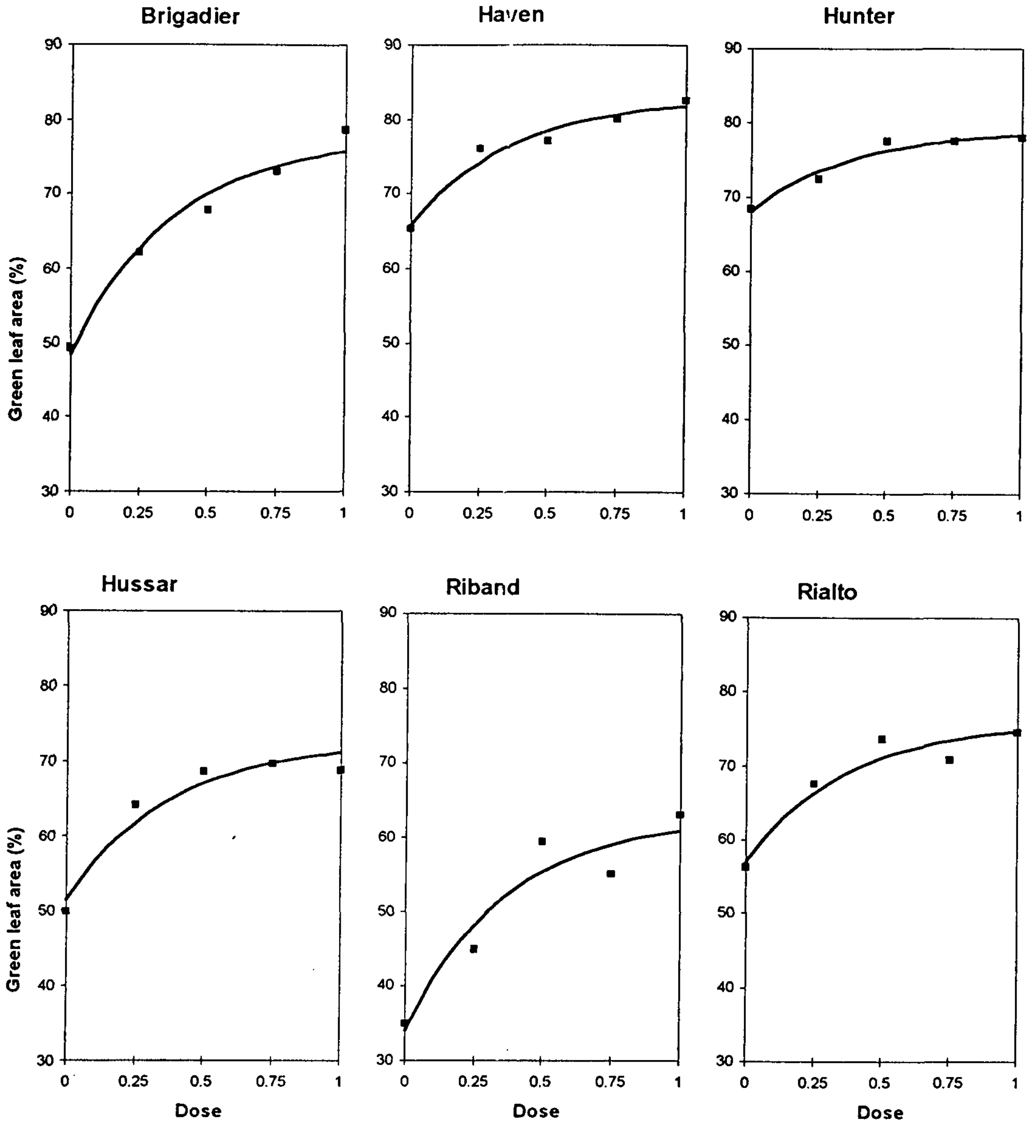


Table 5. Cross-site parameter estimates for fitted green leaf area dose response curves

Variety	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Brigadier	77.7	-29.2	-2.69	48.4	75.7	94.2
Haven	83.0	-17.1	-2.69	65.9	81.9	92.3
Hunter	79.2	-11.1	-2.69	68.1	78.4	91.9
Hussar	72.6	-21.2	-2.69	51.4	71.2	88.2
Riband	62.9	-28.9	-2.69	34.0	60.9	81.5
Rialto	76.1	-19.0	-2.69	57.1	74.8	86.2

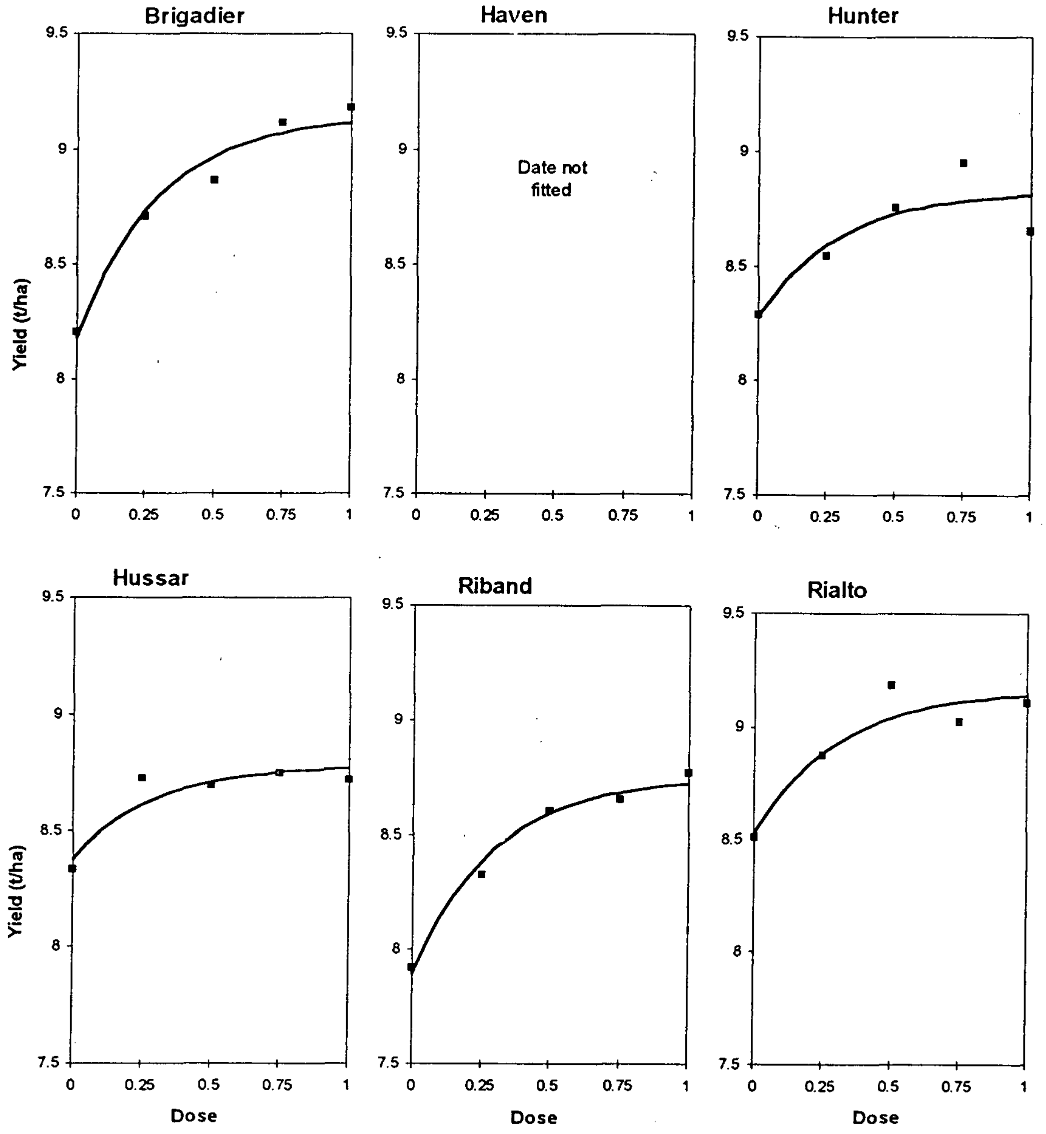
4.1.3 Grain yield

Mean yield potential, as estimated by the a parameter, varied from 8.8 to 9.2 tonnes per hectare (Figure 4 and Table 6). For all varieties, yield values at dose = 1 ($a+be^k$) were close to the yield potential. The magnitude of yield responses to treatment (b parameter) varied from 1.0 tonne per hectare for the responsive variety Brigadier to 0.4 tonne per hectare for Hussar. In general, the size of the yield benefit from treatment was proportional to the level of disease reduction and the consequent increase in green leaf area. However, there was some evidence of varietal variation in the relationship between disease and yield loss. For example, the levels of untreated disease and disease control were similar for Brigadier and Hussar (Table 4), but resulted in substantially different yield responses to treatment (Table 6). High error variability and a small response to treatment, caused an unacceptably low percentage of the variation in the data to be explained by the fitted function for Haven.

Table 6. Cross-site parameter estimates for fitted yield dose response curves

Variety	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Brigadier	9.1	-1.0	-3.37	8.2	9.1	94.0
Haven	Data not fitted					
Hunter	8.8	-0.5	-3.37	8.3	8.8	54.7
Hussar	8.8	-0.4	-3.37	8.4	8.8	71.0
Riband	8.8	-0.9	-3.37	7.9	8.7	96.8
Rialto	9.2	-0.6	-3.37	8.5	9.1	79.8

Figure 4. Fitted cross-site yield dose-response curves



4.1.4 Grain quality

Potential specific weights, as estimated by the a parameter, were closely related to those published in the Recommended List of winter wheat varieties (Anon. 1998); varying from 78.4 kg/hl for Hussar, down to 75.9 kg/hl for Riband (Table 7). Reductions in the absence of treatment were small, generally less than 1 kg/hl. Quarter or half doses were sufficient to prevent loss of specific weight (Figure 5).

Figure 5. Fitted cross-site specific weight dose-response curves

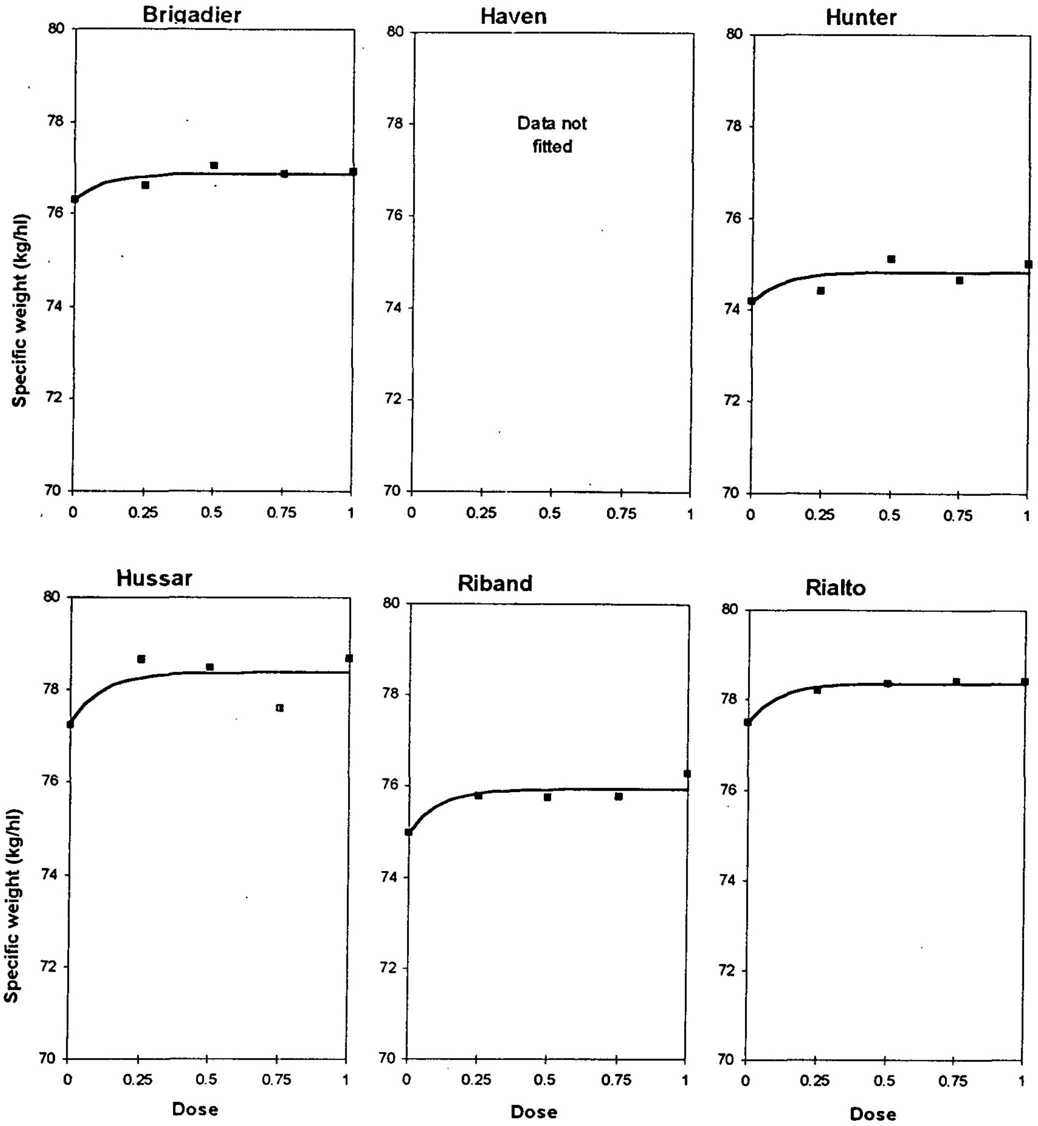


Table 7. Cross-site parameter estimates for fitted specific weight dose response curves

Variety	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Brigadier	76.9	-0.6	-9.45	76.3	76.9	53.2
Haven	Data not fitted					
Hunter	74.8	-0.7	-9.45	74.2	74.8	12.3
Hussar	78.4	-1.1	-9.45	77.3	78.4	4.7
Riband	75.9	-1.0	-9.45	75.0	75.9	61.4
Rialto	78.4	-0.9	-9.45	77.5	78.4	96.2

Thousand grain weight effects were small and inconsistent. There was general trend towards higher thousand grain weight with increasing dose, but in no case did the difference between zero and full dose exceed 2 grams.

4.2 Yellow rust experiments

4.2.1 Disease control

Varieties were selected, on the basis of their Recommended List (Anon., 1998) resistance ratings against yellow rust, to give a spread of disease severities. In practice, all varieties, with the exception of Slejpner, had less than 1% disease severity. Resistance ratings are derived to represent the worst case scenario. The extent to which a varieties' potential for disease is expressed at a site, depends on the presence of virulent yellow rust pathotypes.

With no possibility of a variety by eradicant/protectant category interaction, and protectant data derived only from one leaf layer in one season (1995), eradicant and protectant data were combined prior to function fitting. The combined eradicant/protectant data from Slejpner (Figure 6, Table 8) illustrates the highly curved (large k value) dose-response typical of yellow rust. All of the control is achieved with the first quarter dose, with no additional benefit from higher doses.

Figure 6. Fitted cross-season yellow rust dose-response curve

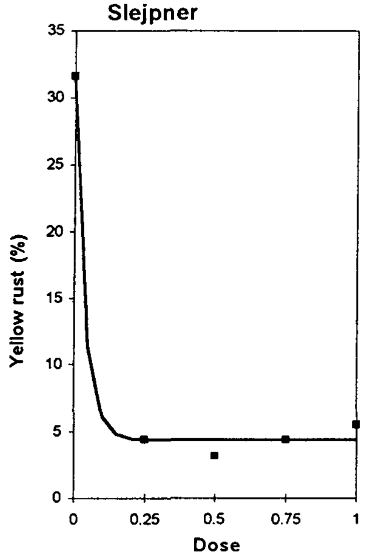


Table 8. Cross-site parameter estimates for fitted yellow rust dose response curve

Variety	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Slejpner	4.3	27.3	-27.16	31.6	4.3	99.1

Septoria tritici was present on Slejpner in 1994, reaching 12% severity on leaf 3. A small proportion of the green leaf area and yield effects of treatment, reported below, may be due to control of this disease.

4.2.2 Green leaf area

The effect of yellow rust on green leaf area was substantial, reducing mean green leaf area from 85% to approximately 40% (Figure 7, Table 9). The green leaf area dose-response curve mirrored the curve for yellow rust, with all of the benefit of treatment to green leaf area achieved with the first quarter dose.

Figure 7. Fitted cross-season green leaf area dose-response curve

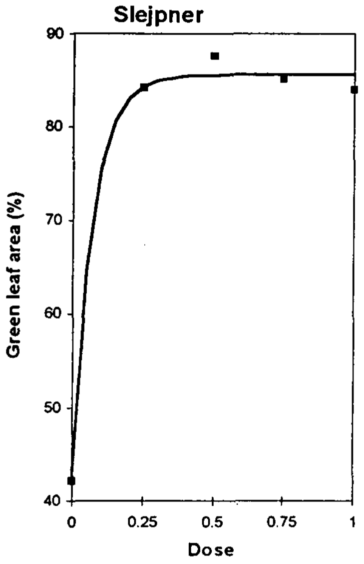


Table 9. Cross-site parameter estimates for fitted green leaf area dose response curve

Variety	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Slejpner	85.6	-43.5	-14.52	42.1	85.6	99.1

4.2.3 Grain yield and quality

A yield response of 3.7 tonnes per hectare was recorded to the control of yellow rust, and specific weight was increased from 70kg/hl to 77kg/hl (Table 10). Both yield and grain quality response curves related to the increases in green leaf area, although there was some indication that doses higher than one quarter were required to achieve the full potential (Figure 8).

Figure 8. Fitted cross-season yield and specific weight dose-response curves

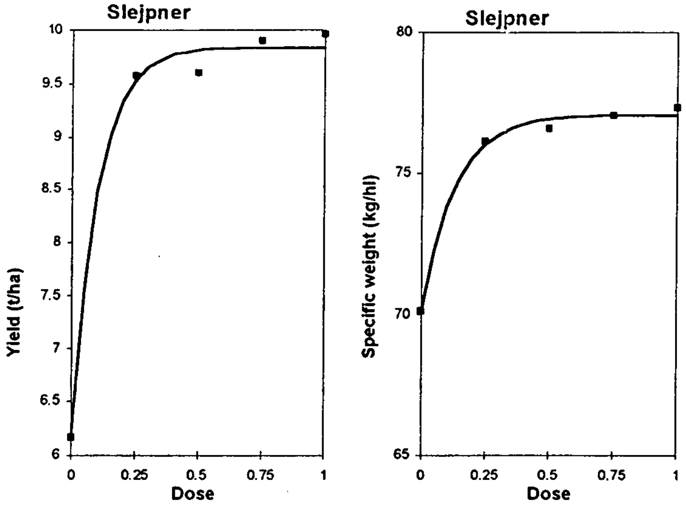


Table 10. Cross-site parameter estimates for fitted yield & specific weight dose response curves

Variety	Parameter estimates					
	a	b	k	a + b	a+be^{k}	Mean R^{2} adjusted
Yield	9.8	-3.7	-9.92	6.2	9.8	98.7
Specific weight	77.1	-7.0	-7.64	70.1	77.1	99.1

4.3 Responses at the Aberdeen site

Varieties were selected at the Aberdeen site to provide a range of resistance levels against powdery mildew. The target disease failed to develop beyond low levels, but in 1996, a moderate epidemic of *Septoria tritici* occurred. These data are presented here, as varieties common to experiments 1 to 6 (Hunter and Hussar), may be used as 'standards' against which other varieties can be compared.

4.3.1 *Septoria tritici*

Untreated disease severity was lower than the 'standards' on Apollo, comparable on Genesis and Hereward and higher on Mercia; although error variation in the data on Hereward and Mercia resulted in fitted functions explaining only 57% and 53% of the variation in the data (Table 11). Response curves (Figure 9) were similar to those from Experiments 1 to 6, with constant k and varying a and b parameters, and a trend for higher untreated disease severity to associate with a higher asymptote.

Figure 9. Fitted eradicant *Septoria tritici* dose-response curves - Aberdeen, 1996

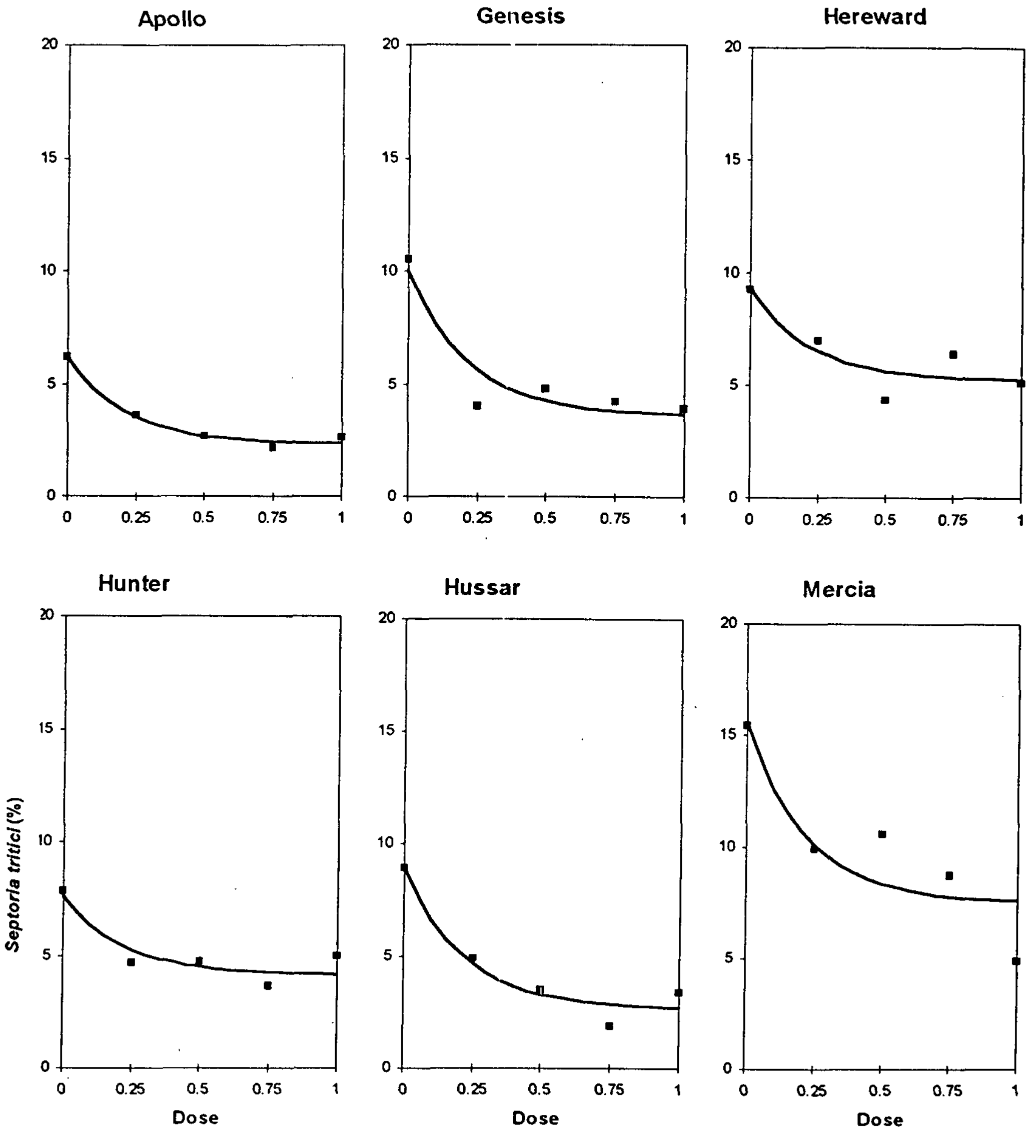


Table 11. Parameter estimates for fitted eradicant *Septoria tritici* dose-response curves - Aberdeen, 1996 harvest year

Variety	Parameter estimates					
	a	b	k	a + b	a+be^k	Mean R^2 adjusted
Apollo	2.3	3.9	-4.59	6.2	2.3	97.1
Genesis	3.6	6.5	-4.95	10.1	3.7	78.9
Hereward	5.2	4.1	-4.95	9.3	5.3	57.0
Hunter	4.1	3.5	-4.95	7.7	4.2	71.8
Hussar	2.7	6.3	-4.95	9.0	2.7	89.7
Mercia	7.5	8.0	-4.95	15.6	7.6	53.8

4.3.2 Green leaf area

Functions could not be reliably fitted to enough varieties to make comparisons of value.

4.3.3 Grain yield and quality

The yields of all varieties at dose = 1 ($a+be^k$) were close to the upper asymptote (Table 12, Figure 10). Hussar indicated a yield potential of 10.2 tonnes per hectare, compared to 8.9 tonnes per hectare from the milling variety Mercia. The other varieties, Apollo, Genesis and Hunter were intermediate. There was some evidence of variation in the relationship between disease severity and yield between varieties. For example, Apollo suffered the least disease, but lost marginally the most yield.

Figure 10. Fitted yield dose-response curves - Aberdeen, 1996 harvest year

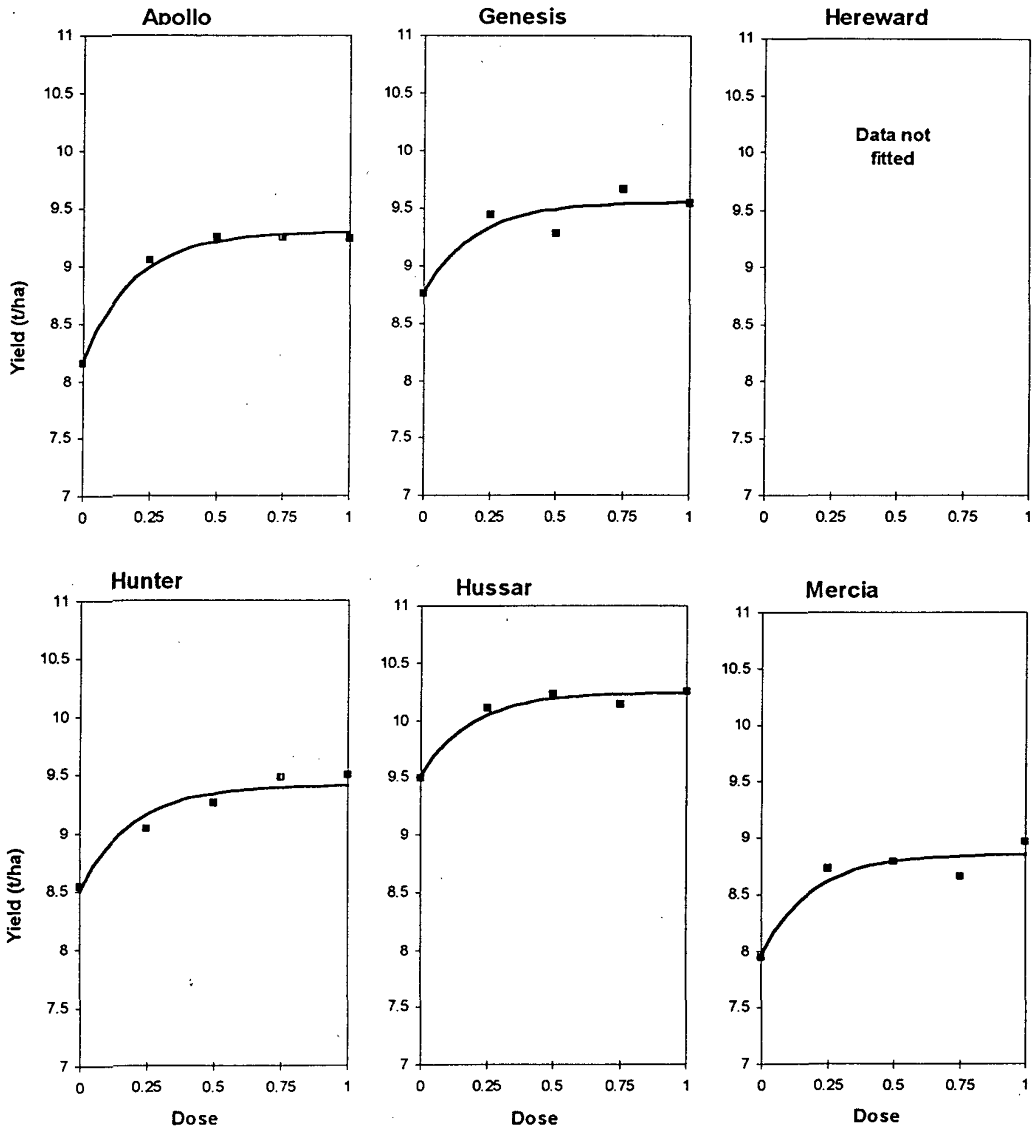


Table 12. Parameter estimates for fitted yield dose-response curves - Aberdeen 1996

Variety	Parameter estimates					
	a	b	k	a + b	$a+be^k$	Mean R^2 adjusted
Apollo	9.3	-1.1	-5.18	8.2	9.3	98.0
Genesis	9.6	-0.8	-5.18	8.8	9.5	71.2
Hereward	Data not fitted					
Hunter	9.4	-0.9	-5.18	8.5	9.4	87.1
Hussar	10.2	-0.7	-5.18	9.5	10.2	92.1
Mercia	8.9	-0.9	-5.18	8.0	8.8	80.3

Thousand grain weight effects were small or inconsistent for varieties Apollo, Genesis and Hussar. A full dose applied to Hereward, Hunter and Mercia increased thousand grain weight by 2, 4 and 3 grams respectively. Most of the increase was obtained from the half dose treatment.

5.0 CONCLUSIONS

5.1 Overview

- The exponential function: $y=a+bk^{dose}$, proved both parsimonious and able to describe the range of dose-response variation experienced across a range of varieties, sites and seasons.

- Fitted exponential dose-response curves describing the effect of fungicides on disease, green leaf area, grain yield and grain quality, typically explained a high proportion of the variance in the data. However, the combination of small treatment effects and error variation in the data, produced unacceptably low R^2 values for some variates.

- Parallel curve analysis produced consistent results for disease, green leaf area, yield and grain quality variates. The data were well described by a model with a constant k parameter across varieties, but varying a and b parameters. Thus a given dose did not simply control a given proportion or amount of the untreated disease severity. At higher untreated disease severity, the *amount* of control was greater and the *proportion* of control lower.

- The constant k value across varieties has important implications for economic dose optima. These are described in section 5.5.

5.2 *Septoria tritici*

- The level of disease escape and genetic resistance of varieties had a significant effect on the development of *Septoria tritici* epidemics; with substantially reduced untreated disease severity on more 'resistant' varieties.

- Lower untreated disease severity resulted in flatter dose-response curves. As a result, resistant varieties carried less severe disease for any given dose input or, viewed another way, required a lower dose to suppress disease to a given level.

- The lower part of the dose-response curve was relatively flat on all varieties. Little loss of disease control resulted from reducing dose to 0.75 of the recommended dose.

- There was no evidence of an interaction between variety and the timing of infection in relation to spray application (represented in these data by eradicant or protectant categories). This should simplify future quantification of the effects of resistance on fungicide requirements.

5.3 Yellow rust

- Despite varieties being selected to provide a spread of disease severity, on the basis of their Recommended List resistance ratings to yellow rust, only Slejpner expressed significant disease. As the ratings represent the worst case scenario, where virulent pathotypes are present, their predictive value is limited in the absence of information on the geographical distribution of pathotypes carrying specific 'virulence' genes.

- The dose-response curves obtained reinforced results from other studies, showing that, where an effective triazole + morpholine mixture is used, a quarter dose is sufficient to provide good control of yellow rust.

5.4 Green leaf area effects

- The shape of the dose-response curves for green leaf area mirrored those for disease.
- The increase in percentage green leaf area with increasing dose was generally greater than the corresponding reduction in disease. There are two explanations for these observations. The first, that the disease assessments may not have attributed all of the green area lost as a result of disease, to disease - particularly where necrotic or chlorotic area did not express typical symptoms. The second, that fungicides were having direct effects on retention of green area, independent of the effect via disease control.

5.5 Dose optima to exploit escape, resistance and tolerance

- Yield dose-response curves mirrored corresponding curves for disease and green leaf area.
- There was some evidence of differences between varieties in their tolerance (the impact of a unit of disease on yield) to disease.
- There was no evidence that higher doses were required to maintain grain quality than were required to protect yield.
- Economic dose optima can be calculated from the fitted yield response curves, for any combination of grain value and fungicide cost, using the equation:

  Dose optima = $(\ln(-n/(g*b*k)))/(-k)$.

  Where n = fungicide cost; g = grain value and b and k are parameter estimates from the fitted dose-response function.

- As common k values could be applied across the fitted yield functions for all varieties within a data set, the dose optimum varies according to variation in the size of the yield response to treatment (b parameter). In the *Septoria tritici* experiments data set, yield response varied between approximately 1.0 t/ha (Brigadier) to 0.4 t/ha (Hussar) and corresponding economic dose optima* from 0.7 to 0.4 (Paveley *et al.*, 1998).

* Assuming a grain value of £80 per tonne and fungicide cost of £27 per hectare.

- Under high disease pressure, the dose-optima moved to the right and under low disease pressure the optima moved to the left, but the differences in optima between varieties were maintained.

- The conclusions above relate to a single treatment applied at GS 37 or GS 39. Results from Experiment 3 of the Appropriate Fungicide Doses series suggest that treatments before or after the current treatment, reduce the current disease risk. Theory suggests therefore, that although dose optima may be lower when a spray forms part of a programme, differences between the dose optima of varieties remain, and apply at each treatment within a programme.

- On the basis of the reasoning above, fungicide inputs on varieties comparable to Hussar should be, on average, approximately 40% lower than those on varieties comparable to Brigadier.

- Evidence from survey data, presented by Stevens *et al.* (1997), suggests that escape, resistance and tolerance are not being exploited in farm practice, to reduce fungicide inputs.

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6.0 APPENDIX - PARAMETER ESTIMATE SUMMARY TABLES

6.1 *Septoria tritici* experiments - dose-response parameter estimates

6.1.1 *Septoria tritici*

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
1	3	188	Haven	-12.8	19.9	-0.5	7.1	-0.3
			Hunter	-6.1	9.5	-0.5	3.4	-0.1
	3	178	Brigadier	-6.2	35.2	-1.1	29.0	5.9
			Haven	-6.3	22.6	-1.1	16.3	1.5
			Hunter	-4.5	16.6	-1.1	12.1	1.2
			Hussar	0.0	21.5	-1.1	21.5	7.4
			Rialto	0.7	18.0	-1.1	18.7	6.9
	4	157	Hunter	1.0	0.9	-152413.4	1.9	1.0
			Hussar	2.4	1.9	-152413.4	4.3	2.4
			Riband	10.2	7.7	-152413.4	17.9	10.2
3	2	177	Haven	0.5	2.0	-4.8	2.5	0.6
			Hussar	-0.1	4.4	-4.8	4.3	0.0
			Riband	3.0	10.0	-4.8	13.0	3.1
		197	Haven	1.7	10.0	-1.9	11.8	3.2
			Hunter	-2.9	11.8	-1.9	9.0	-1.1
			Hussar	-0.5	17.0	-1.9	16.5	2.0
			Riband	11.2	22.6	-1.9	33.7	14.5
			Rialto	-2.3	12.6	-1.9	10.3	-0.4
	3	177	Brigadier	1.5	6.0	-2.0	7.5	2.4
			Haven	0.7	8.8	-2.0	9.5	1.9
			Hussar	0.7	8.3	-2.0	9.0	1.9
			Riband	13.8	21.1	-2.0	34.8	16.8
4	3	193	Brigadier	1.2	4.7	-3.1	6.0	1.4
			Hunter	0.7	3.7	-3.1	4.4	0.9
			Hussar	0.4	3.7	-3.1	4.1	0.6
			Riband	1.5	8.7	-3.1	10.1	1.9
			Rialto	1.1	5.6	-3.1	6.6	1.3
	4	172	Haven	0.7	3.0	-2.5	3.7	0.9
			Riband	2.0	7.7	-2.5	9.7	2.6
			Rialto	0.7	2.2	-2.5	2.9	0.9
5	1	186	Brigadier	0.3	2.4	-8.4	2.7	0.3
			Haven	0.5	0.9	-8.4	1.4	0.5
			Hunter	0.6	1.3	-8.4	1.9	0.6
			Hussar	0.5	2.5	-8.4	3.0	0.5
			Riband	2.5	6.7	-8.4	9.2	2.5
			Rialto	0.4	1.7	-8.4	2.1	0.4
		200	Brigadier	18.4	18.6	-7.0	37.0	18.4
			Haven	14.7	16.1	-7.0	30.9	14.8
			Hunter	12.4	6.7	-7.0	19.1	12.4
			Hussar	18.6	12.0	-7.0	30.6	18.6
	2	186	Brigadier	0.4	3.9	-6.8	4.3	0.4
			Haven	0.4	2.8	-6.8	3.1	0.4
			Hunter	0.7	3.4	-6.8	4.1	0.7
			Hussar	0.9	6.3	-6.8	7.2	0.9
			Riband	2.0	18.1	-6.8	20.1	2.0

			Rialto	0.5	3.4	-6.8	3.9	0.5
		200	Brigadier	21.0	36.3	-2.4	57.4	24.3
			Haven	5.3	38.2	-2.4	43.5	8.8
			Hunter	11.7	26.1	-2.4	37.8	14.1
			Hussar	24.5	26.1	-2.4	50.6	26.9
	3	186	Brigadier	0.5	35.9	-2.3	36.3	3.9
			Haven	-1.1	15.9	-2.3	14.8	0.4
			Hunter	-0.5	14.0	-2.3	13.5	0.8
			Hussar	3.2	25.1	-2.3	28.2	5.6
			Riband	1.2	45.0	-2.3	46.1	5.5
			Rialto	1.5	20.4	-2.3	21.9	3.5
	4	174	Brigadier	19.8	24.4	-8.0	44.2	19.8
			Hussar	21.1	29.8	-8.0	50.9	21.1
			Rialto	11.0	25.6	-8.0	36.6	11.0
6	3	177	Hunter	0.7	1.5	-2.7	2.2	0.8
			Riband	2.3	5.7	-2.7	8.0	2.7
			Rialto	0.5	1.4	-2.7	1.9	0.6
		193	Brigadier	5.4	4.8	-3.7	10.3	5.6
			Haven	0.9	2.4	-3.7	3.3	1.0
			Hunter	0.3	4.7	-3.7	5.0	0.4
			Riband	10.1	22.5	-3.7	32.6	10.7
			Rialto	1.7	7.8	-3.7	9.5	1.9
	4	177	Brigadier	4.0	8.1	-2.9	12.0	4.4
			Haven	1.9	4.4	-2.9	6.3	2.1
			Riband	9.5	15.0	-2.9	24.5	10.3

6.1.2 Green leaf area

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
1	1	188	Brigadier	97.5	-1.8	-4.17	95.7	97.5
			Haven	97.4	-3.1	-4.17	94.3	97.3
			Riband	93.1	-5.4	-4.17	87.6	93.0
	2	188	Brigadier	96.3	-21.0	-12.38	75.4	96.3
			Hussar	94.0	-10.3	-12.38	83.6	94.0
	3	177	Brigadier	96.7	-24.5	-5.36	72.2	96.5
			Haven	96.4	-3.6	-5.36	92.8	96.4
			Hunter	94.0	-15.0	-5.36	79.0	93.9
			Hussar	96.7	-5.0	-5.36	91.7	96.7
			Riband	84.6	-19.9	-5.36	64.7	84.5
		188	Brigadier	78.8	-63.9	-2.30	14.9	72.4
			Hunter	58.8	-40.2	-2.30	18.6	54.8
			Rialto	50.2	-20.9	-2.30	29.3	48.1
2	1	193	Hunter	78.2	-14.1	-153.16	64.1	78.2
	2	178	Hussar	94.7	-3.8	-2.50	90.8	94.4
		193	Hunter	79.3	-41.9	-0.23	37.4	46.1
	3	178	Brigadier	65.5	-28.9	-3.84	36.6	64.9
			Hunter	88.9	-6.5	-3.84	82.4	88.7
			Hussar	74.4	-15.3	-3.84	59.0	74.0
3	2	177	Brigadier	97.7	-2.6	-4.26	95.1	97.7
			Hunter	98.6	-2.5	-4.26	96.1	98.6
			Hussar	98.4	-4.7	-4.26	94.2	9847

