7

Strategy and Tactics in the Use of Fungicides

Key Points

- Fungicides are effective tools to control disease and thus improve the yield and quality of a crop.
- Growers are faced with numerous decisions on how best to use fungicides.
- Strategies are plans fixed at the beginning of the growing season; tactics are plans altered in response to factors emerging during the season. The tactics and strategies are needed to decide:
  - where to apply fungicide – to seed, soil or foliar tissue;
  - which type of fungicide to use;
  - what fungicide dose to use; and
  - when to apply fungicide.
- The optimum answers to these questions will be dependent on myriad factors, only some of which are under the control of the grower. Factors not under farmers' control include:
  - the weather – and how it affects both crop growth and pathogen growth;
  - rainfall during and after fungicide application; and
  - the incidence of disease pressure coming from outside the farmer's property.
- Factors more or less under farmers' control include:
  - disease resistance status (for all relevant diseases) of the crop cultivars used;
  - the timing of sowing;
  - details of seeding – row spacing, seeding rate, row orientation; and
  - fertilizer use.

Where to Apply Fungicide

Seed-applied fungicide

Seed treatment by fungicides has many inherent advantages that favour its widespread use. The first uses of chemicals to protect crops against disease were seed treatments (see Chapter 1). As the seeds can be mixed with fungicides in a closed container, all the seeds should receive a uniform coverage and none of the fungicide can escape into the environment. The fungicide is not brought into contact with soil and so undergoes slower degradation than in the case of in-furrow applications. Furthermore, as the fungicide is automatically physically close to the seed-borne pathogen it has only to penetrate a few cell layers to reach its target. In addition, systemic fungicides will travel up the shoots as the plant germinates and provide some degree of protection for the vulnerable early leaves. Some of the fungicide will leach into the soil where it can suppress soil-borne pathogens.

Seed-borne diseases are very effectively controlled by seed treatments and the treatment is highly cost-effective (Murray and Brennan, 2009, 2010). Theory and experience confirm that seed treatment by fungicide is unlikely to lead to fungicide resistance. Many diseases, such as the bunts and smuts and some powdery mildews, have been effectively neutralized by the current range of seed fungicides.

Soil or in-furrow application

Soil or in-furrow application is more problematic. In this case, the fungicide is mixed with the seeds as they are planted. The targets are pathogens such as take-all and *Rhizoctonia*. These pathogens exist as free-living species in soil and so the goal of the in-furrow application is to suppress the hyphae as they attempt to invade the germinating seed. The fungicide is inevitably bound on to soil particles and suffers microbial degradation due to the soil microflora. As a result, in-furrow applications are restricted to some specialized situations where the disease pressure is high and no options for rotations are available.

Foliar application

The great majority of fungicide applications are to above-ground tissues, including stems, flowers as well as leaves, and referred to as foliar use. Foliar diseases are very obvious to a grower and so there is a large incentive to respond to the presence of the pathogen. In contrast, root diseases are to a large extent 'out of sight and out of mind'.

Which Type of Fungicide to Use

The primary driver to consider when using a fungicide is to reduce or eliminate disease. In principle this would mean spraying the maximum amount of the most effective fungicides at the most frequent permitted intervals. Such a strategy is very unlikely to be the most profitable strategy. It is also likely to be a strategy that promotes the development of fungicide resistance. Hence there has been a great deal of effort in the development of strategies and tactics that aim to use fungicides in the most cost- and time-effective manner. This means that there is no one tactic or strategy that is optimum. The tactics and strategy will vary according the crop species, the variety used (and its resistance to disease), the presence of inoculum and the weather conditions that accompany the growing season. Hence this is a complex subject, requiring the advice of specialist advisors who are knowledgeable about local conditions.

