DECISION SUPPORT TO RATIONALISE WHEAT FUNGICIDE USE

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ABSTRACT

An evaluation of decision models is presented as a precursor to the development of a U.K. decision support system (DSS) for cereal disease control. The systems evaluated included: the Long Ashton 'Splashmeter', the Cereal Diagnostic System, Managed Disease Control and Intergrated Disease Risk. The systems were used to guide fungicide applications to plots in eleven replicated experiments on two wheat cultivatars of differing host resistance. Control of *Septoria tritici* was used as a test case. Data comparing system performance, as quantified by fungicide input, disease control and economic output, are presented in relation to current commercial practice.

INTRODUCTION

The economic pressures of CAP reform will require new knowledge to be effectively exploited in industry practice, in order to reduce the unit cost of cereal production. Rationalising the use of variable inputs such as foliar fungicides could make an important contribution to this process; and in doing so, lessen concern about their real or perceived environmental effects. During the past decade, research on the epidemiology of cereal foliar pathogens has increased understanding of the factors that determine disease progress and of the effects of disease on yield. Similarly, the development of new, more active, fungicides has been accompanied by research to quantify their eradicant and protectant properties, and their interactions with crop and epidemic development (Griffin, 1994).

Several systems have been devised to support cereal disease control decisions. Many of these can claim to have improved the level of technical expertise of those growers and advisers that have used them; but their sustained impact within EU cereal production remains small (Forrer, 1992). A logical precursor to the development of a decision support system (DSS) for UK cereal disease control would be the evaluation of existing decision models and the quantification of potential benefits from their use. This paper describes such work, using the control of *Septoria tritici* - the most economically important UK wheat foliar pathogen - as a test case.

CURRENT EFFICIENCY OF FUNGICIDE USE

The latest published pesticide usage survey data (Davis *et al.*, 1992) showed that 2,794 tonnes of fungicide active ingredient were applied to UK winter wheat in 1992, at a cost in excess of £100m. To evaluate the efficiency of use within this overall figure, data relating product choice, dose and application timing to the level of disease control obtained are needed. The CSL/ADAS cereal disease survey collects data on disease severity and pesticide use from over 300 winter wheat crops each year. In 1993, data on fungicide dose were collected for the first time.

Survey methods

The 1993 winter wheat disease survey was carried out on a random, stratified sample of crops at GS73-75 (Tottman, 1987). The methodology of the surveys has been described by Polley and Thomas (1991). Leaf diseases were assessed at CSL Harpenden, recorded as the percentage laminar area affected on the flag and second leaves, using standard area keys (MAFF, 1976). For comparison with 1993 results from the evaluation of decision model experiments, disease and fungicide use data were extracted from the survey database on varieties Riband (145 samples) and Beaver (31 samples).

Fungicide use

Survey data on fungicide use are summarised in Table 1.

The percentage of crops where all fungicides used were applied at the label recommended doses for the products used, was 6.8% on average. On average, products were applied at 65% of their label dose.

EVALUATION OF DECISION MODELS

The aims of the experiments described here were to: (i) gather epidemiological and meteorological data that will aid the development of current and future DSSs, (ii) measure the performance of current systems in terms of economic output and fungicide input, and (iii) to gain experience in their operation.

Methods

To enable disease control and yield responses to be related, the experiments targeted the main foliar disease of wheat, *S.tritici*. For the multi-disease DSSs (MDC and CDS), only those parts of the system relevant to the target disease were implemented. In the first year (1991/92), three experiments were established on the susceptible cultivar Riband (NIAB *S.tritici* resistance rating 3). In year two (1992/93), four experiments were established, each on two cultivars of differing host resistance to *S.tritici* - Riband and Beaver (NIAB rating 6). Sites were at Bayer Elm Farm Development Station, Suffolk; Long Ashton Research Station, Bristol; Morley Research Centre, Norfolk and (in year two) ADAS Terrington, Norfolk.

TABLE 1. Units† of fungicide use on cvs. Riband and Beaver in 1993

		Maximum*	Mean#	Minimum*
No. of fungicide applications	- R	4	2.15	0.00
	- B	4	2.06	0.00
Fungicide units applied	- R	7.15	2.84	0.00
	- B	7.94	2.83	0.00
Conazole units applied	- R	6.23	1.63	0.00
	- B	4.55	1.65	0.00
Morpholine units applied	- R	2.67	0.47	0.00
	- B	1.74	0.52	0.00
Chlorothalonil units applied	- R	2.17	0.42	0.00
	- B	1.26	0.28	0.00
Dithiocarbamate units applied	- R	1.00	0.06	0.00
	- B	1.00	0.12	0.00
Carbendazim units applied	- R	4.00	0.26	0.00
	- B	1.00	0.26	0.00

R = Riband, B = Beaver; * - on any individual crop; # - mean across all survey samples; † -1 unit = label recommended dose. For the conazoles, dithiocarbamates and carbendazim this was taken to be the label dose where the product is applied alone. For the morpholines and chlorothalonil, which are usually applied in commercial product or tank mixture with a conazole, the label dose was taken to be that recommended when used as a mixture. In some cases the number of conazole units applied exceeded the number of fungicide applications due to the use of conazole mixtures.

Design and treatments

In the first year, experiments were of randomised block design with four replicates. In year two the two cultivars were in adjacent randomised blocks, replicated three times. Statistical analysis was by analysis of variance, with treatment means distinguished by least significant difference (LSD) at the 5% confidence level. Plots were a minimum of 3 m wide and 18 m long. Each treatment received fungicide application/s according to individual need. All spray applications were made in circa 240 litres ha-1 water using flat fan nozzles giving a 'medium' spray quality (as per BCPC definitions), and were of tebuconazole as 'Folicur' at 1 litre commercial product ha-1 (except for IDR treatments where doses were as shown). Treatments were as shown in Table 2 below.

The Bayer Cereal Diagnostic System (CDS) was developed in the eighties by Prof. Hoffman, Dr. Verreet and co-workers at the University of Munich. It forms part of the 'Bavarian wheat growing system' which is run by the Agriculture Department in the State of Bavaria. The system is based on disease threshold values and has now been evaluated in most of the wheat growing areas of the world (Anon. 1991). Managed Disease Control (MDC) was developed by the ADAS Cereal Pathology Group. Decisions on the need for fungicide application are made at a number of key points in crop development, and are based on an assessment of disease, weather criteria, cultivar, time since previous sprays and growth stage. Simplified earlier versions of MDC on winter wheat were published, in flow chart format, as advisory leaflets (Anon. 1986). Updated versions are now maintained as part of the ADAS Cereal Disease Compendium (a computer text-base system). The Long Ashton 'Splashmeter' forms part of a forecasting system to determine the need for, and optimum timing of, fungicide application to control *S.tritici*. The system is based on monitoring rainfall for its ability to transfer spores from the lower to the upper leaves. The energy of rain droplets is measured using a simple 'Splashmeter', which is sited adjacent to the cropping area (Royle, 1990). Prophylactic single- and three-spray treatments were included in the experiment as standards, the former being applied in relation to growth stage and day length (as measured by calendar date), at a timing likely to optimise yield response as determined by ADAS 'wave' experiments. Most of the systems evaluated were developed during a period when fungicides were used predominantly at, or near to, the label recommended dose. There is now a clear move towards flexible use of dose. Whilst this offers potential economic and environmental advantages, it also implies that inappropriate doses may be used; with deleterious effects. One of the DSSs tested was a developmental Integrated Disease Risk (IDR) system (Paveley, 1993). This aims to provide an integrated measure of the risk of disease induced yield loss, which can act as a variable threshold to guide appropriate dose applications. Development of the system awaits data from experiments started in the autumn of 1993.

TABLE 2. Treatments

Treatment no.	Spray criteria
1.	Untreated
2.	ADAS Managed Disease Control (MDC)
3.	Bayer Cereal Diagnostic System (CDS)
4.	LARS Splashmeter - based system
5.	Single spray*
6.	Three spray programme#
7.	Integrated Disease Risk (IDR) developmental system

* - Single spray applied on 20 May or GS 39, whichever was the later; # - Sprays applied at each of GS 32, GS 39 and GS 59.

Data from additional treatments included in these experiments are not presented here.

Treatment decisions

To ensure that system decisions were consistently applied across sites, each site manager contacted an ADAS and Bayer co-ordinator, by fax, each week during the growing season. A spreadsheet of that week's disease assessment and meteorological data enabled the co-ordinators to determine the timing of spray application for their own system. Treatment requests were faxed back to sites by return. Decisions for the LARS 'Splashmeter' system were made each week by site managers after reference to the system guidelines.

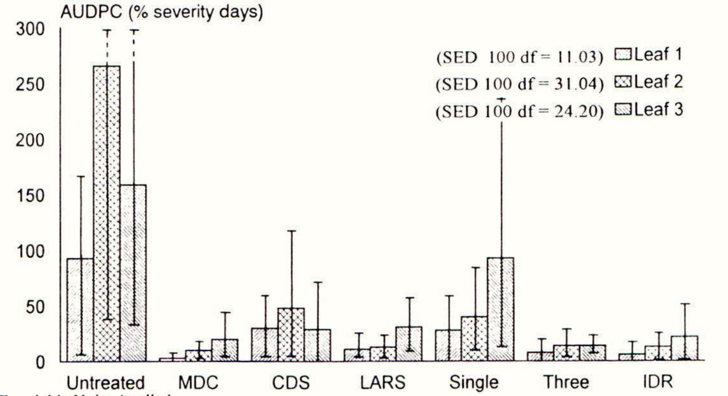
Assessments

Foliar diseases were assessed weekly on each leaf layer of ten randomly selected tillers per plot using standard area keys (MAFF, 1976). All plots were harvested and yield expressed at 85% dry matter.