			Riband	95.9	-9.9	-4.26	86.0	95.8
			Rialto	98.4	-2.3	-4.26	96.1	98.4
		197	Brigadier	87.5	-50.1	-2.19	37.3	81.9
			Haven	85.0	-26.8	-2.19	58.2	82.0
			Hunter	89.7	-25.6	-2.19	64.1	86.8
			Hussar	83.6	-42.9	-2.19	40.7	78.8
			Riband	66.8	-45.5	-2.19	21.2	61.7
			Rialto	77.2	-34.0	-2.19	43.2	73.4
	3	177	Brigadier	99.8	-21.1	-1.87	78.7	96.6
			Haven	102.1	-27.2	-1.87	74.9	97.9
			Hussar	98.8	-16.2	-1.87	82.6	96.3
			Riband	84.9	-49.0	-1.87	35.9	77.4
	2	193	Hunter	85.1	-8.0	-7.41	77.1	85.0
			Riband	78.8	-14.1	-7.41	64.7	78.8
			Rialto	85.1	-18.3	-7.41	66.8	85.1
	3	193	Brigadier	50.8	-23.8	-3.34	27.0	50.0
			Hunter	70.3	-30.9	-3.34	39.4	69.2
			Rialto	66.8	-41.0	-3.34	25.8	65.4
	4	172	Brigadier	94.0	-8.6	-7.22	85.4	94.0
			Hunter	95.7	-5.3	-7.22	90.4	95.7
			Riband	84.4	-11.4	-7.22	73.0	84.4
5	1	186	Brigadier	95.7	-4.6	-8.60	91.1	95.7
			Haven	95.3	-5.4	-8.60	89.9	95.3
			Rialto	95.4	-6.1	-8.60	89.3	95.4
		200	Hussar	32.6	-13.1	-2.86	19.5	31.9
			Riband	26.6	-23.3	-2.86	3.3	25.3
	2	186	Brigadier	96.3	-8.2	-7.46	88.1	96.3
			Haven	96.5	-7.4	-7.46	89.1	96.5
			Hussar	94.6	-9.5	-7.46	85.0	94.6
			Riband	90.0	-20.3	-7.46	69.8	90.0
			Rialto	95.5	-10.0	-7.46	85.5	95.5
		200	Haven	45.6	-34.0	-2.63	11.6	43.2
	3	186	Brigadier	82.2	-54.3	-2.86	27.9	79.1
			Haven	95.3	-31.9	-2.86	63.4	93.5
			Hunter	87.3	-19.9	-2.86	67.4	86.2
			Hussar	70.8	-30.5	-2.86	40.3	69.1
			Riband	83.3	-66.6	-2.86	16.7	79.5
			Rialto	90.2	-41.7	-2.86	48.4	87.8
	4	174	Brigadier	67.2	-39.8	-6.06	27.4	67.1
			Rialto	81.0	-37.1	-6.06	44.0	81.0
	2	193	Brigadier	92.2	-9.1	-5.55	83.1	92.2
			Hussar	91.6	-3.8	-5.55	87.7	91.6
			Riband	85.5	-12.8	-5.55	72.7	85.4
	3	177	Brigadier	99.1	-8.7	-1.38	90.4	96.9
		193	Brigadier	74.7	-16.8	-4.58	58.0	74.6
			Haven	87.8	-9.4	-4.58	78.4	87.7
			Hunter	88.6	-11.1	-4.58	77.4	88.4
			Hussar	75.8	-14.6	-4.58	61.2	75.6
			Riband	67.5	-40.4	-4.58	27.1	67.1
			Rialto	79.0	-19.4	-4.58	59.6	78.8
	4	177	Brigadier	193.6	-146.8	-0.17	46.8	69.7

6.2 Yellow rust experiments - dose-response parameter estimates

6.2.1 Yellow rust

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
7	1	182	Slejpner	2.7	35.9	-1.000E+09	38.7	2.7
		192	Slejpner	6.6	19.4	-4.217E+03	26.0	6.6
	2	182	Slejpner	10.8	47.6	-1.720E+02	58.3	10.8
	3	182	Slejpner	7.6	21.4	-1.206E+05	29.0	7.6
8	1	164	Slejpner	0.1	13.9	-1.183E+01	14.0	0.1
		185	Slejpner	0.5	47.9	-5.170E+00	48.4	0.8
	2	164	Slejpner	0.1	27.9	-1.676E+01	28.0	0.1
		185	Slejpner	0.0	26.7	-2.234E+01	26.7	0.0
	3	185	Slejpner	0.0	11.6	-1.395E+01	11.7	0.0

6.2.2 Green leaf area

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
7	1	182	Slejpner	93.9	-37.9	-3E+07	56.0	93.9
		192	Slejpner	90.0	-47.0	-6030.2	43.0	90.0
	2	182	Slejpner	83.0	-48.7	-624.53	34.3	83.0
	3	182	Slejpner	59.9	-16.6	-9.80	43.3	59.9
8	1	164	Slejpner	98.0	-14.7	-12.30	83.3	98.0
		185	Slejpner	94.2	-50.6	-6.51	43.6	94.1
	2	185	Slejpner	95.8	-87.5	-2324.6	8.3	95.8
		164	Slejpner	97.7	-28.3	-17.88	69.3	97.7
	3	185	Slejpner	87.2	-64.2	-11.28	23.0	87.2

6.3 *Septoria tritici* Aberdeen experiments - dose-response parameter estimates

6.3.1 *Septoria tritici*

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
12	2	204	Apollo	0.3	2.5	-5.6	2.9	0.4
			Genesis	0.2	3.8	-5.6	4.0	0.2
			Hereward	0.4	1.8	-5.6	2.2	0.4
			Hunter	0.4	2.1	-5.6	2.6	0.4
			Hussar	0.5	3.1	-5.6	3.5	0.5
			Mercia	1.0	6.8	-5.6	7.8	1.1
	3	191	Mercia	2.2	8.7	-0.9	10.9	5.8
		204	Apollo	1.7	6.1	-3.7	7.8	1.9
			Genesis	2.0	8.0	-3.7	10.0	2.2
			Hereward	4.2	3.1	-3.7	7.3	4.3
			Hunter	2.4	6.4	-3.7	8.8	2.6
			Hussar	2.5	7.4	-3.7	9.9	2.7
			Mercia	5.6	9.3	-3.7	14.9	5.9
	4	191	Apollo	5.5	5.2	-6.1	10.7	5.5
			Genesis	9.6	10.3	-6.1	19.9	9.6
			Hussar	6.4	10.5	-6.1	17.0	6.5

6.3.2 Green leaf area

Experiment	Leaf	Date	Variety	a	b	k	a+b	a+be**k
12	2	204	Apollo	94.6	-3.2	-4.64	91.4	94.6
			Genesis	92.0	-4.9	-4.64	87.1	91.9
			Hussar	96.4	-5.4	-4.64	90.9	96.3
			Mercia	90.5	-8.2	-4.64	82.3	90.4
		204	Apollo	90.8	-15.0	-5.44	75.8	90.7
			Genesis	88.9	-13.4	-5.44	75.5	88.8
			Hereward	83.2	-10.5	-5.44	72.8	83.2
			Hunter	89.5	-14.5	-5.44	75.0	89.4
			Hussar	89.2	-22.1	-5.44	67.1	89.1
	4	191	Apollo	87.1	-9.7	-9.79	77.4	87.1
			Genesis	84.7	-13.1	-9.79	71.6	84.7
			Hussar	86.7	-22.0	-9.79	64.7	86.7

6.4 Yield - dose-response parameter estimates

Experiment	Variety	a	b	k	a+b	a+be**k
1	Brigadier	9.1	-1.9	-4.05	7.2	9.1
	Rialto	8.6	-0.7	-4.05	7.9	8.6
3	Brigadier	8.0	-0.9	-1.73	7.1	7.8
	Haven	8.0	-0.5	-1.73	7.5	7.9
	Hunter	8.2	-0.8	-1.73	7.5	8.1
	Riband	7.7	-1.1	-1.73	6.6	7.5
5	Brigadier	9.5	-0.6	-3.22	8.8	9.5
	Haven	9.6	-1.0	-3.22	8.5	9.6
	Hunter	9.3	-0.4	-3.22	8.9	9.3
	Hussar	9.3	-0.5	-3.22	8.8	9.3
	Riband	9.4	-1.3	-3.22	8.2	9.4
	Rialto	9.4	-0.6	-3.22	8.8	9.4
6	Riband	9.7	-0.5	-5.61	9.1	9.7
	Rialto	9.9	-0.4	-5.61	9.5	9.9
7	Slejpner	9.4	-3.2	-16290.0	6.2	9.4
8	Slejpner	10.4	-4.3	-6.16	6.1	10.4
12	Apollo	9.3	-1.1	-5.18	8.2	9.3
	Genesis	9.6	-0.8	-5.18	8.8	9.5
	Hunter	9.4	-0.9	-5.18	8.5	9.4
	Hussar	10.2	-0.7	-5.18	9.5	10.2
	Mercia	8.9	-0.9	-5.18	8.0	8.8

6.5 Specific weight - dose-reponse parameter estimates

Experiment		a	b	k	a+b	a+be**k
1	Riband	75.7	-2.5	-210.46	73.1	75.7
	Rialto	77.6	-1.2	-210.46	76.4	77.6
5	Riband	77.6	-1.2	-5.82	76.4	77.6
	Rialto	80.6	-1.1	-5.82	79.5	80.6
6	Rialto	80.7	-0.5	-5.87	80.3	80.7
7	Slejpner	78.0	-3.3	-4.31	74.6	77.9
8	Slejpner	76.3	-10.7	-9.66	65.6	76.3
12	Mercia	78.7	-0.6	-486.37	78.0	78.7

6.6 Thousand grain weight - dose-response parameter estimates

Experiment	Variety	a	b	k	a+b	a+be**k
1	Brigadier	48.3	-2.8	-3.38	45.5	48.2
	Hunter	46.3	-4.6	-3.38	41.6	46.1
	Riband	49.9	-4.2	-3.38	45.7	49.8
5	Brigadier	47.2	-2.7	-5.82	44.5	47.2
	Haven	50.6	-3.3	-5.82	47.3	50.6
	Hussar	47.3	-2.2	-5.82	45.1	47.3
	Rialto	49.6	-2.8	-5.82	46.8	49.6
12	Hereward	49.4	-2.3	-5.35	47.1	49.4
	Hussar	47.6	-3.7	-5.35	43.9	47.6
	Mercia	45.7	-3.1	-5.35	42.6	45.7

Note: variates have been excluded from the tables above, where the Genstat routine was unable to converge.

APPROPRIATE FUNGICIDE DOSES FOR WINTER WHEAT

EXPERIMENT 3:

Dose/timing combinations in multiple spray programmes

(Pages 1-63)

by

W.S. Clark

ADAS Boxworth, Boxworth, Cambs. CB3 8NN

Project leader: N.D. Paveley, ADAS High Mowthorpe

CONTENTS

1.0 INTRODUCTION

MAFF Pesticide Usage surveys in recent years have shown that over 97% of wheat crops receive a fungicide treatment with an average of 2.2 sprays (Garthwaite and Thomas, 1997). These are frequently applied outside the optimal timings and at rates which are inappropriate. Choice of products is also questionable in many circumstances. In short, there are many opportunities for improving fungicide application to the wheat crop.

The experiment described here is aimed at providing information to the industry which will allow better targeting of fungicide inputs. The experiment evaluates the effects of fungicide dose and timing in single and multiple spray programmes and the effects of earlier spray timings on the effectiveness and appropriate dose for subsequent spray applications.

1.1 Objectives

The main objectives of the experiment are:

1. To investigate the effect of fungicide input on yield and profitability of winter wheat production.

2. To determine the effects of timing of fungicide inputs on disease control and yield response.

3. To determine the 'residual' effects of earlier timings on subsequent timings of fungicide input.

4. To determine the effect of dose/timing combinations on the planning of fungicide programmes.

The experiment is designed to determine the effects of spray timing, fungicide dose at individual timings and total fungicide input, on yield response and profitability. The aim being to minimise fungicide and application costs, whilst maximising disease control, yield and grain quality. At each of four fungicide timings tested (GS32, GS33, GS39 and GS59) fungicides were applied at one of four possible rates - full, ½ and ¼ of the label recommended dose and zero. This resulted in a wide range of fungicide spray programmes based on 1-, 2- or 3-spray applications, under a range of disease risk conditions.

The experiment also aims to gather data to help understand how active fungicide metabolites remaining from previous applications affect the appropriate dose required for the current application. This allows adjustments to be made to the fungicide input in order to optimise disease control and profitability. Using the information derived from this experiment, it is possible to visualise how the yield of varieties under differing disease pressures responds to fungicide input. More importantly, it allows the profitability of different fungicide programmes to be compared.

1.2 Sites

The experiment was carried out at four sites in each year:

1: ADAS Rosemaund
Preston Wynne
Hereford. HR1 3PG

2: ADAS Terrington
Terrington-St-Clement
King's Lynn
Norfolk. PE34 4PW

3: Morley Research Centre
Morley,
Wymondham
Norfolk. NR18 9DB

4: SAC Aberdeen
Scottish Agricultural College
581 King Street
Aberdeen. AB9 1UD

1.3 Treatments

At the *Septoria tritici* target sites (ADAS Rosemaund and Morley) the fungicide used in the spray programmes was tebuconazole (as c.p. Folicur, Bayer plc.). At the yellow rust site (ADAS Terrington) and the mildew site (SAC Aberdeen) the fungicide used was tebuconazole + fenpropidin (as c.p.Patrol, Zeneca). Sprays were applied at full, ½ and ¼ of the label recommended dose. In the final year of the experiment the doses of the fungicide treatments at ADAS Terrington were reduced to ½, ¼ and $^1/_8$ of the label recommended dose in an attempt to gather information on efficacy of lower fungicide doses.

Sprays were applied as 1-, 2-, and 3-spray programmes with timings at :

i) Eventual leaf 3 fully emerged (typically GS 32).
ii) Eventual leaf 2 fully emerged (typically GS 33).
iii) Eventual leaf 1 fully emerged (GS 39).
iv) Ear emerged (GS 59).

The timing of the main component of the total fungicide input is always at GS39. Any dose applied earlier or later than GS39 is never higher than that applied at GS39.

1.3.1 Treatment list

	Growth Stage					Growth Stage			
Treat No.	**32***	**33****	**39**	**59**	**Treat No.**	**32***	**33****	**39**	**59**
1#	0	0	0	0	**27**	.25	.5	1	0
2#	0	0	.25	0	**28**	.5	.5	1	0
3	0	.25	.25	0	**29**	1	.25	1	0
4	.25	0	.25	0	**30**	1	.5	1	0
5	.25	.25	.25	0	**31**	.25	1	1	0
6	0	0	.5	0	**32**	.5	1	1	0
7	.25	0	.5	0	**33**	1	1	1	0
8	0	.25	.5	0	**34**	0	.25	1	.25
9	.25	.25	.5	0	**35**	0	.5	1	.25
10	.5	.25	.5	0	**36**	0	.25	1	.5
11	.25	.5	.5	0	**37**	0	.5	1	.5
12	.5	.5	.5	0	**38**	0	1	1	0
13	0	.25	.5	.25	**39**	0	1	1	.25
14	0	.5	.5	0	**40**	0	1	1	.5
15	0	.5	.5	.25	**41**	0	1	1	1
16	0	0	.5	.25	**42**	0	0	1	.25
17	.25	0	.5	.25	**43**	0	0	1	.5
18	.5	0	.5	0	**44**	0	0	1	1
19	.5	0	.5	.25	**45**	.25	0	1	.25
20	0	0	1	0	**46**	.25	0	1	.5
21	.25	0	1	0	**47**	.5	0	1	.25
22	.5	0	1	0	**48**	.5	0	1	.5
23	0	.25	1	0	**49**	1	0	1	0
24	.25	.25	1	0	**50**	1	0	1	.25
25	.5	.25	1	0	**51**	1	0	1	.5
26	0	.5	1	0	**52**	1	0	1	1

Treatments 1 and 2 to appear 3 times each in each of the two replicate blocks, i.e. 6 plots of each in total.

* Eventual leaf 3 fully emerged

** Eventual leaf 2 fully emerged

2.0 RESULTS

2.1 Disease Progress Curves

Disease development is commonly assessed measured by sequential assessments of the percentage area of the leaf affected by disease. This method of assessment has limitations if attempts are made to relate yield response to disease control. However, it can give a good representation of the way in which a disease epidemic progresses. The value of using area under the disease progress curve (AUDPC) rather than % disease will be discussed Section 2.3

2.1.1 Disease progress curves - *S. tritici*

Figure 1 shows the range of disease progress curves of *S. tritici* at Morley on leaf 3 in 1995, according to the total dose of tebuconazole applied. The total dose is made up of 1-, 2-, and 3-spray fungicide programmes (Section 1.3).

There is a considerable effect of fungicide on the rate of disease progress, even at low doses of fungicide. However, there is a timing aspect to consider when looking at the effect of low doses of total fungicide applied, because a total fungicide input of 0.25 in this experiment was achieved by a single application at GS39. Similarly a total input of 0.5 will include a single treatment at GS39. In this example, even the 0.25 input (0.25 l/ha of Folicur at GS39) had a significant effect on disease progress on leaf 3. At higher total doses, more of the treatments would have included applications at GS32 - (the timing closest to the emergence of leaf 3) in which case a greater effect on disease progress would be expected. Clearly, in Figure 1 once the total dose reaches 0.5 and greater, disease development is reduced - at the higher rates for several weeks. Even at the lower total dose input, there is a reduction in disease which would have reduced the risk of spread of disease from leaf 3 to the flag leaf.

The effect of fungicide reducing of disease development is even more clearly illustrated if levels of *S. tritici* on leaf 2 and leaf 1 are examined (Figures 2 & 3). Because fungicide applications at GS39, GS33 and GS32 can have indirect effects on disease on leaf 2, it might be anticipated that total fungicide input, weighted towards application at GS39, would have a significant effect on disease progress on leaf 2, and their greatest effect on the flag leaf.

The effect of fungicide reducing disease development is even more clearly illustrated if levels of *S. tritici* on leaf 2 and leaf 1 are examined (Figures 2 and 3). Because fungicide applications at GS39, GS33 and GS32 can have indirect effects on disease on leaf 2, it might be anticipated that total fungicide input, weighted towards application at GS39, would have a significant effect on disease progress on leaf 2 and their greatest effect on the flag leaf (Figure 3).

Figure 1. Disease progress curves for *S. tritici* on leaf 3, Morley 1995, at different levels of total dose applied

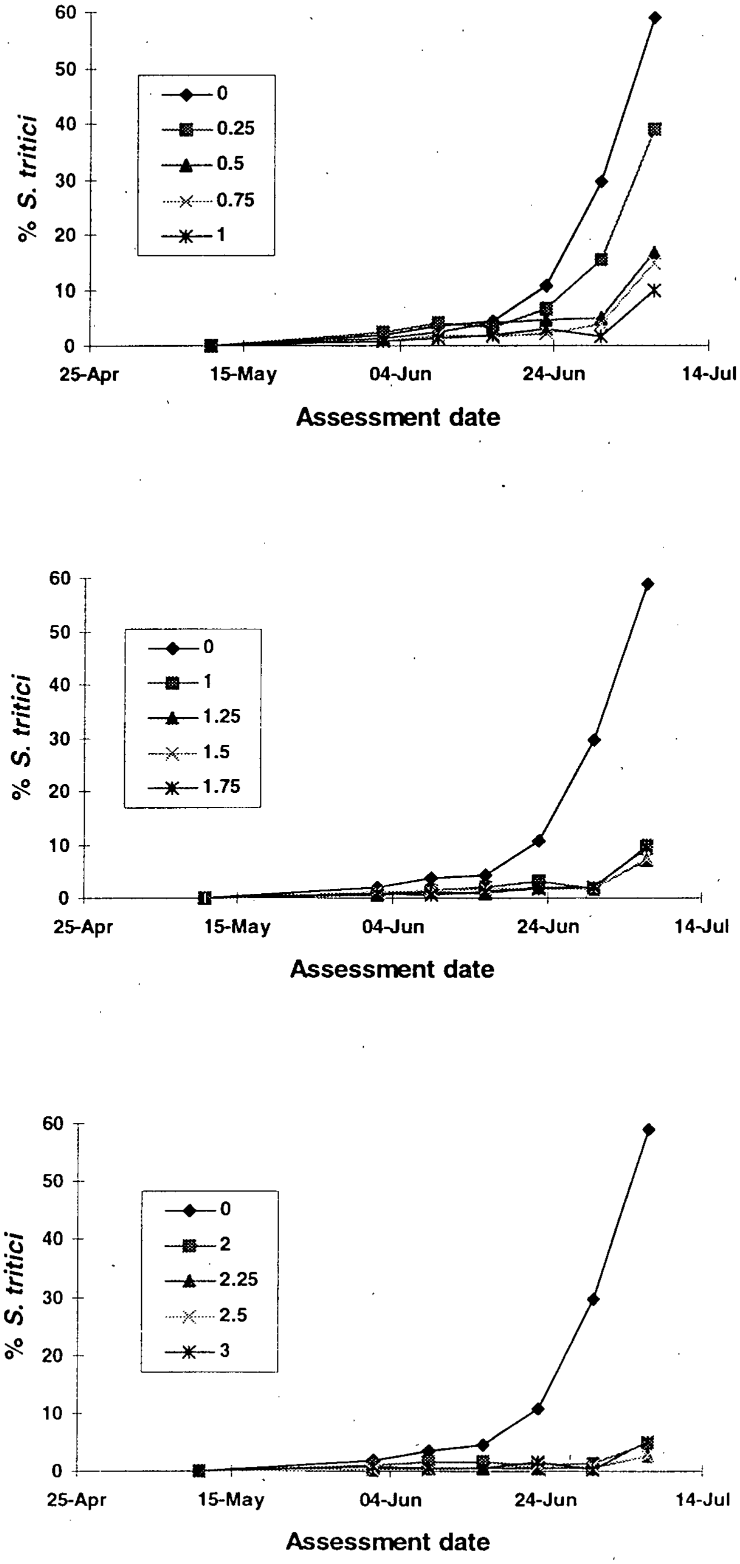
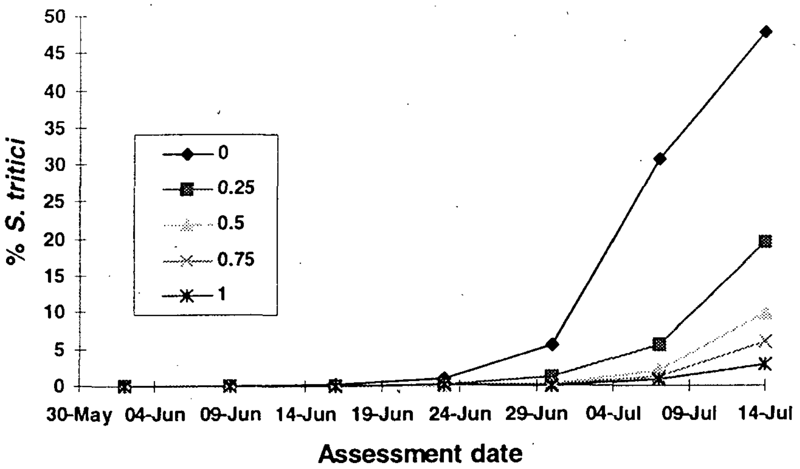
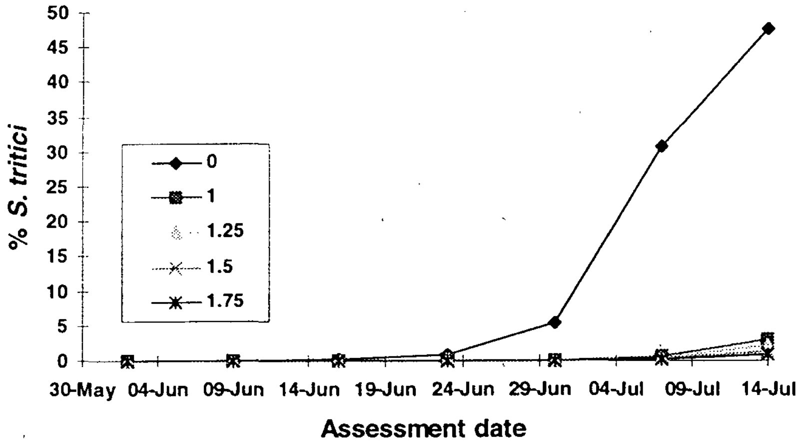


Figure 2. Disease progress curves for *S. tritici* on leaf 2, Morley 1995, at different levels of total dose applied





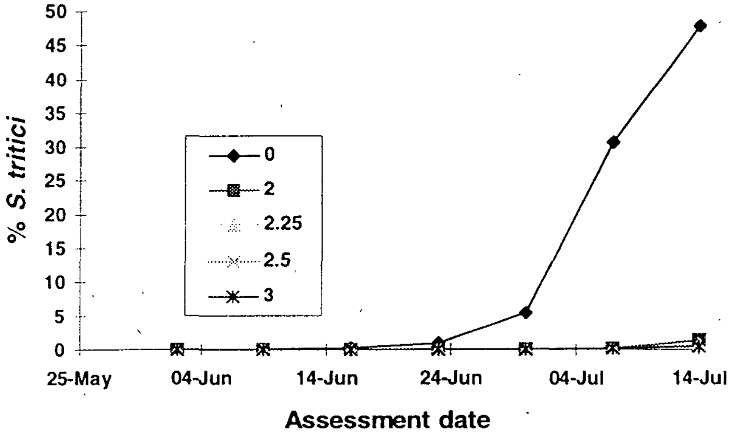
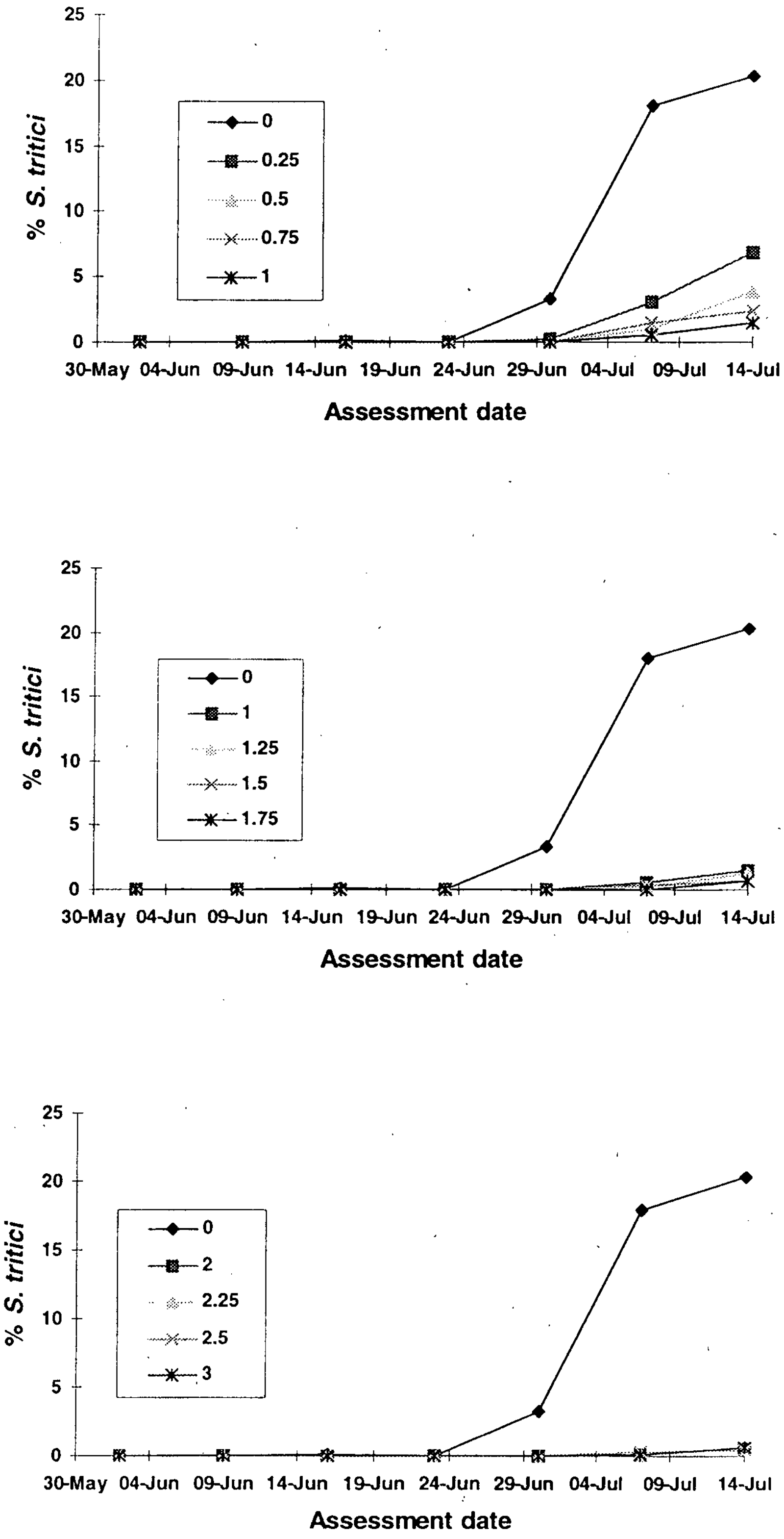


Figure 3. Disease progress curves for *S. tritici* on leaf 1, Morley 1995, at different levels of total dose applied



Disease progress curves such as those above can be represented as surface charts allowing the range of disease progress curves to be viewed simultaneously.

Figure 4. Disease progress curves of *S. tritici* on leaf 3 for all total dose inputs, Morley 1995

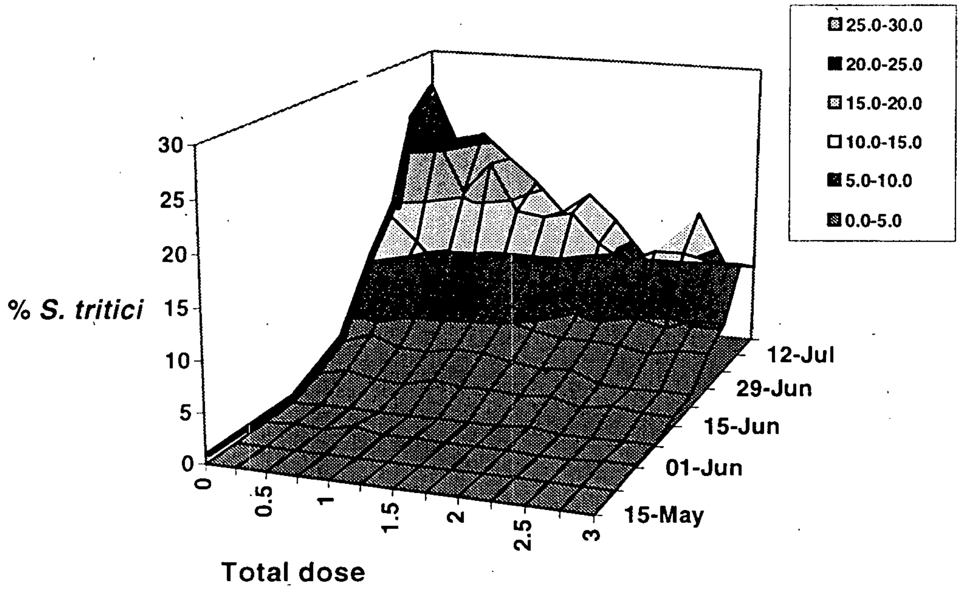


Figure 4 shows the disease progress curves of *S. tritici* on leaf 3 under the range of fungicide inputs from zero to three full doses of tebuconazole. The bold line shows the disease progress curve on the untreated plots. As fungicide dose increases, the rate of disease progress is slowed and the final level of disease is reduced. This confirms similar work by Jorgensen (1990) in Denmark and Griffin (1994) in the UK. In this example, disease levels reached almost 30% in the untreated plots, whereas in the plots receiving three full doses of tebuconazole, the disease level reached only 10%.

The reduction in disease levels, particularly on the upper leaves is significant in terms of yield response, but the reduction in disease on the lower leaves, particularly leaf 3 and 4, can also be significant. The effect of disease control on lower leaves is to reduce the likelihood of the spread of *S. tritici* from leaves 3 and 4 to the emerging flag leaf and the next leaf (leaf 2). Because of the position of leaf 2 and the flag leaf at GS37 there is a risk of direct transfer of inoculum from the lower leaves to the upper 2 leaves (Figure 5). If inoculum is present on leaf 3 and 4 as the flag leaf is emerging then the risk of direct transfer is high. Fungicide applications at GS31/32 have the effect of delaying disease progress on leaves 3 and 4 beyond the time when the flag leaf is emerging. Once further stem extension occurs and the flag-leaf is fully emerged, disease development on leaves 3 and 4 poses less of a risk to the upper leaves because of the spatial separation. The variability of this effect is demonstrated at the Morley sites in 1994 and 1995 where the emergence of the flag leaf in relation to disease development on leaves 3 and 4 is shown in Figures 6 & 7. During 1994, flag leaf emergence began at the end of May at which time untreated plots had *S. tritici* sporulating on leaf 4 and leaf 3. Where a GS32 spray had been applied, the disease progress on these leaves was delayed until well after full flag-leaf emergence. During the 1995 season at Morley the development of *S. tritici* on leaf 3 or 4 and the emergence of the flag-leaf were such that no inoculum was present on leaves 3 and 4 during flag-leaf emergence. Thus, the risk of direct transfer of inoculum to the flag-leaf was very small.

The risk of spread of *S. tritici* from lower leaves to the emerging flag leaf is important in both wet and dry seasons. In seasons when heavy rainfall occurs during flag leaf emergence the proximity of inoculum on leaves 3 and 4 makes infection of upper leaves more likely than where inoculum must be splashed from the base of the plant. However, in seasons where rainfall does not occur during flag-leaf emergence the presence of inoculum on leaves 3 and 4 can be particularly significant as spread can occur when leaves are wet with dew or light rain. These are conditions when farmers and advisers may consider the risk of *S. tritici* to be low and delay the flag-leaf application. In this situation, the result is often poor control of *S. tritici* on both the flag-leaf and leaf 2.

Figure 5. Position of leaf 3 in relation to the emerging flag leaf at GS37.

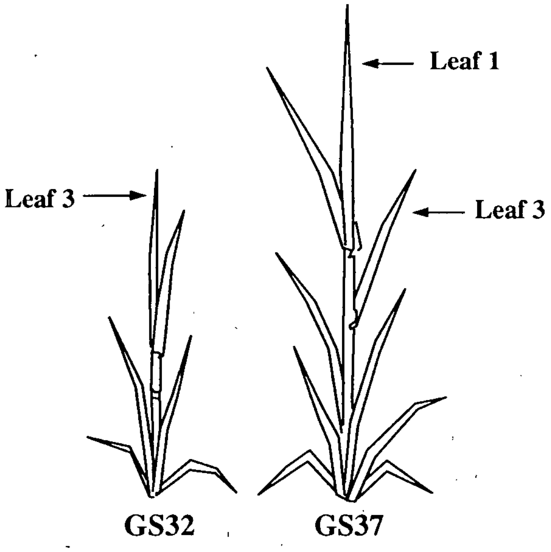


Figure 6. Disease progress curves for *S. tritici* on top four leaves, Morley 1994.

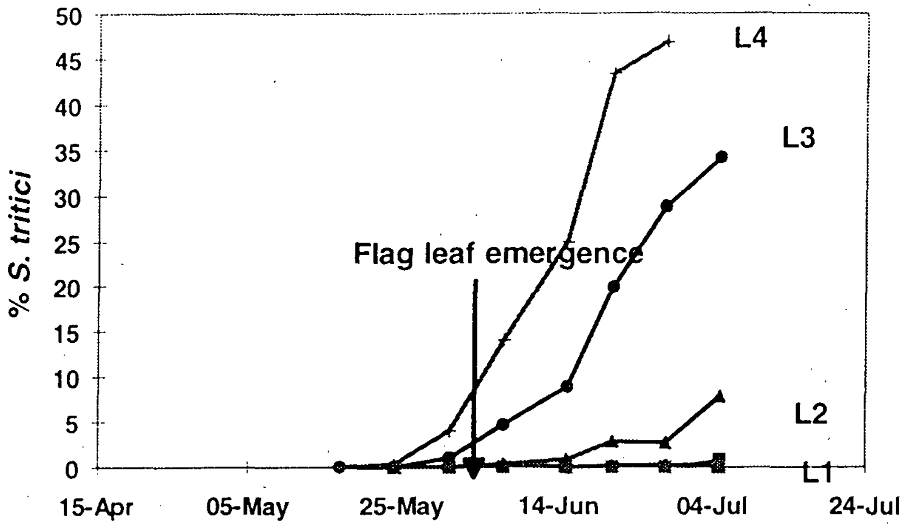


Figure 7. Disease progress curves for *S. tritici* on top four leaves, Morley 1995

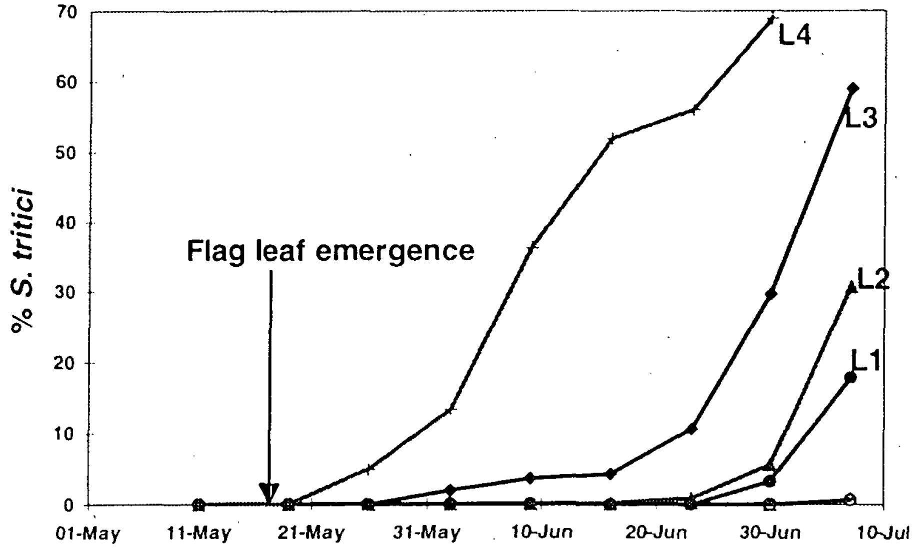


Figure 8. Disease progress curves on leaves 1-3 for all total dose inputs, Morley 1996

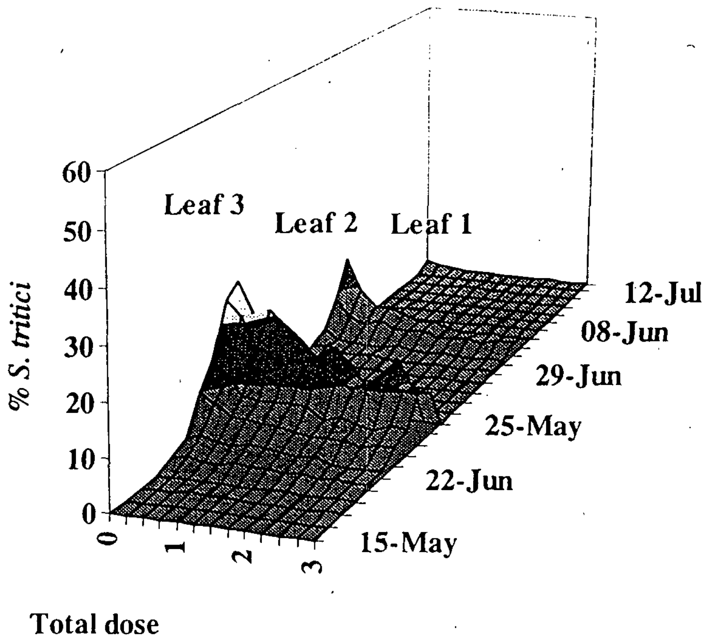


Figure 8 shows the disease progress curves on the top 3 leaves for *S. tritici* at Morley in 1996. Compare the disease levels with those of 1994 and 1995, shown in figure 13. Clearly, in 1996 the *S. tritici* epidemic was confined to leaf 3 and leaf 2 as dry conditions during May and June prevented spread and subsequent disease development on the flag-leaf.

2.1.2. Disease progress curves - yellow rust

The previous examples of the effect of fungicide dose on disease development have dealt largely with *S. tritici*. The disease progress curves of yellow rust are very different from *S. tritici* and the effect of dose is much more marked. Compare the disease progress curves of yellow rust at ADAS Terrington in 1995 (Figures 21-23) with those of *S. tritici* at ADAS Rosemaund, Morley and Aberdeen (Figures 25-27). In the yellow rust epidemics the rate of disease progress was much higher and the final levels of disease much higher. With yellow rust disease development is almost totally prevented by fungicide applications. Almost complete disease control was achieved by all doses above 0.25 (tebuconazole + fenpropidin). The 0.25 dose would have been a single application at GS39 and this significantly reduced the rate of disease progress and reduced the final disease level on the flag-leaf, leaf 2 and leaf 3 compared with the untreated. Higher rates of fungicide and multiple applications both had very significant effects on the disease, typically preventing disease progress beyond levels present at the time of application.

The position of inoculum within the canopy with respect to the yellow rust epidemic compared with a typical *S. tritici* epidemic is of note. When comparing the *S. tritici* epidemics at Morley in 1994 and 1995 it is clear that under particular circumstances of leaf emergence and inoculum position it is possible to get direct infection of the flag-leaf from inoculum on leaves 3 and 4. This event is dependant on critical timing of infection and sporulation of the pathogen on leaf 3 and 4, coinciding with the emergence of the flag-leaf. This is because of the long latent period of the pathogen, typically taking 3-4 weeks from infection to symptom production and sporulation in the summer months. A yellow rust epidemic is very different, largely because of the much shorter latent period of 7-10 days in the summer months. It can be seen from the yellow rust disease progress curves at ADAS Terrington in 1995 (Figure 9) that infection levels were higher on the upper 2 leaves than on leaf 3 and that there was active sporulation on leaf 2 as the flag-leaf was emerging. Because of the short latent period, yellow rust infection and sporulation can keep pace with leaf emergence, so each new leaf layer becomes infected as it emerges. The relationships between dose applied and yellow rust disease progress for 1994-1996 are shown in Figure 13. Clearly low doses of fungicide are capable of having significant effects on disease progress. This is a reflection of the inherently high efficacy of tebuconazole and fenpropidin against yellow rust. In attempt to obtain information on efficacy at rates below 0.25 on the 1996 treatment list was amended to include 0.5, 0.25 and 0.125 doses. Disease levels were low in 1996 and efficacy data with very low rates were not obtained.