Diagnosis

There is a clear need to identify the fungus causing the disease as different fungicides have different spectra. The use of fungicides that are ineffective against the pathogen that is present would clearly be a waste of time and money. Prochloraz, noted for its activity and utility against *Pseudocercosporella herpotrichoides* and SEPTRI, is often used in attempts to control *Puccinia* spp., a genus that is not sensitive. Similarly, the same product is used to control ERYSGT – a pathogen that is sensitive to prochloraz – but because of the relatively immobile nature of the chemical, only disease suppression may be achieved, inferior to the control given by a morpholine fungicide.

Products may be wrongly used because of poor commercial advice, but a significant factor may be the inability of many growers to recognize the cause of crop disease. The most common pathogens tend to be recognized successfully, but even in those cases may be confused with totally unrelated organisms. In cereals in 1986, powdery mildew was not positively identified by 11% of farmers; only 80% correctly diagnosed true eyespot, and 28% confused *P. hordei* with *R. secalis* (Smith and Webster, 1986; Table 7.1). More recently, misdiagnosis of herbicide damage as a fungal disease has become common.

Identification aids, usually comprising a series of photographs of symptoms, are now available to growers. The agrochemicals industry also provides information on the identification of pathogens as a promotional tool. Some computer-based packages incorporate diagnostic modules. Others are specific aids to diagnosis, for example the Muskmelon Disorder Management System (MOMS), which caters for the diagnosis of 17 crop disorders including fungal infections, nutrient deficiencies and environmental damage. This system includes the additional sophistication of a capacity to use uncertain data and will provide a probability of successful diagnosis if the situation prevents the complete expression of symptoms. However, it is the need to identify pathogens during their early biotrophic and non-symptomatic growth phase that has stimulated the development of sensitive and highly specific diagnostic aids.

The accurate and timely identification of the causal organisms of crop disease is vital to effective crop protection. The array of fungicides available to the grower and the range of their possible uses against specific pathogens, in combination with other products or in an integrated farming programme, increase the need to make correct diagnoses.

Table 7.1. Ability of farmers to recognize cereal diseases. (From Smith and Webster, 1986.)

Disease	% of farmers correct	% of farmers incorrect	% of farmers who ‘don’t know’	Disease most often confused with
ERYSGT	89	3	8	SEPTRI
Eyespot	80	4	16	*Fusarium*
PUCCRT	72	5	23	Scald
Yellow rust (early)	13	28	59	Insect
Yellow rust (late)	57	18	35	PUCCRT
SEPTRI	28	27	45	PUCCRT
LEPTNO (early)	24	23	53	*Fusarium*
LEPTNO (late)	23	38	39	Bunt/smut
Foot rot (*Fusarium*)	12	39	49	SEPTRI
Stress disorders	37	35	28	SEPTRI
Nutrient deficiencies	8	38	54	PUCCRT

Methods of identification are worthless if they are not reliable. At worst, they must provide the grower with a good probability of success and list possible alternatives. In addition, diagnostic techniques must operate under a variety of environmental conditions.

The performance and, to some extent, the availability of suitable fungicides are linked to the stage of growth of the pathogen. Regardless of their reliability, diagnostic tests that are slow to carry out may be of little value to the grower if the appropriate control measures cannot be employed in a timely manner. The urgency attached to diagnosis is made more acute in regions that are subject to sudden weather change. In Europe, for example, there are very few days in the growing season that are suitable for the efficient application of foliar fungicides. Reliance by farmers on a tardy diagnostic technique may force them to apply products in suboptimal conditions or at a stage of fungal development that is not ideal, resulting in poor disease control.

Diagnostics must be easy to use and the results obtained by a farmer sitting on the back of a tractor, or by a company representative in a car, must be equivalent to those achieved under laboratory conditions. Traditionally, growers diagnose disease by eye. The method requires experience but is very rapid and allows immediate and appropriate action to be taken. Diagnostic techniques that are inferior in practice to currently accepted methods are unlikely to be adopted. After all, in many cases the farmer may choose to apply a broad-spectrum protectant product rather than commit to the use of a complex diagnostic programme and risk missing a good spray window or increase his overall input costs by having to spray different fields at different times.