Results

Rainfall during May and June in 1992 and 1993 produced substantial *S.tritici* epidemics on the upper leaves of both cultivars in untreated plots at most sites. In Figures 1, 2 and 3, damage caused by *S. tritici* is expressed as the area under the disease progress curve (AUDPC) for each of the upper three leaf layers of the crop canopy. AUDPCs provide a useful measure of photosynthetic area lost to disease, as they combine severity of damage with the time period over which it occurred. As a guide, a leaf with an AUDPC of 300 would typically have 15-30% of its area affected by disease prior to senescence. Upper and lower limits shown on each bar in Figures 1, 2 and 3 represent the highest and lowest AUDPCs recorded for each leaf layer of each treatment across the sites; providing a measure of the consistency of diseas control obtained. Those treatments that provided good control of septoria also reduced the rusts and powdery mildew to low levels. Values beneath each figure show the maximum and minimum number of tebuconazole units called for by each of the decision system treatments across the sites, and the mean.

Figure 1. Comparison of *Septoria tritici* control and fungicide inputs on cv. Riband : mean of three sites in 1992
(Upper and lower limits on bars = range of AUDPCs at the three sites)

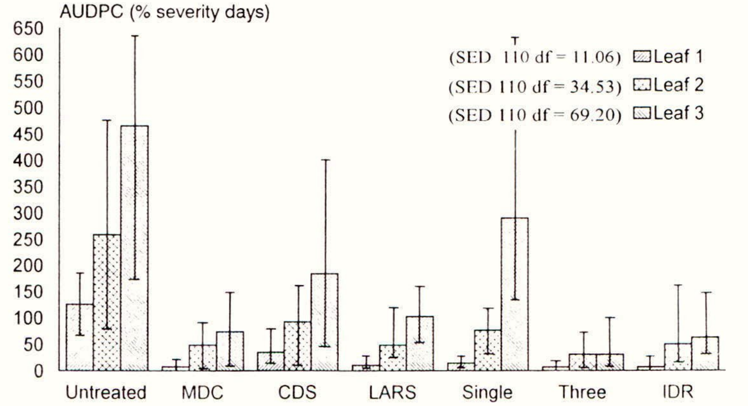


Fungicide Units Applied

	Untreated	MDC	CDS	LARS	Single	Three	IDR
Max.	0	3	2	2	1	3	1.75 (4)*
Mean	0	2.7	1.7	1.7	1	3	1.60 (3.7)
Min.	0	2	1	1	1	3	1.50 (3)

* - Values in brackets = number of spray applications to IDR treatments. For the other systems, number of applications = number of units applied.

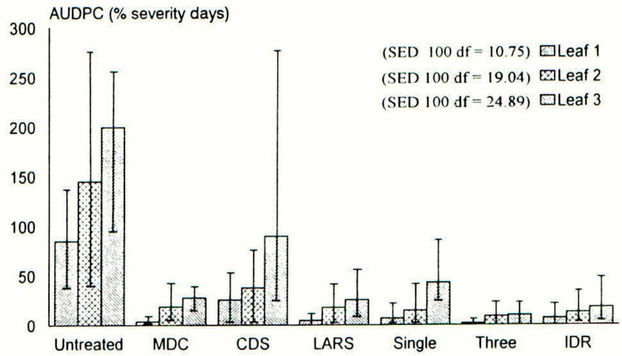
Figure 2. Comparison of *Septoria tritici* control and fungicide inputs on cv. Riband : mean of four sites in 1993
(Upper and lower limits on bars = range of AUDPCs at the four sites)



Fungicide Units Applied

	Untreated	MDC	CDS	LARS	Single	Three	IDR
Max.	0	3	2	2	1	3	1.75 (4)
Mean	0	2.5	1.3	2	1	3	1.60 (3.3)
Min.	0	2	0	2	1	3	1.50 (2)

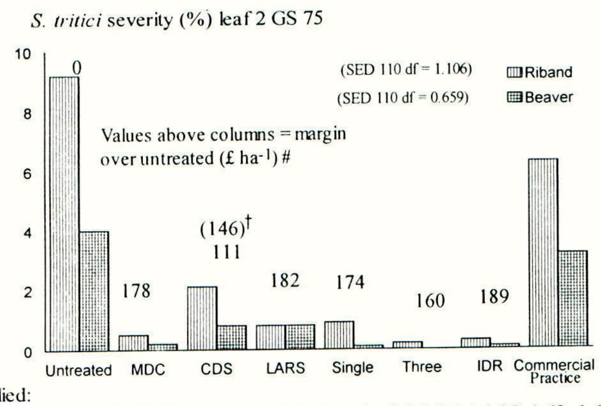
Figure 3 Comparison of *Septoria tritici* control and fungicide inputs on cv. Beaver : mean of four sites in 1993
(Upper and lower limits on bars = range of AUDPCs at the four sites)



Fungicide Units Applied							
Max.	0	2	2	2	1	3	1.25 (3)
Mean	0	2	1	2	1	3	1.25 (3)
Min.	0	2	0	2	1	3	1.25 (3)

To permit comparisons of experimental results against commercial practice, Figure 4 shows 1993 leaf 2, GS 75 *S.tritici* levels, and the fungicide inputs used to achieve them, and data from the cereal disease survey (which measures disease severity on leaves 1 and 2 at GS 75). Economic data meaned across the four experiments on each cv. in 1993 are also presented.

Figure 4. Comparison of *Septoria tritici* control by experimental decision systems* and in commercial practice+ 1993



Units applied:																
Conazole	0.0	0.0	2.5	2.0	1.3	1.0	2.0	2.0	1.0	1.0	3.0	3.0	1.6	1.25	1.63	1.65
Morpholine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.47	0.52
Chlorothalonil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.42	0.28
Dithiocarbamate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.06	0.12
Carbendazim	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.26	0.26

- Value of grain yield response over the untreated, minus fungicide and application costs. Assuming grain value = £95 tonne^{-1}, tebuconazole = £27 ha^{-1} unit^{-1} and application costs £8 ha^{-1} application^{-1}. Mean of four sites for each of the two cultivars in 1993. * - Mean of four sites per cultivar. + - Mean of 145 samples (Riband) and 31 samples (Beaver). † - Margin excluding site 4 in 1993.

DISCUSSION

Commercial practice

The efficiency of fungicide use can be measured by the amount and cost of fungicide input relative to the degree of disease suppression obtained and the value of the associated yield response. In farm practice it is easy to measure input costs, but difficult to quantify the success of disease control and yield protection.

On cv. Riband, and to a lesser extent cv. Beaver, the main foliar disease risk is from *Septoria tritici*. Using *S. tritici* as a test case, the survey results suggest that the level of disease control being obtained in commercial practice is poor in relation to the fungicide inputs being made. The high levels of input to some crops cause concern (five or more fungicide units applied being not uncommon), as do cases of severe disease despite treatment. These latter seem to relate more to poor timing and product choice than to any suggestion of a shift in pathogen sensitivity to fungicides. Despite clear evidence of the economic importance of controlling disease on the upper leaves of the crop canopy, 37% and 23% respectively of the Riband and Beaver crops surveyed received no fungicide application between GS 32 and GS 55.

Decision Support Systems (DSS) evaluation

For a DSS to be attractive to potential users it should offer some tangible benefit over the perceived efficiency of the user's current management policy. One benefit could be to demonstrate that pesticides are used only according to need and in accordance with the principles of integrated crop management. However, unless environmental pressures increase, substantial DSS uptake is unlikely unless financial benefits accrue from use. Decreased costs and/or increased output, leading to accumulated economic benefits over a number of seasons should result from DSS use, but not at the risk of exposure to occasional severe losses (that the farm business might not survive). Hence a DSS should respond appropriately to high and low disease risk situations and should exploit input savings made possible by genetic host resistance. Judged by these criteria in comparison to current commercial practice, all of the decision models evaluated are potentially useful.

Results from the prophylactic single- and three-spray treatments reinforce the practical experience that good disease control can be obtained by applying a fixed number of applications appropriate to the disease susceptibility of the cultivar. However, such prophylactic programmes must consistently over-apply on average, to avoid suffering occasional severe losses in high disease risk situations. Both the Managed Disease Control (MDC) and LARS Splashmeter systems provided consistent good control. Comparing the former to the latter suggests that, using tebuconazole as the test fungicide, the MDC system tended to apply more material than required. In the form tested the Splashmeter system applied the same inputs to Riband and Beaver within each site; suggesting scope for inclusion of a varietal component in the decision process, other than that currently provided via an assessment of inoculum level at GS 30. The Cereal Diagnostic System (CDS) was the only system based on the use of disease thresholds (measured by incidence on indicator leaf layers) to determine the need for treatment. In general, a spray was indicated around GS 37-39 with a second application, at some sites, around GS 59. At site four in 1993, the incidence thresholds were missed by a small margin in a season when the disease subsequently became severe. Such an occurrence would be less likely with assessors more experienced in the use of the system, or making routine use of a binocular microscope to assess the presence or absence of infection. The Integrated Disease Risk (IDR) system used measures of inoculum and weather conduciveness to epidemic development from the CDS, MDC and Splashmeter systems. These were combined with measures of host resistance and sensitivity of the crop to disease induced loss of green leaf area. The system worked in a consistent manner, although the number of applications was typically one more than the number required with 'conventional' full dose systems. As over 90% of UK winter wheat crops currently receive fungicides at reduced doses, it seems logical that a DSS should guide inputs to make the dose used appropriate to the disease risk.

Conclusions

Direct comparisons between results from systems experiments and commercial practice need to be made with caution, due to the different fungicides used, the subjective nature of disease assessment (albeit using standardised keys) and the ability of experimental sites to represent the disease risk experienced across the country. Nevertheless, it seems reasonable to conclude that, given appropriate decision support, substantially better disease control could be obtained from the level of inputs currently being used, or equivalent control could be obtained from substantially lower inputs.

Work is underway to develop delivery of wheat disease control decision support, in a form that recognises the costs of time spent monitoring crops, and the logistical limitations within which fungicides are used. In this regard much can be learned from experiences with other crop protection DSSs (Secher *et al.*, 1993) within the EU.