Figure 9. Yellow rust disease progress on untreated plots for the upper three leaves, ADAS Terrington 1995.

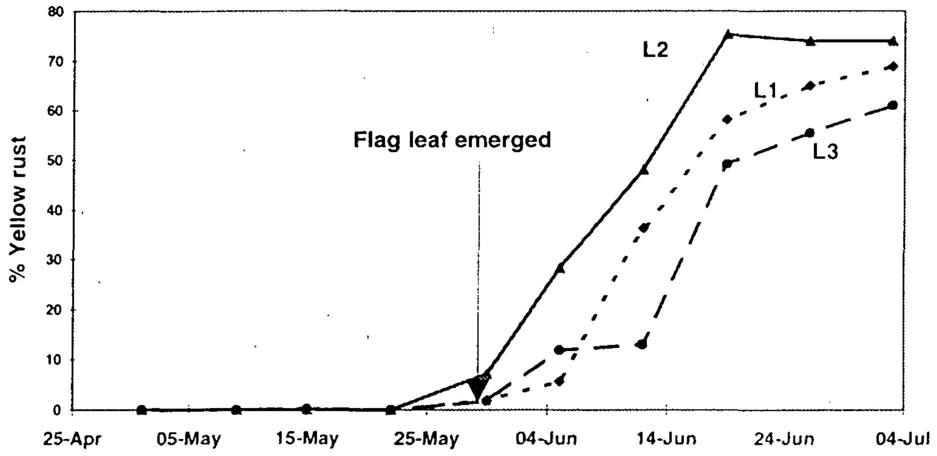


Figure 10. Yellow rust disease progress curves, flag-leaf, ADAS Terrington 1995

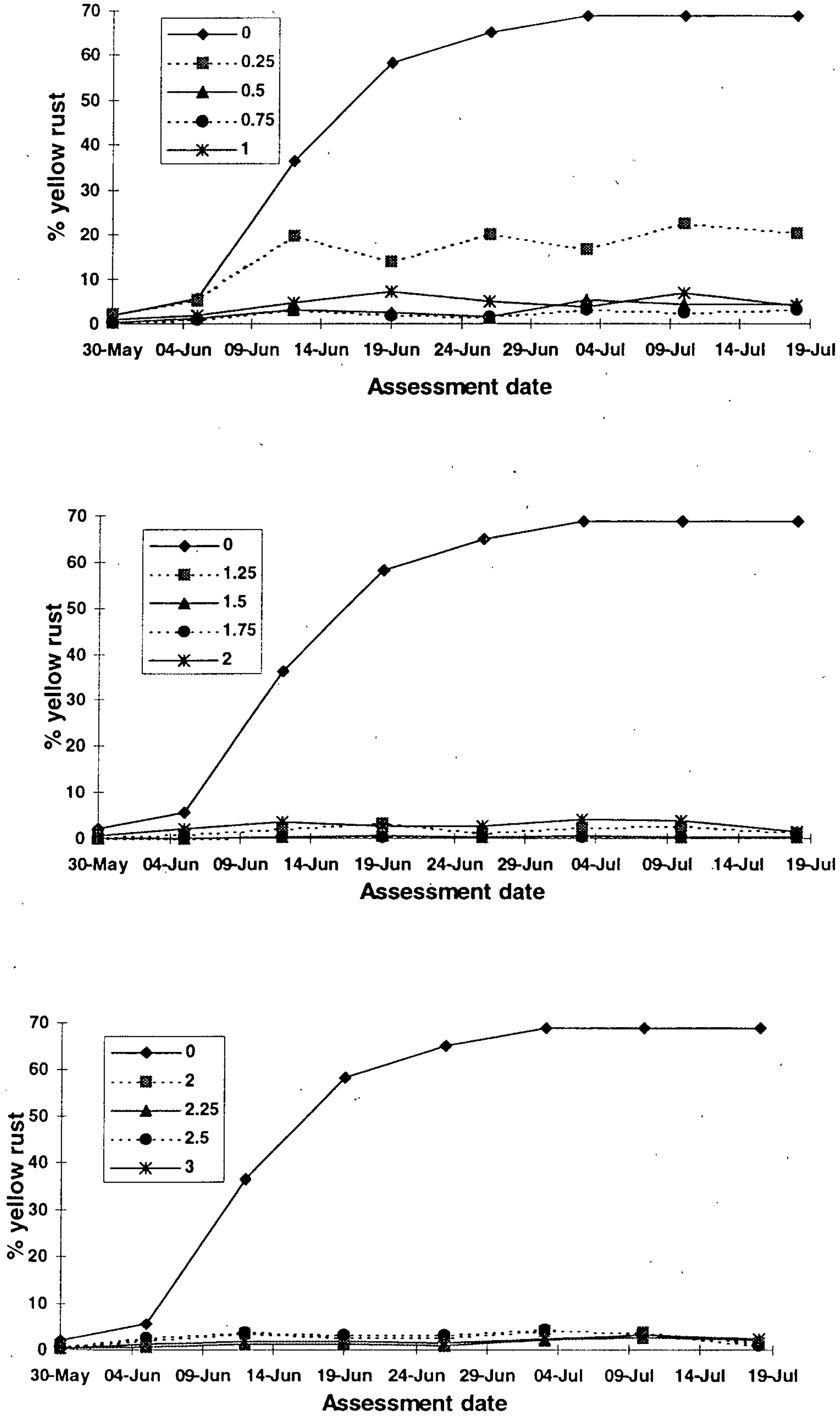


Figure 11. Yellow rust disease progress curves, leaf 2, ADAS Terrington 1995

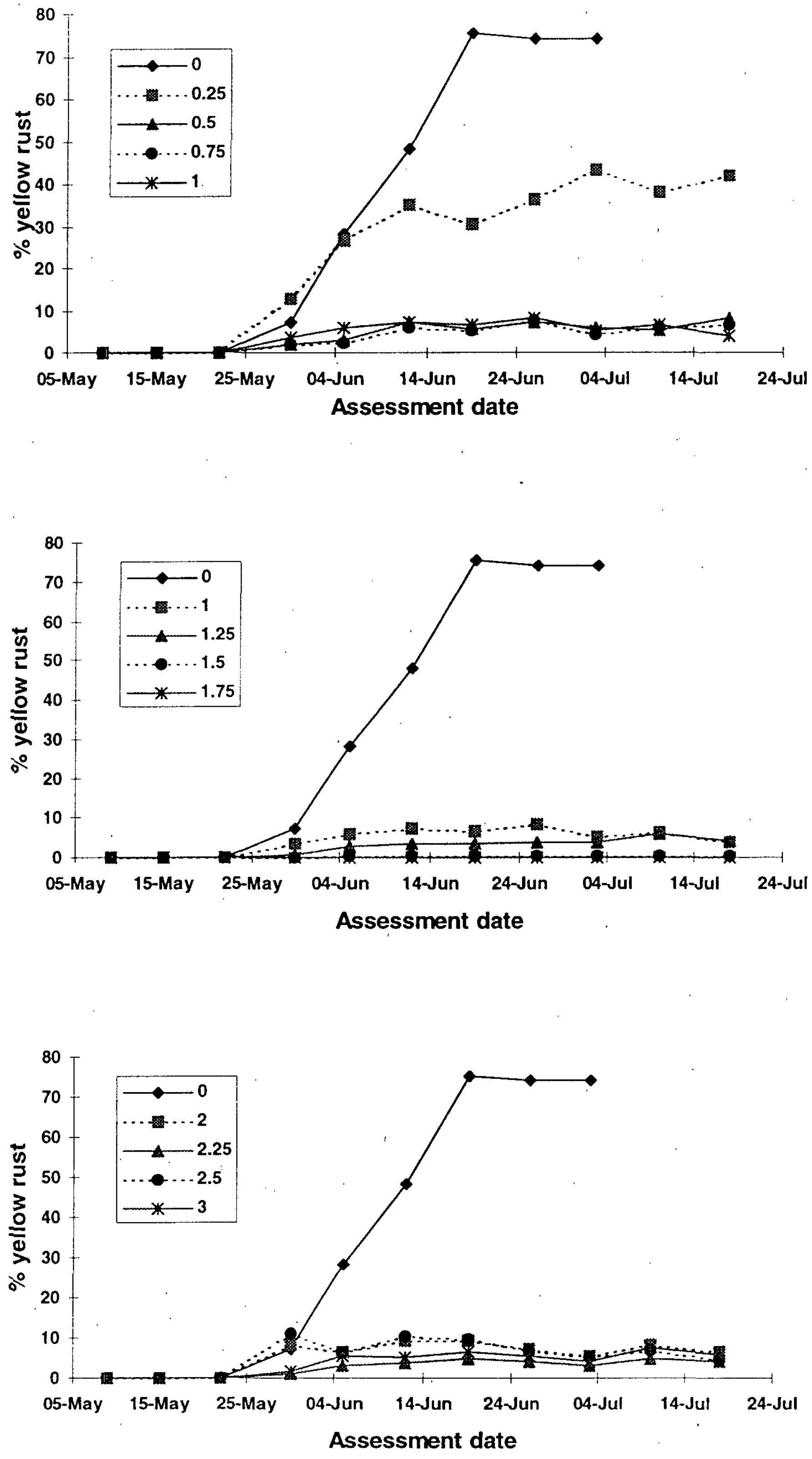


Figure 12. Yellow rust disease progress curves, leaf 3, ADAS Terrington 1995

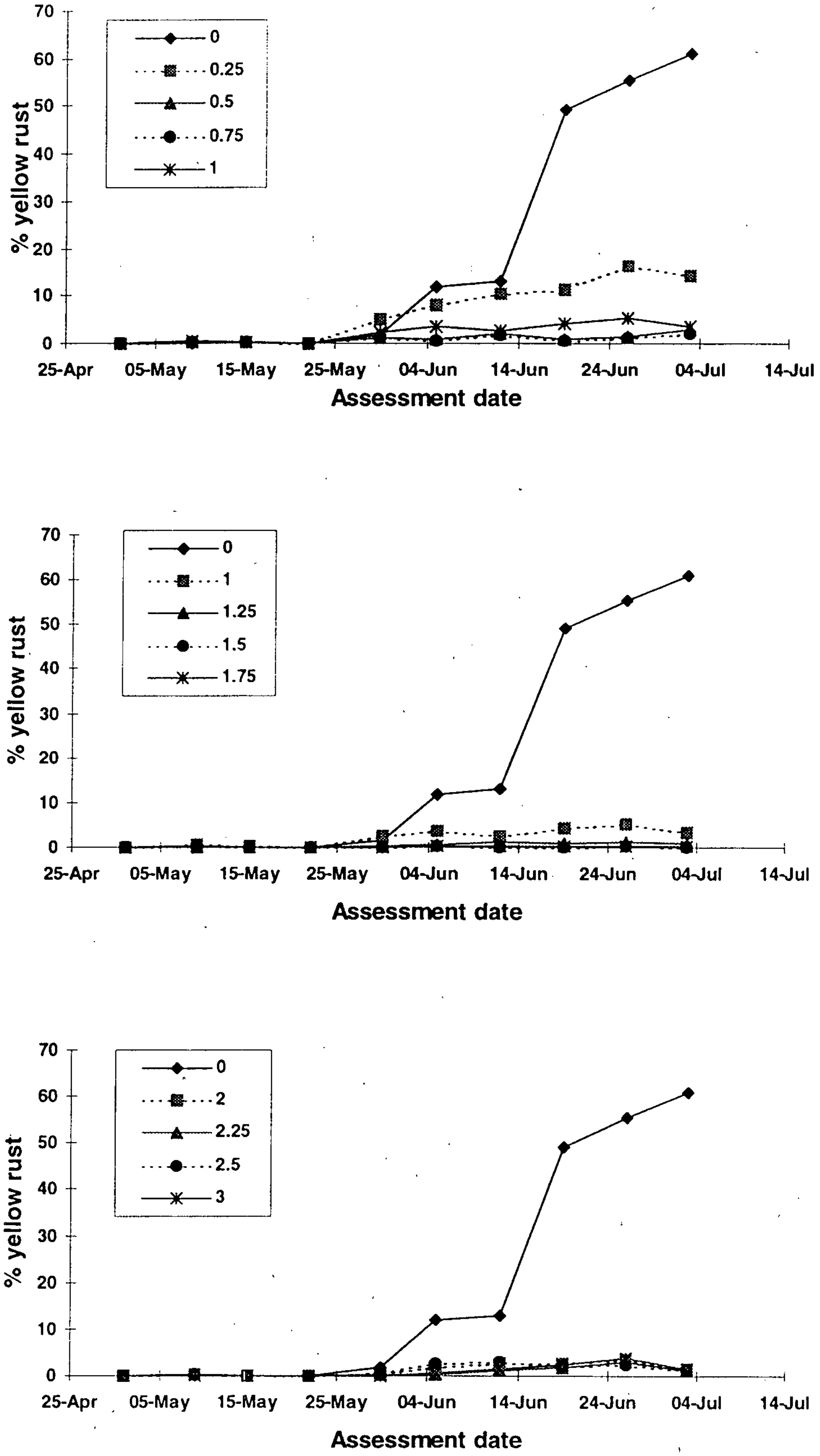


Figure 13. Disease progress curves on leaves 1-3 for all total dose inputs, ADAS Terrington 1994-96

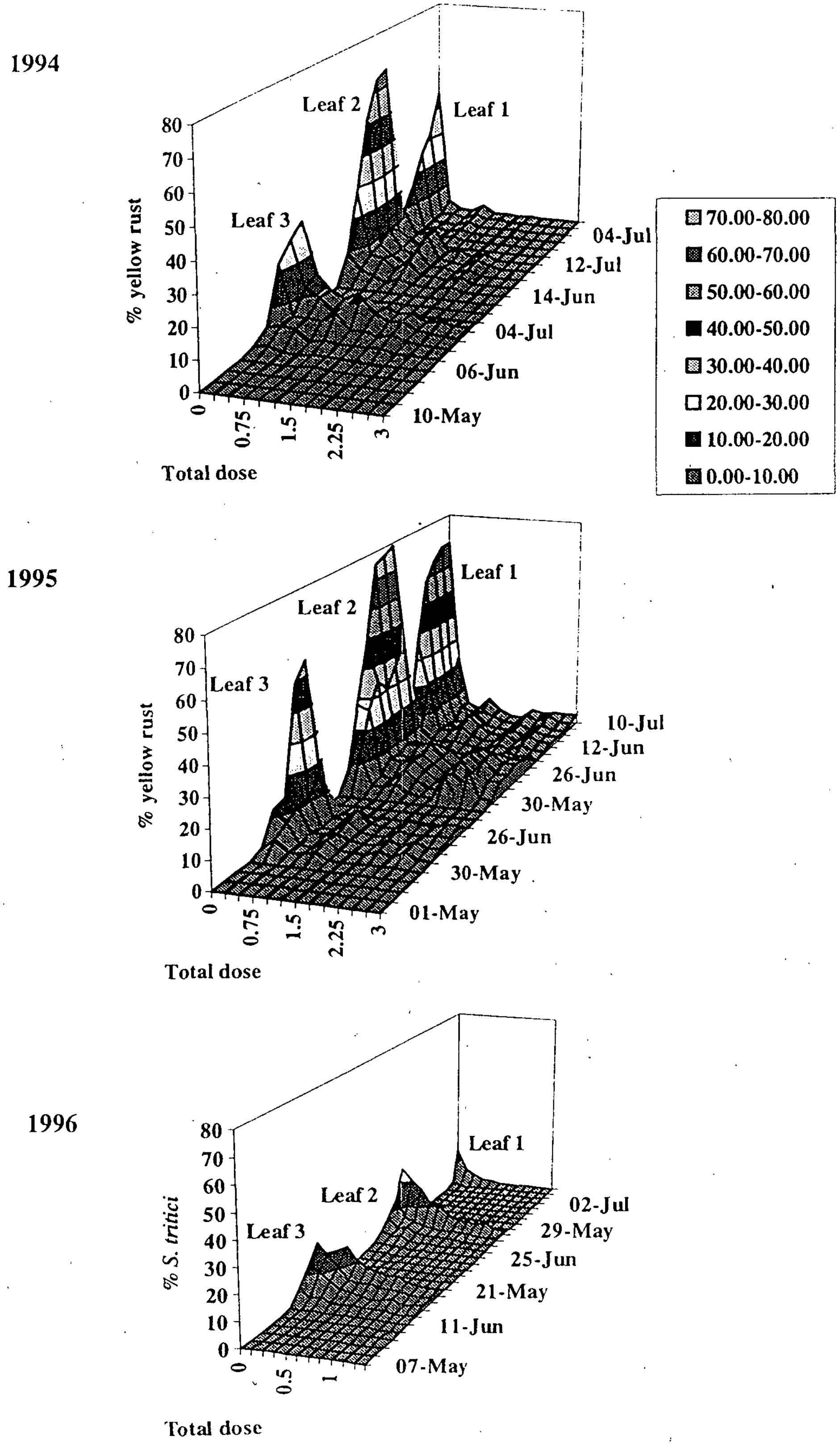


Figure 14. Disease progress curves, on leaves 1-3 for all total dose inputs ADAS Rosemaund 1994-96

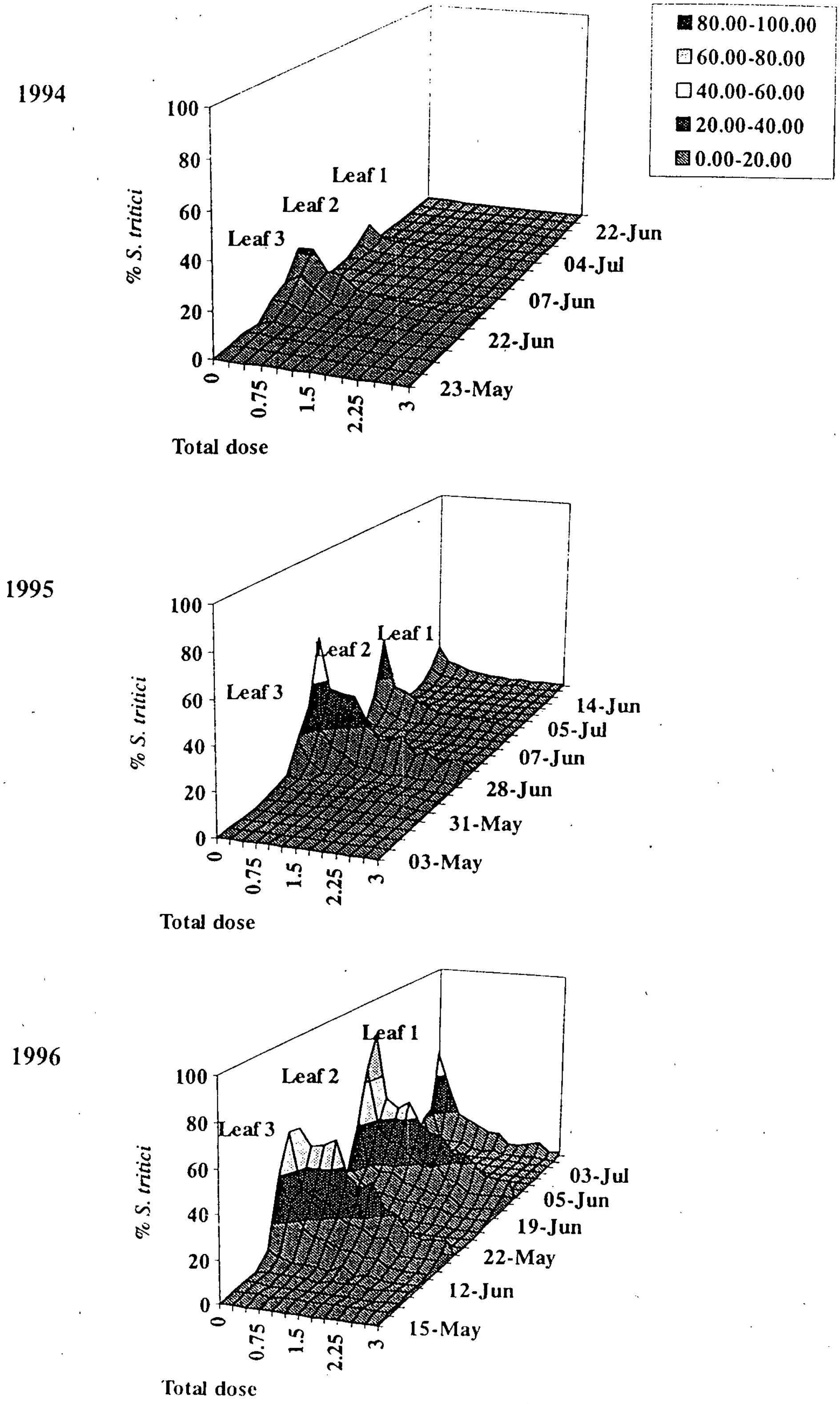
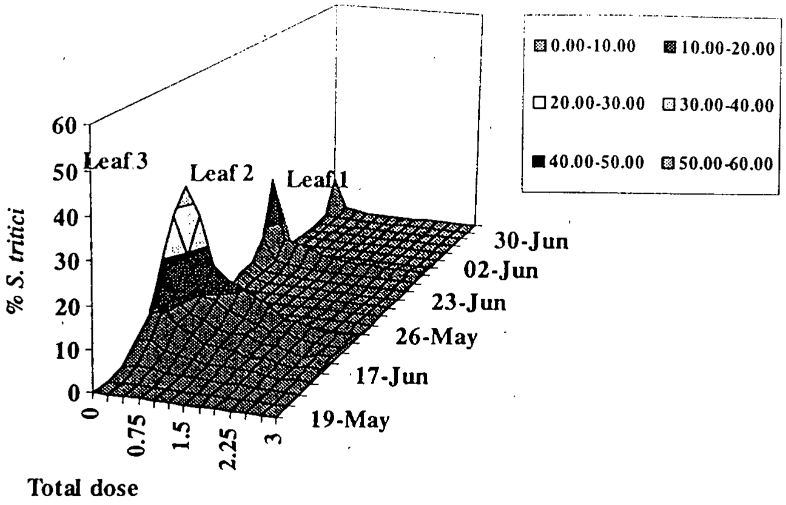
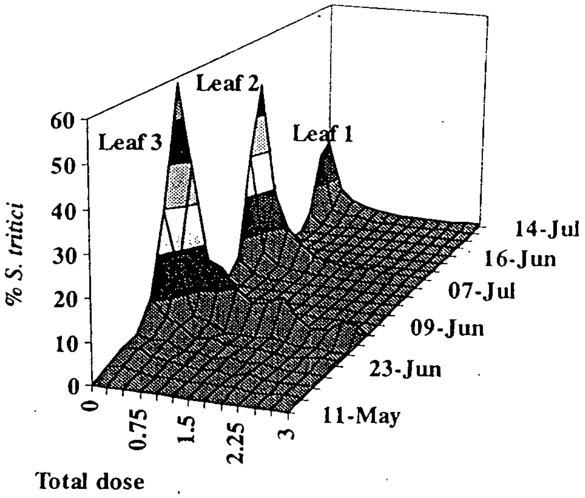


Figure 15. Disease progress curves for all total dose inputs, Morley Research 1994-96

1994



1995



1996

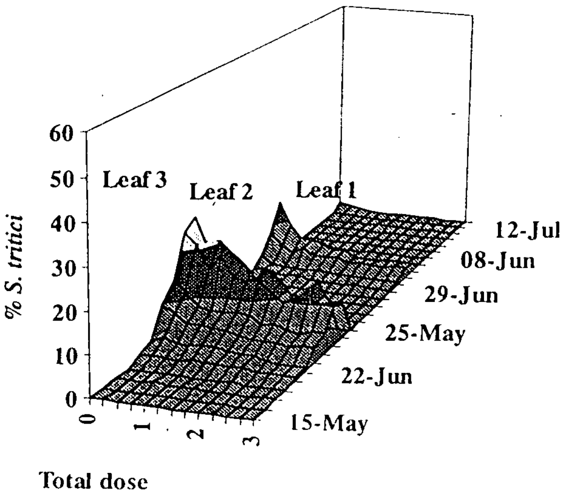
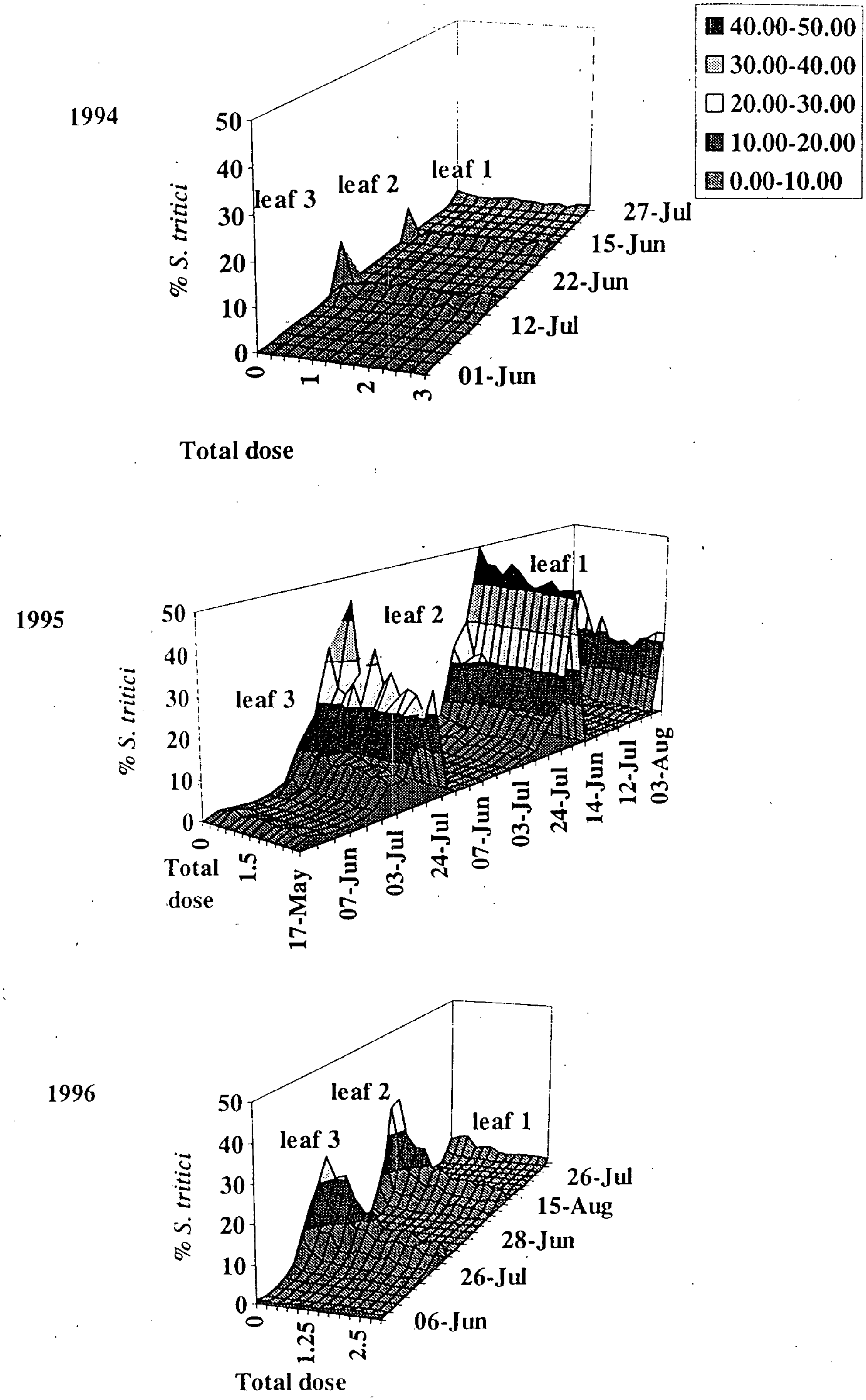


Figure 16. Disease progress curves, for all total dose inputs Aberdeen 1994-96



2.2 Effects of fungicide timing on disease progress

The previous section explained how increasing the total amount of fungicide applied to a wheat crop can have significant effects on the time of onset of disease, the rate of disease progress and the final level of disease. The design of this experiment allows the timing component of the fungicide input to be isolated. This section describes the effects of timing of fungicide applications on disease development.

Each fungicide application was applied at any one of four timings:

1. GS32 (emergence of leaf 3)
2. GS33 (emergence of leaf 2)
3. GS39 (emergence of leaf 1)
4. GS59 (emergence of ear)

In the following charts, these timings are represented by seven codes (excluding the untreated code):-

	Fungicide applied at growth stage:			
Code	GS32	GS33	GS39	GS59
0	x	x	x	x
0010	x	x	✓	x
0011	x	x	✓	✓
0111	x	✓	✓	✓
1110	✓	✓	✓	x
1011	✓	x	✓	✓
1101	✓	✓	x	✓
1010	✓	x	✓	x

The use of these codes allows us to examine the timing effect of application in isolation and to determine if particular timings have significant effects on disease development and yield response.

2.2.1 S. tritici - effect of timing on disease progress

Figures 28 and 29 show the disease progress curves of *S. tritici* on leaves 3 and 4 at ADAS Rosemaund in 1995. The codes indicate the timing of the applications. The disease progress curve in the untreated plots (0) rises steeply, reaching a peak at 35% by the end of June. The flag-leaf treatment alone (0010) had a significant effect on disease progress on leaf 3, restricting the rate of disease progress and reducing the final level to 10%. This effect of a flag-leaf application affecting disease on leaf 3 is unusual, but in this experiment disease progress on leaf 3 was later than normal, indicating that the leaf had become infected late - probably in late April - early May. All treatments which included a treatment at GS32 or GS33 maintained disease levels well below 5% throughout June. A similar comparison of the effects of timing on disease on leaf 4 (Figure 28) shows little effect of any spray programme on disease progress. This is because even the earliest spray timing (GS32) could not eradicate established infection of *S. tritici* which was already present on leaf 4 at the time of the fungicide application.

Figure 17. Effect of spray timing on *S. tritici* disease progress curves on leaf 3, ADAS Rosemaund 1995.

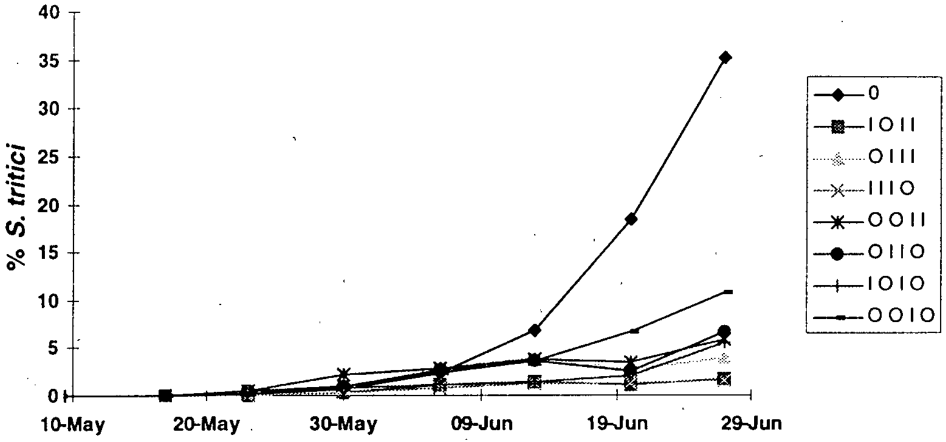
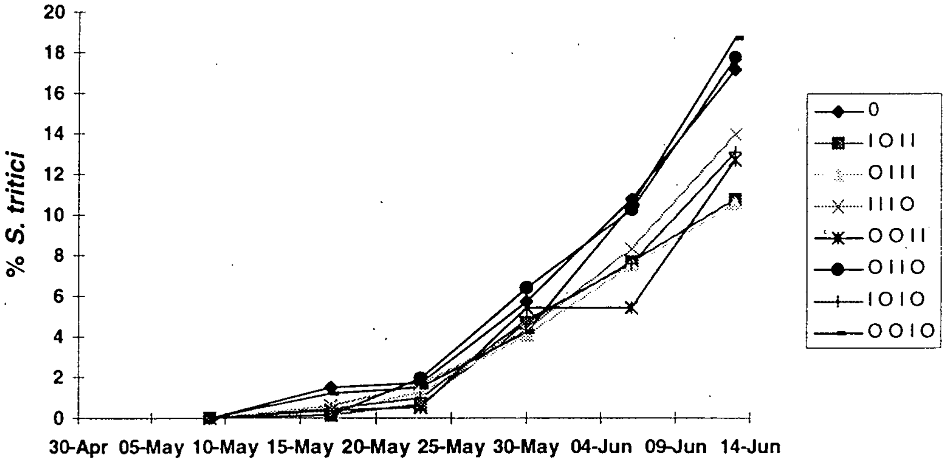


Figure 18. Effect of spray timing on *S. tritici* disease progress curves on leaf 4, ADAS Rosemaund 1995.



The disease progress curves for *S. tritici* and the effects of fungicide timing on disease progress at Morley are shown in Figure 19. Disease progress was greatest on leaf 3 and all programmes which include a GS32 or GS33 spray timing significantly reduced the progress of disease on that leaf. Disease progress on leaves 2 and the flag leaf was dramatically reduced by all spray programmes (all of which included a GS39 treatment). These data confirm the findings at ADAS Rosemaund, showing the importance of applications of fungicide to the final leaf 3 in reducing the progress of disease on that leaf layer.

Disease progress on the flag-leaf is affected by applications of fungicide at GS59 (ear emergence) as well as at GS39 (flag-leaf emergence). The GS59 spray is often applied to commercial crops in an attempt to control ear diseases but it clearly has the effect of prolonging disease control on the flag-leaf. This can be seen clearly in Figure 19 (Morley 1995) where development of *S. tritici* on the flag-leaf and leaf 2 is reduced by programmes containing a GS39 application, and further reduced by the addition of a GS59 application.

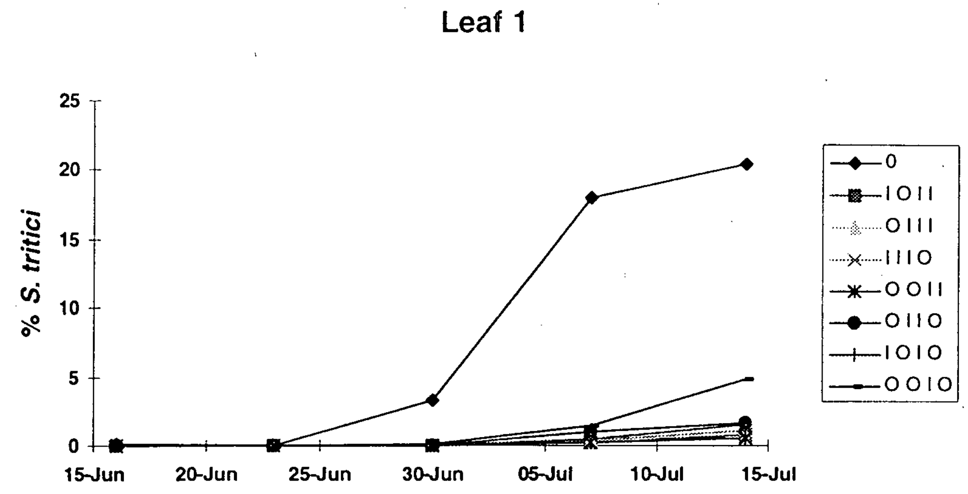
The flag leaf timing of fungicides has the greatest effect on disease progress on the main yield-producing leaf layers (flag leaf, and leaf 2). The addition of a later spray timing at GS59 (ear emerged) can further prolong disease control on the flag leaf over and above that achieved by the flag leaf alone.

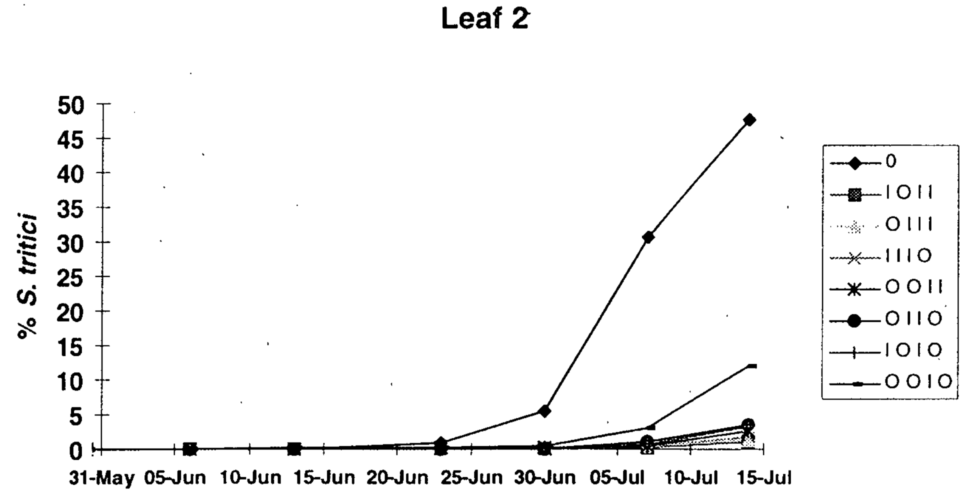
Earlier timings at GS32 and GS33 delay disease progress on lower leaf layers (leaf 3 and occasionally leaf 4) which can be important in reducing the likelihood of *S. tritici* spreading from those layers to the flag leaf and leaf 2.

2.2.2 Yellow Rust - effect of timing on disease progress

There is a considerable contrast between the effects of fungicide timing on the control of yellow rust and on the control of *S. tritici*. Because yellow rust progresses so much more quickly than *S. tritici* the effects of timing are often more apparent (Paveley 1993). The disease progress curves for yellow rust at ADAS Terrington in 1995 illustrate some of these features. Figure 20 shows the effects of spray timing on the development of yellow rust on the top three leaves. Firstly, disease levels are higher on leaves 1 and 2 than on leaf 3. Because of the weighting of all spray timings towards application at GS39, a high degree of disease control on the flag-leaf was achieved by all treatment timings. The rate of disease progress in the untreated plots was high and this was virtually halted by all applications, maintaining yellow rust levels well below 10%. The disease control on leaves 2 and 3 mirrors that on the flag leaf, with all timing treatments giving good control of the disease.

Figure 19. Effect of spray timing on *S. tritici* disease progress curves on leaves 1-3, Morley 1995


Leaf 1


Leaf 2

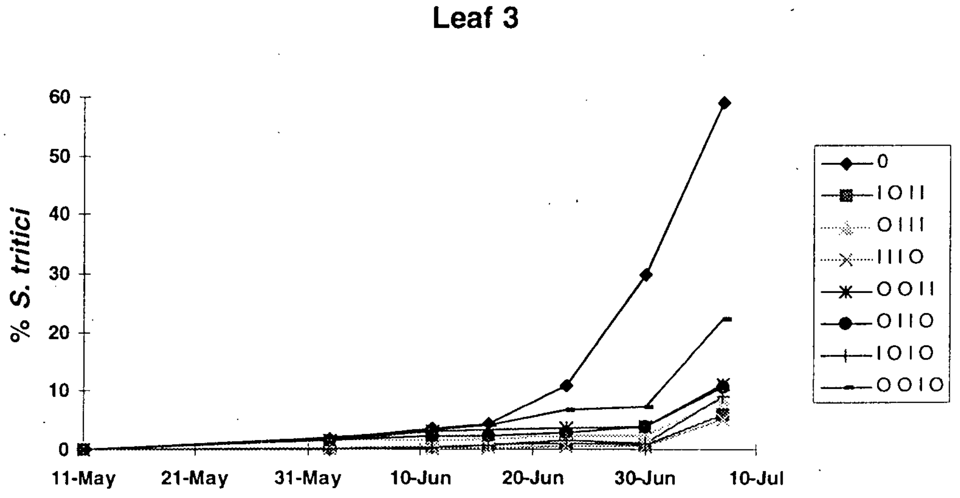
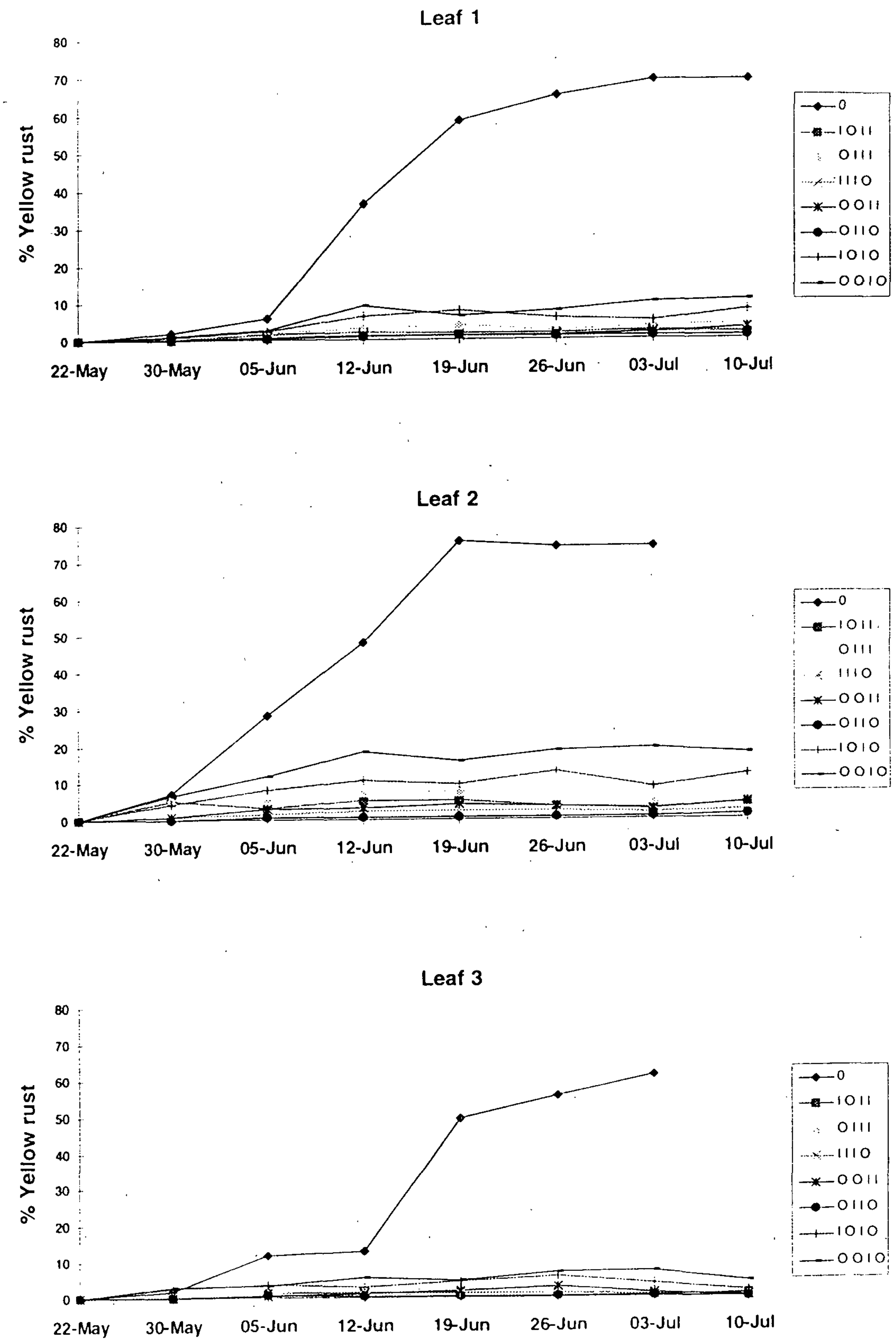

Leaf 3

Figure 20. Effects of spray timing on yellow rust disease progress curves on leaves1-3, ADAS Terrington 1995.