In other instances, especially in cereals, the appearance of one pathogen may signal to the grower the need to apply a broad-spectrum product. For example, mildew infection may be controlled using a specific product such as fenpropidin. However, it is more usual for the farmer to combine a fenpropidin/fenpropimorph treatment with a triazole. The second component provides the farmer with an insurance against attack by other pathogens, hence reducing the number of excursions into the crop and lowering total cost.

The use of diagnostics is valuable in improving the reliability of disease identification but has to provide the farmer with cost benefits that are at least equal to those that are currently achieved. However, in those situations where fungal infection is difficult to detect or to diagnose correctly, or when a decision is made to use fungicides only as required, modern diagnostic methods present the grower with highly accurate methods of identification.

Immunology

Immunological detection techniques are of increasing importance in the management of crop diseases (Fox, 1993; Schots *et al.*, 1994). Adapted from similar methods used in medicine, they are rapid and rely upon the detection of an antigen from the fungus under test, visualized as a colour change in the assay. An antigen is any material that can induce an immune response, resulting in antibody production, and immunological methods use the characteristic of antigens to bind specifically with corresponding antibodies. Fungi produce characteristic molecules, often on their surfaces or readily accessible by straightforward extraction methods. The role of immunodiagnostics in plant disease diagnostics is to infer the presence of a potential pathogen when such fungus-specific antigens are detected through their interaction with an appropriate antibody.

Immunoassays can be used to identify pathogens, for example SEPTRI and LEPTNO, which elicit latent or indistinct symptoms within the host. The tests may be poly- or monoclonal based. Polyclonal-based assays contain a cocktail of antibodies manufactured by test animals challenged by the antigen, usually presented as an injection of a crude extract of the test fungus. Polyclonal assays are non-specific, being able to recognize all fungi containing the components of the antigen. However, many fungi, including non-pathogenic species, produce non-specific antigens, thereby reducing the diagnostic value of polyclonal-based tests. Monoclonal-based assays are highly specific, permitting the detection of particular fungal species or strains. Combinations of the two, of known specificity, can be constructed to support the identification of a predetermined spectrum of pathogens.

Several test kits have been produced, enabling results to be obtained within a timescale that permits a flexibility of response by the grower (Miller *et al.*, 1992; Fox, 1993). In a matter of hours, the presence or absence of a disease threat can be determined, with the extent of any colonization of the tissue under test being proportional to the intensity of the colour change in the assay.

In particular, ELISA techniques have allowed immunodiagnostic methodology to be used successfully in practical situations. Several methods are available but two, the multi-well assay and the dip-stick assay, are probably the most widely adopted. The first employs 96-well microtitre plates, each well coated with the antibody specific to the pathogen to be assayed. Test samples from plants suspected to be infected by the fungus are dispensed into the wells. If the fungus is present, antigens in the extract conjugate with the antibodies on the walls of the microtitre wells. The result is developed after the addition of a second aliquot of antibody, complexed with an enzyme capable of producing a colour change in the test medium. The second method, the dip-stick assay, effectively transfers the ELISA technique to a convenient form. The assay involves the use of nitrocellulose sticks coated with the appropriate antibody. When dipped into a crude extract from plants suspected to be infected, a colour change on the surface of the stick quickly reveals the presence of the pathogen. The technical challenges behind these techniques can be said to have been solved, but except in specialist situations the products remain too expensive for routine use in crop pathology.

Nucleic acid-based diagnostics

Nucleic acid-based methods have inherent advantages over antibody-based tests. The identity of any organism is essentially in the organization of its relatively stable nucleic acid, or genetic code. Methods based on PCR can reveal a one-base-pair difference in one molecule of DNA. Thus DNA-based methods have extreme sensitivity and specificity (Fox, 1993).

The basis of such diagnostic techniques lies in the slight but constant genetic variations that occur between unrelated organisms. Despite this, practical applications of molecular diagnostics are few and far between (Ophel-Keller *et al.*, 2008). Methods remain too slow and certainly too expensive for general use. The costs of a test would seem to be insignificant when considering a decision to buy a farm. Infestation of the land with *Rhizoctonia* would seem to be a very credible reason to use the available test. However, such kits have not been a commercial success and their use is very largely restricted to researchers.