ACKNOWLEDGEMENTS

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STRATEGIES FOR OPTIMAL FUNGICIDE USE IN LESS-INTENSIVE CEREAL GROWING SYSTEMS

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ABSTRACT

The implementation of disease control strategies in less-intensive arable production systems must be built upon the exploitation of beneficial effects of crop management practices that minimise the risk of disease becoming sufficiently severe to justify routine sprays and, thereby, offer greater flexibility in disease control. A carefully selected crop rotation, combined with cultivar resistance and rational manipulation of crop structure by adjustments in sowing date, nitrogen amounts and timing, have decreased the rate of disease development and severity of attack on wheat, barley and oats with a consequent reduction in fungicide requirement for cost-effective control.

Using data on the inherent properties of fungicides that underlie their activity against a range of cereal diseases, permitted exploitation of the most appropriate fungicide and dose in order to interrupt cyclic regeneration of pathogens and/or protect the topmost two leaves until the end of grain filling. Intervention decisions were either targeted to "scaled-up" disease thresholds or nitrogen-induced crop disease response. The decision models thus employed have given satisfactory and cost-effective disease control over the past three years, with significant reductions being achieved in both the number of treatments and the amounts of active ingredient/ha applied.

INTRODUCTION

Since the mid-1970 s and, until recently, arable crops have been grown under increasingly intensive management regimes, mainly in response to changes in agricultural policy and the consequent introduction of new technology. Plant breeders have provided new cultivars with higher yield potential, which was realised when crops were sown earlier and grown with increased fertiliser use. In such systems, the carry-over of inoculum from crop to crop is largely influenced by the number and sequence of susceptible crops in the rotations. Thus, many of these changes have increased infection frequency and severity of attack and, as a consequence, increased the fungicide requirement for control.

Although several fungal diseases can infect cereal crops throughout the year, many of them only exert a major constraint to yield and quality at specific periods during crop growth and development. On wheat and barley, foliar diseases are only constraints to yield at very early stages in crop establishment prior to tillering (Brooks, 1972; Jordan *et al.*, 1985), or from late-spring onwards when either singly or collectively, they can cause loss of green leaf tissue on the topmost leaves, and affect ears, impairing both grain yield and quality. Nevertheless, various strategies have been adopted for control, based upon data generated from many fungicide trials done under intensive crop management systems, where disease control is directed towards economically justified maximum yield responses, and reliant upon comprehensive spray programmes. These approaches have led to routine prophylactic sprays, or managed disease control programmes, or sprays targeted to specific risks, with a wide range in frequency of applications. As a consequence, over 90% of winter cereals in the UK were treated with fungicides, with 34% of winter barley crops receiving two or more sprays, and 24% of wheat crops receiving between three and seven fungicide sprays annually (Polley, 1991). These strategies involved applications for selective or collective control of stem, leaf and ear diseases at pre-determined stages of plant growth, and gave a range of cost-effective control responses. As epidemics differ from year to year, these growth stage-orientated treatments were randomly timed and, thus, only randomly successful. Expert systems, that support decision making in a single crop, are reliant upon correct disease recognition. However, some diseases, such as Septoria, are often diagnosed incorrectly (Smith & Webster, 1986); thus, some treatments may be unnecessary and economically unsound. Threshold values developed for wheat control in Germany, based on integrating pathogen population dynamics, agronomy and environmental parameters (Verreet & Hoffmann, 1990) have been successfully implemented. Recent attempts to lower fungicide inputs in cereal crops have aimed at decreasing the number of treatments and/or amounts of active ingredient applied, mainly by modifying treatments against specific diseases in crops grown under conventional intensive management. This has been done by utilising the inherent biological activities of fungicides in order to improve timing and control response (Jordan *et al.*, 1986; 1988; 1991), or by using reduced dose fungicide programmes (Wale, 1992).

Information is presented on optimal fungicide use in less-intensive crop management systems where the primary consideration for disease control is the placement of specific crops in rotations to reduce the disease carry-over and infection frequency. This, combined with integration of cultivar resistance, crop establishment, sowing date and balanced nutrient supply, can reduce the risk of disease becoming sufficiently severe to justify routine sprays, and offer greater flexibility in disease control options. These strategies have been successfully used in the LIFE project during the past five years (Hutcheon & Jordan, 1994).

INFLUENCE OF CROP MANAGEMENT ON DISEASE

Within integrated farming systems research at Long Ashton, the LIFE project compares, conventional systems of production to achieve optimal yields and maximise profits, with less-intensive systems managed under integrated production guidelines (El Titi *et al.*, 1993).

For conventional first and second wheats, barley and oat crops, cultivars with high yield potential are sown in September, and given optimal nitrogen supply as an early dressing in February (40 kgN/ha) with the balance applied at stem extension. In such crops, powdery mildew, eyespot (wheat and barley), *Septoria* spp.(wheat), *Rhynchosporium*, net blotch (barley) and mildew, crown rust (oats), frequently prevail and collectively are sufficiently severe to justify annual managed disease control programmes. By comparison, the less-intensive systems are designed around a multi-functional crop rotation involving placement of specific disease-resistant crops in cropping sequences, whereby only "first wheats" are grown and the use of profitable break crops optimised. This has lowered potential carry over of soil-borne, trash-borne and splash-dispersed diseases from crop to crop. In addition, delaying sowing dates until mid-October reduced the incidence of foliar diseases, which together with judicious use and modified timing of applied nitrogen, influenced canopy structure and leaf susceptibility sufficiently to reduce the progress and severity of foliar diseases and allow minimum fungicide use. Disease progress curves in each production system are shown in Figure 1, and data from monitoring inoculum potential of *Septoria* spp. during early spring are shown in Table 1.

Fig.1 Disease progress (Septoria) in Conventional and Less Intensive Systems

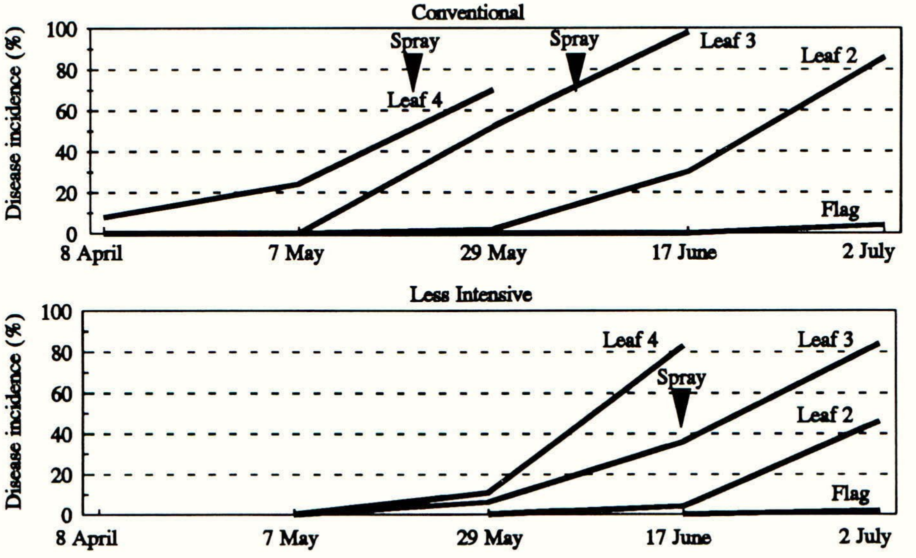


TABLE 1. Inoculum potential of *S. tritici(St)* and *S. nodorum(Sn)* (spores/tiller x 1000) in wheat systems, 1992-1994.

		Conventional wheat			Less-intensive wheat		
		1992	1993	1994	1992	1993	1994
Jan	-*St*	100.8	374.2	74.6	45.5	75.6	13.4
	-*Sn*		39.6	16.4		8.2	0.4
Feb	-*St*	4026.4	568.5	917.0	255.7	257.6	86.3
	-*Sn*		51.5	18.4		31.9	0.7
Mar	-*St*	519.8	752.9	591.6	637.1	297.2	354.0
	-*Sn*	254.5	84.7	78.8	103.5	47.4	54.8
Apr	-*St*	293.6	331.2	1194.3	303.5	54.3	542.4
	-*Sn*	100.8	15.8	99.1	80.4	9.7	64.5

DISEASE CONTROL IN LESS-INTENSIVE WHEAT SYSTEMS

Manipulation of crop management and husbandry practices in less intensive wheat systems, minimises disease at early stages of crop development and allows fungicide use to focus on protecting the topmost leaves from flag leaf emergence until the end of grain filling. In such systems, powdery mildew and rusts are adequately contained by cultivar resistance occasionally supplemented by a morpholine fungicide. The main disease threat, however, is *Septoria* as it occurs regularly and severely in the mild wet climate of south-west England. Cultivar resistance in quality wheats is currently insufficient to prevent epidemic development in some years. Previous research (Jordan *et al.*, 1986), on biological properties of triazole fungicides against phases of disease cycles of *Septoria* spp. identified potential curative ("kick-back") activity that provides opportunities for modifying disease progress that can be used in decision making. Further research was therefore done on more recently introduced fungicides, to determine their relative effectiveness against *Septoria* spp.

Cyproconazole, flusilazole, flutriafol, and tebuconazole were evaluated for control of *S. tritici* when applied at manufacturers' recommended rate, 3/4 rate, ½ rate, or ¼ rate, to wheat plants inoculated with 50,000 spores/ml 7, 14 or 21 days after spray application, or to wheat plants 7, 14 or 21 days after inoculation. Disease symptoms were first observed on untreated plants 29 days post inoculation, with incidence and severity measured on all plants at weekly intervals thereafter.

When evaluated as protectants, symptoms failed to develop on any sprayed plants that were inoculated 21 days after application, and observed for a further 35 days until leaf senescence. When fungicides were applied 7 days after infection, all four fungicides prevented symptom development for 56 days, irrespective of concentration. When applied 14 days after infection, all fungicides prevented disease at manufacturers' recommended rates, but cyproconazole and tebuconazole also prevented symptom development at lower concentrations. When applied 21 days after infection, none of the fungicides prevented symptom expression at any concentration, but only tebuconazole reduced the severity of attack for a further 21 days (Fig. 2).