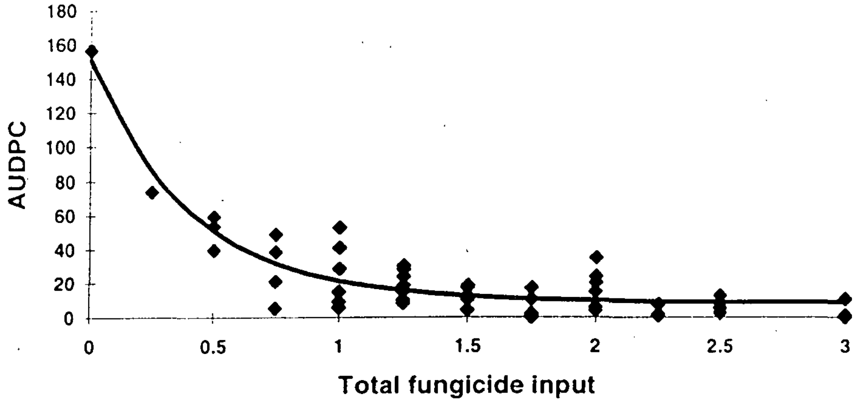
2.3 Area under disease progress curves

Disease epidemics are usually quantified by measuring disease severity, in this case the percentage of the leaf area expressing visible symptoms. The examples prior to this section use disease data, represented as % disease, collected at single points in time. In order to represent the disease data more fully and facilitate cross-site analysis, the area under each disease progress curve (AUDPC) was calculated, representing both the severity of disease and the period of time over which the crop was affected (Bryson 1997). Figures 21 and 22 show the effect of increasing fungicide input on the AUDPC for *S. tritici* at ADAS Rosemaund and Morley in 1995. Clearly as fungicide input increased, the AUDPC reduced. As total fungicide input increased from zero there was a rapid decrease in AUDPC which then slowed as fungicide input continued to increase. The shape of the AUDPC curve provides an indication of the efficacy of the fungicide against the pathogen on a particular leaf layer, thus giving information about the eradicant and protectant nature of the fungicide. There is a marked contrast in the shape of the AUDPC curve when the pathogen under consideration is *Puccinia striiformis* (yellow rust) rather than *S. tritici*.

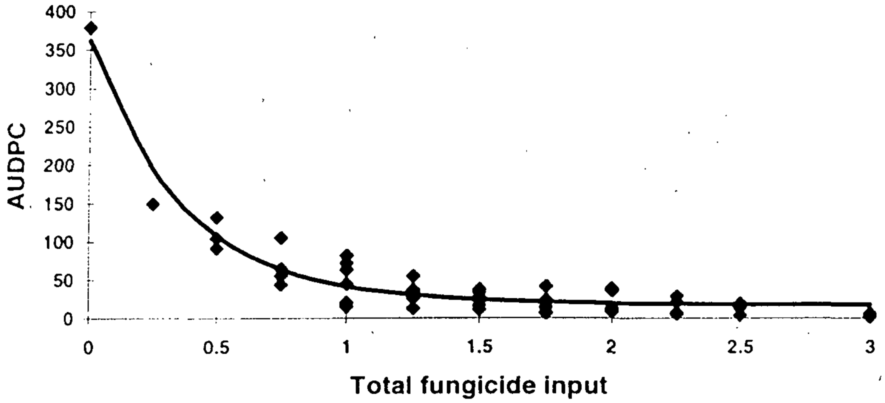
Figure 23 shows the AUDPC for yellow rust on the flag-leaf at ADAS Terrington in 1995. Note the much higher AUDPC Figures than for *S. tritici* at Rosemaund or Morley in the same year. The rate of decline in AUDPC as fungicide input increases is also much greater than with *S. tritici*, indicating the very high efficacy of tebuconazole and fenpropidin against yellow rust.

Figure 21. Effect of increasing fungicide input on AUDPC for *S. tritici*, leaves 1, 2 and 3, ADAS Rosemaund 1995.

Leaf 1



Leaf 2



Leaf 3

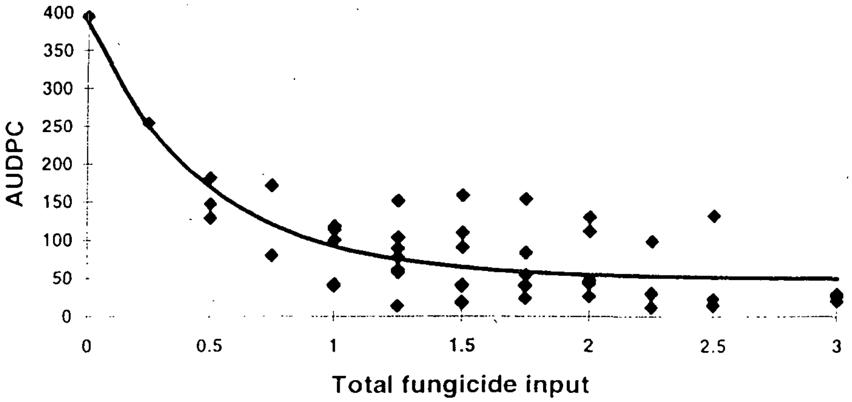
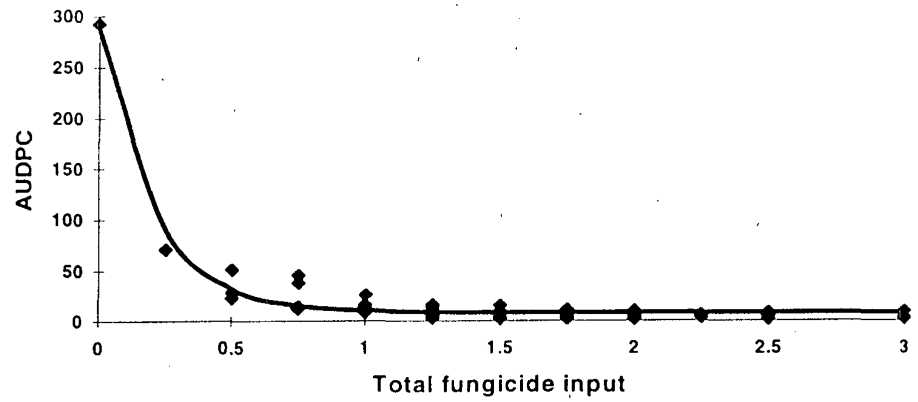
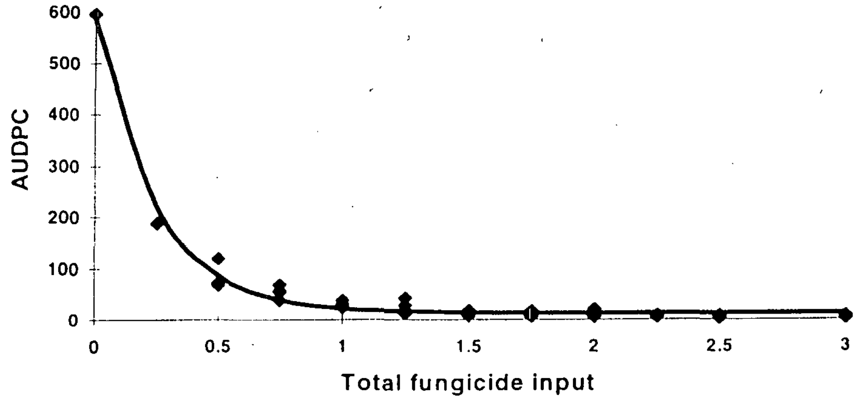


Figure 22. Effect of increasing fungicide input on AUDPC for *S. tritici*,leaves 1, 2 and 3, Morley 1995.

Leaf 1



Leaf 2



Leaf 3

95

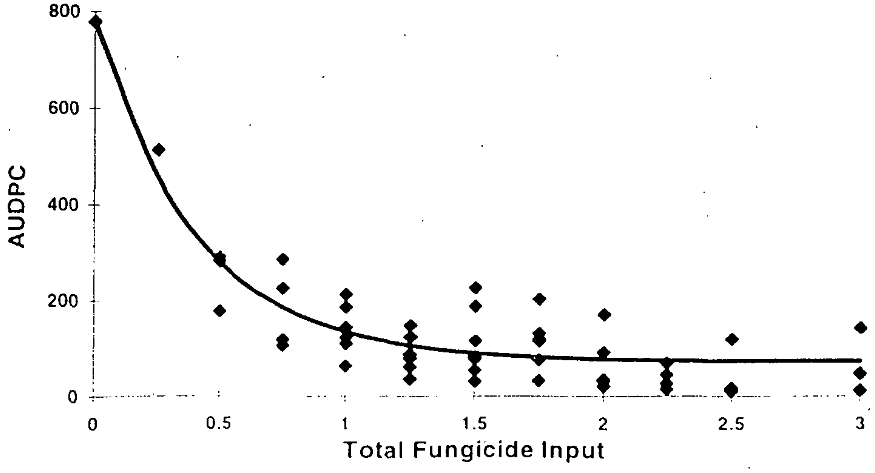
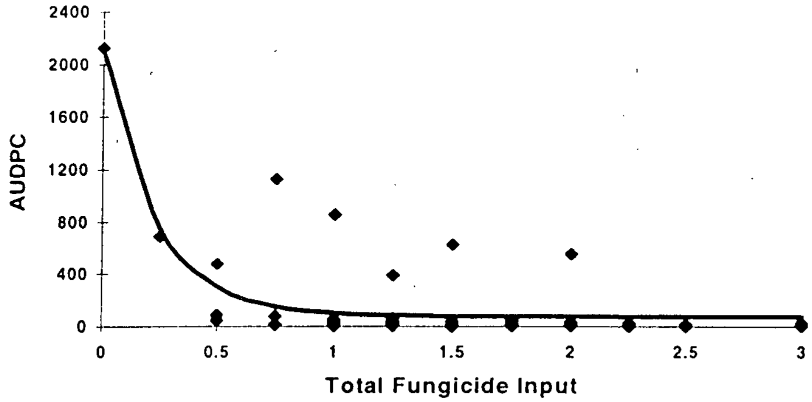
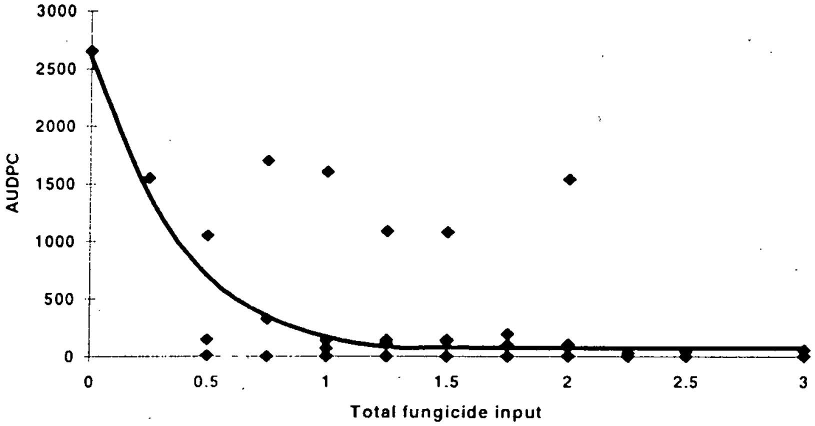


Figure 23. Effect of increasing fungicide input on AUDPC for yellow rust, leaves 1,2 and 3, ADAS Terrington, 1995.

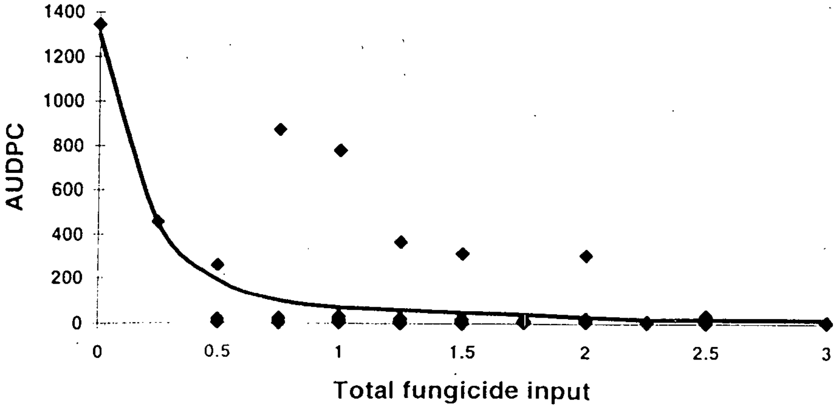
Leaf 1



Leaf 2



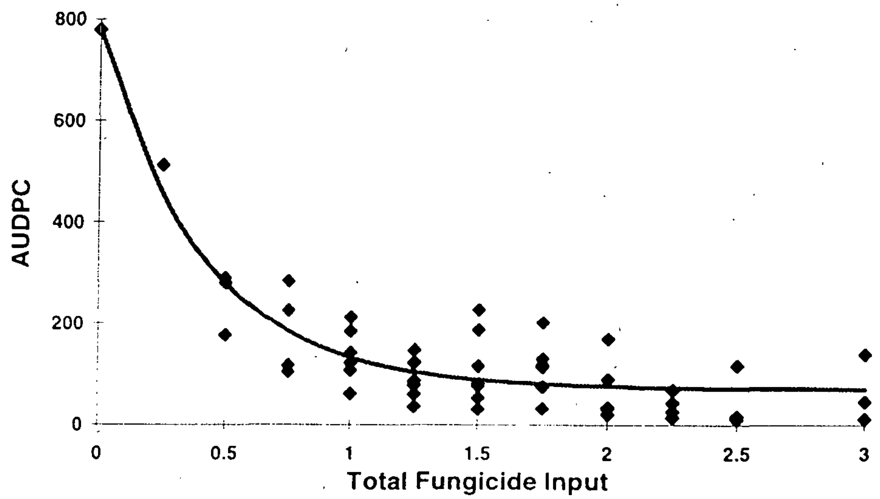
Leaf 3



2.4 Value of AUDPC in determining timing optima

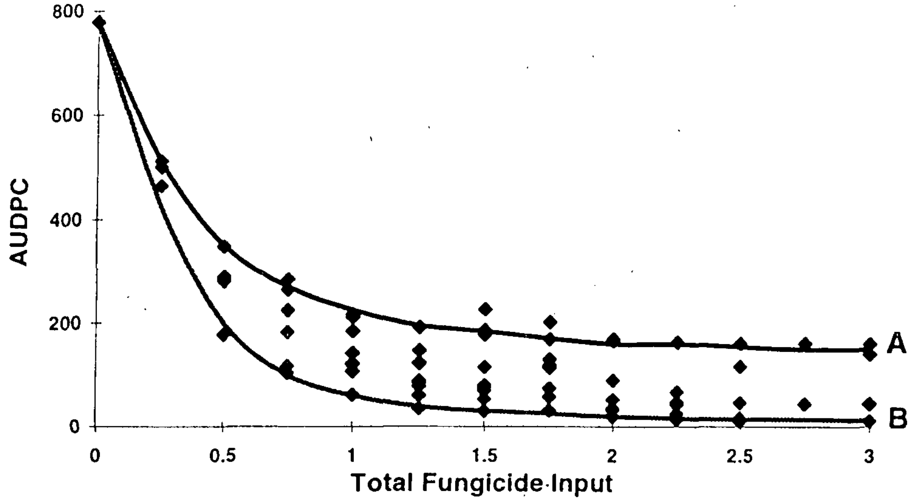
Figure 24 shows AUDPC values for *S. tritici* on leaf 3 at Morley in 1995, with a fitted exponential curve. It is possible to fit an exponential function to the data points for any AUDPC data set. The variation in AUDPCs for any single value of fungicide input is due to error variation and variation in the timing of the fungicide application. In Figure 25 the uppermost data points (line A) represent the poorest disease control achieved for any fungicide input, whereas the lowermost data points (line B) represent the best disease control achieved by any fungicide input.

Figure 24. Fitted exponential curve for AUDPC data, *S. tritici*, Morley 1995



It is a reasonable approximation to say that the vertical distance between the two lines represents the improvment in disease control that can be obtained for a given fungicide input, and the horizontal distance, the reduction in dose possible with good timing while achieving the same level of disease control.

Figure 25. Upper and lower limits of AUDPC data, *S. tritici*, Morley 1995



The degree of scatter of data points in the AUDPC charts, is an indication of the variation in disease control brought about both by timing and by the number of sprays applied. Data points can represent the result of 1-, 2-, or 3-spray programmes. In the AUDPC data for Rosemaund and Morley 1995 (Figures 21 & 22) it is clear that there is much less scatter of data points relating to AUDPC's on leaves 1 and 2 than there is on leaf 3. This is not unexpected, as the treatments are biased towards application at GS39. Thus most of the treatments include application of some fungicide at GS39 - a timing which should ensure good disease control on leaves 1 and 2. However, application of fungicides at GS39 would not be expected to give good control of *S. tritici* on leaf 3 which would have been emerged for several weeks and could also be carrying latent disease which would not be controlled by later treatments. However, many treatments do give a reduction in the AUDPC for *S. tritici* on leaf 3. Examination of the data sets to determine the timing components of those treatments giving good control of *S. tritici* on leaf 3 show that fungicides applied at GS32 give the greatest reduction in AUDPC (Figure 27). The curves fitted through the 2 data sets in Figure 27 show that where a GS32 application is included in the spray programme (curve B) the AUDPC for *S. tritici* on leaf 3 is lower than where no GS32 application is included (curve A). The same effect, but to a higher degree, is seen with the effects of timing of fungicide applications on the control of yellow rust (Figures 28-29).

Figure 26. AUDPC for *S. tritici* on leaf 3 at Morley 1995. Comparison of treatments which include a GS32 treatment, against those without a GS32 treatment. Codings show spray timings of high AUDPC data points.

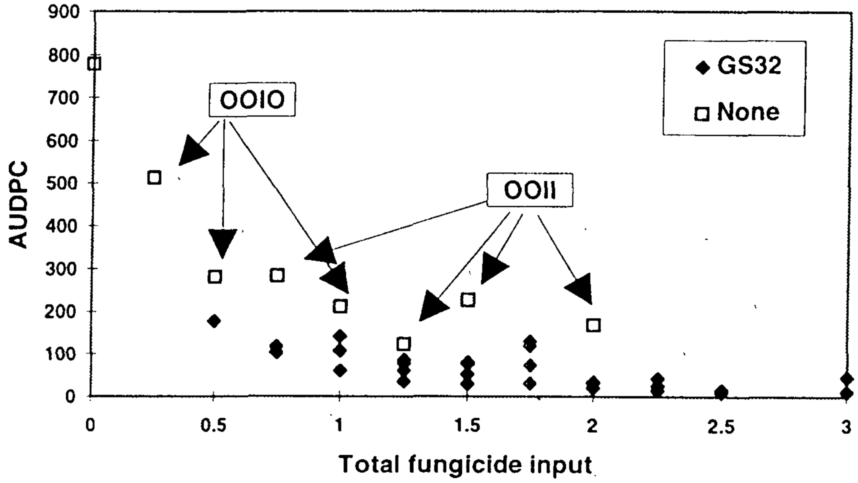


Figure 27. AUDPC for *S. tritici* on leaf 3 at Morley 1995. Comparison of all treatments which include a GS32 treatment, against those without a GS32 treatment.

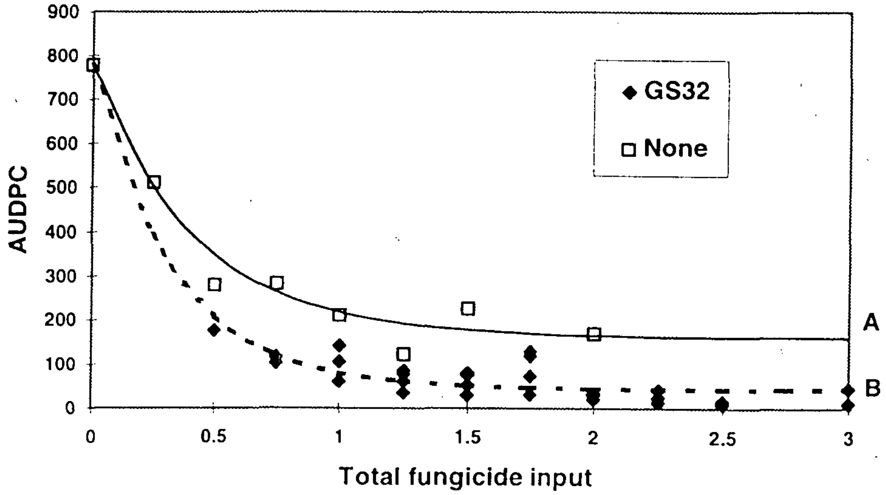


Figure 28. AUDPC for yellow rust on leaf 3 at ADAS Terrington 1995. Comparison of treatments which include a GS32 treatment against those without a GS32 treatment. Codings show spray timings of high AUDPC data points.

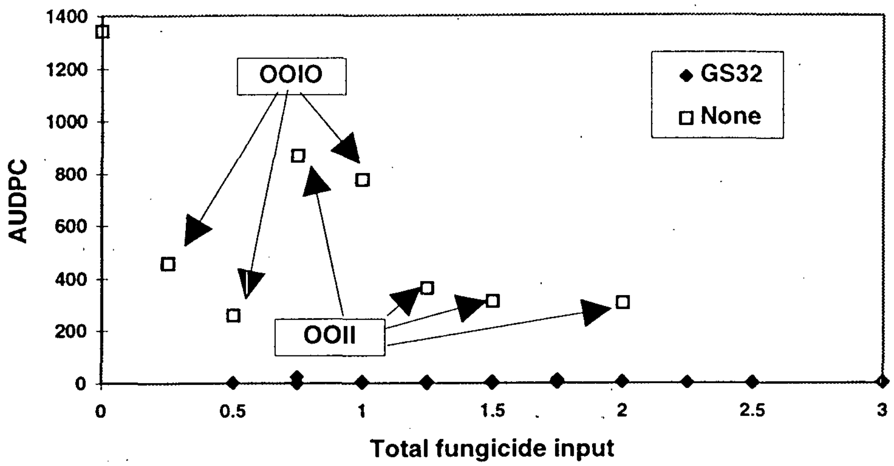
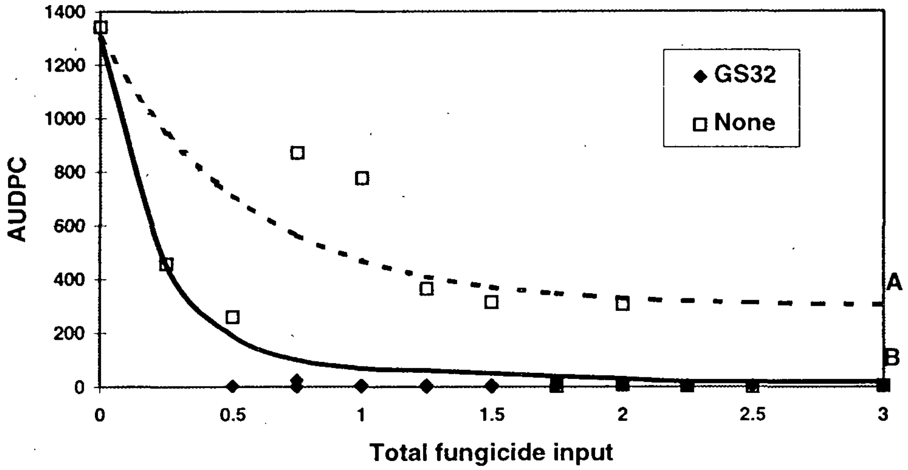


Figure 29. AUDPC for yellow rust on leaf 3 at ADAS Terrington 1995. Comparison of all treatments which include a GS32 treatment against those without a GS32 treatment.



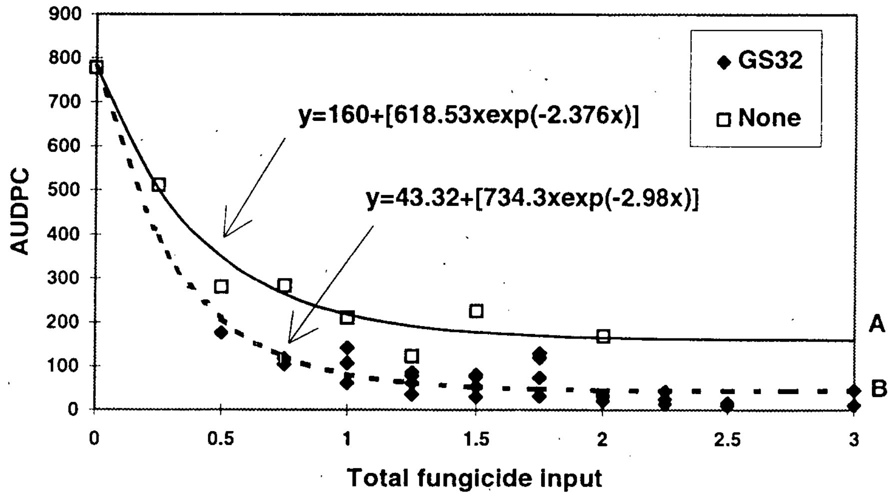
By fitting curves through these data sets the AUDPC can be used to test the significance of fungicide timing effects.

2.5 Parallel curve analysis

In order to determine if the apparent effects of various spray timings were significant, the curves for AUDPC, described in the previous section, were compared using parallel curve analysis (Ross, 1990).

Figure 30 shows the 2 curves generated to describe the reduction in AUDPC of *S. tritici* with increasing fungicide input, taking account of the timing component of the spray applications.

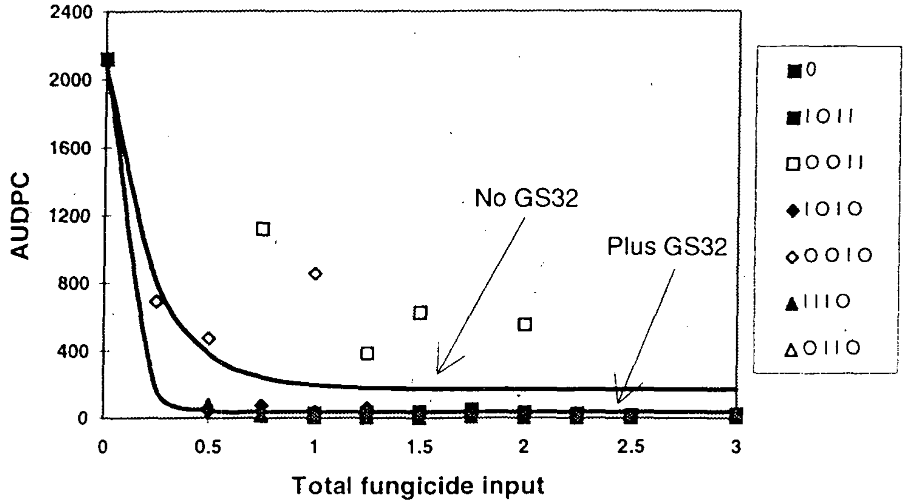
Figure 30. AUDPC for *S. tritici* on leaf 3 at Morley 1995. Comparison of all treatments which include a GS32 treatment, against those without a GS32 treatment.



The timing of fungicide applications at GS32 and the effect on disease progress and AUDPC on leaf 3 is the most significant of any of the treatment timings. Applications at GS33 frequently had similar effects on disease control on leaf 3 and no significant differences were found between AUDPC curves for *S. tritici* on leaf 3 derived from programmes containing GS32 or GS33 timings (Figures 32 & 33). Applications at GS32 in these experiments did not have any significant effect on the progress of *S. tritici* on the flag-leaf (Figure 38).

2.5.1. Parallel curve analysis - Yellow rust

Figure 31. AUDPC of yellow rust on leaf 1 from fungicide timings with and without a GS32 application timing, ADAS Terrington 1995



The shape of the fitted curves are described by the following exponential functions:

With GS32 spray: $y = 171.6 + 1914.7 \times Exp(-4.4x)$

No GS32 spray: $y = 36.6 + 2086.2 \times Exp(-10.6x)$

Analysis showed that there is a significant difference in the position of the curves (i.e. the lower asymptote) but not in the shape of the curves (Figure 31). Thus, applications of fungicide at GS32 had a significant effect on the level of disease on the flag-leaf as measured by the AUDPC.

The same comparison, but of GS33 against no GS33 application gave a similar result:

With GS33 spray: $y = 18.0 + 2104.9 \times Exp(-7.0x)$

No GS33 spray: $y = 483.3 + 1641.3 \times Exp(-9.0x)$

Figure 32. AUDPC of yellow rust on leaf 1 from fungicide timings with and without an application at GS 33, ADAS Terrington 1995.

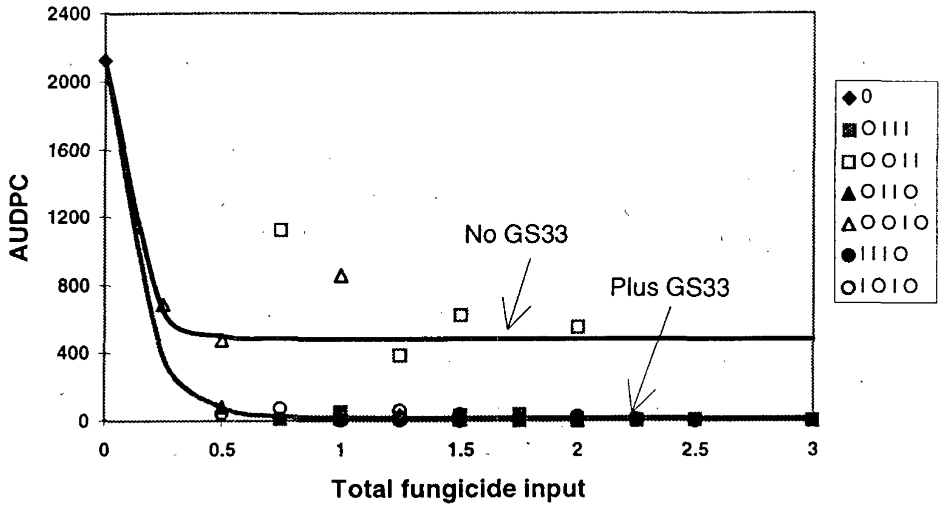
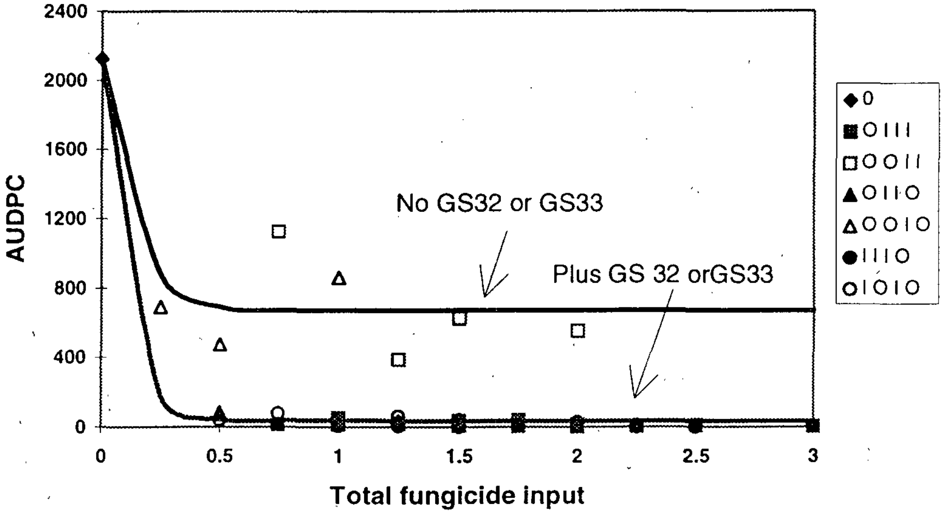


Figure 33. AUDPC of yellow rust on leaf 1 from fungicide timings with and without an application at GS32 or GS33, ADAS Terrington 1995



The shapes of the fitted curves are described by the following exponential functions:

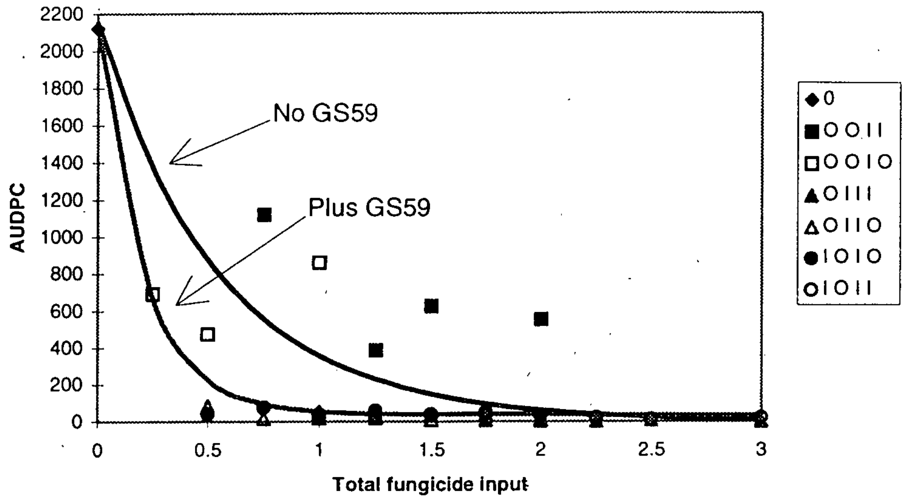
With GS32 or GS33 spray: $y = 670.9 + 1452 \times Exp(-18.1x)$

No GS32 or GS33 spray: $y = 36.6 + 2086.2 \times Exp(-10.6x)$

There was a highly significant difference in the position of the lower asymptote, but not in the shape of the curves (Figure 33). Thus, applications of fungicide at GS32 or GS33 have a significant effect on the level of disease on the flag-. From the earlier comparison of the effect of the GS33 applications, it is clear that they have a greater effect on levels of yellow rust on the flag-leaf than applications at GS32.

The effect of a GS59 fungicide application on disease on the flag-leaf is shown in Figure 34. It is clear that in this case there is a difference in the shape of the curve, even though there is little difference in the AUDPC's at the higher fungicide inputs. This suggests that where flag-leaf applications are applied at low doses then the ear spray can be important in prolonging fungicide activity on the flag-leaf. Where fungicide doses applied to the flag-leaf are higher, (greater than 1.5 units) or where a spray has been applied at GS 32 or 33, the addition of an ear spray no longer improves disease control..

Figure 34. AUDPC of yellow rust on leaf 1 from fungicide application timings with and without an application at GS59 , ADAS Terrington 1995

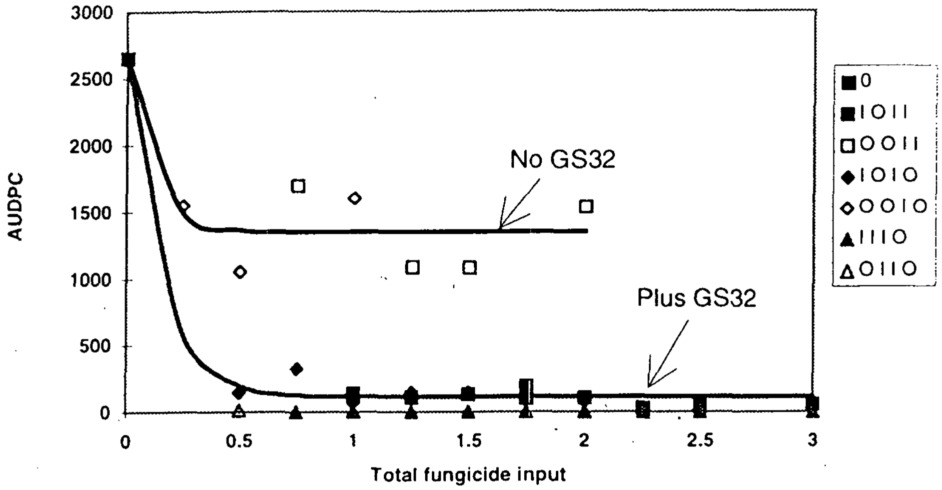


With GS59 spray: $y = 37.6 + 2085.9 \times Exp(-4.8x)$

No GS59 spray: $y = 2.5 + 2152.8 \times Exp(-1.8x)$

The effects of GS32 and GS33 timings on disease control on leaf 2 are similar, but greater than, on leaf 1 (Figures 46 and 47).

Figure 35. AUDPC of yellow rust on leaf 2 from fungicide timings with and without an application at GS32, ADAS Terrington 1995

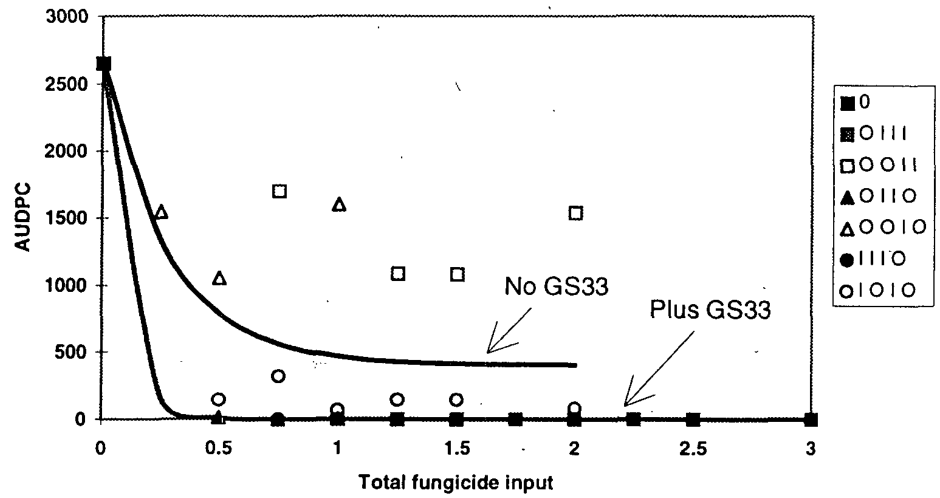


With GS32 spray: $y = 113.0 + 2539.8 \times Exp(-6.8x)$

No GS32 spray: $y = 1347.2 + 1309.0 \times Exp(-8.8x)$

Analysis showed a significant difference in the position of the curves (i.e. lower asymptote) but not in the shape of the curves (Figure 35). Thus, applications of fungicide at GS32 had a significant effect on the level of disease on leaf 2 as measured by the AUDPC.

Figure 36. AUDPC of yellow rust on leaf 2 from fungicide timings with and without an application at GS 33, ADAS Terrington 1995.