What Fungicide Dose to Use

All applications of fungicide follow a dose–response or 'efficacy' curve. Figure 7.1 illustrates a typical efficacy curve. The amount of disease declines with increasing fungicide dose. The curve is steep at first but is subject to diminishing returns at higher dose. Reducing disease typically (but not always) has a noticeable effect on yield, which rises to a plateau with dose. The extra yield will translate into greater farm-gate value. The cost of fungicide includes both the application costs (including the use of the spray equipment and staff time) plus the direct costs of the fungicide product. Subtracting the cost of fungicide from the farm-gate value generates a curve that peaks at a middle dose and declines at both low dose, when disease reduces yield, and at high dose, when uneconomical fungicide use reduces overall profit. In most cases, growers will use the fungicide dose that maximizes profit. The maximum dose that can be used might be limited by legislation or by the need to limit the risk of resistance.

The exact value of the parameters illustrated in Fig 7.1 will vary depending on the value of the crop, the cost of fungicide and the progress of the season. All parameters will be subject to year-by-year variability. Some crops, such as many horticultural products including grapes, are sufficiently valuable that the costs of fungicide applications are comparatively minor. In these cases, growers are likely to take a 'safety first' approach and apply fungicide regardless of the prospects for disease. In others, such as broad-acre cereal crops and especially where yields are less than 2–3 t/ha, fungicide costs are significant and therefore controlled tightly. Growers will think carefully before deciding whether to apply or not.

When to Apply Fungicide

Having decided whether to apply a fungicide, the next question is when to apply the product. Three strategies are in use: (i) to apply when the crop reaches a certain

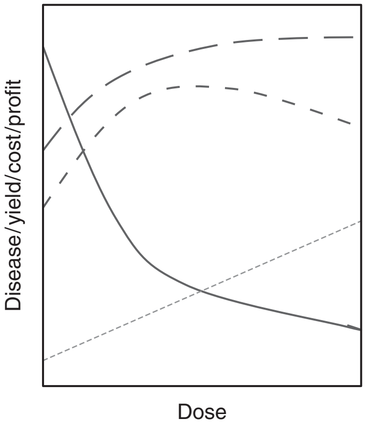

Fig. 7.1. An idealized efficacy curve in which the *x*-axis plots dose and the *y*-axis plots disease (——), yield (— — —), fungicide cost (· · · · ·) and profit (– – –). The amount of disease will decline with increasing fungicide dose. The resultant yield will increase with dose and plateau. The cost of fungicide increases with both dose and number of applications. The resultant profit curve will typically peak at a level at which some disease is apparent.

growth stage; (ii) to await a certain threshold level of disease; and (iii) to use a disease-threat model.

Growth stage strategies

Growth stage strategies are best suited when both the crop value and the probability of disease are high. Figure 7.2 illustrates the options for a cereal crop. The principle underlying this strategy is to place a dose of fungicide on the plant so that the most productive leaves are protected from disease by the pathogens. In higher-yielding areas with dense canopies, the flag leaf contributes the dominant fraction of the yield and so strategies to protect this stage are optimal. On the other hand, an earlier spray may prevent the multiplication of the inoculum and so lead to less disease overall.

Disease threshold strategies

Disease threshold strategies rely on monitoring of the crop to determine when the threat level is high enough to warrant the application of the fungicide. Clearly a threshold strategy is dependent on the vigilance of the grower detecting the disease and the rate of development of the epidemic from this point forward. It also depends on the speed with which the grower can mobilize a spray programme. Spraying requires appropriate weather conditions; too much or too little wind can prevent spraying as can imminent rain.