Thresholds/timing in relation to crop morphology

There is no scientific evidence to show that foliar disease is a constraint to yield from stem extension (GS 30) up to flag leaf emergence (GS 37). Therefore, fungicide intervention during this period appears inappropriate and is not considered in less-intensive wheat systems. The following strategy has been developed to provide cost-effective disease control. In order to minimise disease-induced yield loss, it is necessary to protect the flag leaf and leaf 2 until the end of grain filling. Data on wheat morphology in the UK (Porter *et al.*, 1987), has shown that the period from anthesis until the end of grain filling requires 650 day degrees which, averaged over the past 10 years at Long Ashton equates to 45 days. Similarly the accumulated day degree requirement from flag leaf fully emerged (GS39) to anthesis equates to 16 days. This indicates that a 60-day period of disease protection is required from flag leaf fully emerged to minimise disease-induced yield loss. As the optimum regeneration time for *S. tritici* in field crops is 21 days (Royle *et al.*, 1986; Verreet & Hoffman, 1990), protection of the topmost leaves is only required from emergence until 21 days before the end of grain filling. In other words, infection and/or cyclic regeneration of *S. tritici* needs to be prevented for a period of 40 days from emergence. The recommended rates of triazole fungicides evaluated in this study have this capability, thereby justifying a single application at GS 39 where disease risk warrants treatment. However, what additional options are available for disease control, and for dose reductions when crops are not at risk at this stage of crop development, and how may they be effected? Currently, disease control strategies are targeted to pre-determined stages in crop development with dose reductions made as considered appropriate. However, as triazole fungicides have a minimum curative period of 10 - 14 days, then, providing that the time of infection can be correctly identified, applications can be delayed accordingly. New research in disease forecasting and the use of "diagnostic kits" are likely to provide greater precision in this decision making process, as optimal exploitation of these fungicidal properties is dependent upon knowing precisely when leaf 2 becomes infected. However, in the absence of this information, biologically-based disease threshold decisions have provided acceptable control in conventional wheat systems (Verreet & Hoffman, 1990). Using data extrapolated from this research, the following threshold-based system has been developed and successfully tested in less-intensive wheat systems within the LIFE project and on commercial "Pilot Farms" in south west England.

Foliar diseases are identified and their progress monitored during the growing period, to determine the potential disease threat. From GS 37 onwards, leaf 3 (flag leaf - 2) is the indicator leaf for fungicide intervention. In each crop, 300 leaves are collected at random from a "W" pattern within the crop and the diseased area (%) estimated on each leaf. When the mean value exceeds 2% leaf-area-diseased, then a fungicide spray is required, with choice based upon disease(s) prevalence. If this threshold is met at GS 39, the fungicide is applied at the manufacturers' recommended rate. If not, this process is repeated at 7-day intervals thereafter, with the threshold and indicator leaf remaining the same. When the threshold is reached (at later stages in crop development), fungicide dose rate is adjusted on a sliding scale according to the inherent fungicide property and accumulated day degree data, in order to provide sufficient protection until the end of grain filling. This strategy has been developed for *S. tritici*, but it needs some modification should *S. nodorum* be the prevalent pathogen. In such situations, leaf 3 remains the response indicator leaf but, because of the relatively shorter latent period, and relative differences in fungicide performance, only flusilazole or tebuconazole are considered to possess the biological activity necessary for implementation of the threshold-based model. Both compounds need to be applied at full rate if the spray decision is made prior to anthesis. Thereafter, cost-effective control responses from dose reductions with these, and the other fungicides evaluated, have been inconsistent.

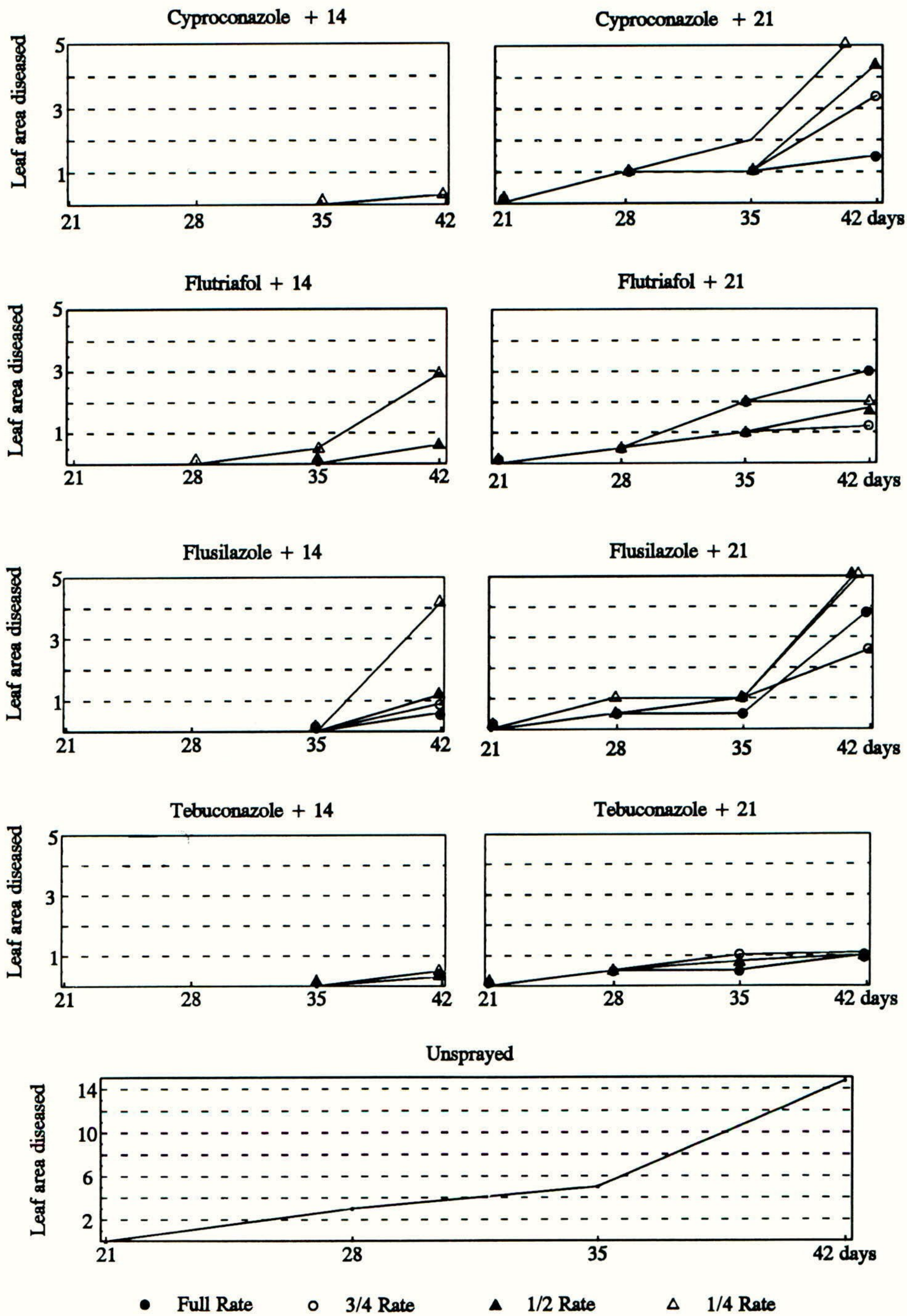
The threshold decision models employed, have been evaluated and have given satisfactory and cost-effective disease control in wheat crops grown under less-intensive management, within the integrated farming systems "LIFE" project during the past five years (Hutcheon & Jordan, 1994). Significant reductions have been achieved in both the number of fungicide treatments, and the amounts of fungicide active ingredient/ha applied (Table 2).

DISEASE CONTROL IN BARLEY AND OATS

Over the past ten years, successful and consistent disease control in winter barley has been achieved, irrespective of production system. The strategy adopted has been based upon data generated from research that exploited knowledge of the interactions between nitrogen timing, crop canopy structure and disease development, coupled with the use of properties of specific fungicides (Jordan & Stinchcombe, 1985; Jordan *et al.*, 1991).

In winter oats, crown rust is the main disease threat to yield, especially in the mild, wet climate of south-west England, and requires intervention at the onset of symptoms for effective managed disease control. However, in 1993, crown rust reached epidemic levels on conventionally-grown winter oat crops in Cornwall, and was only partially controlled by

Fig.2 Fungicide timing in relation to symptom expression of *S. tritici*



routine fungicide programmes. By comparison, on "less-intensive" winter oats grown in adjacent fields, delaying the main nitrogen top dressing until May not only influenced crop growth and canopy development but also reduced disease incidence and severity. In these less-intensive oat crops, triadimenol + tridemorph applied at half the recommended rate at symptom appearance (27 May), gave a 28-day period of disease control, but was insufficient to protect the crop until end of grain filling. However, a further half-rate spray, applied on 24 June 1993, gave effective control until harvest with a considerably lower fungicide input than the adjacent conventional crops. During the past five years, with the exception of the Cornish farm in 1993, a single reduced rate fungicide treatment has given effective control of both crown rust and powdery mildew. Where powdery mildew was the only target disease, spray intervention was based upon the same threshold criteria as described above for wheat.

TABLE 2 Fungicide inputs (kgAI/ha) used in the LIFE systems comparisons 1990 - 1992. (SFP = Standard farm practice, LI = Less intensive)

	Average fungicide input (kgAI/ha)			
Production System	1990	1991	1992	Overall
Conventional/SFP	1.29	1.23	1.33	1.29
Conventional/LI	0.19	0.26	0.30	0.25
Integrated/SFP	1.59	1.85	1.75	1.73
Integrated/LI	0.26	0.23	0.34	0.28

DISCUSSION

Whilst optimal disease control strategies in conventional cereal production systems have been directed towards economically justified maximum yield responses, they currently involve either arbitrary dose reductions targeted to stages in crop development, or are based upon rational fungicide use targeted using prediction and forecasting schemes against specific diseases. Such strategies pay little attention to utilising interactions of potentially beneficial husbandry factors that decrease disease.

