THE DEVELOPMENT OF A SEQUENTIAL SAMPLING PLAN FOR MANAGEMENT OF STRIPE RUST (*Puccinia striiformis* West.) IN WINTER WHEAT (*Triticum aestivum* L.)

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MICHAEL J. COLE

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MICHAEL J. COLE

Stripe rust caused by *Puccinia striiformis* West., was studied in three seasons between 1981 and 1984, on the susceptible wheat cv. Rongotea. A sample unit of the top three leaves on a W-shaped sample pattern provided the basis of a reliable and sensitive stripe rust sampling program to detect disease incidence, as measured by low relative variability and high incidence values. A consistent relationship existed between severity and incidence on the top three leaves at incidence below 40%.

The spatial pattern of stripe rust infections on the top three leaves was a slight aggregation of disease foci. This was defined by regression techniques based on mean crowding and mean density, and supported by variance to mean and mean crowding to mean density ratio dispersion indices, and by fitting observed frequency distributions to distribution models. Mean crowding : mean density regressions provided a more accurate and less density dependent description of spatial patterns than the use of mean to variance or mean crowding to mean density dispersion indices or frequency distribution model fits.

A 0.2% severity on the top three leaves was established as an action level for fungicide application, based on a study of severity-yield relationships. A critical period of crop monitoring and applying fungicides for stripe rust was established from G.S. 15 to G.S. 61. No empirical linear or quadratic critical point model of severity-yield loss was fit significantly to observed data consistently.

Based on information on sampling methods, spatial patterns and action levels, a sequential sampling plan was constructed for use in a stripe rust management program. It is recommended sampling begin at the five leaf stage (G.S. 15) and end at anthesis (G.S. 61). Fields would be sampled until a 0.2% severity action level on the top three leaves was detected, estimated by 10% incidence. In the 1984-85 season the management program was compared to scheduled spray programs in commercial fields, and its use resulted in a reduction in sampling time with a high degree of reliability and a reduction in fungicide use compared to scheduled spray programs.

KEYWORDS: action levels: disease management: _Puccinia striiformis_: sampling methods: sequential sampling: severity-incidence relationships: spatial patterns: stripe rust: _Triticum aestivum_: wheat.

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CHAPTER 1

INTRODUCTION

1.1 PEST MANAGEMENT

Disease management is one aspect of pest management, which can generally be defined as the optimization of pest control in a sound ecological and economical manner to manipulate and maintain pest populations below a level at which economic damage will occur (National Academy of Science, 1969; Watson _et al_., 1975; Apple, 1977; Zadoks and Schein, 1979; Pimental, 1981; Metcalf and Luckman, 1982). Pest can be defined as any organism which injures or causes damage to crops and includes pathogens, insects, weeds, mammals and birds (Watson _et al_., 1975; Pimental, 1981; Metcalf and Luckman, 1982). Disease management using fungicides differs from prophlylactic and scheduled fungicide spray programs, which attempt to maintain a disease free crop, in that levels of disease which are determined not to cause economic damage are tolerated and treatment is applied only when an economic threshold is reached. An economic threshold is the level of disease at which control should be applied to prevent the disease from reaching the economic injury level, or level of disease which produces an incremental reduction in crop value greater than the cost of control (Stern, 1973; Headley, 1972; Apple, 1977). Crop losses are reductions of both quality and quantity (Carlson, 1979). In the absence of definite economic thresholds and economic injury levels, action levels may be estimated which are empirical and more subjectively derived, but can be used for pest management (Lincoln, 1978).

Many pest management concepts have been developed by entomologists but these are applicable to disease management (Zadoks and Schein, 1979; Pimental, 1981; Metcalf and Luckman, 1982). The development of a pest management program is dependent on the definition of the following components (Watson *et al*., 1975; Zadoks, 1979; Pimental, 1981; Metcalf and Luckman, 1981):

1. the biology and ecology of the pest,
2. a reliable sampling technique,
3. the economic threshold,
4. a control strategy.

The pest under examination must first be identified and information on the biology and ecology of the pest gained to determine how the pest may behave under various environmental conditions and possible management techniques (Apple, 1979; Pimental, 1981). An understanding of the life cycle of the pest and factors which may influence reproduction and survival is required, as is a knowledge of the agroecosystem in which a pest exists and interacts. Methods of crop production and the management of other pests may also influence pest development (Metcalf and Luckman, 1982).

A reliable sampling technique is required to establish economic thresholds or action levels (James, 1974; Walker, 1981) and to monitor pest populations when implementing thresholds (Chiarappa, 1974; Sterling and Pieters, 1979; Teng, 1983). The spatial pattern of a pest, or arrangement of pest occurrence in the field, should also be defined because it may influence sampling techniques and the detection of crop loss (Teng, 1983).