Detecting the disease can be as simple as walking through the grower's field or talking to neighbours. Vineyards have traditionally grown roses at the ends of rows. Rose mildew is caused by a different pathogen but the conditions that cause it are

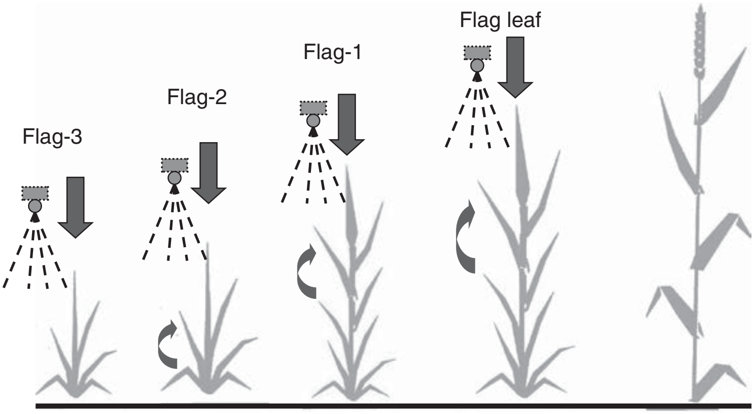

Fig. 7.2. Disease control across a cropping season; time and growth stage. The growth of cereals is accompanied by the emergence of successive layers of leaves up until the flag leaf. Growth stage fungicide strategies apportion fungicides to protect the most productive leaves.

similar to those that cause grape mildew. It therefore is simple (and pleasant) to walk through a vineyard and examine the roses for mildew. Detecting can also take the form of spore traps operated from research stations, vehicles or even flying drones. Detection and monitoring of pathogen populations is a very active area of research.

This strategy depends on the principle that prevention is better than cure. Fungicides differ in their preventive and curative activities, as described in Chapter 5. In general, preventive activity is much better than curative. However, too early application of a fungicide means that it will decay in concentration due to solar radiation and being washed away by rain, before the pathogen arrives. Too late and the disease level will have built up so that it overwhelms the fungicide. The weather prediction is also important. Most diseases are promoted by wet weather, so if rain is not forecast it may be safe to ignore a small level of disease. Conversely, a forecast of rain may justify a fungicide spray.

Disease-threat models

Disease-threat models use weather data to predict when particular diseases are likely to reach a level when spraying is warranted. Such models input parameters of temperature and humidity in real time. The parameters are best worked out for the downy and powdery mildew diseases of grapes. The parameters predict hours of leaf wetness, and when a threshold is reached, spraying is initiated. Experience has shown that such models need to be reduced to simple rules of thumb before they are well adopted. In the future we can expect mobile phone alerts initiated by state or university researchers, advisory services or even fungicide resellers to become the norm.

Frequency of application

Most fungicides have a relatively short window during which they are effective. Sun, rain and transport through the plant will reduce the effective concentration of the fungicide over a period of time most likely to be less than 2 to 3 weeks. Therefore if the disease threat spans a longer time period it is likely to be economic to spray more than once; indeed in high-value crops and high disease situations, sprays may be a frequent as weekly. If sprays are close together, the effective concentration never declines to zero (Fig. 7.3). Wider spacing may allow a window during which infection can initiate. The timing of the individual sprays can, like for a one-spray strategy, be driven by growth stage, disease levels or prediction models.

Multiple sprays are more expensive than a single spray and therefore must be justified by greater yields. The cost of multiple sprays can be mitigated by applying a reduced dose – so-called split-dose strategies. In most countries, labels specify the total concentration in the growing season, rather than at any one spray. Furthermore, residues in the final crop may be an issue that prevents sprays occurring after a certain period.

Having decided to spray more than once, it is generally a good strategy to alter the fungicide that is used, ideally using a different MOA. Using different fungicides improves the spectrum of disease that is controlled and mitigates against resistance (Hobbelen *et al.*, 2013).