Strategies for disease control in less-intensive cereal production systems are based on minimising the risks of disease becoming sufficiently severe to justify intervention, through exploitation of the variability resulting from changing areas of crops, the positioning of crops in cropping sequences and natural regulatory mechanisms. The aim should be to achieve the minimum fungicide use required to provide adequate control in order to limit disease-induced yield loss, and to strike the optimum balance between cultivar, disease risk, methods of chemical and biological control and crop management practices. This has been achieved through an integrated farming systems approach to crop production within the Long Ashton LIFE programme, where the effective use and manipulation of crop husbandry practices has decreased disease sufficiently to make routine fungicide treatments inappropriate for cost-effective control. The use of the aforementioned strategies for disease control in these less-intensive cereal production systems has proved successful during the past five years and, by comparison with disease control strategies in conventional production systems, has resulted in >80% reduction in fungicide use.

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REDUCED FUNGICIDE DOSES FOR CEREALS - A PRACTICAL PERSPECTIVE ON THEIR USE

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ABSTRACT

Effective disease control is possible in cereals with considerable reductions in total fungicide dose. The maximum reduction is only possible if timing is optimal and careful consideration is given to factors that influence the success of reduced fungicide use. Whilst some reduction in fungicide dose is possible in many situations, the practicalities of cereal production mean that timing and other factors are frequently not optimal and thus maximum reductions are not achieved. The influence of farming practice on use of reduced doses is discussed.

INTRODUCTION

Some growers have been using fungicides below the full dose recommended by manufacturers for many years. However, during the 1970's and early 1980's when grain prices were high and maximum yield was the target, there was little incentive to reduce dose. As the industry moved away from production subsidies, more attention was given to inputs such as fungicide timing and dose. Recent CAP reforms pushing market prices in the EU down have continued this process and forced growers to study their inputs further.

Using a reduced fungicide dose represents an increased risk and distinguishing the situations where doses can be safely reduced is a challenge (Finney, 1993). Thus, a greater level of management and technical expertise is required to select the dose appropriate to the disease risk that will give adequate and cost effective control.

In 1985, in the north of Scotland, trials were initiated by SAC into the control of spring barley diseases using reduced fungicide doses (Wale, 1990). The main disease was powdery mildew and the results indicated that low dose morpholine and triazole mixtures could control the disease as effectively as full dose morpholine fungicides and thereby increase profitability. An important element that emerged from these early trials was that timing was crucial if the use of reduced doses was to succeed. After further studies, funded by the Home-Grown Cereals Authority, a threshold approach for accurate timing was adopted (Wale, 1993; Wale *et al*, 1993).

From 1990 to 1992, studies on reduced doses extended to winter wheat. Due to its complex of diseases and longer growing season, however, the use of a simple threshold approach similar to that for spring barley was inadequate. Trials during this period established that profitability could be sustained when using reduced rather than full doses at standard timings even on disease susceptible varieties (Wale & Oxley, 1992).

That accurate timing is essential to achieve disease control at the lowest dose possible is well understood. In the case of yellow rust of wheat, Paveley & Lockley (1993) showed that even a quarter dose of a triazole fungicide applied protectively at the time of emergence of a leaf layer gave an extremely high level of control of the disease. Used protectively, the fungicide dose response curve was very flat. For *S. tritici*, control improved with increasing dose although a reduced dose applied at the time of leaf emergence or when spores were splashed up to a leaf layer was as effective as a full dose. A half dose applied at the optimal time generally gave equivalent or better control than a full dose applied 7-14 days too early or too late. In artificially inoculated trials, work by Jorgensen (1991) supported this finding.

There is sufficient information now to suggest that given careful management, accurate timing and careful selection of fungicide, considerable reductions in total dose applied can be achieved. There are, however, practical considerations that restrict many growers from achieving the minimum total dose possible. The purpose of this paper is to discuss some practicalities of cereal production that influence the use of reduced fungicide doses. The comments are based on both trial results and practical advisory experience in northern Britain. Thus they have a largely Scottish perspective but many of the points will be relevant elsewhere in the UK.

FACTORS INVOLVED IN THE USE OF APPROPRIATE FUNGICIDE DOSES

When a decision is taken on whether a fungicide application is required, which fungicide to apply and the appropriate dose, the decision taker is considering (consciously or unconsciously) a large number of factors. In essence he/she is acting like a systems analyst. Paveley (1993), has listed some of the factors involved in evaluating the magnitude of disease induced yield loss and thus dose selection. These and others are listed in Table 1.

Some of these factors are relatively easy to measure, some rely on local knowledge and for some the necessary information is not available and best estimates are required. The occurrence of disease in a crop is fundamental to decision making on fungicide use. Experience would indicate that assessments of severity are less objective than incidence of disease. Thus the threshold to trigger an application for mildew in spring barley has been established at 75% of plants showing infection (Wale *et al*, 1993). Accurate identification of disease is essential and while mildew is easy to diagnose, there are a number of symptoms which to the untrained eye could be confused with disease (e.g. pollen scorch and *S. tritici*).

Factors such as distribution of virulence genes and occurrence of insensitivity to fungicides in local pathogen populations are often unknown. Similarly, the relative performance of fungicides at different doses has not been evaluated and in the absence of trial data, experience is used to compare products.

Disease resistance ratings (Anon., 1994) are indicators of disease risk based on historic data from variety trials and inoculated tests. They summarise in a single figure the likely severity of infection by a disease when conditions are favourable and compatible races are present. The figure combines the effect of race specific and race non-specific resistance but cannot indicate how tolerant of disease a variety is. The emergence and build up of a new race

TABLE 1. Factors involved in selecting appropriate fungicide doses.

Factor	Description
Inoculum	Accurate identification of disease
	Incidence and/or severity of diseases within crop
	Presence of disease in locality
	Previous crop
Cultivar resistance	Race specific
	Race non-specific
	Tolerance
	Distribution of virulence genes
Climatic factors	External temperature, humidity & rainfall
(historic & predicted)	Canopy microclimate
Crop sensitivity	Developmental growth stage
Yield potential	Leaf area index and dry matter accumulation
	Incident radiation
	Canopy structure
	Crop nutrition
	Soil moisture content
	Date of sowing
Fungicide	Protectant/curative activity
	Persistence
	Time from last treatment
	Occurrence of insensitive strains
Frequency of crop inspection	
Management inputs	Time to spray crop
	Time to respond to spray decision
	Relative importance of crop protection treatments
	Cost of application
	Importance of other farm activities

that can overcome race specific resistance can have a major impact on the success of reduced doses.

TIMING

Despite good intentions, optimal timing is not always possible. Where sub-optimal timing is enforced, fungicide doses cannot be the lowest possible. There are a number of possible reasons why this can occur:

difficulty in ascertaining the optimum timing; lack of suitable weather for spraying;
compromises in: cereal inputs and whole farm management;
need to keep fixed costs to a minimum

Difficulties in determining the optimum timing

Determining the optimum time for fungicide application is difficult for diseases that exhibit a long latent period such as *S. tritici* and *Rhynchosporium secalis*. For both these diseases, when crop sensitivity to infection is high, it is crucial to apply fungicides early in the latent period. It is difficult, however, for growers to establish when infection has occurred. For example in two trials in Scotland in 1993, application of a fungicide at GS 33 gave more effective control of *S. tritici* than at GS 32 (Table 2). At present the use of rainfall criteria is the main way in which spray timings are judged. The trials illustrated in Table 2 took place in a season when there were few days when rain did not fall. Growers who applied a fungicide at GS 32 would have considered that their timing was good and that a subsequent application at GS 39 would protect the flag leaf and eradicate any infection on leaf 2. Few growers would have considered an additional treatment at GS 33 or would have realised that delaying the GS 32 application to GS 33 would have been more beneficial in a continuously wet season.

Lack of suitable weather for spraying

Crop spraying should only take place when weather conditions provide a reasonable expectation of even and economic application to the target and when safety to nearby non-target crops is ensured. Unfortunately, the variable nature of the climate in the UK often results in delays to spraying operations or spraying has to be extended over a number of days. The use of low ground pressure tyres, air assisted sprayers and a willingness of operators to spray early or late in the day does improve the chance of achieving optimum timing. Unfortunately, Scotland seems to have fewer spray occasions than elsewhere in the UK (Spackman, 1983).

Compromises in cereal inputs

Fungicides are only one input in cereal production. To minimise sprayer passes, growers have to consider not just fungicides but other inputs: herbicides, growth regulators, insecticides and micro-nutrients. When a spray application is being considered, several inputs may be applied at the same time. A decision will be made about which is the most important input and the treatment will be optimised for that input. Other components of the tank mix could well be applied sub-optimally or inputs included for convenience. For example, in winter wheat, GS 30/31 is the best single timing for a chlormequat application to reduce stem height and lodging risk. Growers attempting to minimise sprayer passes opt to include a fungicide at this time. However, whilst GS 31 has been a traditional timing for fungicides in the past, GS 32 is now considered more appropriate for the control of foliar diseases as, at this growth stage, leaf 3 (flag leaf = 1) is emerging and this is an important leaf contributing to yield and is worth protecting. Another approach is to split the chlormequat between mid-tillering/GS30 and GS 32. In this way a fungicide can be applied at either growth stage but it requires two sprayer passes. In a similar way, on winter barley, growth regulators are applied frequently between GS 32 and 49 to reduce lodging risk in Scotland. A fungicide is often included at this timing, although the need for the fungicide may be assumed rather than based on disease criteria.

TABLE 2. Effect of time and dose of fungicide application on yield, disease (leaf 2) and margin over cost (m/c) in two wheat trials. Cv. Riband 1993, Edinburgh and Aberdeen.