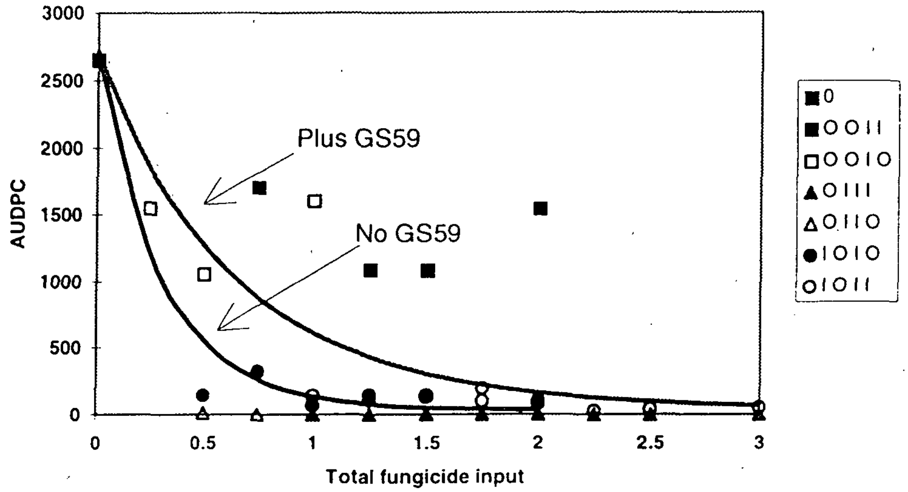
With GS33 spray: $y = 1.1 + 2652.3 \times Exp(-11.1x)$

No GS33 spray: $y = 404.6 + 2275.1 \times Exp(-3.6x)$

Analysis showed a significant difference in the position of the curves (i.e. the lower asymptote), and in the shape of the curves (Figure 36). Thus, applications of fungicide at GS33 had a significant effect on the level of disease on leaf 2 as measured by the AUDPC, particularly where low total doses were applied.

The effects of applications of fungicide at GS59 on yellow rust on leaf 2 are shown in Figure 37.

Figure 37. AUDPC of yellow rust on leaf 2 from fungicide timings with and without an application at GS59, ADAS Terrington 1995



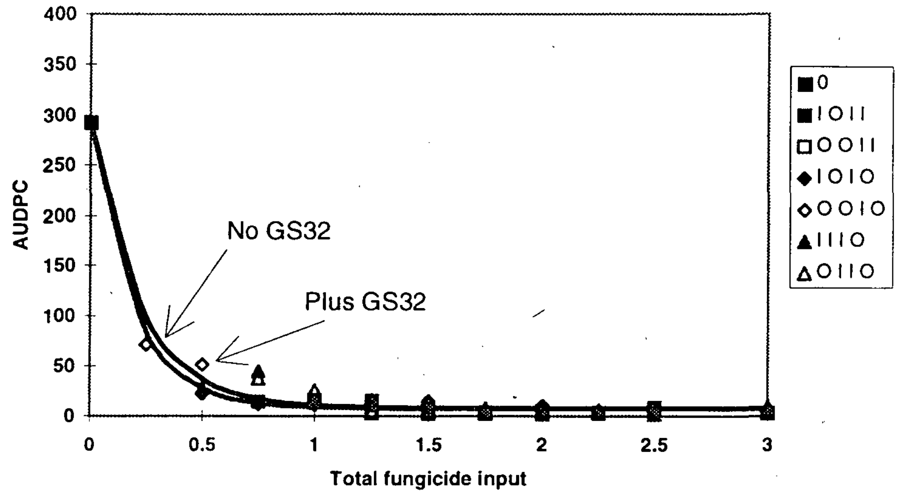
GS59 sprays did not have a beneficial effect on yellow rust levels on leaf 2 (Figure 37). The apparent reduction in control can be attributed to lower doses being applied at effective timings (GS32, 33 or 39), at any given total dose input, in those treatments which included a GS 59 spray.

With GS59 spray: $y = 42.8 + 2656.2 \text{ x } Exp(-1.5x)$

No GS59 spray: $y = 31.5 + 2677.7 \text{ x } Exp(-3.3x)$

2.5.2 Parallel curve analysis - *S. tritici*

Figure 38. AUDPC of *S. tritici* on leaf 1 from fungicide timings with and without an application at GS32, Morley 1995

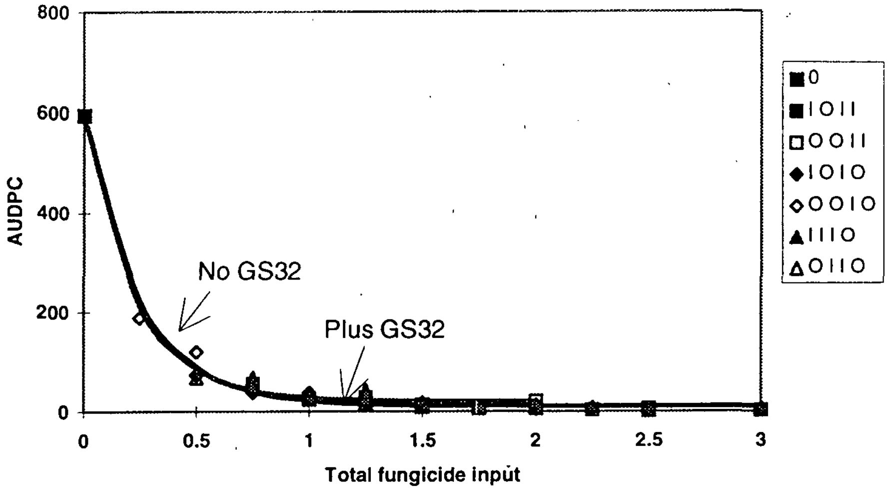


With GS32 spray: $y = 7.9 + 283.7 \times Exp(-4.5x)$

No GS32 spray: $y = 7.4 + 283.0 \times Exp(-5.2x)$

There was no significant effect of the application of fungicides at GS 32 on disease on the flag-leaf (Figure 38). The reason for this was explained in Section 3.1, where it was shown that physical spread of inoculum from leaf 3 to the flag leaf could not have occurred at Morley in 1995 because of the spatial separation of inoculum on leaf 3 from the emerging flag leaf. If physical spread does not happen then any subsequent spread of *S. tritici* must occur by rainsplash, from lower leaves and is thus not dependant on inoculum present on leaf 3 (which applications at GS32 are likely to affect). Figure 39 shows a similar situation for leaf 2.

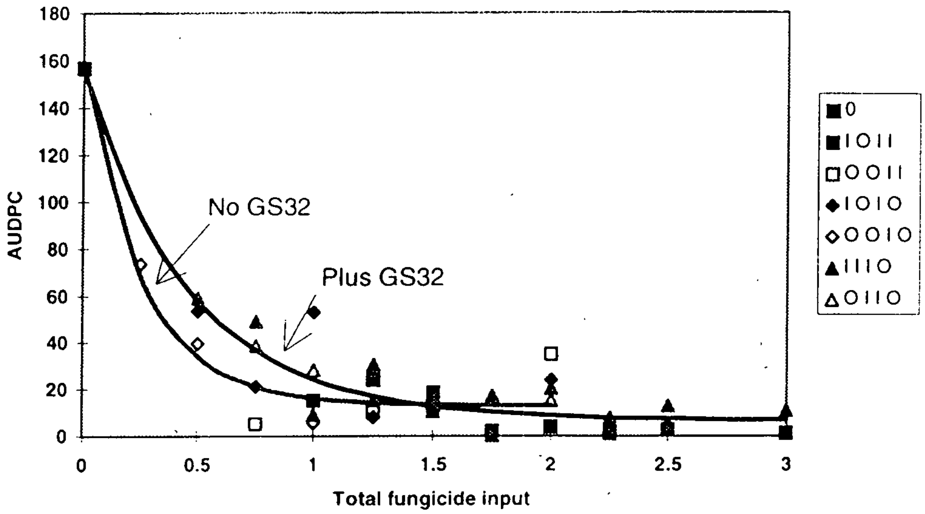
Figure 39. AUDPC of *S. tritici* on leaf 2 from fungicide timings with and without an application at GS32, Morley 1995.



With GS32 spray: $y = 11.1 + 583.1 \times Exp(-4.0x)$

No GS32 spray: $y = 20.4 + 570.3 \times Exp(-4.3x)$

Figure 40. AUDPC of *S. tritici* on leaf 1 from fungicide application timings with and without aa application at GS32, ADAS Rosemaund 1995.

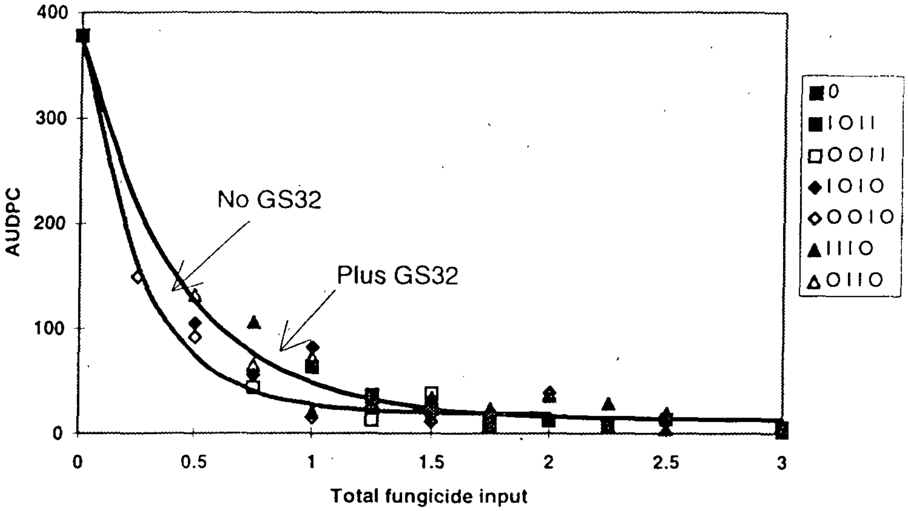


With GS32 spray: $y = 6.6 + 148.9 \times Exp(-2.1x)$

No GS32 spray: $y = 13.0 + 145.2 \times Exp(-3.9x)$

Figure 40 shows that there is little effect of GS32 applications on levels of *S. tritici* on leaf 1,under low disease pressure at Rosemaund.

Figure 41. AUDPC of *S. tritici* on leaf 2 from fungicide application timings with and without an application at GS32, ADAS Rosemaund 1995.

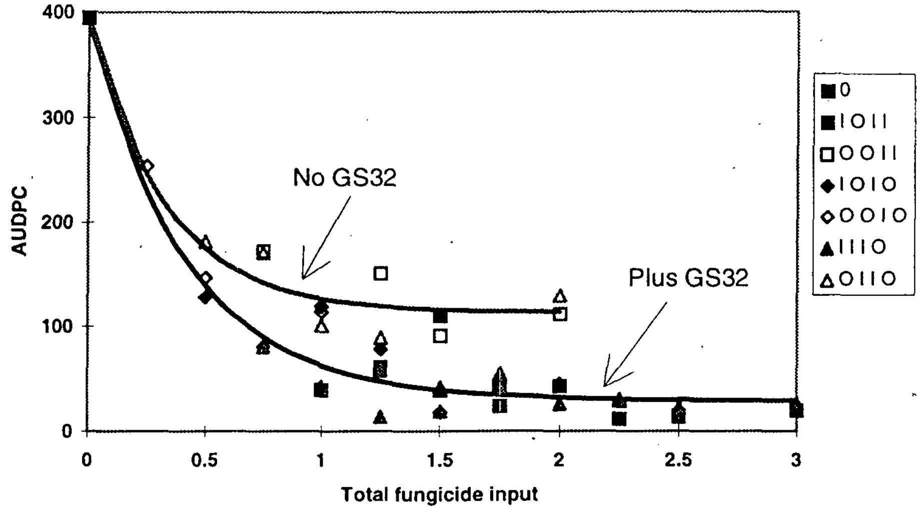


With GS32 spray: $y = 12.9 + 362.8 \times Exp(-2.3x)$

No GS32 spray: $y = 18.5 + 358.1 \times Exp(-3.7x)$

Figure 41 shows little effect of GS32 applications on levels of *S. tritici* on leaf 2.

Figure 42. AUDPC of *S. tritici* on leaf 3 from fungicide application timings with and without an application at GS32, ADAS Rosemaund 1995.



With GS32 spray: $y = 29.1 + 362.4 \times Exp(-2.4x)$

No GS32 spray: $y = 113.2 + 282.2 \times Exp(-3.0x)$

A clear displacement of the curves indicates a highly significant effect of the GS32 application timing on disease levels on leaf 3 (Figure 42).

2.6 Yield response and profit curves

The yield response curves for all sites and seasons are shown in Figures 46-49. There is clearly considerable variation in the shape of the curves from site to site and season to season. Where the main disease was *S. tritici*, disease levels were high and the site had a high yield difference between the treated and untreated yields, the yield response curve is steep initially, reaching a plateau at some point beyond 1.5 total dose units.. The yield response at Morley in 1995 is typical of this type of response (Figure 44). The shape of the fitted curve was described by the following exponential function:

$$y = (-1.37) \times Exp(-2.39x) + 9.68$$

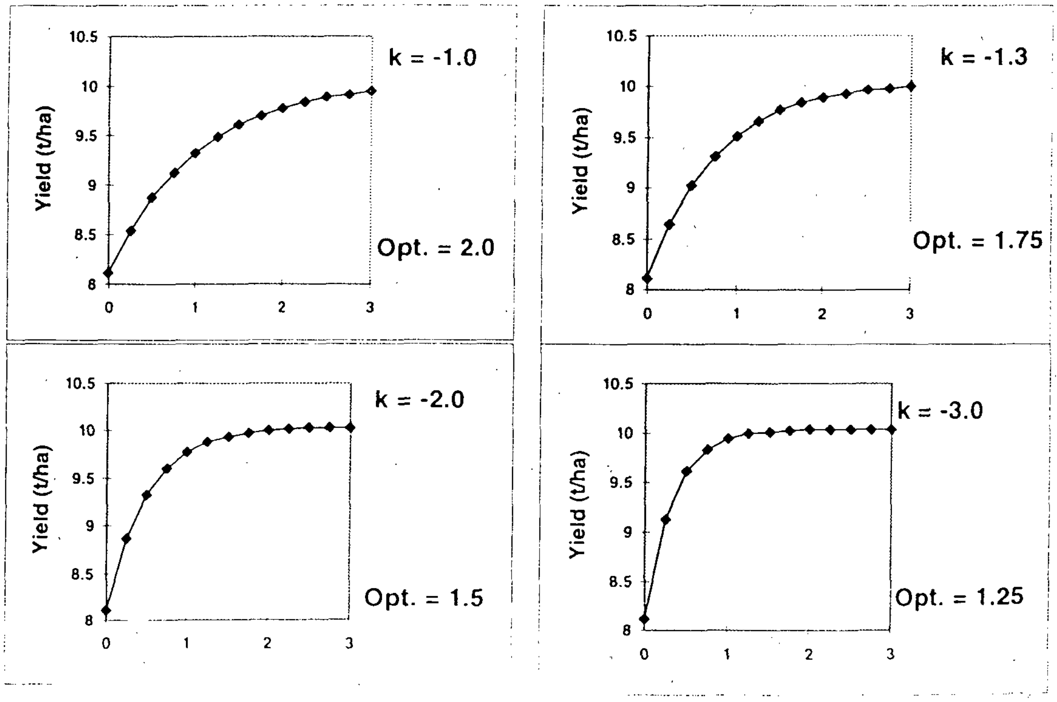
This can be simplified to:

$$y = A \times Exp\ (k) + C$$

where:

A is the difference between the untreated yield and the upper asymptote
C is the yield plateau (upper asymptote)
The value 'k' describes the shape of the curve between the y-axis intercept and the yield plateau. Figure 43 shows the effect on the shape of a curve, and the economic optimum (opt.) of changes in the value of 'k' when A and C are kept constant.

Figure 43. Example of yield response curves with a range of 'k' values



At the Morley site in 1995 the value of 'k' in the exponential equation was -2.39. Contrast this with the yield response curve at Terrington in 1995 where yellow rust was the main disease (Figure 45). The 'k' value in this case was -4.12, indicating that the yield maximum was approached at a lower total fungicide input. This indicates that the yellow rust fungus *Puccinia striiformis* was much more sensitive than *S. tritici* to the fungicides applied. The sensitivity of pathogens to fungicides has a significant effect on the economic fungicide optimum.

Where disease levels were very low and there was consequently little yield loss due to disease, the yield response curves flatten with the value for 'k' approaching zero, such as at Morley (1996) and Aberdeen (1994) (Figures 46 & 47).

Figure 44 Yield response to fungicide input, Morley 1995 (k = -2.39)

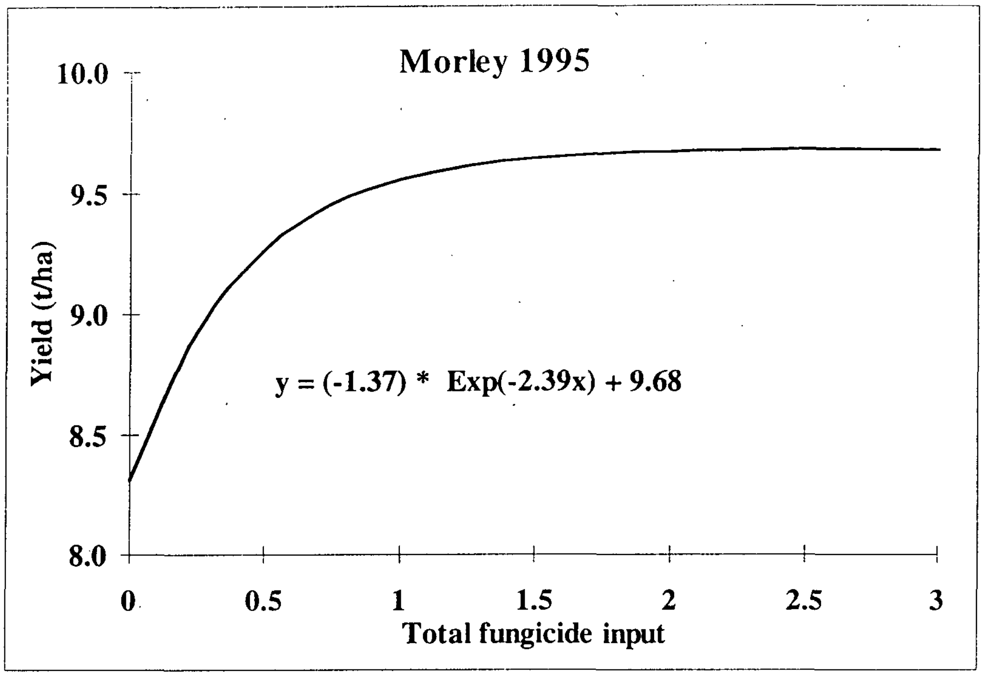


Figure 45. Yield response to fungicide input, Terrington 1995 (k = -4.12)

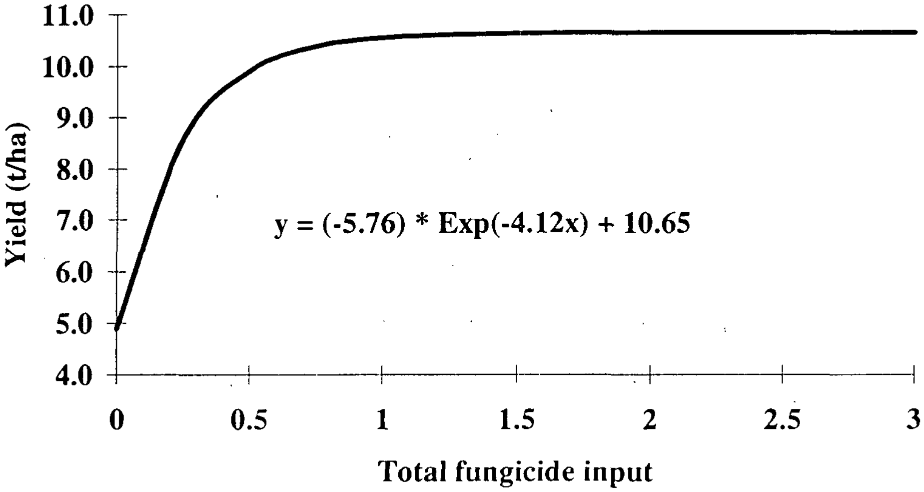


Figure 46. Fitted curves for yield response to fungicide input, Aberdeen

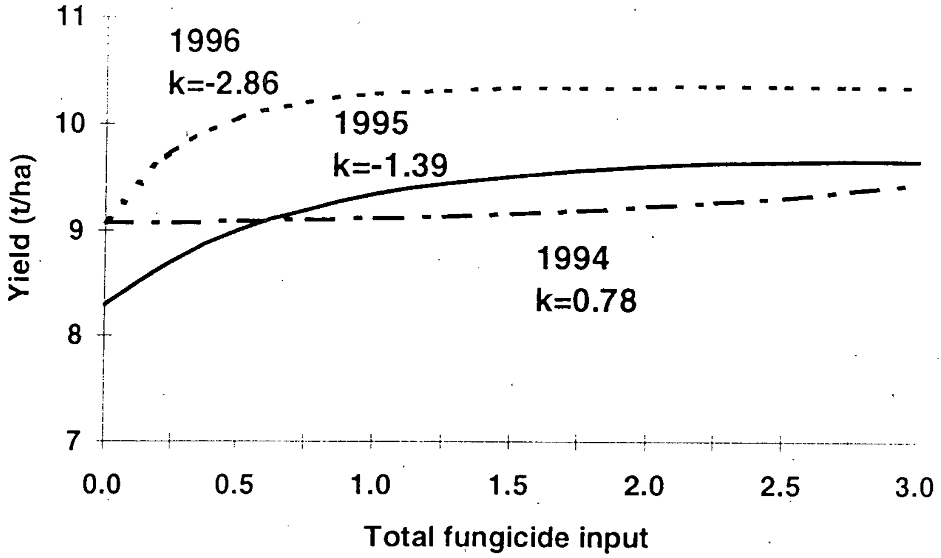


Figure 47. Fitted curves for yield response to fungicide input, Morley

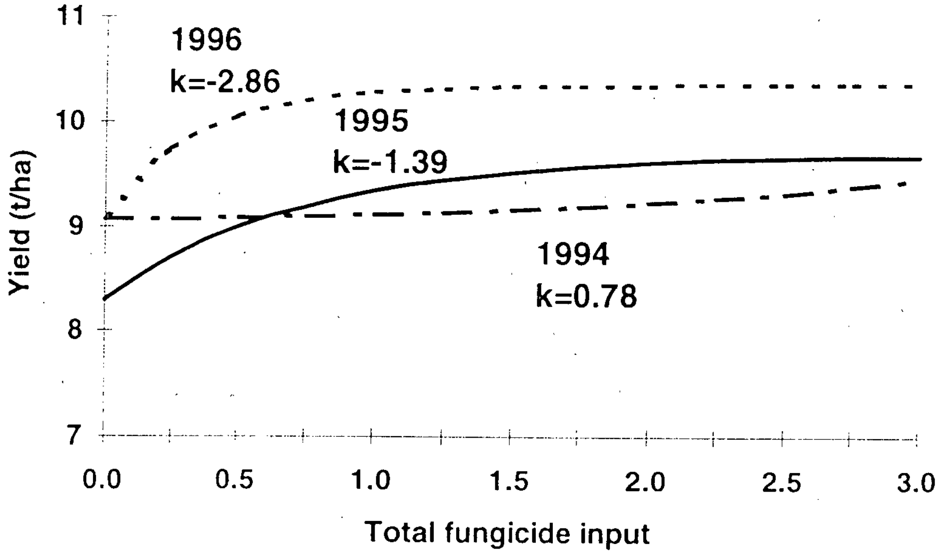


Figure 48. Fitted curves for yield response to fungicide input, Rosemaund

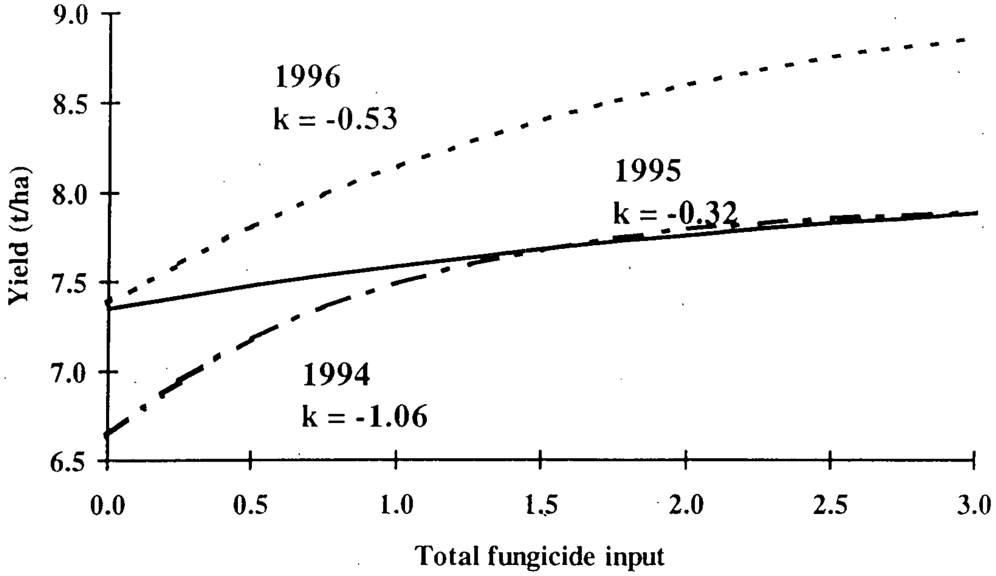
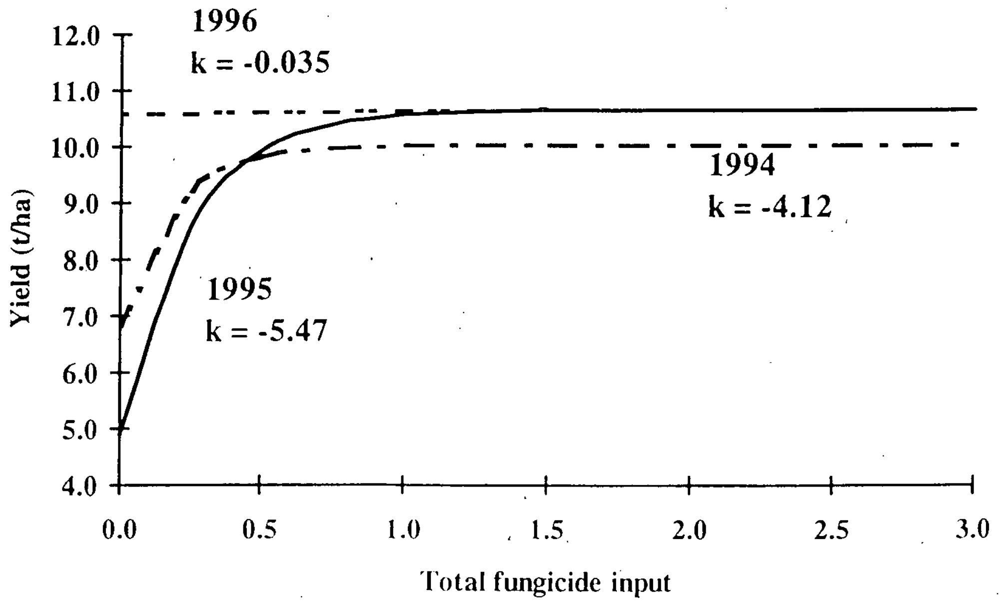


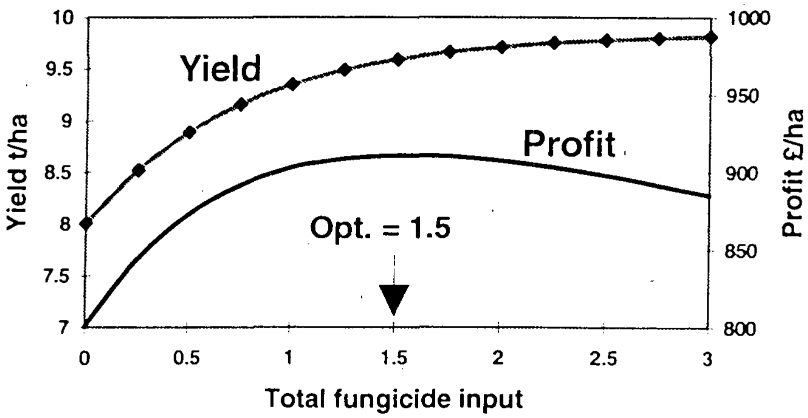
Figure 49. Fitted curves for yield response to fungicide input, Terrington



2.7 Derivation of 'Profit' curves from yield response curves

As fungicide input increases, yield tends to increase exponentially, eventually reaching a plateau. A point is reached on the curve when the monetary value of the increase in yield is matched by the cost of the added fungicide. The total fungicide input at that point is the fungicide optimum for that site/season combination. The yield response curves, derived profit curves and fungicide optima for all site/season combinations are shown in Figures 51-54. A typical profit curve derived from a yield response curve is shown in Figure 50. Because of the shape of the yield response curve, the profit curve typically rises sharply from a fungicide input of zero, reaches a plateau and then declines fairly slowly. The 'profit' in this context is the margin over fungicide cost, excluding application costs. The profit curves shown in the report costed with wheat at £100/t unless otherwise specified and tebuconazole (as Folicur) at £32/litre and fenpropidin (as Patrol) at £20/litre. The shape of the profit curve is significant in terms of on-farm decisions. as the risk to profits is higher when application rates are below the optimum than when they are above the optimum.

Figure 50. Typical yield response curve and derived profit curve



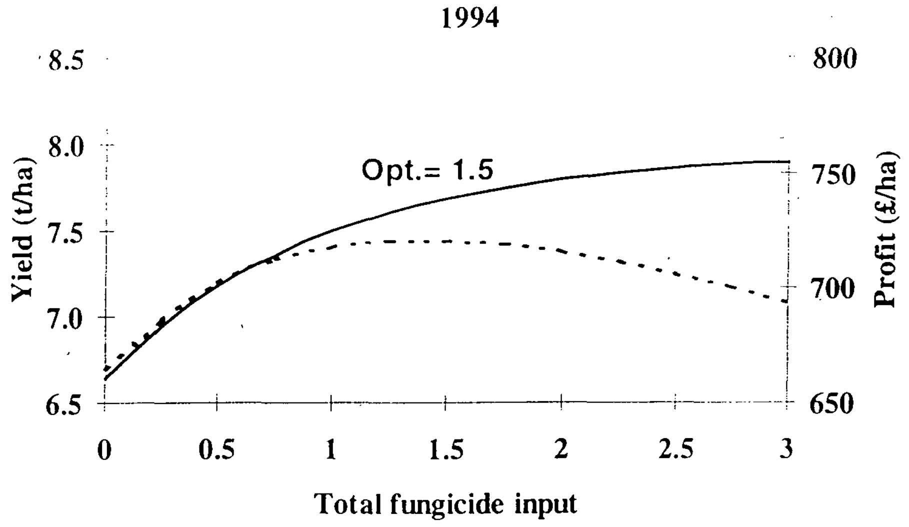
In site/season combinations with high levels of *S. tritici* and large yield responses, the fungicide optimum was usually between 1.0 and 1.5 fungicide units. The Rosemaund site in 1994 (Figure 51) and the Morley and Aberdeen sites in 1995 (Figures 52 & 53) are typical of such responses. The yield response to the control of yellow rust was very large and most of the yield response was achieved with low fungicide input. Note the Terrington site in 1994 and 1995, where the yield responses to treatment were 3.0 and 5.7 t/ha respectively with a fungicide input optimum of only 0.75 or 1.0 units (Figure 54). At Terrington in 1995, where the maximum yield response to fungicide treatment was 5.7 t/ha, 87% of that response (5.0 t/ha) was achieved with only 0.5 units of fungicide. These low economic optima reflect the low k values of the yield response curves at the yellow rust sites (-4.12 and -5.47 in 1994 and 1995 respectively) (Figure 49) compared with -0.3 to -2.3 for *S. tritici* sites (Figures 35 - 48).

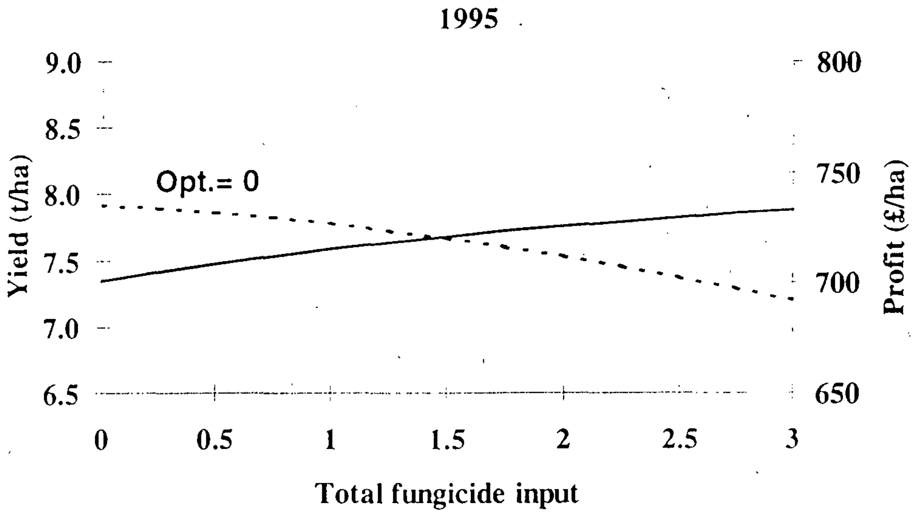
Where disease levels were low and/or the site/season was unresponsive, profit curves showed an optimum fungicide input ranging from zero to 0.5 fungicide units (Morley and Aberdeen 1994, Rosemaund 1995, Morley 1996) (Figures 51-53).

2.8 Quality considerations

The relationship between yield and specific weight of the grain is frequently well correlated (Clark 1993). In these experiments the correlation was was good when large yield responses to treatment were achieved, for example at ADAS Terrington where yellow rust caused large yield reductions (Figure 55). At sites where yield responses to treatment were low, grain quality responses were also small or absent as at ADAS Rosemaund and ADAS Terrington in 1995 and 1996, (Figures 55 and 56).

Figure 51. Yield response and profit curves, ADAS Rosemaund 1994-1996





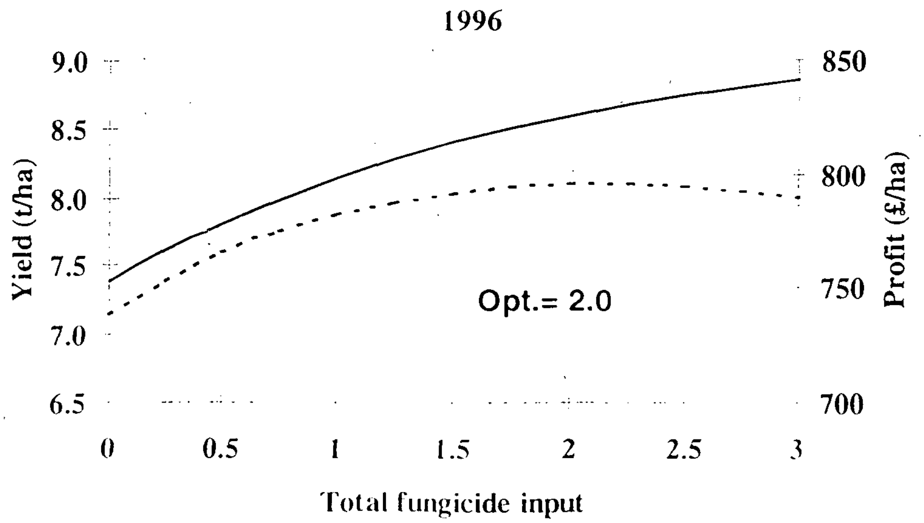


Figure 52. Yield response and profit curves, Morley 1994-1996

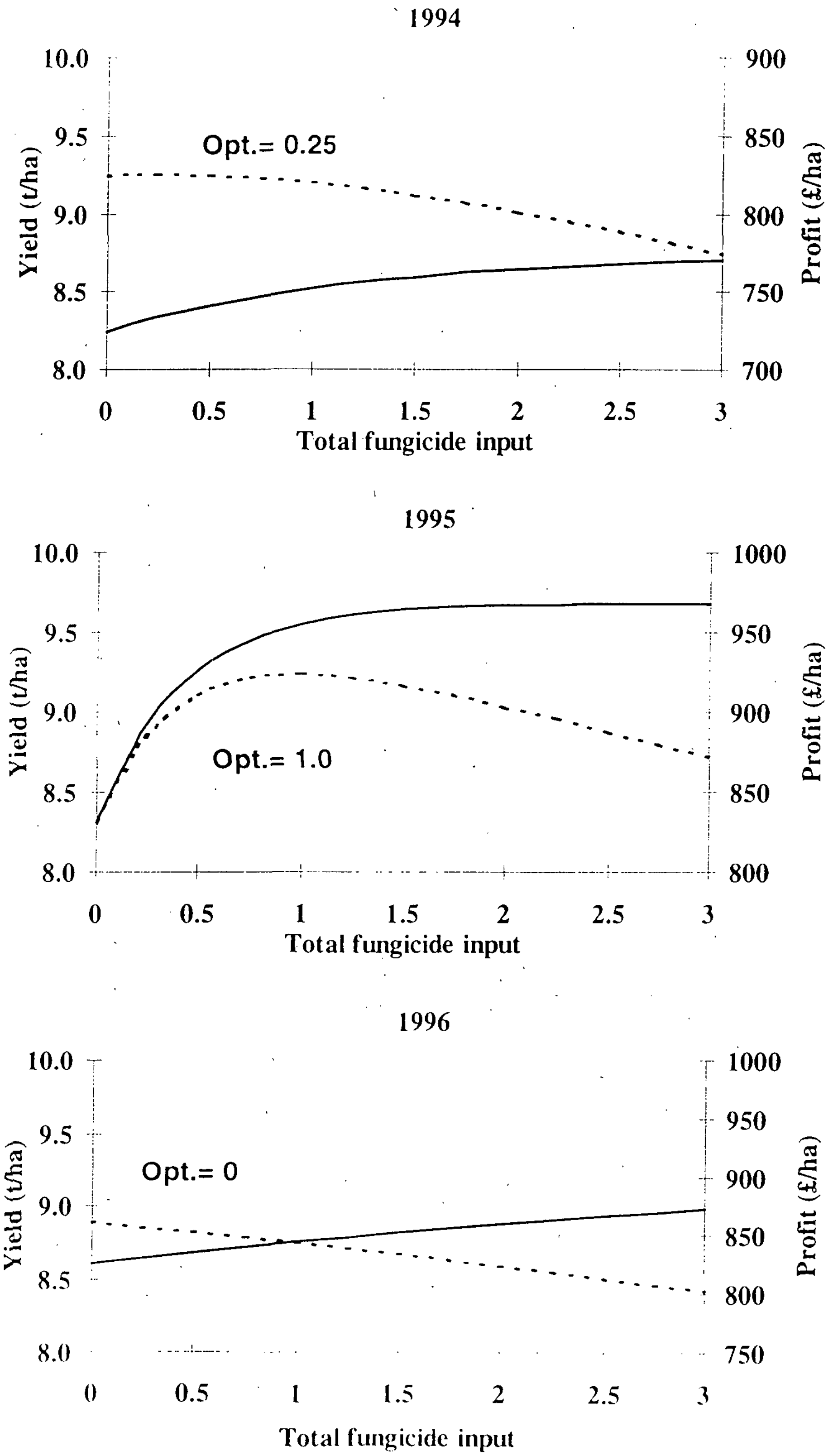


Figure 53 Yield response and profit curves, Aberdeen 1994-1996

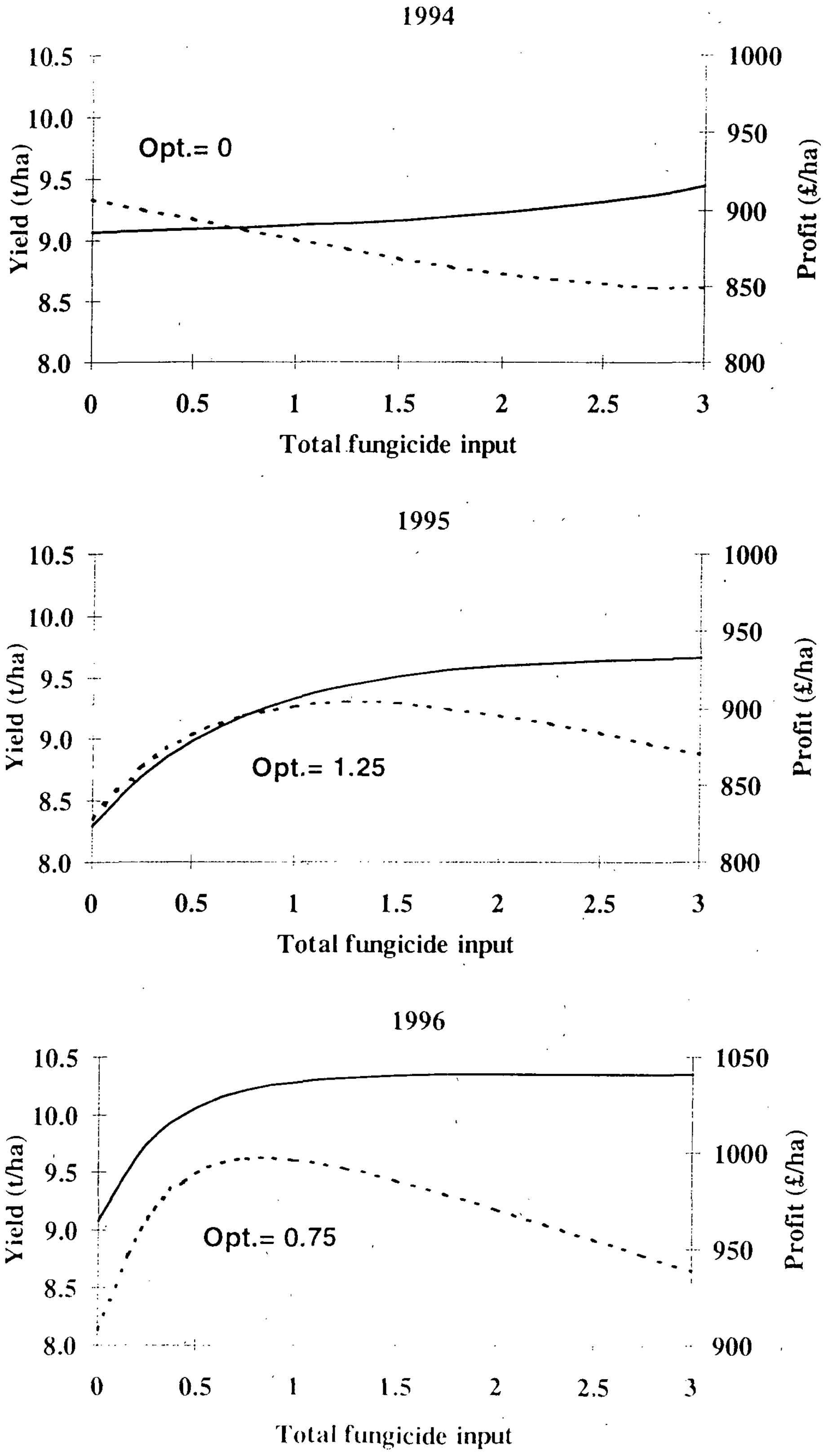


Figure 54. Yield response and profit curves, ADAS Terrington 1994-1996

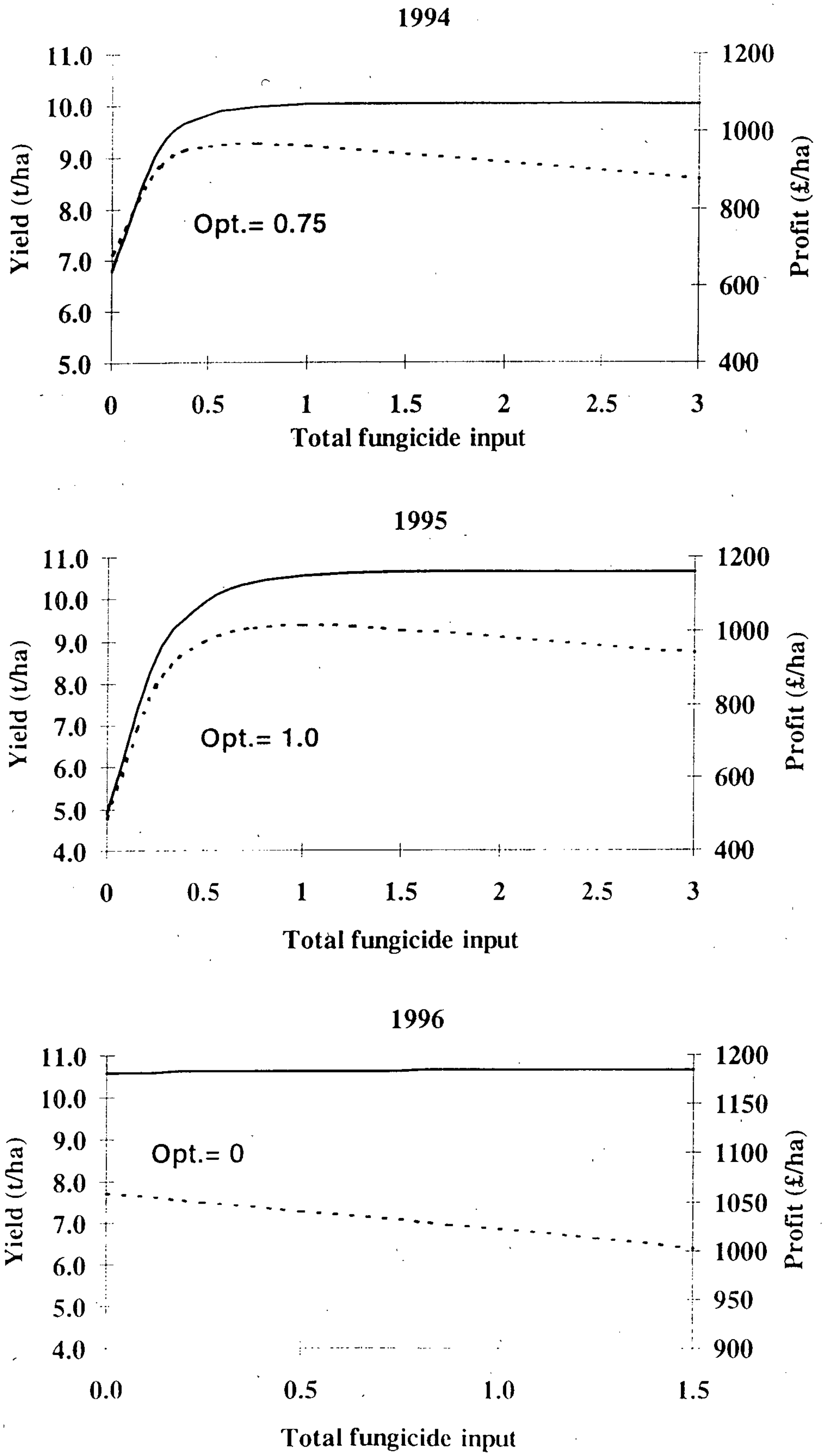


Figure 55. Relationship between yield and specific weight 1995.