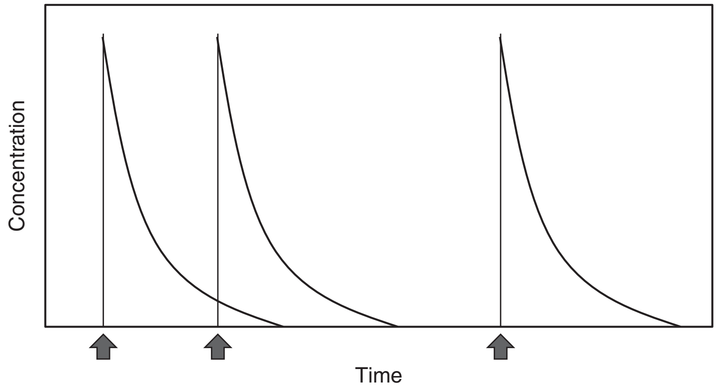

Fig. 7.3. Fungicide concentration as a function of application frequency (fungicide applications indicated by arrows).

The different fungicides can be incorporated into the spray programme as mixtures or as alternations (Fig. 7.4). Most likely the dose will be split between several applications. It is clear that there are essentially infinite parameters than can be altered. The success of a particular strategy can only be predicted with moderate confidence, even after extensive field trials. Thus the strategy used will be a combination of prediction, experience and convenience.

Interaction with Fertilizers

Crop nutrition has always been recognized to interact with crop protection. Indeed, right through the latter part of the 19th century the concept that disease was due to poor crop nutrition rather than microbial pathogens was maintained by Lawes (Money, 2006). It is not surprising that he was a fertilizer manufacturer, but we can be grateful that his fortune was used to establish the research centre at Rothamsted (http://www.rothamsted.ac.uk/), a key site of disease and fungicide research for over 170 years.

The basis of the controversy lingers because of the evidence that crops that have suboptimal fertilizer regimes are more susceptible to disease. This is a complex area and firm conclusions are hard to make. However, there is some support for the view that over-fertilized crops (and particularly for nitrogen) are hypersusceptible to pathogens and especially biotrophs. Effects on necrotrophic pathogens are less clear (Solomon *et al.*, 2003). A particular effect of potassium on disease has been noted (Brennan and Jayasena, 2007). The clear message is to make sure the fertilizer regime is balanced and at an appropriate level.

Apart from direct or indirect interactions between fertilizer and pathogens, there is a deeper level of interaction expressed as optimizing the levels of both fertilizer and fungicide. Fungicides generally increase yields by reducing the losses caused by pathogens. However they can also improve yield by increasing the length of time that green leaf area is maintained by crops. Green leaf area duration (GLAD) improvements due to fungicides are very significant in some areas and some crops (Dimmock and

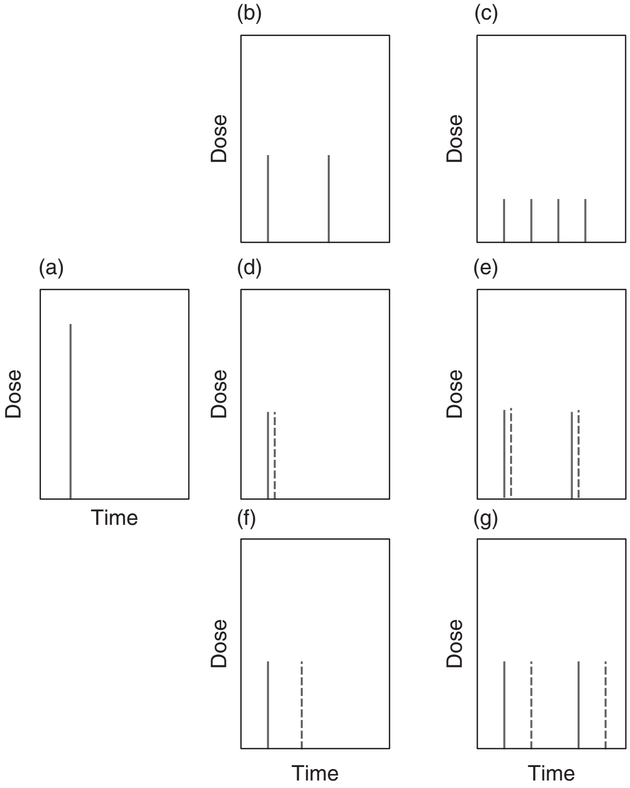

Fig. 7.4. Different strategies of mixtures and alternations: (a) single dose; (b) 2× split dose; (c) 4× split dose; (d) mixture; (e) 2× split mixture; (f) alternation; (g) 2× split alternation.