Treatment - dose and timing*				SAC-Edinburgh			SAC-Aberdeen		
GS32	GS33	GS39	GS59	Yield (t/ha)	S trit. GS71	m/c** (£)	Yield (t/ha)	S trit. GS71	m/c** (£)
-	-	-	-	6.30	21.7	-	4.15	31.6	-
0.5	-	0.5	0.5	8.72	2.0	168	5.96	10.5	111
-	0.5	0.5	0.5	9.30	0.4	224	6.49	3.8	161
-	0.25	0.5	0.5	9.12	0.7	214	6.48	5.8	168
-	0.5	0.75	0.5	9.21	1.3	207	6.61	2.1	165
1	-	1	1	9.50	0.1	196	6.57	2.2	122
			SED	0.287	1.69	-	0.269	2.93	-

* Fungicide was tebuconazole (trade name Folicur). Full dose (1 l/ha) costed at £31/litre
** Assumes value of grain = £95/t and cost of application £5/ha

Compromises in whole farm management

Farming is a continuous series of compromises and whole farm management impinges on whether fungicides are or are not applied at the optimal timing. Dedicated arable growers have the greatest opportunity to achieve optimal timing. For mixed stock and arable farmers, priorities will vary according to the needs and profitability of each enterprise at any particular time. For example, silage making is crucial to successful beef production and when the grass is ready for cutting and ensiling, this labour intensive operation could take precedence over a fungicide application.

Need to keep fixed costs to a minimum

One consequence of recent CAP reforms has been a re-evaluation of fixed as well as variable farm costs. If growers have reduced their fixed costs by, for example, reducing their work force or choosing to use a machinery ring for spraying, the opportunity for optimal timing may be less.

Approaches to timing

Currently, several approaches to fungicide timing in winter cereals can be identified. A 'little and often' approach can work well but requires more passes of the sprayer. Whilst very low doses are frequently applied in this approach, the fungicides are being used prophylactically in the main. Further savings might be achieved by making a risk analysis at each potential timing and omitting one or two applications where the risk is low. Another approach is to apply a single full dose at the most critical timing. This approach is only suitable for highly resistant cultivars and is inappropriate if the disease pressure is high or continuous. Most growers, however, adopt two or three standard timings for practical reasons and adjust the dose according to the perceived disease risk.

YIELD POTENTIAL AND YIELD RESPONSES

In determining the appropriate fungicide dose for any growth stage, the crop sensitivity or likely yield response must be estimated to calculate the cost-effectiveness of the action. The yield response will depend on the yield potential of the crop, the lower the yield potential, the smaller the response. Yield potential is not easy to gauge. Certainly growers can use historical farm yield data if they have it, tempered by a knowledge of sowing date, winter survival etc. Frequently it is the weather after all fungicide treatments have been applied that has a major influence on final yield and this cannot be predicted.

In the north of Britain, because of a cooler climate, a long grain filling and ripening phase occurs in wheat. Thus the retention of green tissue is crucial to high yield. Consequently the control of ear diseases and maximum prolongation of green leaf area after ear emergence is required. Early studies (Munro & Wale, 1987) demonstrated that GS 59 fungicide treatments were important in most seasons in Scotland. Table 3 shows the average yields for seven sites throughout the UK in two recent seasons from five standard fungicide programmes alongside the yields for the most northerly site at Aberdeen only. Levels of *S. tritici* at the Aberdeen site were either similar to or less than that at other sites. In the two years, yield responses at Aberdeen to the GS 59 treatment were always greater than the other sites which were all in the southern half of England. Thus there are likely to be regional differences in the most appropriate fungicide dose and product choice for any given situation around the country.

TABLE 3. Effect of one, two and three spray fungicide programmes on yield (t/ha). SAC-Aberdeen and mean of seven sites. Cv. Riband.

Treatment (GS)			1991		1992	
32	39	59	SAC-Abdn only	All sites	SAC-Abdn only	All sites
-	-	-	6.14	7.36	5.79	7.41
-	+	-	8.08	8.52	7.00	8.50
-	+	+	9.43	9.31	8.21	9.00
+	+	-	8.54	8.95	8.55	9.09
+	+	+	10.25	9.83	9.10	9.27
		SED±	0.423	0.089	0.338	0.098
Av. yield response to GS59 treatment			1.53	0.84	0.88	0.34
Av. % yield response to GS59 treatment			18.4	9.6	11.9	4.0

Fungicides applied:
GS 32 prochloraz (Sportak 45 - 0.9 l/ha) + fenpropimorph (Corbel - 0.75 l/ha)
GS 39 triadimenol + tridemorph (Dorin - 1.0 l/ha) + chlorothalonil (Bravo 500 - 2.0 l/ha)
GS 59 propiconazole (Radar - 0.5 l/ha) + fenpropidin (Patrol - 0.75 l/ha)

CONCLUSIONS

The way in which the most appropriate dose for a particular situation is selected is not yet a precise science. However, from the data accumulated so far it seems that growers can reduce fungicide dose to some extent on the majority of occasions. For the few who are able to monitor crops regularly, who have a strong technical background and who are able to apply fungicides close to the optimum time, it seems that fungicide dose can be often reduced dramatically with concomitant increase in profitability. However, it may be the expectation of some growers that dose can be cut with impunity on every occasion. There is a danger in this belief.

If there is a continuing pressure on cereal inputs then it could be that in the future many growers will need to alter their approach to disease control and take a more responsive approach to spraying. This might result in some seasons in more passes through the crop with consequent cost implications.

Whichever way a cereal crop is managed there is a need for a Decision Support System (DSS) to assist in deciding whether a fungicide is required and what is the most appropriate dose. One system proposed in the UK for disease control in wheat is the Integrated Disease Risk Strategy (IDR) (Paveley, 1993). This is a quantitative system designed to give a single numerical value that represents the risk of disease induced yield loss for each of the four major foliar diseases of wheat. The four variables used to derive the numerical values are: inoculum, host resistance, weather conduciveness and crop sensitivity. Whether other variables can be incorporated into the system to improve reliability remains to be seen. IDR joins a number of other DSS's using appropriate doses, most notable and advanced of which is PC-Plant Protection, established in Denmark (Murali, 1991). DSS's need to be relatively straightforward. They must be sufficiently flexible to cope with diverse management approaches to disease control and the possibility that timing may not be optimal. Any Crop monitoring required should not be labour intensive but must provide data of sufficient accuracy to allow correct decisions to be made. A DSS should be robust enough to ensure a high probability of success and DSS's need to be able to take regional differences into account. From trial data currently available in the UK, probably the best that any DSS for winter cereals can give is a guide to the dose required. A greater technical understanding will be required before precise recommendations on fungicide dose can be given.

Trials investigating appropriate fungicide doses frequently identify the benefits in yield and quality terms. This is not sufficient if growers are to judge the effectiveness of treatments in financial terms. The translation of trials into meaningful cost and profit terms is not straightforward due to the variation in input costs, application costs and returns from producer to producer. Average prices are usually used to interpret trial results but ideally in any decision support system, the growers own costs should be included as far as possible. To make decisions the average response from trials is used but the range of responses, the standard error of response or the probability of response would also help decision making.

Whilst dose response curves and interaction of dose with cultivar disease resistance rating has been studied intensively elsewhere in Europe as a basis for DSS's, in the UK such studies are only in their infancy, particularly for winter cereals. More information is also required on disease/weather relationships to establish the criteria that influence disease development. The paucity of synoptic weather stations in parts of the UK and the locality of certain types of weather (e.g. showers, thunderstorms) mean that in the future on-farm met stations may be required to fully incorporate weather criteria into a DSS on a farm by farm basis.

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DURATION OF EFFECT OF EBI-FUNGICIDES WHEN USING REDUCED RATES IN CEREALS

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ABSTRACT

Trials have been carried out in the glasshouse, under semi-field conditions and in field trials in order to investigate the duration of biological effect when using reduced rates of fungicides. In a glasshouse trial using artificial inoculation with *Puccinia striiformis*, triadimenol gave 100% control for more than 17 days. After 14 days a slight dose response was seen for this product. Fenpropimorph showed a clear dose response after 7 days and generally a lower effect on yellow rust. In a semi-field trial using artificial inoculation of *Septoria nodorum* full rate of the co-formulation propiconazole + fenpropimorph gave 85% control when measured 24 days after application. 12.5% of normal rate gave 48% control one day after spraying while the other dosages gave a gradual reduction in efficacy. Field trials with reduced dosages of flusilazole + fenpropimorph, propiconazole + fenpropimorph and prochloraz + fenpropimorph have shown that the level of attack at the time of application has a considerable influence on the duration of effect, and also that the level of epidemic disease development after treatment influences the duration seen for the different rates. The biological persistence was measured on *Erysiphe graminis* in winter wheat and spring barley, *Puccinia hordei* in winter barley and *Septoria* spp. in winter wheat. Full dose generally lasted for 40-45 days. If, however, the disease developed very rapidly the effect did not last for more than 25-30 days. Half rate lasted for approximately 35-45 days and only 25-25 days in a severe attack. Quarter dose lasted for approximately 25-30 days and only 0-15 days in a severe attack.

INTRODUCTION

Research on reduced rates of pesticides has been going on in Denmark since 1986. Results have shown good possibilities of using lower dosages, compared to the dosages normally recommended by the chemical companies. The Danish farmers have generally adopted the use of reduced rates (Jørgensen & Nielsen, 1992).

In literature, information is only available on the residual effect using full rates of fungicides. Propiconazole is described to have a residual effect on *Erysiphe graminis* for 3-4 weeks and 4-6 weeks for *Puccinia striiformis* (Urech et al., 1979). Fenpropimorph has a residual effect lasting 3-4 weeks on *E. graminis* and *Puccinia* spp.(Bohnen et al., 1979). None of the published data give information on the residual effect when lower dosages are used.

Danish farmers have with their widespread use of reduced rate generally asked what the long term durability of reduced rates are. Data on the residual effect of adjusted dosages of fungicides has also been found to be important information when building decision support systems which include consecutive applications.The work described in this article tries to provide data to answer this question.