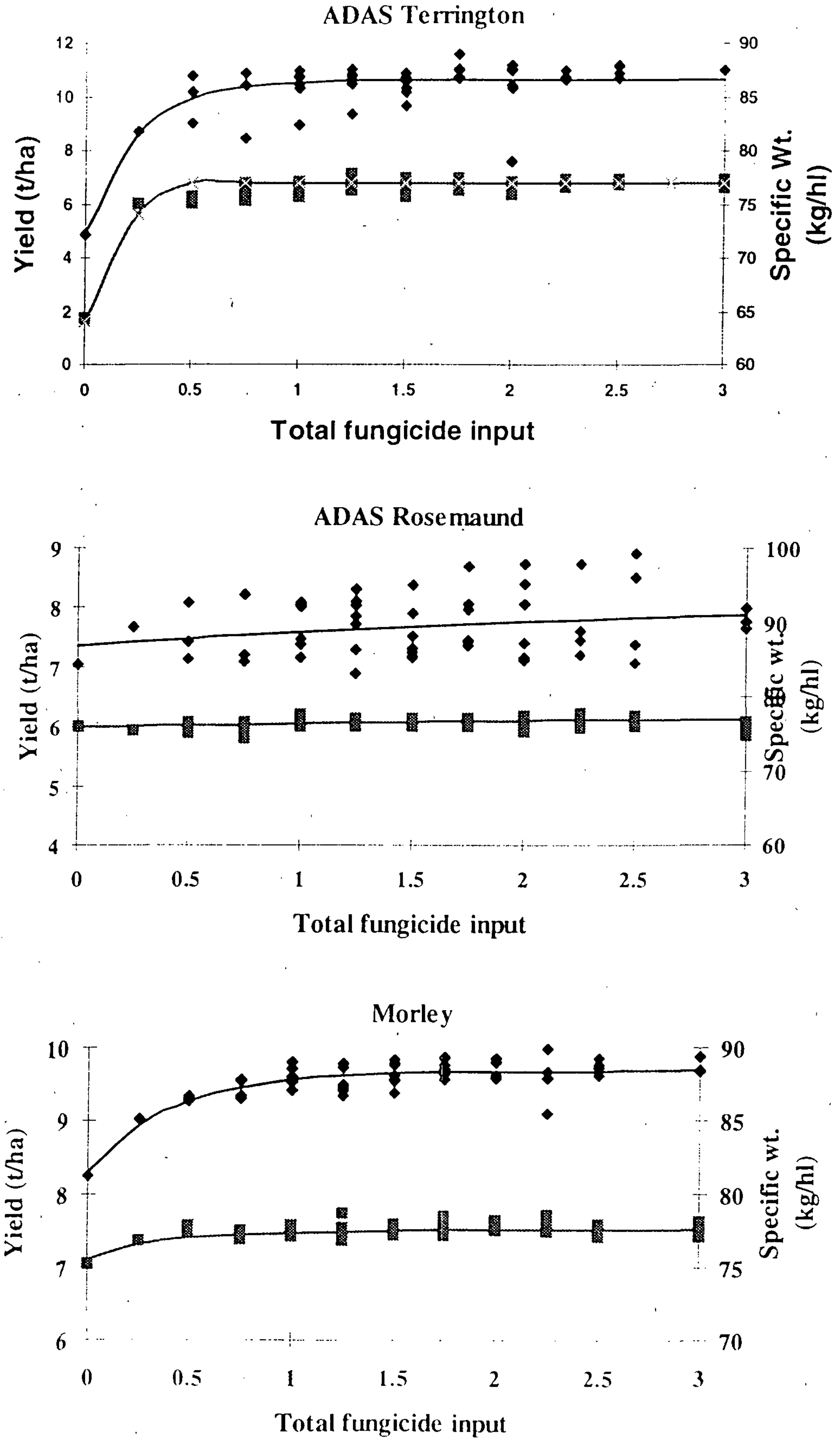
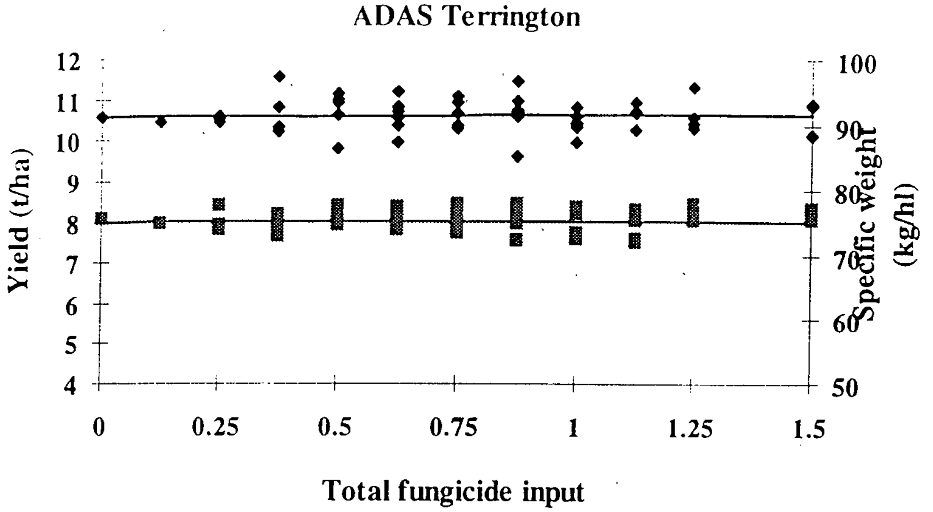
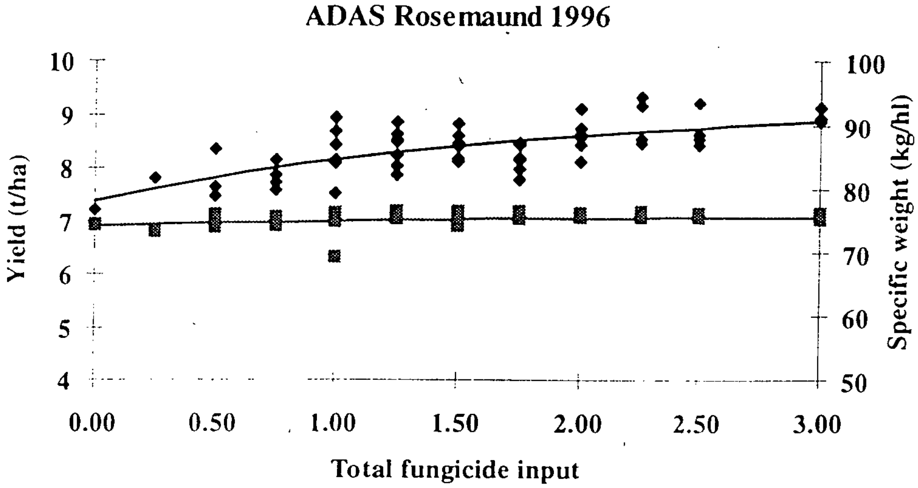
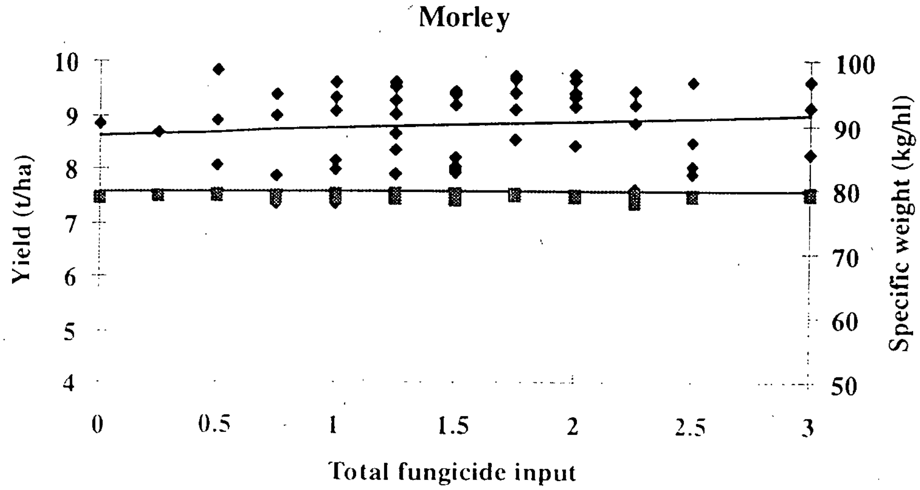


Figure 56. Relationship between yield and specific weight 1996.







3.0 CONCLUSIONS

The majority of wheat crops receive fungicides as 2- and 3-spray fungicide programmes. There is clearly scope for optimising rates of use and timing of applications provided that crop managers understand the basis for fungicide use, the implications of rate choice and the effects of previous fungicide applications on subsequent applications. Several systems have been developed to assist crop managers but none has been particularly successful in changing managers understanding (Anon. 1986, Verreet and Hoffman. 1990). This experiment, although complex in design, has given some clear messages in terms of fungicide dose and timing. The main findings from this experiment are summarised below.

- The main effects of fungicide input are to:

    1. Delay the onset of disease.
    2. Reduce the rate of disease progress, and hence
    3. Reduce the final level of disease.

- There is a considerable effect of fungicide input on disease progress, even at low doses of fungicide, particularly with yellow rust.

- Yield responses are generally associated with disease control on the upper three leaves.

- A reduction in disease development on the lower leaves, particularly leaf 3 and 4, can be significant with regard to *S. tritici* control. The effect of delaying the onset of disease on lower leaves is to reduce the likelihood of the spread *of S. tritici* from leaves 3 and 4 to the emerging flag leaf and leaf 2. Fungicide applications at GS 32 have the effect of delaying disease progress on leaves 3 and 4 beyond the time when the flag leaf is emerging.

- In seasons where rainfall does not occur during flag-leaf emergence the presence of inoculum on leaves 3 and 4 can be particularly significant as spread can occur when leaves are wet with dew or light rain. These are conditions when farmers and advisers may consider the risk of *S. tritici* to be low and delay the flag-leaf application. In this situation the result is often poor control of *S. tritici* on both the flag-leaf and leaf 2 on susceptible varieties

- In a typical yellow rust epidemic the short latent period of 7-10 days results in yellow rust infection and sporulation keeping pace with leaf emergence, so each new leaf layer becomes infected as it emerges. Early spray timings at GS32/33 are important in delaying the onset of disease, allowing the main GS39 treatment to be applied before disease becomes established on the upper leaves.

- Low rates of tebuconazole plus fenpropidin (0.25 x label recommended dose) can be highly effective in controlling yellow rust.

- The flag-leaf timing of fungicides has the greatest effect on disease progress on the main yield-producing leaf layers (flag-leaf and leaf 2).

- Disease progress on the final leaf layer (flag-leaf) is affected by applications of fungicide at GS59 (ear emergence) as well as at GS39 (flag-leaf emergence). The GS59 spray has the effect of prolonging disease control on the flag-leaf. The benefits of a GS 59 spray are most apparent where the GS 39 spray was at a sub-optimal dose

- Disease control is usually better when a programme of 2 or 3 sprays is applied, rather than a single application timing, whatever the total fungicide dose applied.

- There was no evidence that applying more than 3 sprays would be beneficial.

- As the fungicide input to a crop increases, the yield of the crop tends to increase exponentially, eventually reaching a plateau. A point is reached on the response curve when the monetary value of the increase in yield due to increased fungicide input is matched by the cost of the added fungicide. At this point there is no longer an economic benefit from further increasing yield by increasing fungicide input. This point is the fungicide optimum for that site/season combination.

- In site/season combinations with high levels of *S. tritici* and large yield responses the fungicide optimum is usually between 1.0 and 1.5 fungicide units (1 unit = 1litre/ha Folicur).

- Yield responses to the control of yellow rust are very large and most of the yield response is achievable with low fungicide input(0.75 or 1.0 units) provided that effective products are used and timing is good

- Input optima for yield exceeded or were equivalent to those for specific weight. Hence, there was no evidence to suggest that additional inputs were required to ensure grain quality.

- The optimal fungicide input is a potentially useful guide to the way in which varieties respond to treatment. It allows crop managers to plan fungicide programmes and use fungicide rates which are high enough to obtain good disease control and optimal yield response, without incurring excessive input costs.

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MATCHING CROP MANAGEMENT TO GROWTH AND YIELD POTENTIAL

(Pages 64-102)

by

R.J. Bryson

ADAS Boxworth, Boxworth, Cambs. CB3 8NN

Project leader: R. Sylvester-Bradley, ADAS Boxworth

CONTENTS

1.0 INTRODUCTION.

As illustrated in Part I, a disease epidemic can be quantified by calculating the area under the disease progress curve (AUDPC). This approach was used in Part I to demonstrate the effect of fungicide dose and timing on disease on individual leaf layers within the crop canopy. However, measurements of disease severity alone may not fully reflect the effects of disease on the yield forming process in the host. In Figure 57 the relationships between yield and total AUDPC values for leaves 1, 2 and 3 are given for *Septoria tritici* epidemics at Aberdeen, Morley and Rosemaund. AUDPC values relate reasonably well to yields at Morley ($R^2 = 0.66$), but poorly at Aberdeen and Rosemaund ($R^2 = 0.36$ and 0.01). AUDPC values of over 1500 at Morley were found to relate to similar yields as values of less than 500 at Rosemaund. If data from a yellow rust epidemic (Terrington) is compared with *S. tritici* data (Figure 58) it can be seen that AUDPC values of 4000 for yellow rust relate to similar yields as AUDPC values of between 0 and 2000 for *S. tritici*. Clearly, AUDPC values cannot be used to predict yield between sites.. It may be argued that this was a site effect However, when AUDPC values of *S. tritici* epidemics from different seasons on the same site are compared (Figure 59) then again AUDPC values could not be used as predictors of yields with values of approximately 300 relating to yields of between 7.5 and 10 t/ha in one year (1996) and 500 relating to 7.9, 9.4 and 8.7 t/ha in 1994, 1995 and 1996 respectively.

Figure 57. The relationship between total AUDPC (L1 - L3) of *S. tritici* and grain yield (t/ha) at Aberdeen, Morley and Rosemaund in 1995.

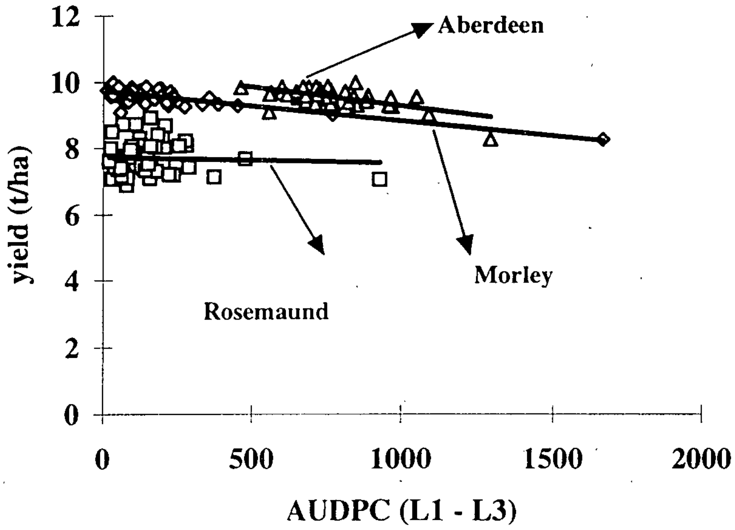


Figure 58. The relationship between total AUDPC (L1 - L3) of *S. tritici* and yellow rust and grain yield at Aberdeen, Morley, Rosemaund and Terrington in 1995.

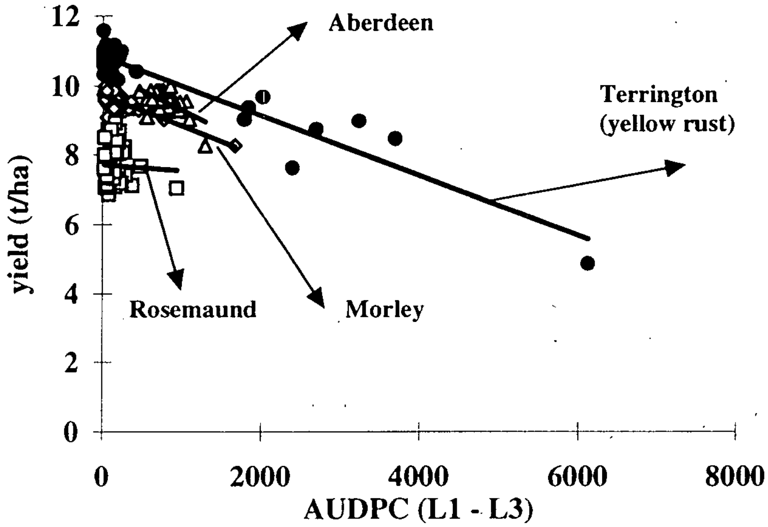
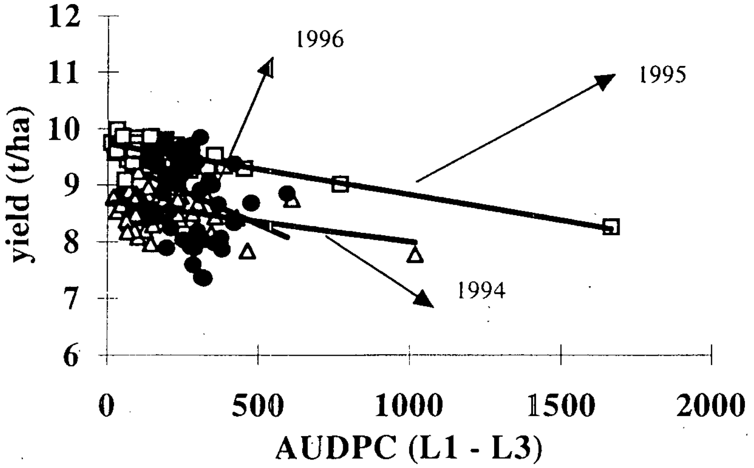


Figure 59 The relationship between total AUDPC (L1 - L3) of *S. tritici* and grain yield at Morley in 1994, 1995 and 1996.



The relationship between disease and yield-loss is more complex than is implied by simple AUDPC:yield relationships. A single AUDPC value may describe a severe epidemic for a short time or a minor epidemic for a long time. Single point, multiple point and integral models such as AUDPC all rely on measures of percentage disease severity and as such have only an indirect link to the productivity of the host plant. Also, they do not take account of environmental conditions which affect yield potential. Hence, relationships between disease severity and yield have generally proved poor over sites and seasons.

There are two important practical implications of this variation in the relationship between disease and yield. Firstly, the success of a disease control programme cannot be judged accurately by observations of disease later in the season. In crops where the disease:yield loss relationshiop is steep, even a small amount of disease remaining after treatment may be economically unacceptable. Whereas in crops where the relationship is shallow, even moderate levels of disease would have negligible impact. Secondly, the ability to identify, at the time of fungicide treatment decisions, those crops which will provide an economic yield response, is prejudiced if the physiological state of the crop is not taken into account.

A better alternative may be to base disease management decisions on an understanding of the effects of disease on crop function. Yield is predominately determined by the crop's capacity to intercept light energy and utilise it for growth. Potential yield is directly related to the amount of photosynthetically active radiation intercepted by green tissue (Monteith, 1977). This can be described formally by an equation derived from Beer's Law (Monteith & Unsworth, 1990): $f = \mathbf{1 - exp(-kL)}$, where f = fraction of light intercepted, **k** = extinction coefficient (which is dependent on canopy geometry) and **L** = green leaf area index (GLAI). GLAI is defined as the number of units of planar area of leaves per unit area of ground. The Beer's Law analogy implies that there is an optimal canopy size, considering all green tissues, at which the cost of creating or protecting a further increment in canopy size may prove uneconomic in terms of growth.

In order to explain more fully the effects of fungicide dose and timing on disease development and hence crop yield, experiments were carried out on and within the main Appropriate Fungicide Dose (AFD) experiments (Part I) at Morley, Rosemaund and Terrington in 1994, 1995 and 1996. Data were also used from the Aberdeen site but intensive crop physiology analysis was not possible due to its location. The hypothesis behind these experiments was that yield loss due to disease can be better explained using measurements of green leaf area and radiation interception than by assessments of disease severity alone.

2.0 INTEGRATED PLOT EXPERIMENT.

2.1 Materials and method.

At each of the three experimental sites, in each season, full growth analysis was carried out on integrated plots within the main experiment. Four replicate plots per treatment per site were given one of two treatments; full fungicide treatment (Treatment 33 - Section 1.4.1) and the zero fungicide treatment (Treatment 1- section 1.4.1).

2.1.1 Determination of GLAI and dry matter in the laboratory using a leaf area meter.

A 0.75 m^2 sample was taken from each plot from pre-determined areas to avoid local bias. A gap of at least 20 cm was left between sample areas with at least 50cm from the end of the plots and/or tramlines. Plants were cut from the sample area at ground level with scissors. All the above ground material was placed in plastic bags and stored for a maximum of 3 days in a cold room at 4-6 °C prior to growth analysis. In the laboratory the total sample fresh weight was recorded. Two randomly selected sub-samples SS1 (approximately 10%) and SS2 (approximately 20%) were taken and weighed. SS1 was analysed in the laboratory to determine green leaf areas and shoot numbers m^{-2}. SS2 was placed in an oven at 80^0C for 48 hr in order to determine total dry matter. The total green leaf area was measured using a calibrated leaf area meter. For the diseased and senescing leaves it was necessary to make a subjective judgment as to how much of the leaf was green. If dead, non-green or diseased areas of the leaf were patchy, it was necessary to assess the percentage of the leaf area affected; that amount was removed from the leaf and the remaining area was then classed as green and measured.

2.1.2 Incident radiation measurements.

Total incident radiation was measured using a dome solarimeter (Delta - T Devices Ltd., Burwell. Cambridge) placed above the crop. Readings were taken every minute and then averaged every hour to determine a value of total incident radiation per day ($MJm^{-2}day^{-1}$).

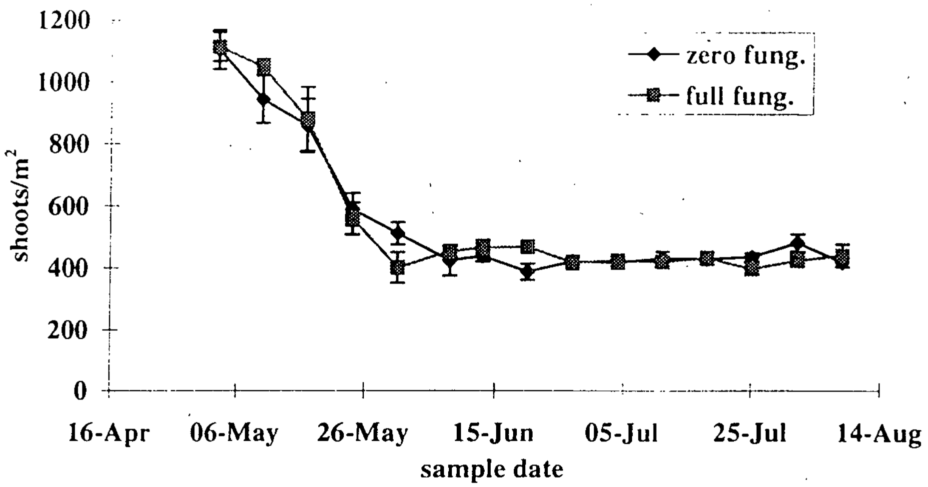
2.2 Results and discussion.

2.2.1 Shoot numbers.

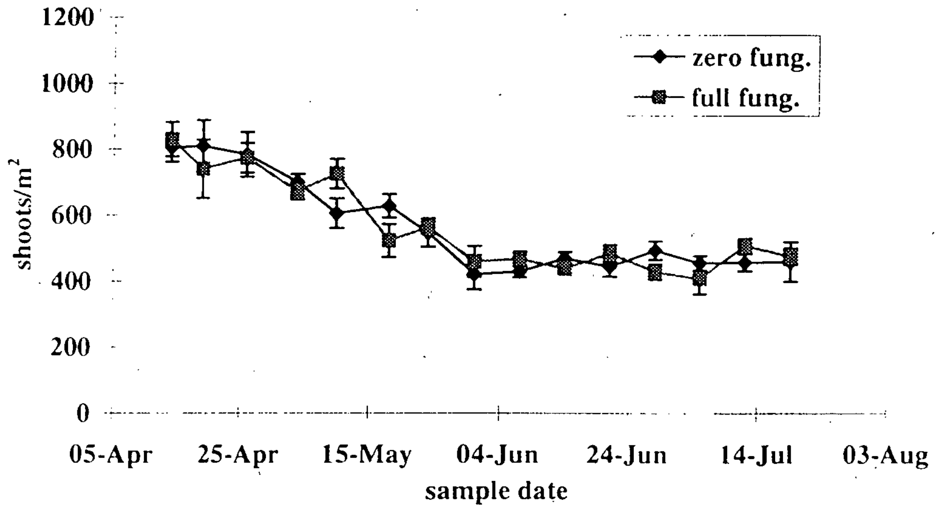
Figures 60 - 62 give the shoot numbers/m^2 at the three experimental sites over all three seasons. In all cases , shoot numbers started high and then declined due to shoot death to reach a plateau just after GS39. In no situation was there a significant difference in shoot number between the full and zero fungicide treated plots. The highest mean shoot numbers occurred at Terrington with 598, 706 and 773 shoots/m^2 in 1994, 1995 and 1996 respectively (Figure 62). This was probably due to the high levels of soil mineral nitrogen and moisture, indicative of the silt soil of Terrington as compared witho the two other sites. Mean shoot number at Morley and Rosemaund were similar between both sites and seasons with 427, 461 and 528 shoots/m^2 at Morley (Figure 60) and 560, 472 and 504 shoots/m^2 at Rosemaund (Figure 61) in 1994, 1995 and 1996 respectively.

Figure 60. Shoots/m^2 in full dose and zero fungicide treated plots at Morley.

1994



1995



1996

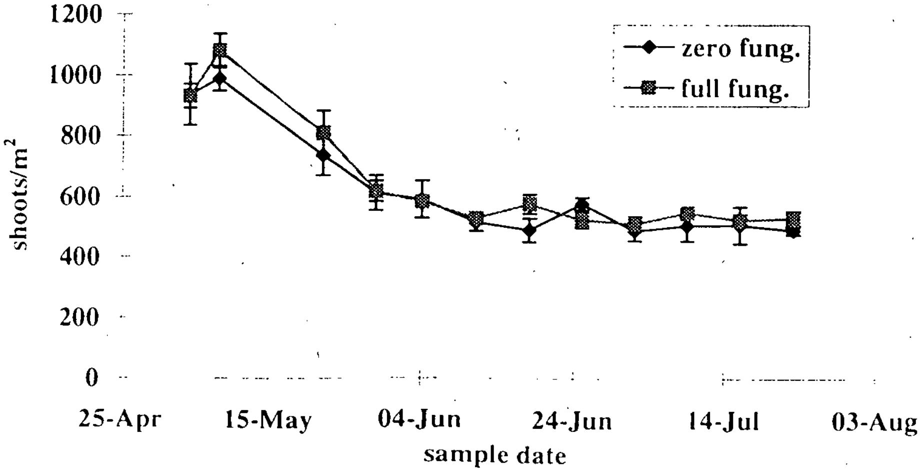
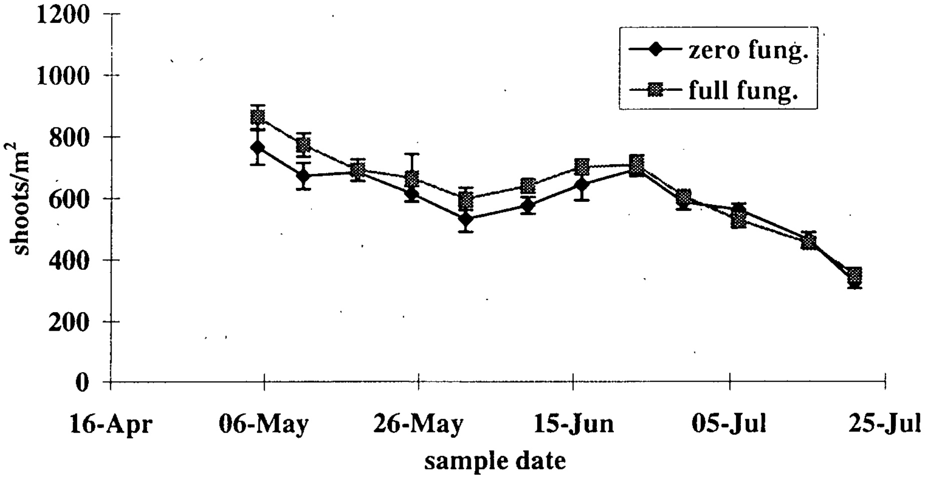
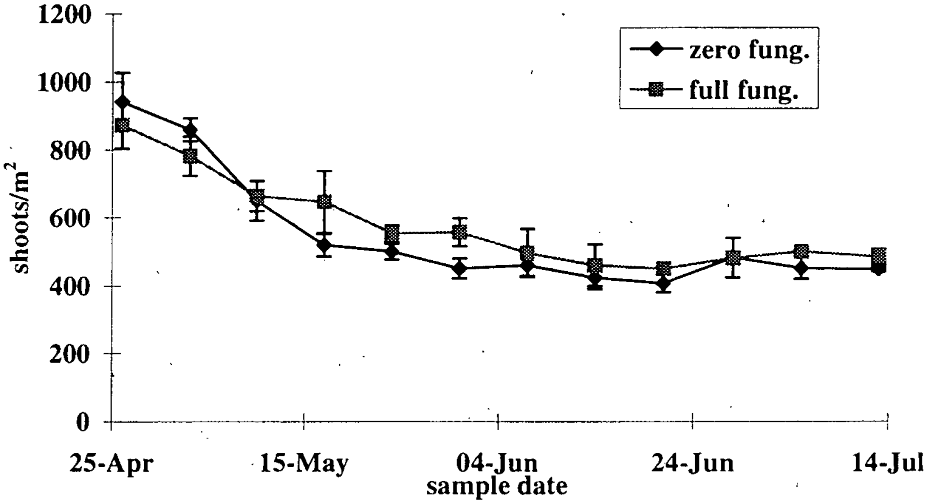


Figure 61. Shoots/m^2 in full dose and zero fungicide treated plots at Rosemaund.

1994



1995



1996

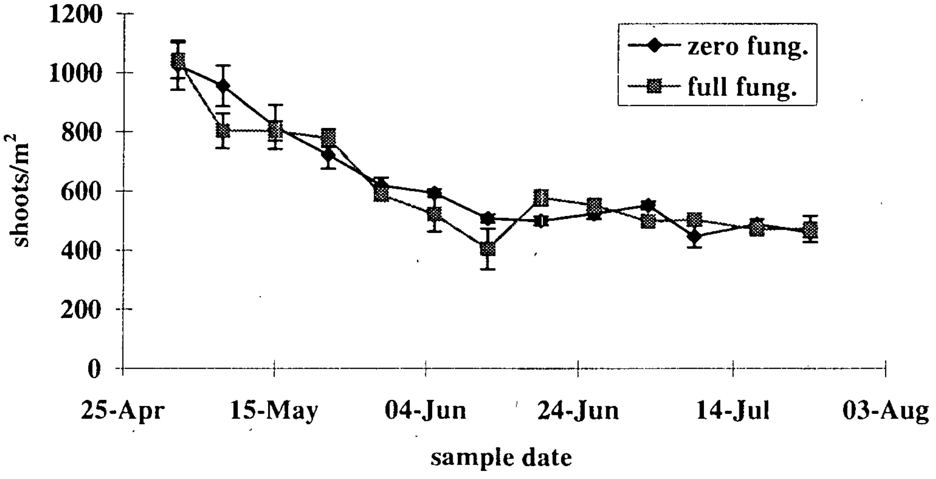
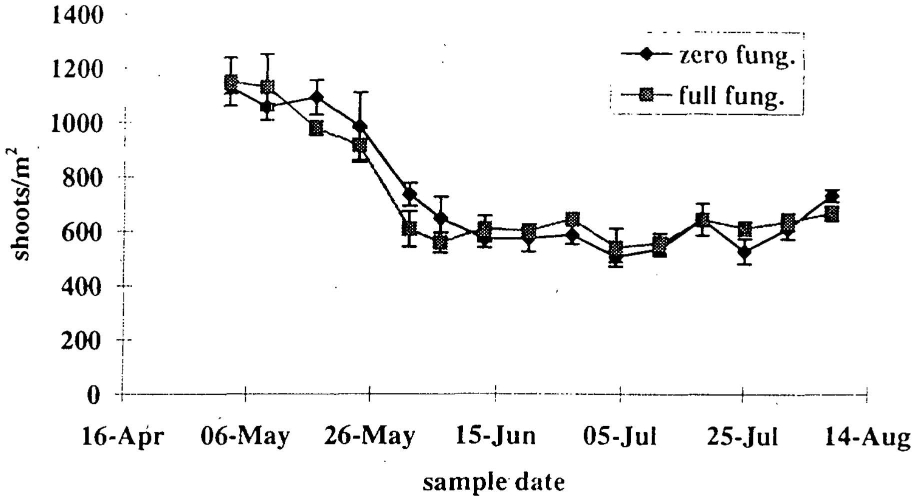
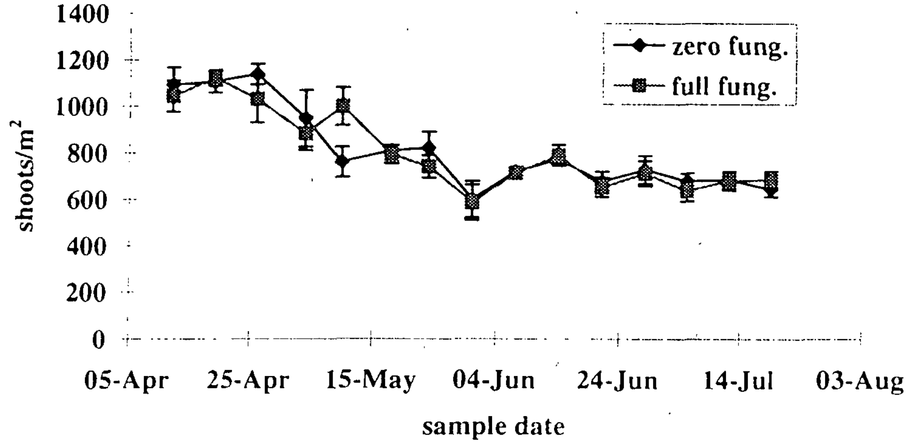


Figure 62. Shoots/m^2 in full dose and zero fungicide treated plots at Terrington.