Gooding, 2002; Ruske *et al.*, 2003; Pepler *et al.*, 2005; Berdugo *et al.*, 2012). They are poorly understood but they are associated with QoI and SDHI fungicides in particular and less so with DMIs.

If the fungicide increases the yield, the dose of fertilizer that is optimum will also increase (Berry *et al.*, 2010). Nitrogen response curves will show an economic optimum; however if the yield effects of the fungicide are high, the optimum nitrogen level can be shifted towards higher levels. This is turn may justify a further increase in the intensity of the fungicide regime (Fig. 7.5). Similar curves will no doubt also apply to phosphate and potassium levels.

Summary

In summary therefore, fungicides are best seen as part of a package of inputs used by the grower to produce the most profitable crops. Numerous interactions apply between the inputs. It will never be possible to delineate the optimum strategy even for one farm due to changing weather conditions and pathogen loads. Risk-averse farmers are likely to err on the side of reduced inputs as a small decrease in fungicide or fertilizer level is very unlikely to have a serious negative impact on

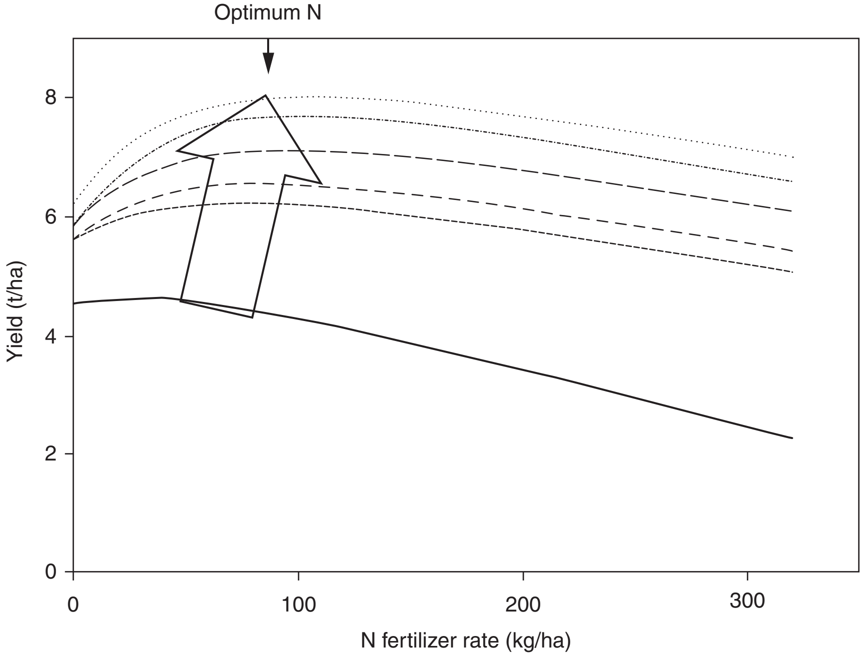

Fig. 7.5. Disease and fertilizer interactions. The optimum nitrogen rate (arrow) increases from 25 to 100 kg/ha as the dose of fungicide increases (relative fungicide dose rate: ——, nil; - - -, 0.125; – – –, 0.25; — — —, 0.5; – · – · –, 1; · · · · ·, 2) allowing greater canopy development. (From Berry *et al.*, 2010 with permission.)

profitability. In contrast, maximizing profitability may require higher inputs. Careful, locally based research can provide clear guidelines for growers and limit the range of parameters that are most likely to be close to optimal. It will then be up to the grower to choose a strategy and apply tactics that fit the risk level s/he is willing to endure.

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