MATERIALS AND METHODS

The duration in effect of different fungicides and rates were tested in pot trials in glasshouse, under semi-field conditions and in ordinary field trials.

In a pot trial carried out in glasshouse the long lasting protective performance of different rates of triadimenol (normal rate = 125 g AI/ha) and fenpropimorph (normal rate = 750 g AI/ha) was tested when controlling *P.striiformis* in the variety Anja. The plants were sprayed on the 3-leaf stage, and subsequently inoculated with *P. striiformis*, 3, 7, 10, 15 and 17 days after spraying. The plants were grown in growth chambers at approximately 15°C and a r.h. of 70-80%. The plants were inoculated in a settling tower using 0.5 mg uredospores mixed with 5 mg talc per pot. The plants were then kept in darkness and covered with polyethylene for 3 days at 10°C and 100% r.h. The effect of the spraying was measured at the 3rd and 4th leaf. The effect measured at the 4th leaf reflected a systemic transport of the sprayed chemical. The latent period for *P. striiformis* varied between 9-11 days. Assessments were done 2-3 days after appearance of pustules.

In a semi-field trial, winter wheat variety Pepital was grown in 1 m^2 plots. All plots were sprayed using a knapsack sprayer at GS 39-45 (26. of June). The co-formulation propiconazole + fenpropimorph (normal rate = 125+375 g AI/ha) was applied at 100, 50, 25 and 12.5 % of the normal rate. Plots were artificially inoculated at 5-6 days intervals using *Septoria nodorum* and covered with plastic for 48 hours to ensure optimum infection conditions. The concentration of inoculum was 1-2 x 10^6 spores per ml, varying slightly between the 6 days of inoculation. The latent period varied between 6-10 days. The average attack of *S. nodorum* in untreated was 65 %. For each dosage and time of inoculation one plot was not inoculated but only exposed to the natural infection of the field. All plots were harvested.

The field trials were carried out between 1987 and 1993 using a complete randomized block design with 4 replicates. Plots were sprayed with different dosages at different levels of attack and growth stages of the crop (GS 29-37). The trials make it possible to study the efficacy of a given dosage at different levels of established attacks, and thereby assessing the residual effect of the dosages under conditions with natural infection. When the attack in the treated plots of the field trials was extending 2-3% on leaves, which were not diseased at the time of spraying the residual effect was estimated to have stopped. Trials were carried out both in winter wheat, winter barley and spring barley.

The fungicides were applied with a knapsack sprayer under low pressure (3 bar) using flat fan nozzles and 300 l/ha. In the trials either of 4 co-formulations flusilazole + fenpropimorph (normal rate = 160+375 g AI/ha), propiconazole + fenpropimorph (normal rate = 125+375 g AI/ha), prochloraz + fenpropimorph (normal rate = 225+375 g AI/ha) and tebuconazole + triadimenol (normal rate = 250 + 125 g AI/ha) were used. The duration of effect on *Septoria* spp. was tested in 1987 and 1991. Assessments were made after 2 applications carried out at GS 31 and 45-55. *Septoria tritici* dominated the Septoria attack in these years.

Disease assessments were carried out as per cent coverage of all green parts by the individual disease at 7-10 days intervals. All field trials were harvested.

RESULTS

In the glasshouse trial with *P. striiformis* a significant response was observed both to dosage and time of inoculation, combined with a significant interaction between dosage and day of inoculation. This was the case for both triadimenol and fenpropimorph. There was a distinct difference in the residual effect of the 2 products (Figure 1). A preventive treatment with 1/1 and 1/2 dosage of triadimenol gave a good effect for at least 17 days, even 1/16 dosage gave more than 50% effect in that period. For fenpropimorph a considerable reduction was seen in the effect of 1/1 and 1/2 dosage at 15 days, whereas for the lower dosages (1/8 and 1/16) the effect was reduced considerably after 3 days.

In the semi-field trial with artificial inoculation of *S. nodorum* a significant response was observed for the propiconazole+ fenpropimorph dosage, the time of inoculation and for interaction between dosage and date of inoculation. On average the disease level in untreated plots was 65% on the upper 2 leaves. Full dosage gave a stable and only slowly decreasing effect during the 24 days test period (Figure 2). The effect of 1/2 and 1/4 dosage decreased rapidly after 6 days, whereas the effect of 1/8 dosage dropped after 1 day. The harvest results showed a significantly lower yield in the inoculated plots (7.68 t/ha) compared to the non-inoculated plots (8.50 t/ha). Because of the small size of the plots it was not possible from the trials to make more precise conclusions concerning the relationship between the effect on yields, date of inoculation and controlling effect. However, the first date of inoculation caused the largest difference in yield between inoculated and non-inoculated plots (1.85 t/ha).

Field trials on *S. tritici* from 1987 showed good residual effect of all 4 dosages (1/1, 3/4, 1/2 and 1/3) for 3 weeks. Approximately 5-6 weeks after treatment a reduction in effect was seen particularly for dosages less than 3/4 (Figure 3). This very late drop in effect did, however, not have any impact on yield and only the 1/3 normal dose gave a significantly lower yield response. Trials in 1991 showed similar results. Here dosages lower than 1/2 gave a large reduction in the residual effect, which again gave a reduced yield response compared to 1/1 and 1/2 dose (Figure 4).

For *E. graminis* in the winter wheat field trials the results from 1992 and 1993 have been divided according to level of attack at the time of spraying (Table 1). This shows a considerable difference in the residual effect of the dosages depending on level of attack at spraying. Disease development after spraying also influenced the biological effect. If spraying was carried out on a well established attack, insufficient control was obtained. The development stage of the crop did not influence disease control or fungicide residual effects.

Similarly for *P. hordei* in winter barley field trials a considerable variation in the residual effect of the different dosages was seen (Table 2). An early spraying at GS 29-31 has shown a good residual effect for all dosages. For sprays applied at GS 37-45, at which time disease was spreading rapidly, the residual effect decreased with decreasing dose, with only 8-10 days being realised at 1/4 rate. This short residual effect was also reflected by a significant fall in the yield response for treatments using 1/4 rate as compared to 1/1 and 1/2 rates.

For *E. graminis* in spring barley the results from 1990 to 1993 again were divided depending on the level of attack at the time of spraying and the level of disease development after treatments. (Table 3). If the level of attack was between 2 and 5% at the time of spraying and the epidemic development only moderate the residual effect for 3/4-2/3 dosage lasted approximately 41 days. By reducing the dosage to 1/8 or 1/10 the residual effect was reduced to approximately 30 days. If applications were carried out under conditions more favourable for disease development - although the initial level of attack was low - the residual effects were reduced between 10 and 20 days depending on the used dose. If very low dosages were used at high levels of attack (7-15%) the controlling effect of these low dosages was completely insufficient, to such an extent that no residual effect was seen. Data in Table 1-2 are average values for the different fungicides mentioned.

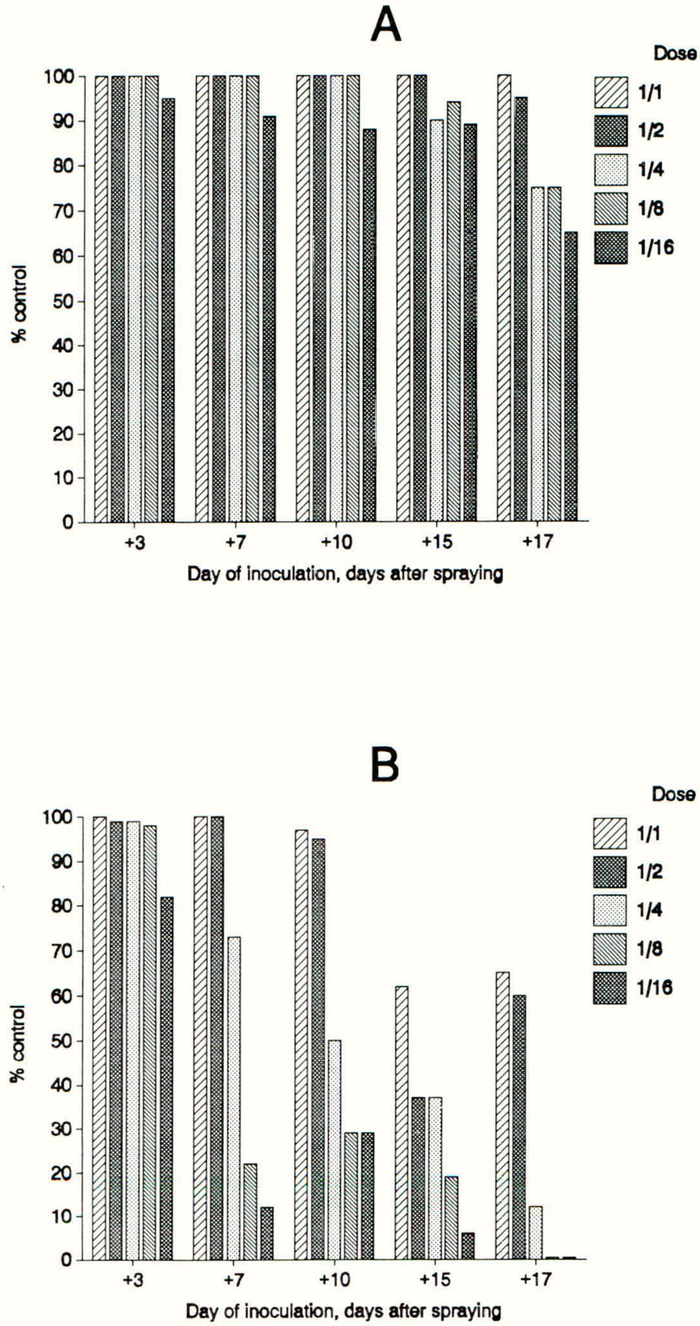

Figure 1. Per cent control of *Puccinia striiformis* in winter wheat using protective application of different dosages of triadimenol (A) and fenpropimorph (B). The trial was inoculated with *P. striiformis* at different days after spraying, glasshouse trial.