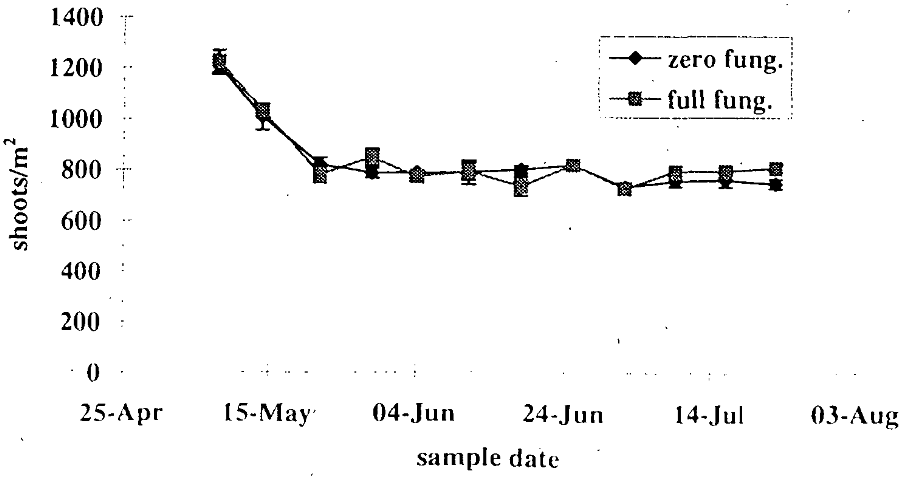
1994



1995



1996



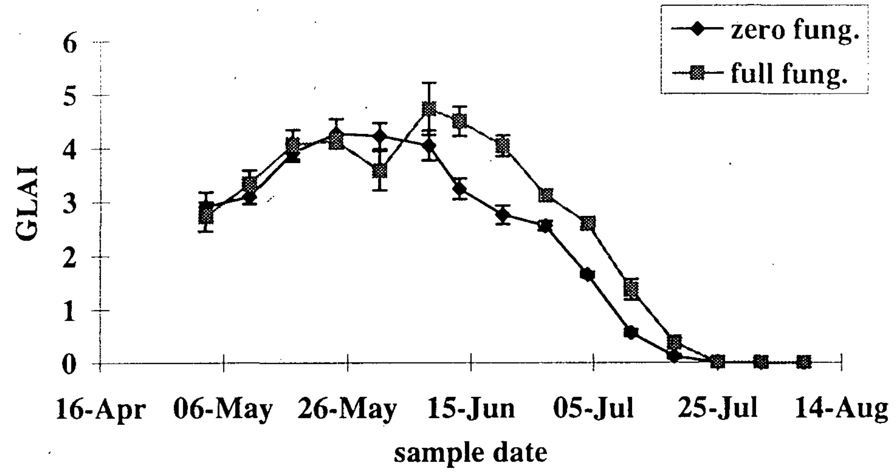
2.2.2 Green leaf area index (GLAI)

Figures 63 - 65 show the GLAI of the crop with and without fungicide treatment. As both *S. tritici* and yellow rust are foliar diseases, it is likely that the greatest effect of not applying a fungicide is going to be on GLAI. In the majority of cases in this study the difference in GLAI between the treated and untreated plots is directly attributable to the loss of green leaf area due to the expression of disease symptoms, primarily on the top three leaves (see Figures 13 - 15 - Section 2.1, Part I). At both of the *S. tritici* sites (Morley and Rosemaund) when disease epidemics occurred, GLAI was less persistent than in treated plots. At Morley in 1996 and Rosemaund in 1995, GLAI did not reach the same maximum as the fungicide treated plots, due to the early season occurrence of disease symptoms. In comparison, when the epidemic developed later in the season, maximum green areas were equivalent but GLAI started to decline earlier and at a faster rate in the presence of disease (Figures 63 and 64, Morley 1994 and Rosemaund 1996).

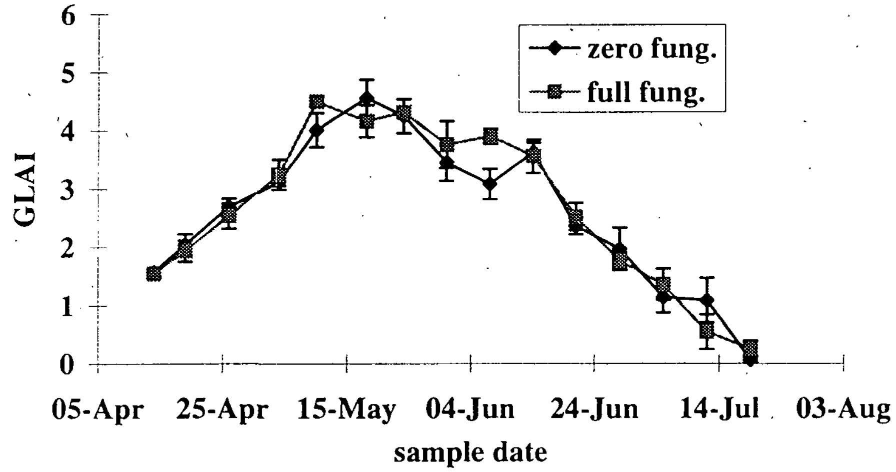
Yellow rust at Terrington (1994 and 1995 -Figure 13) had a dramatic effect on the persistence of green area. . In Figure 65, maximum GLAI was similar in both treatments, with a maximum GLAI of approximately 6.0 and 8.0 in 1994 and 1995 respectively. However, with the onset of the disease epidemic early in June in the two seasons, the rate of green area loss was faster than the loss of green area due to natural senescence in the fungicide treated plots. It is also interesting to note that although shoot numbers were approximately 100 shoots/m^2 higher in 1995 than 1994, a larger maximum GLAI was achieved in 1994. This is probably due to an increased amount of green area per shoot as a result of higher moisture availability in 1994. In 1996 there was no yellow rust epidemic at Terrington and only a small amount of *S. tritici*, hence GLAI was similar in both treatments until late in the season.

Figure 63. GLAI in full dose and zero fungicde treated plots at Morley.

1994



1995



1996

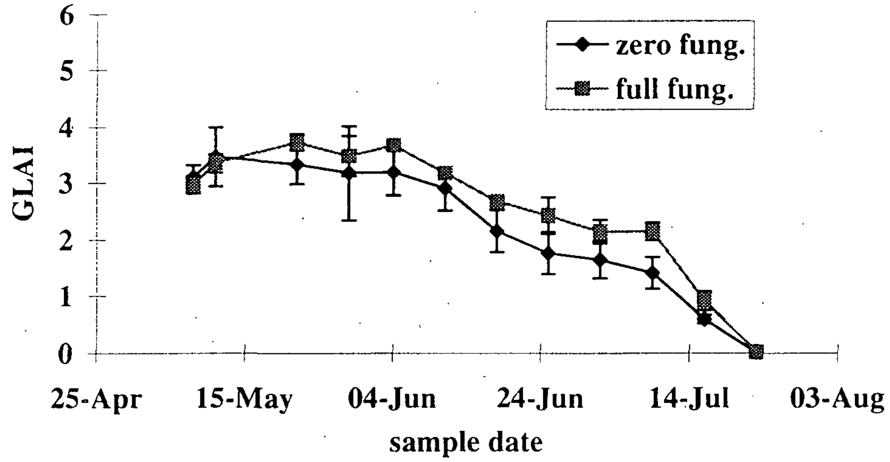


Figure 64. GLAI in full dose and zero fungicde treated plots at Rosemaund.

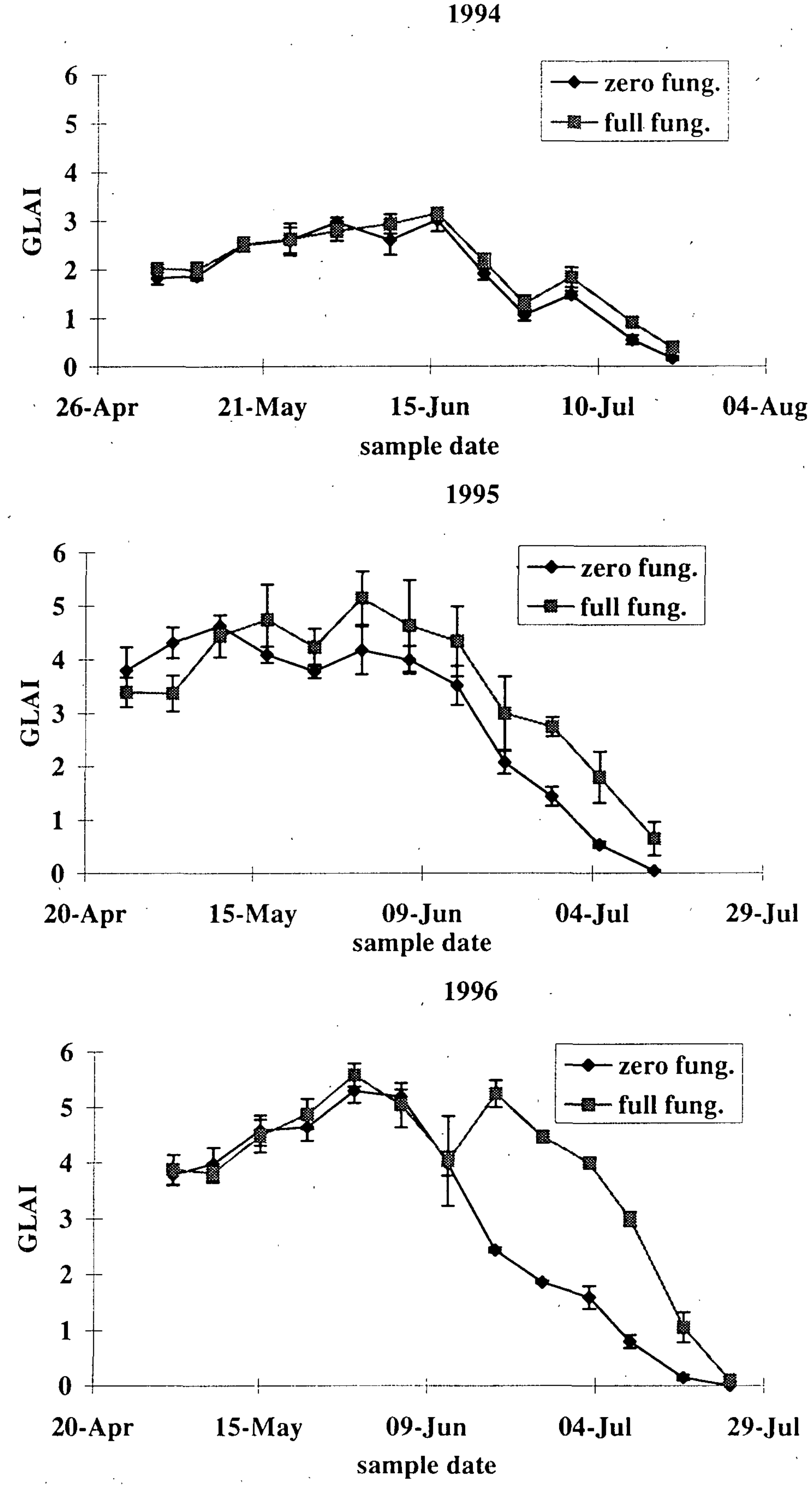
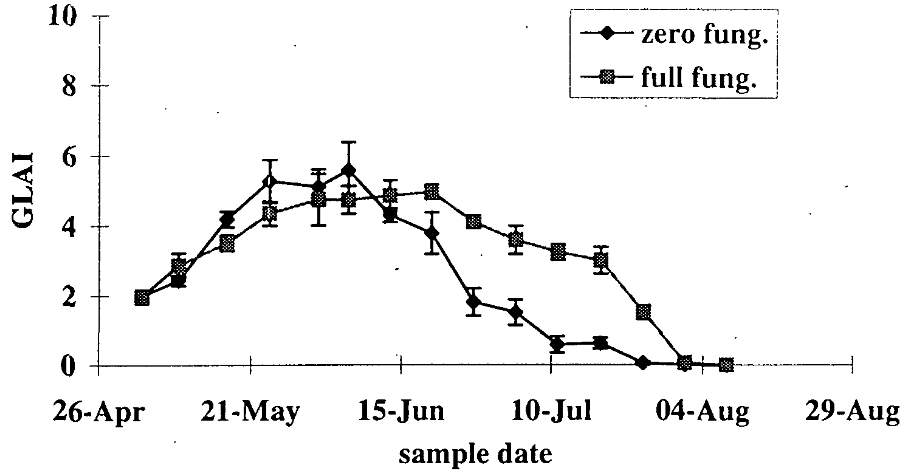
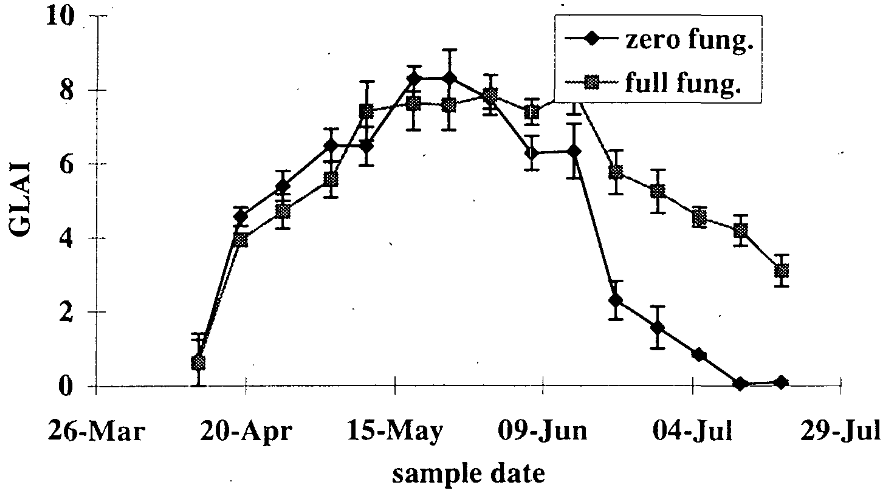


Figure 65. GLAI in full dose and zero fungicde treated plots at Terrington.

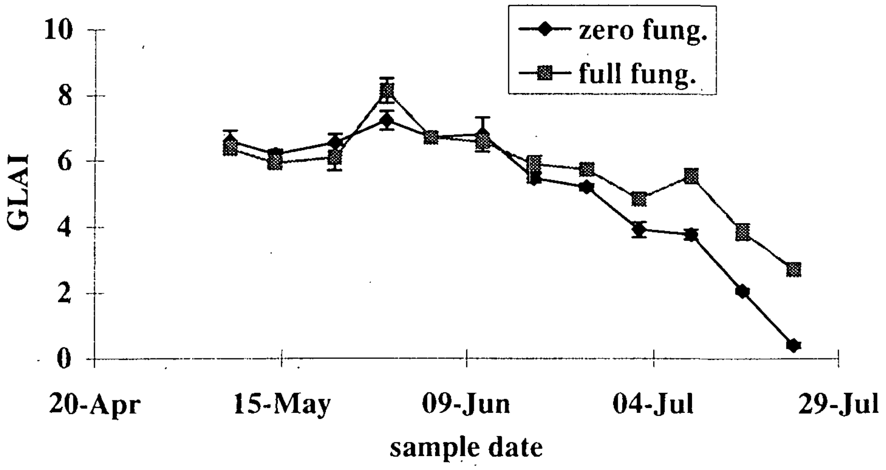
1994



1995



1996

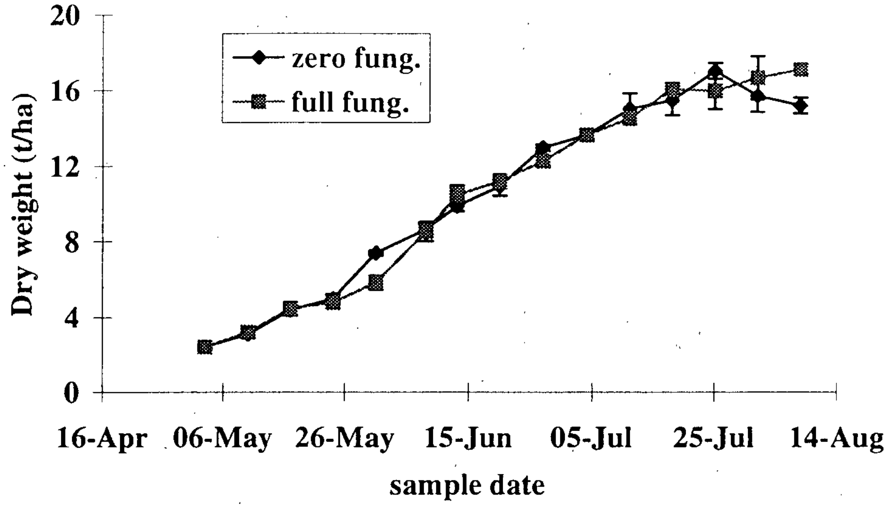


2.2.3 Total crop biomass.

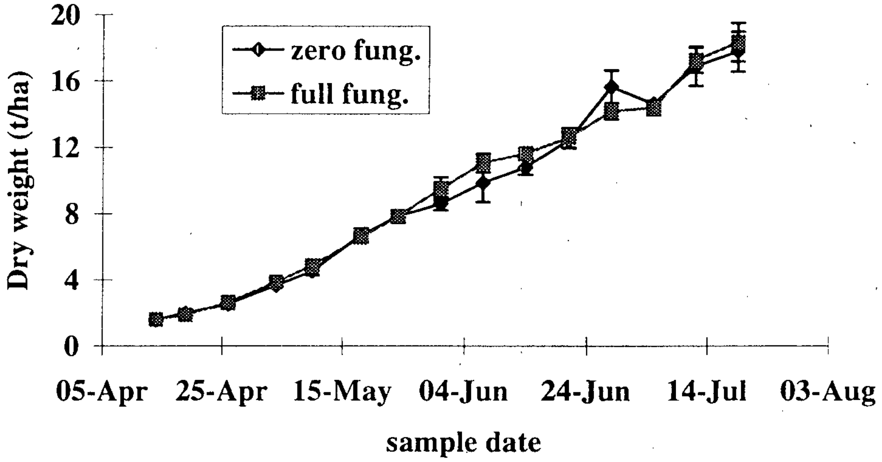
Figures 66 - 68 show total crop biomass through the season. Generally, differences in crop biomass between the two treatments correspond to differences in GLAI as shown in Figures 63 - 65. This is best illustrated at Terrington (Figure 68) where in 1994 and 1995 there was almost a 5t/ha difference in total biomass at harvest. Large differences in GLAI duration also occurred in these two years. The differences in total biomass are less distinct at the other two sites as were the differences in GLAI. At Morley, when GLAI differences were significant in 1994 and 1996, there were corresponding differences in biomass (Figure 16). The situation is less clear at Rosemaund (Figure 67). GLAI duration was far less in the zero fungicide treatment in 1996 but there was only a 2t/ha difference in biomass at harvest. In 1995, GLAI in diseased plots was consistently lower than in the fungicide treated plots, but at harvest, biomass was not significantly different between the two treatments.

Figure 66. Total crop biomass (t/ha) at Morley.

1994



1995



1996

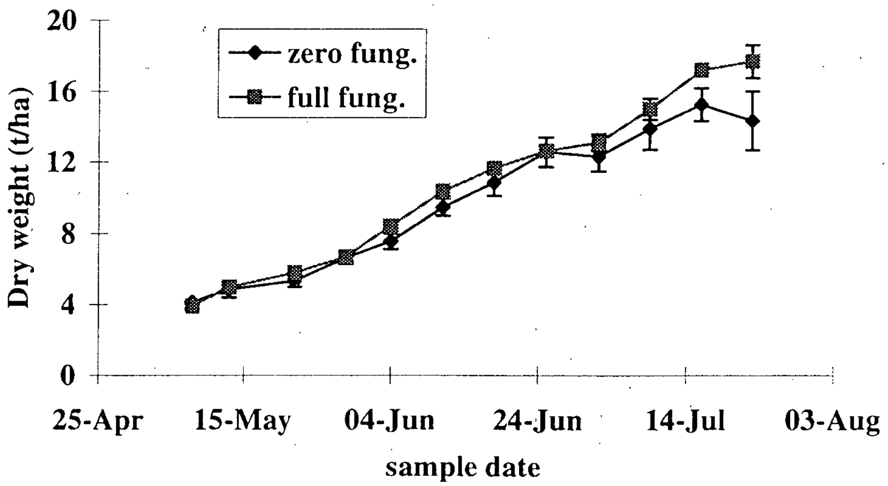


Figure 67. Total crop biomass (t/ha) at Rosemaund.

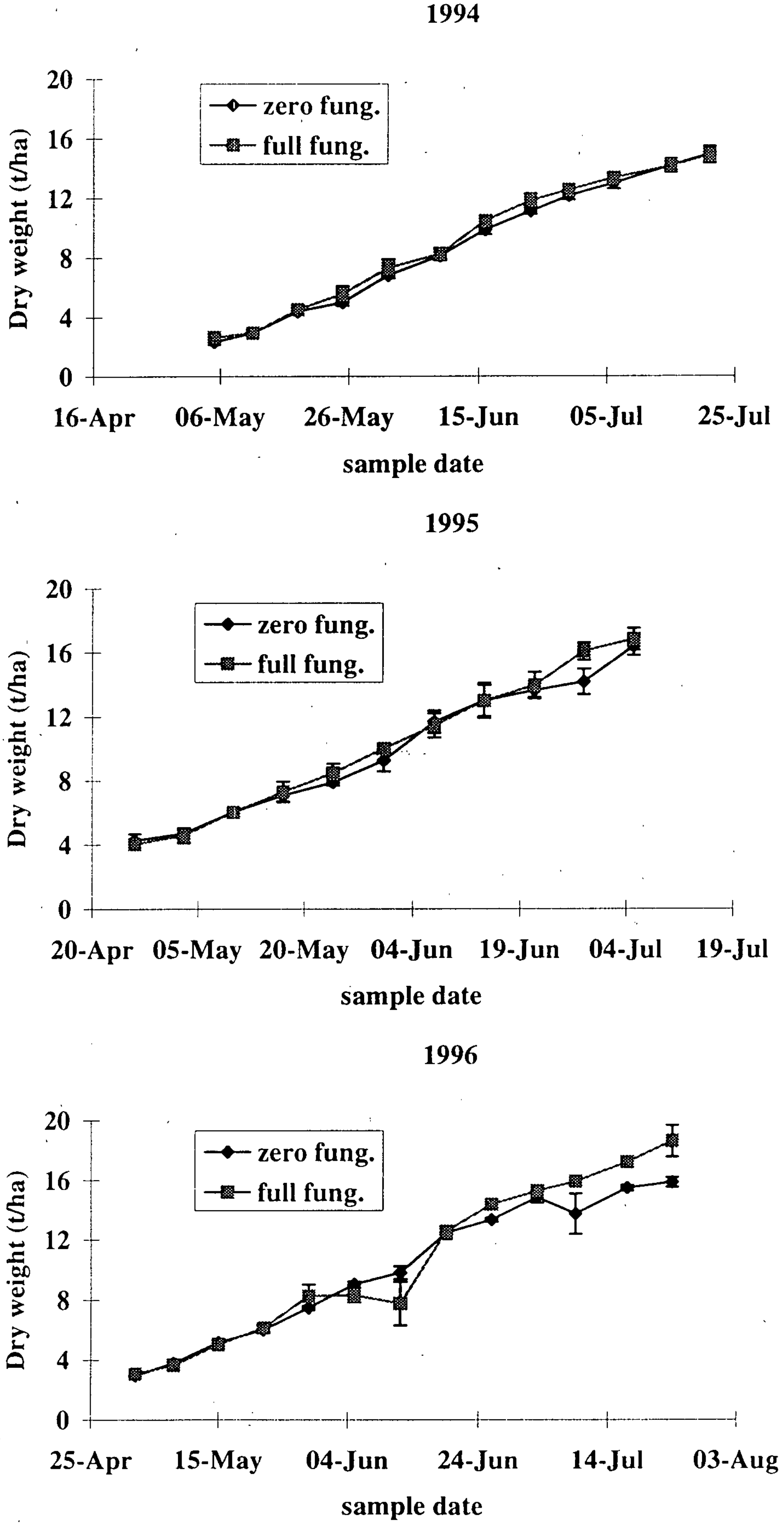
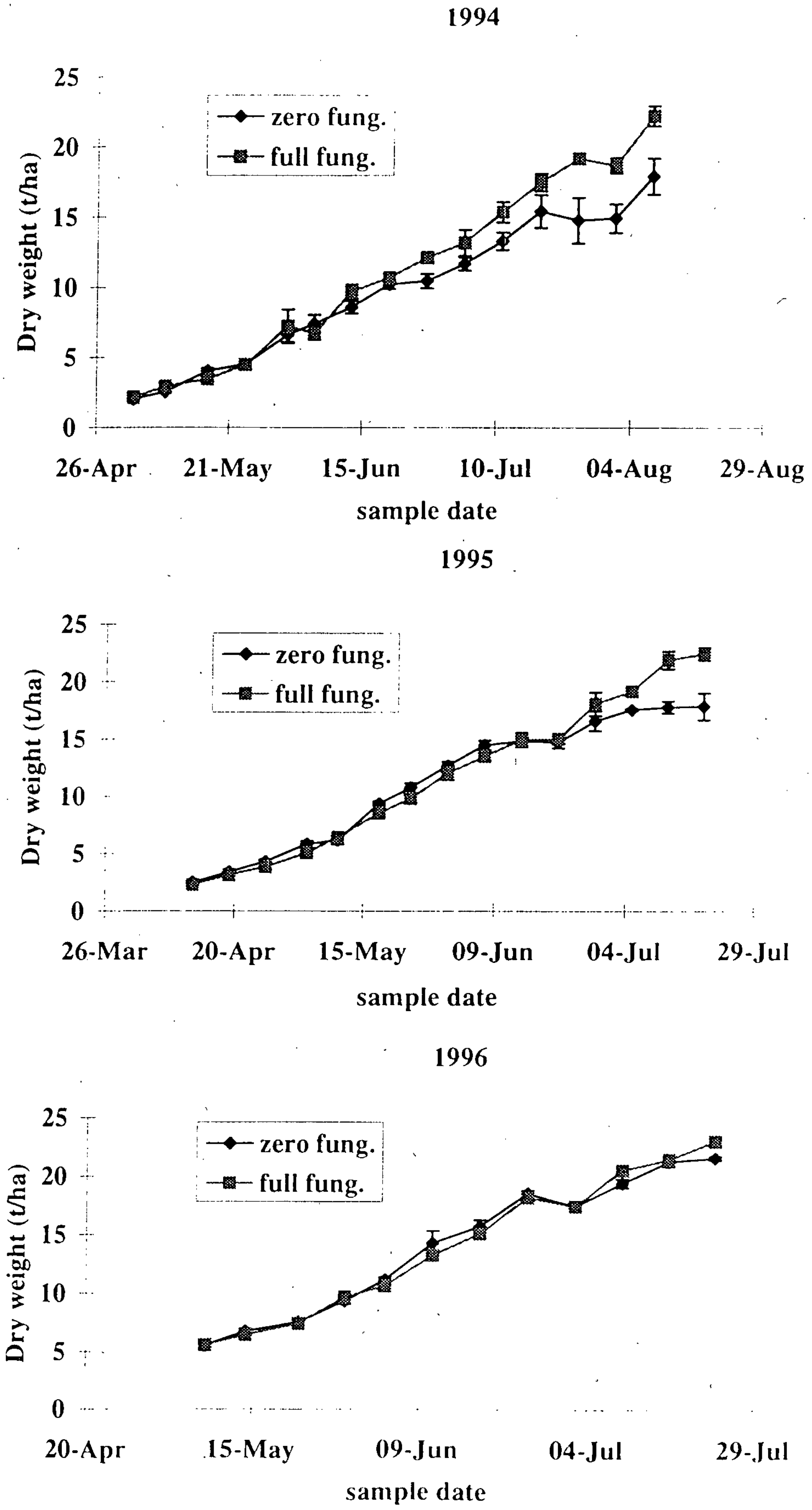


Figure 68. Total crop biomass (t/ha) at Terrington.



3.0 NON- DESTRUCTIVE MEASUREMENT OF CROP CANOPIES.

3.1. Introduction.

As described in Section 2.0, measurements of green area are becoming increasingly important to accurately assess the impact of foliar pathogens on yield. However, despite the improvements in yield loss predictions that may be achieved by measuring the effect of disease on GLAI, there has been a reluctance to adopt this approach in routine studies. Green area measurements in the laboratory, using a planimeter or leaf area meter, involve destructive sampling and are notoriously time consuming, and hence expensive. As a result limited numbers of samples can be processed. For the routine analysis of green area, in both healthy and diseased crops, a non-destructive, quick and accurate method is needed.

3.1.3 Leaf dimensions.

Comparison of leaves with pictorial standards or geometric shapes has been used in broad leaf crops to measure leaf area, but cannot be applied easily to cereal leaves. An alternative approach is the use of linear measurements. This method has been used successfully by several workers rice (Owen, 1968). It was therefore decided that an attempt would be made to devise a method to enable quick and accurate measurements of GLAI in the field..

3.2 Materials and Methods.

3.2.1 Determination of winter wheat leaf form factor.

To allow accurate determination of leaf area from length and width measurements taken in the field it was necessary to determine a leaf form factor. Leaf samples were taken at GS39 (Tottman, 1987) from the fungicide treated plots of a variety experiment at ADAS Terrington, Norfolk. The experiment was a fully randomised block design with three replicate blocks of 20 varieties; Admiral, Andante, Avalon, Beaver, Brigadier, Cadenza, Estica, Flame, Galahad, Haven, Hereward, Hornet, Hunter, Hussar, Longbow, Mercia, Norman, Riband, Rialto and Zodiac. A 0.5 m^2 sample was taken randomly from each plot by cutting plants from the sample area at ground level. Green leaves were randomly selected from each sample to represent leaves at different layers in the crop canopy, cut from the stem and leaf sheath immediately above the ligule (50 leaves/$plot^1$) and wrapped in moist paper towel prior to measurement in the laboratory. The total area (cm^2) of the 50 leaves from each plot was determined using a calibrated leaf area meter. The length and width of each individual leaf was then measured using a grid measuring 350 × 50mm, and delineated into 5 mm units on the length-axis and 1mm on the width-axis.

3.2.2 Comparison of GLAI using a leaf area meter and linear leaf measurements

GLAI is a function of the amount of green leaf area per shoot and the number of shoots per unit area of ground. Leaf length and width measurements taken in the field were used in conjunction with a form factor and shoot counts to calculate GLAI. These estimates were then compared with laboratory based leaf area meter measurements on both healthy and diseased crop canopies. In order to test the method rigorously, wheat canopies of different sizes were measured weekly from GS39 until canopy death. Crop sampling for both methods was carried out on an experiment at ADAS Terrington. The experiment was a fully randomised block design with 4 replicate blocks each of 6 treatments. The treatments were the factorial combination of three levels of nitrogen (60, 180 and 270 kg/ha), with and without yellow rust (*Puccinia striiformis* (Westend.)), on a susceptible variety Hornet (Bryson *et al.*, 1995). Yellow rust plots were inoculated at GS33 by the introduction of yellow rust infected, pot-grown wheat plants. Plots without yellow rust were prophylactically treated with the fungicide tebuconazole (as c.p. Folicur - Bayer plc).

3.2.3 Determination of GLAI in the field using leaf length and width measurements.

Measurements were carried out weekly on 10 randomly selected, destructively sampled shoots per plot. Leaf length and width were measured as described above. When the leaf was not fully expanded (i.e. no ligule visible), the length measurement was taken from just the emerged portion of the leaf. Leaf width was measured to the nearest mm by flattening the widest part of the leaf (generally just above the ligule) on the base scale. Assessments of the percentage of leaf area expressing disease symptoms (Anon, 1976) and the percentage of remaining green area were made on the same shoots and at the same time as leaf dimensions. Each leaf layer was assessed for the presence of yellow rust (*P. striiformis*), brown rust *(Puccinia recondita)*, *Septoria spp.* (*S. nodorum* and *S. tritici*) and mildew (*Erysiphe graminis* f.sp. *tritici*). As shoot number remains constant after GS 55, an assessment of the number of shoots/m^2 was only recorded on one occasion prior to harvest, when fertile shoots could be most easily identified. Shoot number/m^2 was calculated from counts of the number of fertile shoots in four, randomly selected 1.0m length rows per plot (row spacing = 12.5 cm).

3.2.4 Determination of GLAI in the laboratory using a leaf area meter.

GLAI determined from the in-field method was compared with measurements of GLAI of samples from the same experimental plots carried out in the laboratory (as described in Section 2.1).

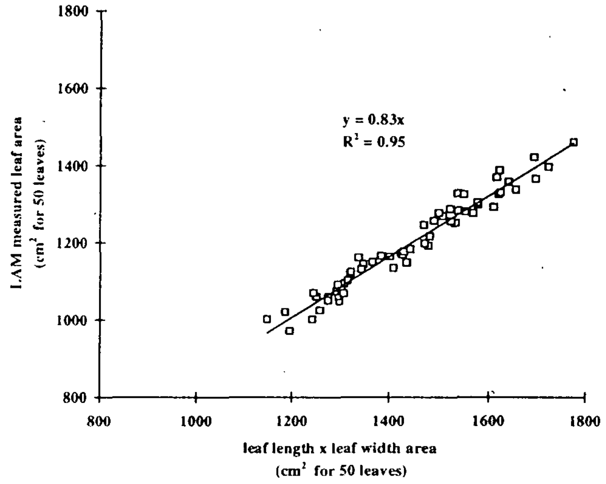
3.3 Results.

3.3.1 Winter wheat leaf form factor (F).

Therefore, the relationship between leaf area obtained by the leaf area meter and by the product of length and width was determined using the equation $\mathbf{y} = \mathbf{Fx}$ where $\mathbf{y}$ (leaf area meter leaf area) and $\mathbf{x}$ (leaf length × width area) were the means of their respective populations and **F**, the leaf form factor, where the intercept was equal to zero (Figure 69) (Bhan & Pande, 1966). Length and width measurements did not vary greatly between varieties. Mean width ranged from 1.4 cm (Cadenza, Estica) to 1.7 cm (Admiral, Longbow, Norman) and mean length, from 17.5 cm (Longbow) to 21.5 cm (Hornet). The relationship $\mathbf{y = 0.83x}$ was derived from all the data points over the twenty varieties tested, giving a leaf form factor of 0.83 ($R^2 = 0.95$; Figure 69). There was no significant difference in leaf form factor between varieties. The form factor was not assessed at growth stages before or after GS39, but the consistency that was found, irrespective of varying relationships between length and width, supports the use of a single value throughout crop growth. Inspection of individual leaves showed that there was little evidence of significant variation in rectangularity. The difference from rectangularity which the form factor represents occurs mainly at the leaf tip. It appears that this portion of the leaf is a consistent proportion of the whole.

Most modern varieties of winter wheat, despite their genotypic differences, generally have similar canopy morphology if compared with older varieties (Gale & Youssefian, 1985). F derived in this study was not only consistent between varieties but was similar to F values of 0.85 and 0.82 determined by Owen (1968) for the older wheat varieties Gabo and Mexico. Also Bhan & Pande (1966) reported that F = 0.80 for several different varieties of rice. This suggests that the relationship of leaf length and width, and thus leaf shape, may be consistent across species of cereals possibly allowing the use of a single figure for F in future cereal crop leaf area studies.

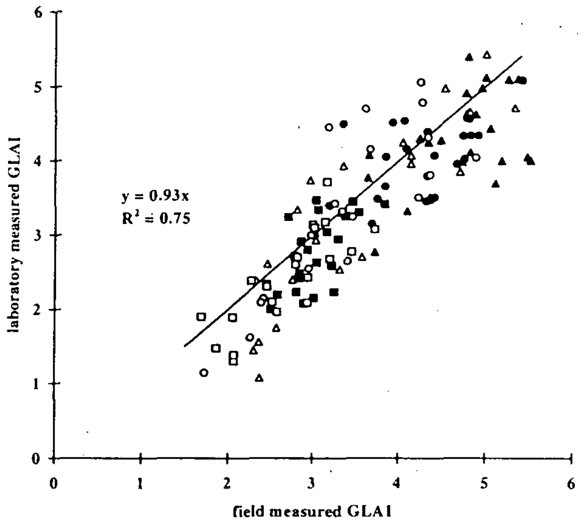
Figure 69. The data used to derive a leaf form factor (F) for winter wheat at flag leaf emergence stage (GS39), points are from 50 leaves from each of three replicate plots of 20 varieties. F, the slope of the relationship was 0.83 ($R^2 = 0.95$).



3.3.2 Comparison of field and laboratory measured GLAI.

Field GLAI was calculated in both yellow rust inoculated and fungicide treated plots, F was taken as 0.83. Shoot numbers were assessed in the field at GS 75 and were not significantly different from the shoot numbers obtained in the laboratory from the quadrat samples. A single figure for shoot numbers/m^2 was used to calculate field GLAI at each nitrogen rate (N1 = 330, N2 = 410, N3 = 418 shoots/m^2). Laboratory calculated GLAI was determined using both green area and shoot number measurements determined for each individual quadrat at each sampling time and in each nitrogen rate. Comparisons of GLAI from field and laboratory measurements are shown in Figure 70 for both the fungicide treated and yellow rust inoculated plots. Field and laboratory GLAI did not differ significantly from a one to one proportionality, **y = 0.93x** ($R^2 = 0.75$). However, the field measurement of GLAI was slightly overestimated compared with the laboratory measurements. A possible reason for this was that length and width measurements in the field were made on main shoots (i.e. those shoots selected for disease assessments) whereas quadrat samples consisted of a range of shoot sizes, which may have resulted in smaller mean leaf areas. It is also possible that although care was taken to minimise sample damage, sampling and processing of the quadrat samples may have resulted in dehydration or accidental loss of green area, resulting in a decrease in GLAI in the laboratory as compared with field measurements. Laboratory and field determination of GLAI in diseased samples both rely on the visual assessment of the percentage of leaf area expressing symptoms. In this study, percentage disease and green area assessments were made by the same individuals in both the field and laboratory and should not have contributed to the small differences found between the two techniques.

Figure 70. Comparison of green leaf area index (GLAI) calculated using the in-field method compared with GLAI assessed in the laboratory from green leaf area measured with a meter and fertile shoot counts. GLAI is shown for yellow rust inoculated plots (□ N1, ○ N2, △ N3) and fungicide treated plots (■ N1, ● N2, ▲ N3) at three N rates.



3.4 Discussion.

The use of length and width measurements, together with the leaf form factor, allowed rapid determination of green leaf area. If this in-field method is to be adopted elsewhere it is important to appreciate its dependence on precise estimates of shoot number. It is also necessary to recognise that assessments of green leaf area, either in the laboratory or in the field, particularly in diseased crop canopies, are based on subjective judgments of the percentage area of the leaf that is green; care must therefore be taken to standardise these assessments (Parker, *et al* 1995). The in-field method of determining GLAI was used to compare canopy sizes, non-destructively, of all the plots treated with contrasting fungicide dose and timings treatments as described in Part I. This large number of measurements would not have been possible using traditional destructive sampling techniques.

4.0 GLAI OF CROP CANOPIES.

4.1. Materials and methods.

Measurements of GLAI were made throughout the life of the project (1994, 1995 and 1996) on all four sites. In this report, crop canopy measurements from two contrasting disease epidemic sites (Rosemaund - *S. tritici* and Terrington - yellow rust) are reported.

In 1994, 1995 and 1996 at Rosemaund and Terrington, experimental plots were set up in a fully randomised block design with two replicate blocks of 60 (1994) and 52 (1995 & 1996) treatments (Part I - 1.4.1) The fungicide mixture tebuconazole (as c.p. Folicur - Bayer) plus fenpropidin (as c.p. Patrol - Zeneca) was applied at either full, 0.5 or 0.25 of the label recommended dose (1 litre c.p plus 0.7 litre c.p/ha respectively). Sprays were applied as a combination of timings at eventual leaf 3 fully emerged (typically GS32), eventual leaf 2 fully emerged (typically GS33), eventual leaf 1 (the flag leaf) fully emerged (GS 39) and ear fully emerged (GS59). Percentage disease and green leaf area assessments were carried out on 10 randomly selected shoots per plot. Leaf length and width measurements were carried out on two of the 10 randomly selected shoots and used to determine GLAI as detailed previously.

4.2 Results.

4.2.1 Rosemaund.- *S. tritici.*

The pattern of GLAI development at Rosemaund over time is illustrated in Figures 71-73. In some cases, measurements did not commence until maximum green leaf area had occurred. The general pattern was for green leaf area to increase to a maximum, plateau and then decline. The pattern and rate of GLAI decline can be seen to be affected by fungicide treatment and also differs between leaf layers. Within each season and leaf layer, the same maximum GLAI was achieved irrespective of treatment. In 1994 and 1996 the lower dose treatments, primarily those below 1.5 total dose, began to lose green leaf area earlier and at a faster rate than the higher doses, particularly those above a total dose of 2.0. If we examine the graphs for disease progress for the three years on this site (Part I - Figure 14) it is obvious that high disease levels in the lower dose treatments in 1996 account for the loss of green leaf area. However, less disease was recorded in 1994 than 1995 and yet green leaf area decline was significant at lower fungicide doses in 1994 but not in 1995. This may be partly explained by comparison of the relative sizes of crop canopies between the two years. In 1995, maximum GLAI was approximately 2.0 whereas in 1995, it was 1.3. Thus a small percentage of a large canopy may have resulted in a larger amount of area loss than a large percentage of a small canopy.