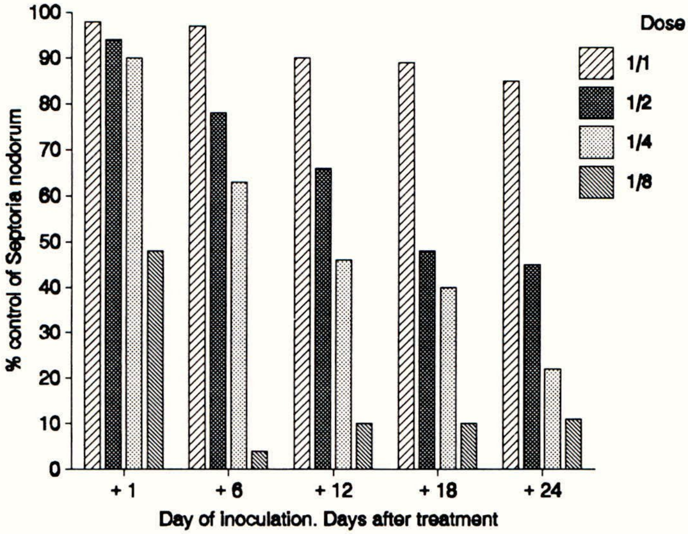

Figure 2. Per cent control of *Septoria nodorum* using protective treatments of different dosages of propiconazole + fenpropimorph (1.0 = 125+375 g AI/ha). The trial was inoculated with *S.nodorum* at different days after spraying. Semifield trial.

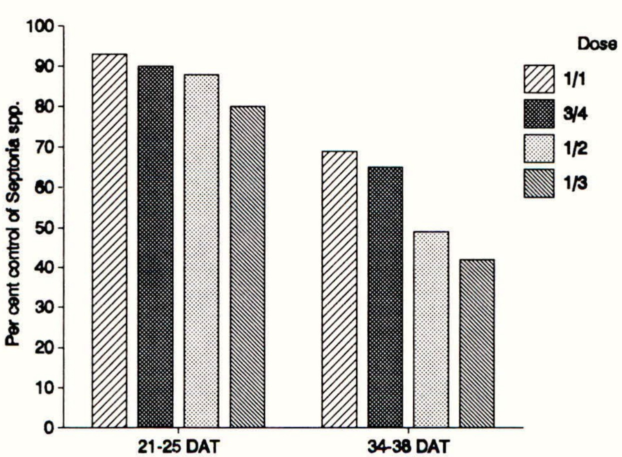

Figure 3. Per cent control of *Septoria* spp. in field trials using propiconazole + fenpropimorph (1.0 = 125+375 g AI/ha) applied at GS 31 and GS 45. Average of 3 trials in 1987. Attack at GS 65 (21-25 days after treatments (DAT) and GS 75 (34-38 DAT) was 11 % and 15 % respectively.

TABLE 1. Residual effect measured in days after spraying for propiconazole + fenpropimorph and flusilazole + fenpropimorph used at different dosages at different levels of attack by *Erysiphe graminis* in field trials of winter wheat. Figures in brackets give range.

Dose l/ha	% attack at time of spraying		
	≤ 1.0	1-5	≥10
1/1	50 (39-54)	44 (31-54)	29 (23-31)
1/2	45 (35-53)	38 (22-48)	17 (0-23)
1/4	37 (33-44)	25 (13-48)	13 (0-23)
% attack in untreated (GS 75)	6-15	3-20	15-50
No. of trials	5	8	4

TABLE 2. Residual effect measured in days after spraying for propiconazole + fenpropimorph and flusilazole + fenpropimorph used at different dosages at different levels of attack by *Puccinia hordei* in field trials of winter barley. Figures in brackets give range.

Dose l/ha	% attack at time of spraying	
	0.5-5 (GS 29-31)	1-2 (GS 37-45) Strong epidemic development
1/1	40 (23-43)	29 (23-35)
1/2	34 (23-43)	19 (13-22)
1/4	30 (19-35)	9 (8-10)
% attack in untreated (GS 75)	18-75	38-75
No. of trials	6	3

TABLE 3. Residual effect measured in days after spraying for propiconazole + fenpropimorph, flusilazol + fenpropimorph and prochloraz + fenpropimorph used at different dosages and on different levels of attack by *Erysiphe graminis* in field trials of spring barley. Figures in brackets give range.

Dose l/ha	% attack at time of application		
	2-5	3-5	7-15
3/4 - 2/3	41 (39-44)	32 (23-42)	27 (26-27)
1/2 - 1/3	38 (30-44)	26 (19-33)	24 (23-25)
1/4 - 1/6	34 (30-39)	18 (11-25)	0 (0)
1/8 - 1/10	30 (18-34)	12 (7-22)	0 (0)
% attack in untreated (GS 75)	7-15	26-52	70
Number of trials	3	6	2

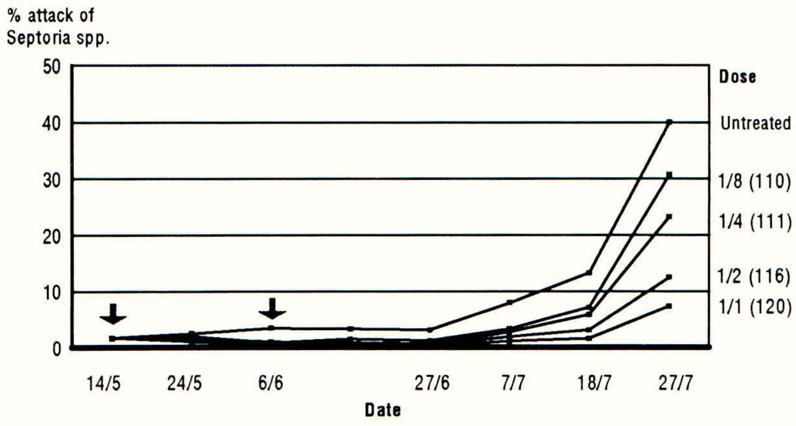

FIGURE 4. Average control of *Septoria* spp. in 6 field trials in 1991 using two applications (GS 31 and 39-45) and different dosages of propiconazole + fenpropimorph (1.0=125+375g AI/ha), flusilazole + fenpropimorph (1.0= 160 + 375 g AI/ha) and tebuconazole + triadimenol (250 + 125 g AI/ha). Average relative yield given in brackets.

DISCUSSION AND CONCLUSION

The glasshouse trial with *P. striiformis* showed large differences between the residual effect of triadimenol and fenpropimorph. Very low rates of triadimenol (1/4-1/16) showed high and stable preventive effect on *P. striiformis* applied up to 14 days after spraying. This agrees with previous experience from field trials where 1/4 of the normal dose of several EBI triazoles gave good effect for a minimum of 3 weeks (Jørgensen & Nielsen, 1994). A shorter residual effect for fenpropimorph compared to several other EBI products has been seen in other glasshouse trials (Gisi *et al.*, 1986) and has also been observed in field trials (Jørgensen & Nielsen 1990; Hims & Cook, 1992), the effect, however, not being as pronounced as in the glasshouse trials.

The semi-field trials with artificial inoculation of *S. nodorum* showed a clear dose response using protective treatments with propiconazole + fenpropimorph. The effect of the full dosage dropped only slowly during the 24 days when the residual effect was investigated. This agrees well with control for more than 3-4 weeks as stated for propiconazole (Urech *et al.*, 1979, Jordan *et al.*, 1986). The dose response in the trial was greater than the responses seen using reduced rates in the curative period. Previous results found for both *S. tritici* and *S. nodorum* have shown higher levels of control for the reduced rates in the first part of the curative period compared to effects seen when using protective treatments (Jørgensen, 1992), which again agrees with findings by Schöfl *et al.*(1994). A trial with artificial inoculation in 1992, similar to the one described here, showed a somewhat better residual effect for the low dosages (incl. 1/8 dosage). The explanation is assumed to be that the dry weather conditions in 1992 were not favourable for a continuation of the epidemic life cycles as was the case in 1993, when the weather conditions at the end of June and beginning July were good for a continued development of the disease. This indicates that the residual effect is correlated to weather conditions and the epidemic development of the diseases. As seen from the field trials 1/2 rate of an effective Septoria fungicide will provide a sufficiently durable effect for the Septoria disease levels normally seen under Danish weather conditions. A late development in *Septoria* spp. attack at GS 85 was not found to have any significant impact on yield.

The results from field trials show a considerable reduction in the residual effect when reduced dosages are used. How rapidly the reduction occurs depends on the level of attack at the time of spraying and disease development after spraying. In wheat and spring barley it has not been possible to correlate the residual effect to the development stage of the crop. However, it is evident that if the level of attack exceeds 5% at the time of spraying the effect of the low dosages is insufficient to such an extent that in many cases the residual effect cannot be said to be acceptable. In winter barley the trials demonstrated a correlation between a relatively late spraying (GS 37-39), epidemic development of *P. hordei* and a rapidly reducing effect from the lowest dosages. From the field trials it can be concluded that the duration of the residual effect of full rate of the broad spectrum fungicides tested is 40-45 days, decreasing to 25-30 days in a severe disease attack. The duration of the effect of half rate is approximately 35-45 days and only 15-25 days in severe attacks. The duration of the effect of quarter rate is approximately 25-30 days and only 0-15 days in severe attacks. When timing applications under practical conditions, a latent period has to be deducted from the durability obtained from the different dosages in order for the farmer to obtain acceptable control.

The results obtained from these trials are used as background for the decision support system, PC-Plantprotection (Secher, 1991), which for control of *E. graminis* and *Puccinia* spp. uses field registrations based on frequencies. Very low per cent attack (0.01-2 %) assessed on all green parts correlates to frequencies between 1-100 %. The recommended and adjusted dosages used in this program are based on disease present, level of attack and growth stage. The thresholds used in the program also take into consideration the susceptibility of the variety.

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