Figure 71. GLAI of leaves 1, 2 and 3 at Rosemaund in 1994 for a range of total fungicide doses

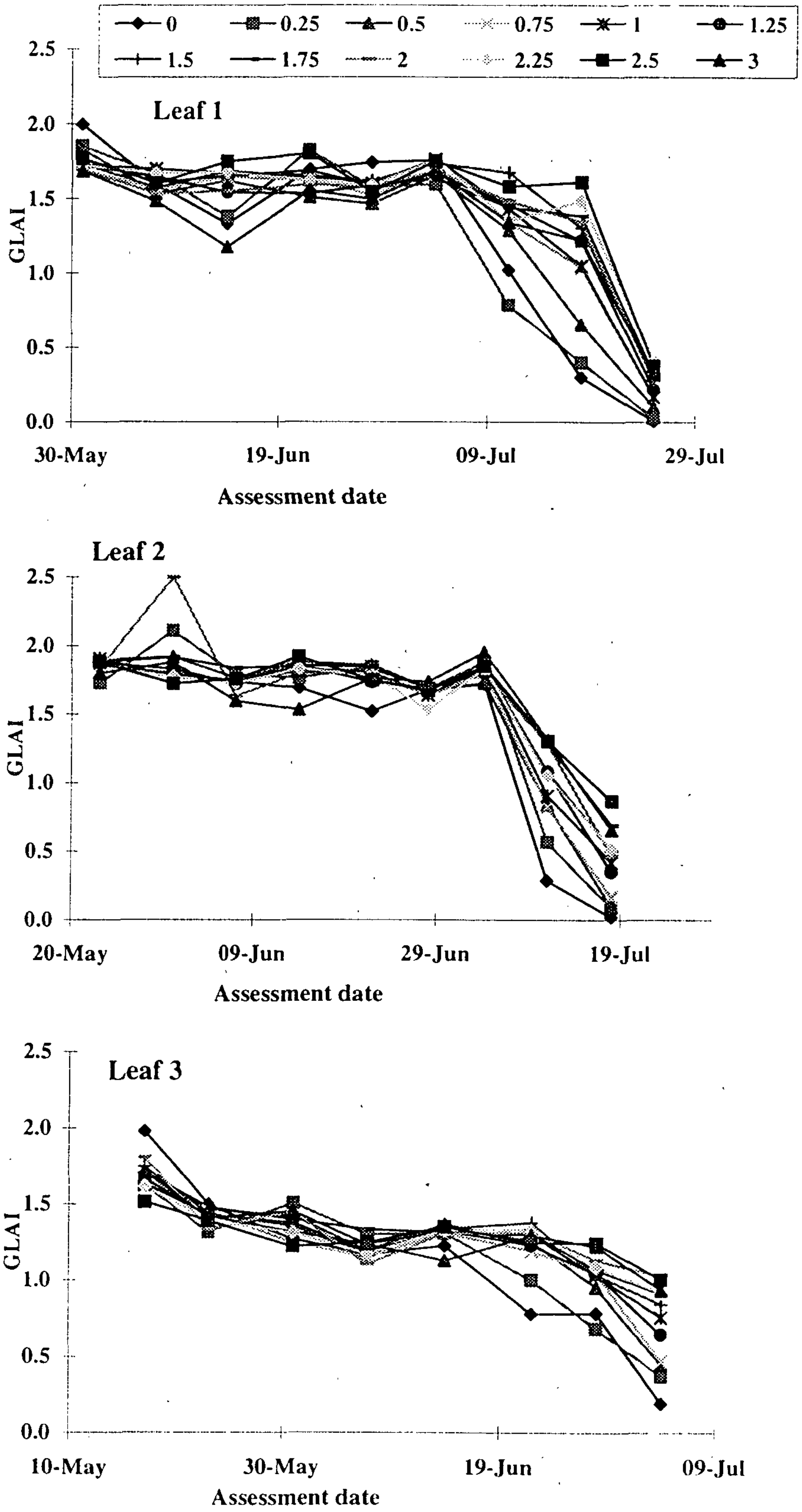


Figure 72. GLAI of leaves 1, 2 and 3at Rosemaund in 1995 for a range of total fungicide doses

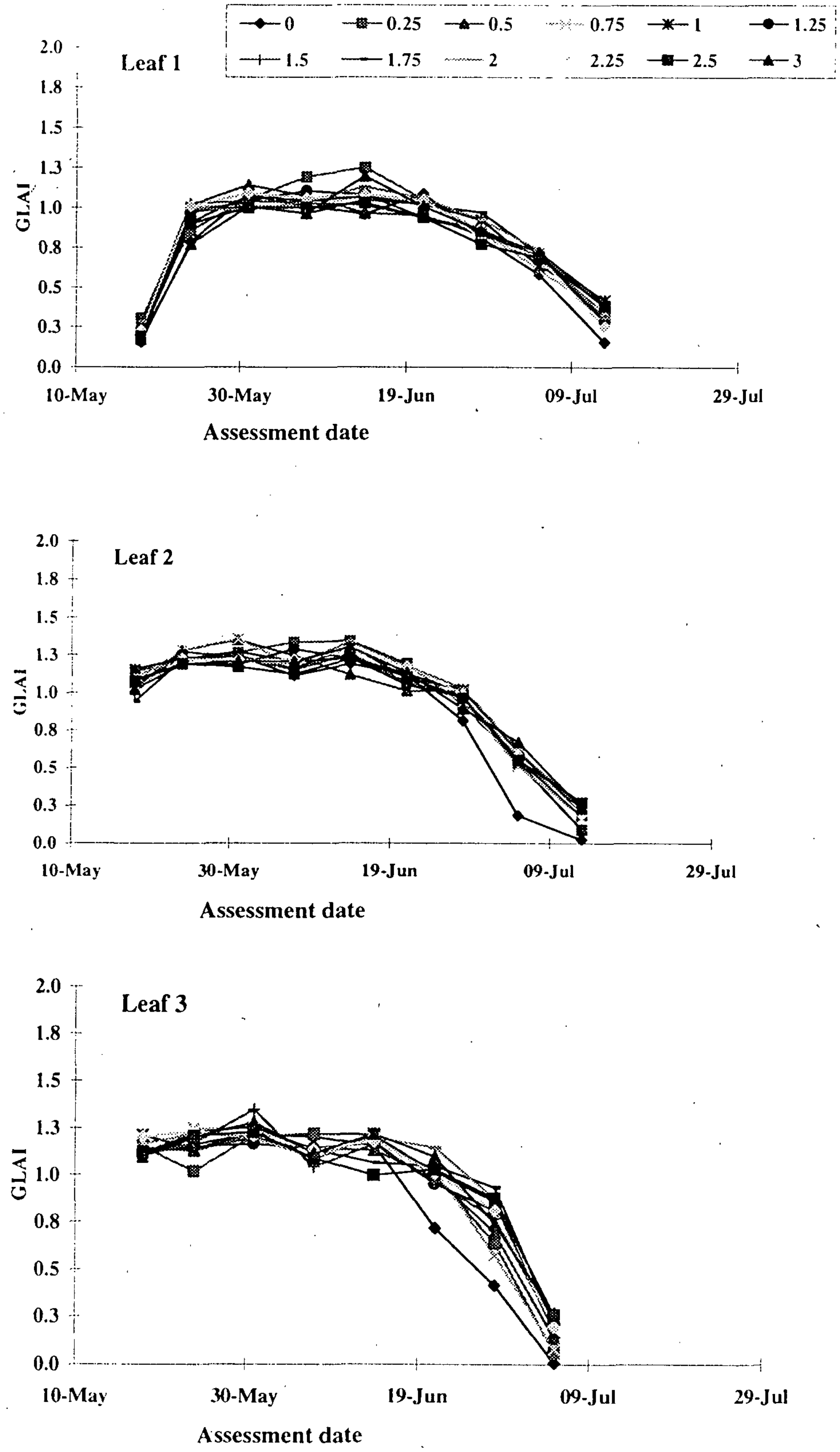


Figure 73. GLAI of leaves 1, 2 and 3 at Rosemaund in 1996 for a range of total fungicide doses

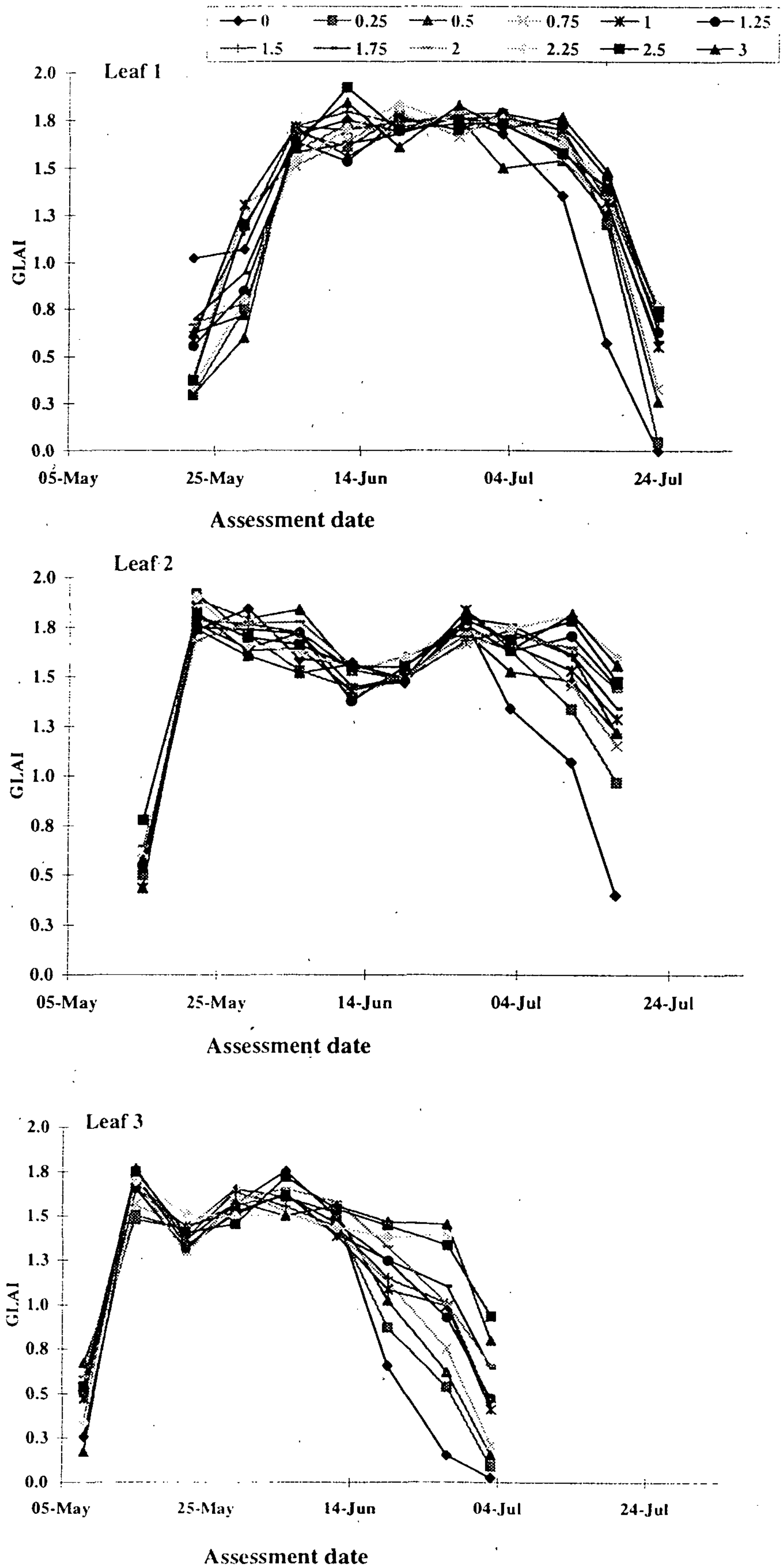


Figure 74. GLAI of leaves 1, 2 and 3 at Terrington in 1994 for a range of total fungicide doses

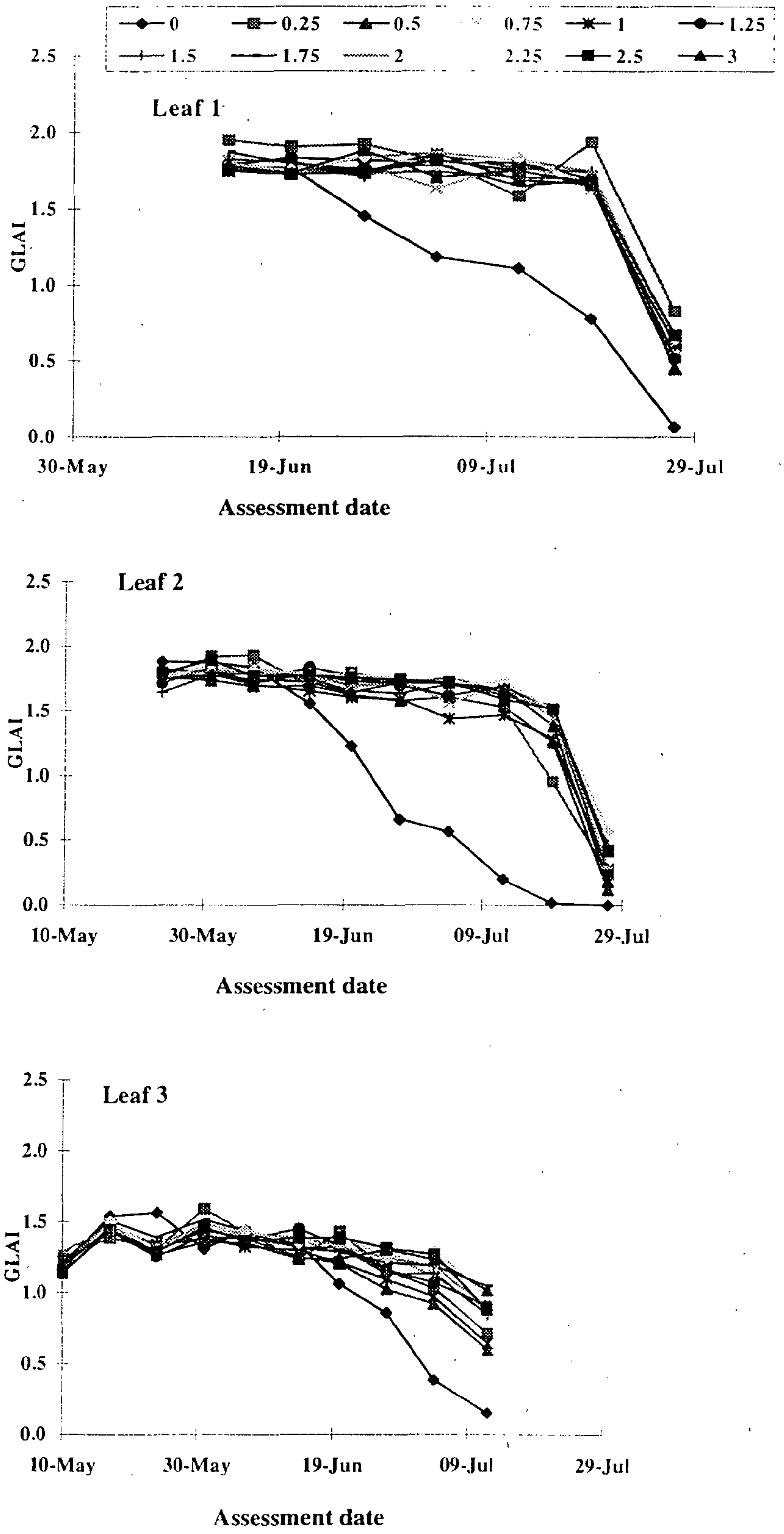


Figure 75. GLAI of leaves 1, 2 and 3 at Terrington in 1995 for a range of total fungicide doses

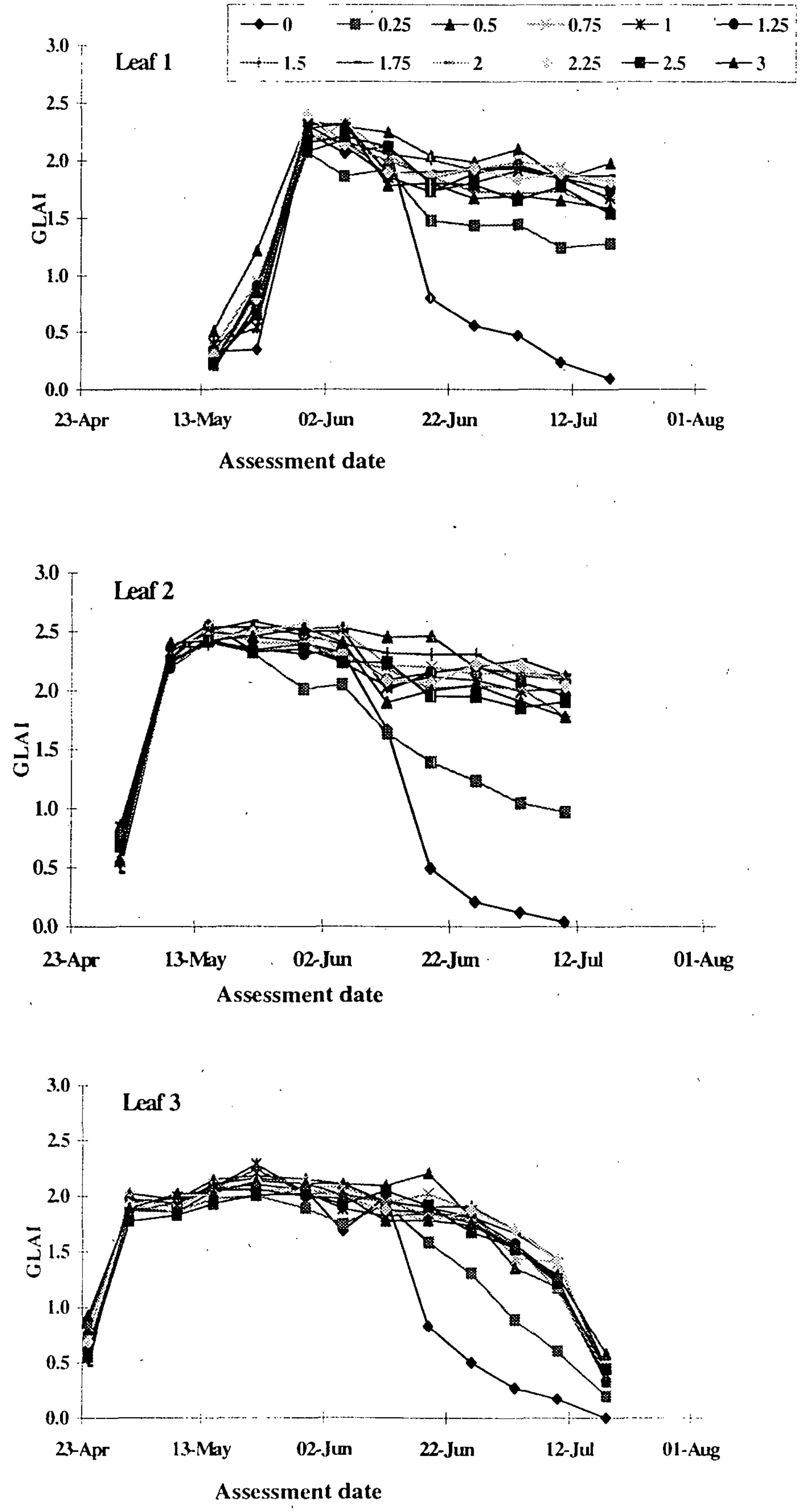
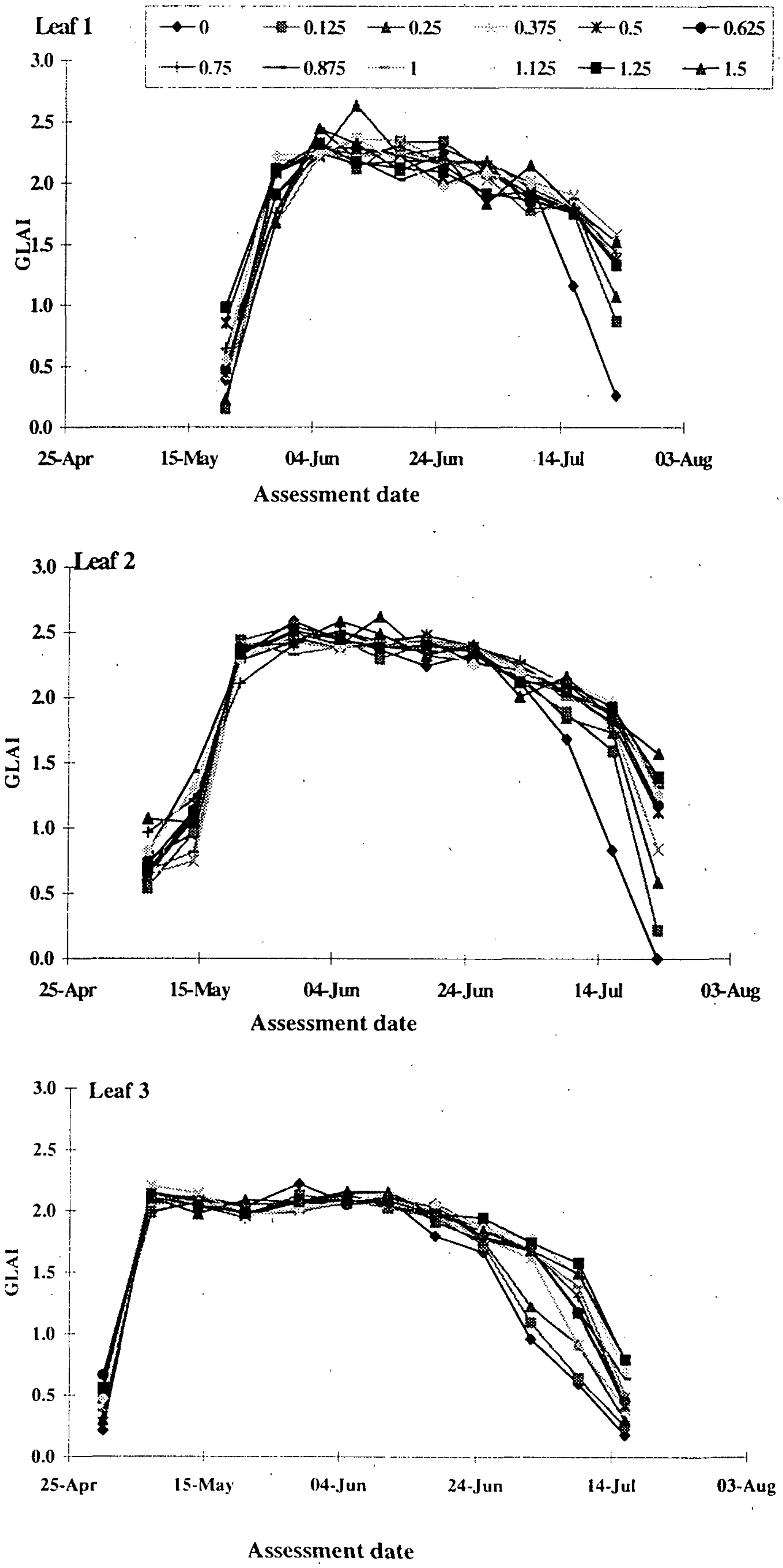


Figure 76. GLAI ofleaves 1, 2 and 3 at Terrington in 1996 for a range of total fungicide doses



4.2.2 Terrington - Yellow rust.

The Terrington site was used in order to target yellow rust. Yellow rust epidemics occurred in 1994 and 1995. The primary disease in 1996 was *S. tritici*. The GLAI of the top three leaf layers of the canopy in each season are given for 1994, 1995 and 1996 in Figures 74-76. It is interesting to note that canopy development and decline in 1996 was very similar to that for Rosemaund in 1994 with similar disease levels (Figure 76 and Figure 13 with Figure 71 and Figure 14). The pattern of GLAI progress over time in the presence of yellow rust is markedly different to that at Rosemaund with *S. tritici*. Although generally all treatments reach the same maximum GLAI within each leaf layer, at low doses, i.e. 0.25 and 0 total dose, the pattern of GLAI decline is different to that seen with *S. tritici* epidemics. In 1994, in the zero fungicide dose treatment, GLAI does not plateau in leaves 1 and 2 (Figure 74). GLAI loss starts earlier than in the other treatments, but declines at a slower rate. In 1995, although GLAI at 0 and 0.25 total dose does plateau, it is not sustained as long as in the other treatments (Figure 75). Again, GLAI decline starts earlier, but is at a slower rate.

4.3 Discussion.

For the first time it has been possible to measure crop canopies in the field throughout the growing season, to obtain information on green leaf area progress in contrasting disease situations and on individual leaf layers. GLAI progress has been shown to differ as a result of the epidemic progress of *S. tritici* and yellow rust. This is likely to be due to the contrasting lengths of latent period between the two pathogens and their relative dependence on weather conditions. *S. tritici* has a long latent period of approximately 21 days and is dependent on the presence of free water for splash dispersal of spores and/or physical contact of plant parts as described in Part I, Section 2.1, Figure 9. Consequently, during canopy expansion a greater proportion of the leaf area is less than one latent period old, and hence unaffected by disease expression. Once maximum green area has occurred, even if disease infection occurs at the start of leaf emergence, there will be a lag time of at least two weeks before symptom expression will affect green leaf area, and hence the plateauing of GLAI even at low total fungicide doses. In contrast, yellow rust has a short latent period of approximately a week. The rate of green leaf area increase was still faster than symptom expression, so that maximum GLAI was reached in all treatments in 1994 and 1995. However, at low fungicide doses where disease progress was rapid, GLAI started to decline much earlier than in the higher fungicide doses but at a slower rate than occurred with natural senescence.

5.0 CROP BASED YIELD-LOSS MODELS.

5.1 Introduction.

Several studies have confirmed that measurements of canopy size, and in particular the effect of disease on GLAI, correlate more closely to yield-loss than estimates of percentage disease severity alone (Lim & Gaunt, 1981, Waggoner & Berger, 1987; Whelan & Gaunt, 1990; Bryson *et al.*, 1995). However, until recently, accurate measures of GLAI over time in multi plot, disease:yield-loss studies and fungicide efficacy experiments have been rare. We have shown in this project that such measures are now possible. Waggoner and Berger (1987), suggested that disease progress should be related to crop growth by taking into account both the amount of green area available for photosynthesis, the 'healthy area duration' (HAD), and the amount of incident radiation absorbed by that healthy area, the 'healthy area absorption' (HAA), using the Beer's law analogy. An attempt has been made here to test whether the HAD and HAA models described by Waggoner and Berger (1987) are applicable to a foliar disease epidemic on winter wheat in a temperate environment and whether these models can be supported by simple in-field measurements of disease severity, GLAI and total incident radiation as previously described.

In this section, the effect of the yellow rust epidemic at Terrington on the winter wheat variety Slejpner is studied in more detail in order to evaluate the relationship between crop canopy green leaf area, radiation interception by that green leaf area and grain yield.

5.2 Results.

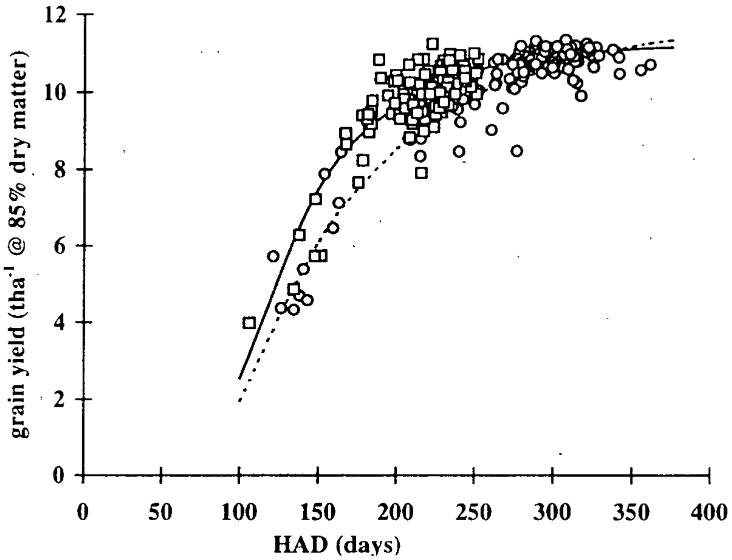
The HAD values reported here are the sum of the integrals of GLAI through time for leaves 1, 2 and 3 (from 31st May, GS39) until no green area remained (19 July, leaf 3 and 25 July, leaves 1 & 2) for both 1994 and 1995. Following the precedent of the definition of HAD and HAA (Waggoner and Berger, 1987), no account was taken of ear green area or interception; in these experiments disease did not affect the ears. HAD from 31st May gave a curvi-linear relationship with yield in both 1994 and 1995 (Figure 77). A simple exponential curve was fitted to the data giving :

1994 $\mathbf{y = 11.22 - 47.52e^{-0.017x}}$ $(R^2 = 0.63)$ (eq. 3)

1995 $\mathbf{y = 11.80 - 29.57e^{-0.011x}}$ $(R^2 = 0.73)$ (eq. 4)

Within each experimental year, HAD and yield related reasonably well (eq. 3 & 4), however, between years all three parameters of the curves were significantly different. In particular, the curve for 1995 was horizontally displaced in relation to 1994 (Figure 77). The HAD model does not take account of either the way light is attenuated by crop canopies of different sizes, the amount of total incident radiation available or interception by ears and other non-leaf organs. These parameters differed between the two seasons with a maximum GLAI in 1994 of 6.03 (SE 0.28) and 1995 of 8.29 (SE 0.34) and total incident radiation from 31st May in 1994 of 1200 MJ/m^2 and 1995 of 1336 MJ/m^2.

Figure 77. The relationship of grain yield to healthy area duration (HAD) after the 31st May of leaves 1 and 2 (until 25th July) and leaf 3 (until 19th July) in 1994 (□---) and 1995 (O ....).



In Figure 78 an estimate of the healthy area absorption (HAA), i.e. accumulated intercepted radiation (MJ/m^2) by green leaf tissue, was calculated after 20th June (approximately GS 61) until no green area remained (18th July) assuming an extinction coefficient of 0.45 (Sylvester-Bradley *et al*, 1990). In both years HAA related directly to yield. The regression equations are given below.

1994	**$y = 0.85 + 0.017x$**	($R^2 = 0.82$)	(eq. 5)
1995	**$y = 1.81 + 0.016x$**	($R^2 = 0.91$)	(eq. 6)

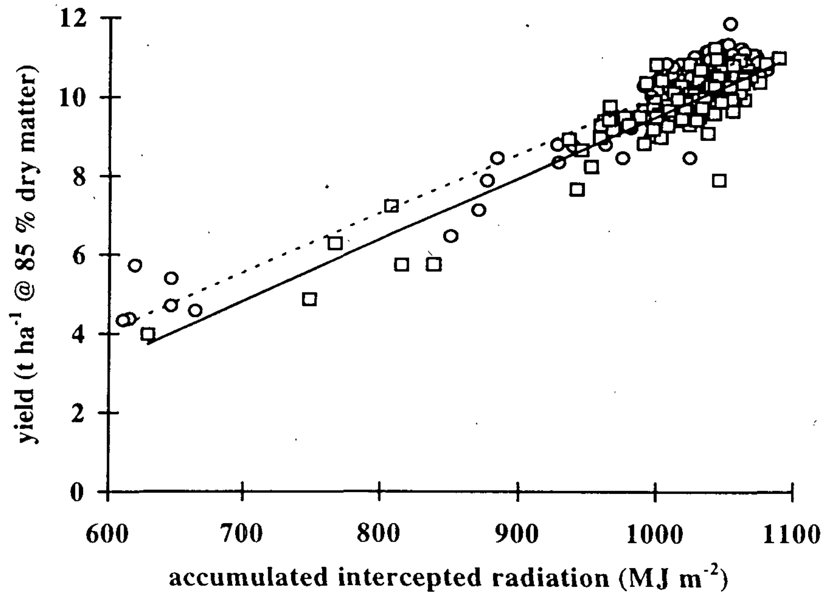
The relationship of yield with HAA in both seasons was closer than the relationship with HAD (eq. 5 & 6; Figure 78). There were no significant difference in slope over the two seasons, but the intercepts were significantly different. It was found that if intercepted radiation was accumulated from earlier than 20th June the slope of the line did not change significantly, but the intercept became increasingly negative. For example, the equations of the regression lines of intercepted radiation accumulated from the end of May were as follows:-

1994	**$y = -4.06 + 0.015x$**	($R^2 = 0.80$)	(eq. 7)
1995	**$y = -3.67 + 0.015x$**	($R^2 = 0.92$)	(eq. 8)

The significant difference in intercept between the two years probably relates to the growth stages at which the effects of disease on intercepted radiation began to relate to grain growth. Since maximum yields were similar in both seasons (Figure 78) the period relating disease effects to yield effects is likely to have started and finished earlier in 1995 than 1994. This is supported by the observation that the yellow rust epidemics were more severe earlier in 1995 than 1994, but were checked sooner by high temperatures in July and August of 1995.

From the slopes of equations 5 and 6 (Figure 78) the mean radiation use efficiency (RUE) by green leaf tissue from 20th June was calculated as 1.41 g grain dry matter per MJ of total intercepted radiation. This is in line with the findings of Monteith (1977) who found that for crops such as barley, beet, apples and potatoes, RUE in unstressed situations was approximately 1.4 g dry matter per MJ of total intercepted radiation. This suggests that in these experiments the primary effect of yellow rust was on radiation interception via GLAI loss, not RUE.

Figure 78. The relationship of grain yield (in 1994 (□---) and 1995(O ....) with radiation interception from 20th June to 18th July by green area of leaves 1, 2 and 3 (Healthy Area Absorption -HAA). Interception was calculated assuming Beers' Law with an extinction coefficient of 0.45.



5.3. Discussion.

Models which rely solely on the quantification of visible disease do not take account of variations in growing conditions which occur between geographically dispersed sites and between seasons, nor do they adequately recognise the period when the disease is causing loss of grain rather than vegatative growth (Teng, 1985). Several workers have already emphasised the need for a more crop based approach to develop disease control strategies, combining an understanding of crop growth with knowledge of disease development (Waggoner & Berger, 1987, Whelan & Gaunt, 1990 Bryson *et al.*, 1995). However, there is still a reluctance amongst pathologists to incorporate crop growth measurements into disease:yield studies and fungicide experiments. It is now possible to measure GLAI in the field at the same time as making conventional disease assessments. The use of length and width measurements, together with the leaf form factor, allowed rapid determination of green leaf area.

In-field measurements of GLAI were used to test whether the HAD and HAA models described by Waggoner and Berger (1987) could improve the explanation of yields over sites and seasons as compared with AUDPC models. The data on peanut plants collated by Waggoner & Berger (1987) for HAD gave a curvilinear relationship with yield. It was perhaps surprising that all of their data for 78 crops of peanuts over 14 years fitted one curve. It may be that, although the peanut crops were grown over several years, environmental conditions were relatively similar and the peanut canopies were not very different prior to defoliation. When the wheat canopies described here differed by a large amount of green area (> 2 GLAI units between 1994 and 1995) and total incident radiation levels differed (by 136 MJ/m^2 between 1994 and 1995), the HAD curves were significantly displaced. In this study, HAD did not give a consistent explanation of yield over the two seasons, although it did demonstrate a decreasing return from increasing green area, suggesting that yield is more closely related to absorption of solar radiation than to leaf area alone. As an integral over time, HAD has a similar disadvantage to AUDPC in that it does not differentiate between large GLAI for a short period and small GLAI for a long period (Johnson, 1987). Nor does it account for the diminishing effect of increasing canopy size on the proportion of light intercepted (Monteith & Unsworth, 1990). This has implications for disease control strategies in that a large canopy may be able to tolerate some loss of green area without an economically significant effect on yield. On the other hand, any loss of green area from a small canopy could have a serious effect on yield, making protection an economic necessity.

The relationship of yield to HAA gave a better correlation than that with HAD in both experimental years. With relatively large canopies, only two seasons to provide variation in incident radiation, and a large proportion of the treatments giving good disease control may, of the data points in this relationship were clumped. A more thorough test of the predictive power of HAA must depend on data from a broader range of circumstances. Nevertheless, the RUE of green leaf tissue determined here was not only consistent between the two seasons, but was similar to the RUE determined from separate disease control experiments at this site (1.2g MJ^{-1}; Bryson et al., 1995) as well as to the radiation conversion coefficients reported for several different crops (Monteith, 1977).

In order for the model to be tested more rigorously, it will be necessary to look at other disease:crop situations such as the effect of *S. tritici* on crop canopy size, duration and radiation interception. Yellow rust and *S. tritici* are contrasting foliar diseases in that the former is a biotroph and the latter, a necrotroph. Therefore they may affect the host plant physiology in a different way which may have implications for the model described above (Section 5.0, Part II).

Although HAA gave the best estimate of harvested yield of the three models tested, the intercept of the relationship was found to be highly sensitive to the start date taken for the period of integration. For example, when the relationship of yield to HAA was tested from the end of May the intercepts of the equations became negative, but the slopes were unchanged. Waggoner & Berger (1987) obtained negative intercepts when they related peanut yield to HAA. They concluded that the negative intercept indicated that no peanuts were set at very small HAA values. The values of HAA presented in this paper were calculated from 20th June in both years so that they could be compared on a common basis. On 20th June both crops were assessed as being at the start of anthesis (GS61; Tottman, 1987). However, assessment of growth stages can be prone to assessor error and the distinction between the beginning and middle of anthesis is uncertain when assessments are made on a weekly basis. It is therefore possible that the wheat crops in 1994 and 1995 were at different developmental stages on this date. It would appear that the integration of intercepted radiation over time must be combined with precise and accurate records of growth stages if the approach, based on HAA, is to lead to an improved capacity to predict yield.

Waggoner & Berger (1987) suggest that the amount of solar radiation intercepted by the green portion of a crop canopy is all that is needed to predict crop loss. This was obviously not the case in this study. Johnson (1987) pointed out that, when used over an entire season, HAA:yield models may not account for different source-sink relationships at different crop stages. Whilst restriction of the HAA model to the period when the harvested portion of the crop was developing provided a consistent relationship in this case, there are likely to be circumstances in which sink limitation will reduce RUE. The period before flowering is particularly important in determining the sink capacity of wheat (Evans & Wardlaw, 1996) and it may be necessary to monitor growth during this earlier period if a crop-based explanation of yield variation is to prove sufficiently robust to support commercial decision-taking. HAD and HAA, as originally defined by Waggoner and Berger (1987), do not take account of ear green area. Diseases other than yellow rust may affect yield by effects on ears (Jones & Odebunmi, 1971).

In conclusion, definition of crop productivity as the product of radiation interception by green leaf tissue and RUE provides a framework for understanding disease induced reductions in yield. The approach described here is not intended for use directly as a practical, predictive tool, but it is envisaged that it will lead to the development of models which may be utilised in crop management decisions.

6.0 CONCLUSIONS

1. Variation in the relationship between disease and yield loss was substantial, across sites and seasons. The evidence suggests that this variation may be nearly as influential in determining response to fungicide treatment, and hence the need for treatment, as the severity of disease.

2. Analysis of associated experiments, on a constant genotype, has shown little relationship between the variation in yield response to disease control and variation in yield potential. This result is counter-intuitive for many crop managers, who feel more justified in applying fungicides to higher yield potential crop, in the expectation that these crops are most likely to provide an economic response to treatment. The work reported here was conducted to understand the mechanisms by which disease affected yield. And from those mechanisms, identify crop traits likely to be associated with high or low response to disease control.

3. The hypothesis that variation in the disease:yield loss relationship was due to variation in the physiological state of the crop, was tested by comparing the effect of disease on yield, against its effect on accumulated light interception (HAA). Predictive ability was substantially improved by this approach; suggesting that most of the effect of disease on the crop could be explained via reduction of green leaf area index, light interception and dry matter accumulation.

4. Practical application of these finding depends on identifying crop traits associated with high or low response to control of unit disease. Two candidate traits are canopy size and capacitance (storage of soluble stem carbohydrate, which can be mobilised for grain filling).

5. The theory described at 3. above, implies that crops with high or very small GLAI canopies will suffer less light interception (and hence yield) loss for a given percentage of leaf area affected by disease. Intermediate canopies will be most affected. However, very small canopies are ineffective at intercepting light, and large canopies are inefficient in their use of nitrogen and more susceptible to biotrophic diseases (rusts and powdery mildew).

6. Any potential benefit from growing a crop with a large canopy in order to 'withstand' disease, is outweighed by increased disease susceptibility. Manipulating nitrogen inputs, to grow crops of a consistently optimal size for light interception, should avoid increased susceptibility to disease and produce crops which respond more predictably to fungicides.

7. The ability to amass soluble stem carbohydrates is known to vary substantially, both between genotypes within a site/season and within a genotype across sites/seasons. Crops with high stem carbohydrates have been shown (in associated experimentation) to be less affected by loss of green area to disease during grain filling. The extent to which the relative capacitance of varieties can be used as a predictor of response to disease control, is being tested as part of the Integrated

Disease Risk programme. Use of site and seasonal variation in capacitance as a component of crop protection decisions depends on the development of rapid measures of stem carbohydrate or information from 'real-time' crop intelligence.

8. There is no evidence from the work presented here, or from concurrent experiments, that *Septoria tritici* or yellow rust epidemics affect the number of fertile shoots. There seems little justification for early season fungicide treatments to encourage shoot survival.

9. The crop canopy expands sufficiently rapidly during the period GS 31 to GS 39 that the most important part of the canopy (that nearest the top and therefore most able to intercept radiation) is less than one latent period old, and therefore unaffected by expressed disease. It has also been shown, in associated experiments, that canopy expansion in not dependant on carbohydrate supply. The combination of these effects suggests that there is little likelihood of early season disease limiting canopy expansion. Fungicide timings can therefore be selected to ensure that the upper three leaves of the canopy are well protected and do not lose green area once canopy expansion has stopped.

10. There was no evidence of disease affecting the radiation use efficiency of green leaf area that was not expressing disease symptoms. The effects of disease on yield could be explained via their effects on green leaf area, although further analysis of the *Septoria tritici* data is required to check for any deleterious effects of latent infections.

11. The green area of the stems and ears makes a substantial contribution to yield, particularly in diseased canopies, where green leaf area has been lost. Fungicide treatment did not increase stem or ear green area in the presence of yellow rust or *Septoria tritici*, but would be expected to do so in the presence of powdery mildew or *Septoria nodorum* (glume blotch).

12. Benefits to green area duration, and hence yield, from late season fungicide treatment are less likely where other factors, such as drought, are limiting.

13. A technique has been developed, validated and the methodology described, to allow measurement of green leaf area index through a rapid and convenient field assessment. It is hoped that this technique will be widely adopted in foliar disease experimentation, where the explanation of the effects of disease or treatment on yield is an objective.

14. The effects of disease on crop function, described here, form the basis of the process model which underlies the prototype Winter Wheat Fungicide Module of DESSAC (Decision Support System for Arable Crops).

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