In field situations, yield losses are usually the result of several pest and agronomic factors and disease management is one component of an integrated pest management program (Chiarappa, 1974; Metcalf and Luckman, 1982; Teng, 1983). EPIPRE, a pest management program developed for wheat in the Netherlands (Zadoks, 1981) and a wheat pest management program used in Montana, U.S.A. (Nissen and Juhnke, 1984) are examples of multidisciplinary programs. The development of pest management programs is complicated by the requirement of taking into account several pests and their interactions in management and crop production practices, which require a multidisciplinary approach (Metcalf and Luckman, 1982; Grainger, 1979). Such multidisciplinary studies create logistic and managerial problems that may prevent integration and hinder pest management research (Miller, 1983). The management of a single disease is in turn only one component of disease management; however, it is often useful to concentrate on a single disease management and crop system as a starting point and integrate with other pests as research continues (Chiarappa, 1974; Tummala and Haynes, 1977; Teng *et al.*, 1978; Zadoks and Schein,1979). Management programs of secondary diseases (those which are not consistently prevalent or damaging) can fit into management of a key disease (one that is consistently prevalent and damaging), through spill-over effects as in the case of broad-spectrum fungicides (Jenkins and Lescar, 1980). Therefore, it is useful to concentrate on a key disease in a disease complex when initiating studies on the development of disease management programs.

Supervised plant disease control (Chiarappa, 1974) or single component pest management (Watson *et al.*, 1975) is a form of pest management which is based on a single control component, such as fungicides, after assessing a disease and estimating crop damage. Although such management programs are not integrated with other pests and control options, they provide a sound basis for the development of pest management programs and provide effective disease control by optimized fungicide usage. Several single component (fungicide) disease management programs have been developed including those for leaf rust of barley (Teng, 1978), powdery mildew of wheat (Large and Doling, 1962) and late blight on potatoes (Krause *et al.*, 1975).

Disease management programs are worthless unless they can be implemented. Disease management programs require a standardized, quick and reliable sampling plan (James, 1977) which allows for the classification of level of disease as high enough to warrant control or not (Iwao, 1975).

Sequential sampling is a technique which classifies populations quickly based on cumulative sample information feedback (Waters, 1955; Iwao, 1975). Few such plans have been developed for disease management (Strandberg, 1973; Rouse _et al_., 1981; Boivin and Sauriol, 1984); however, the application of the technique will undoubtedly gain use in the future (Sterling and Pieters, 1979). Three factors are required to develop a sequential sampling plan: a reliable sampling technique; a description of the spatial pattern; and an economic threshold or action level (Hopkins _et al_., 1981).

1.2 STRIPE RUST BIOLOGY AND ECOLOGY

Stripe rust, caused by _Puccinia striiformis_ West. is considered one of the most important rusts in the wheat (_Triticum aestivum_) disease complex, world wide, with reported yield losses from 8-75% in susceptible cultivars (Doling and Doodson, 1968; Manners, 1971; Gair _et al_., 1972; Mundy, 1973; King, 1976; Roelfs, 1978). Stripe rust is a recent addition to the New Zealand wheat disease complex, which also includes bunt (_Tilletia caries_), loose smut (_Ustilago nuda_), powdery mildew (_Erysiphe graminis_), leaf rust (_Puccinia recondita_), stem rust (_Puccinia graminis_), speckled leaf blotch (_Mycosphaerella graminicola_), eyespot (_Pseudocercosporella herpotrichoides_) and take-all (_Gaeumanomyces graminis_). The first reported stripe rust incidence was in 1980 and it was thought to be dispersed from Australia, via air currents (Harvey and Beresford, 1982). By the 1981-82 season, the disease was present throughout the wheat growing regions of New Zealand and reported yield losses on susceptible cultivars ranged from 10-50% (McCloy, 1982; McCullough, 1982; Chan and Gaunt, 1982). Stripe rust is presently the main target for control in the New Zealand wheat disease complex as measured by grower surveys (Noonan and Close pers. comm., 1984).

P. striiformis is a polycyclic rust pathogen which may complete several cycles in a wheat crop after initial infection. The epidemic stages of overwintering/oversummering, dispersal, infection and sporulation are interrelated and dependent on several environmental and host plant factors. Although the teliospore stage is found on infected plants late in the season, they play no known role in the life cycle (Rapilly, 1979; Harvey and Beresford, 1982). Oversummering and the source of inoculum for initial infections in autumn sown wheat crops occurs as the uredinal stage on volunteer wheat plants (Shaner and Powelson, 1972) and alternative grass hosts (Hendrix *et al.*, 1965). In New Zealand, urediniospores on volunteer wheat plants are considered to be the major source of inoculum for initial infections in autumn sown wheat crops (Harvey and Beresford, 1982), although further studies into the role of alternative grass hosts may be warranted. Urediniospore dispersal can take place over short distances via leaf to leaf contact and rain splash, and over longer distances by wind. However, long range wind dispersal is not as efficient as short range dispersal (Rapilly, 1979).

Stripe rust infection occurs optimally between 7°C and 13°C (Newton and Johnson, 1936; Manners, 1950; Sharp, 1965). Temperatures above 22°C inhibit or reduce infection (Sharp, 1965; Tollenear and Houston, 1965). A minimum period of three hours of leaf wetness is required for infections with an optimum period of eight hours (Shaner and Powelson, 1972).

After infection, there is a latent period for *P. striiformis* in which symptoms and signs are not exhibited. The duration of the latent period is influenced by temperature and a minimum of 7°C mean temperature is required for disease development (Zadoks, 1971). In New Zealand a minimum latent period of 12-14 days was reported during September and October when the mean temperatures were between 16-18°C and a maximum latent period of 30-40 days during August when mean temperatures were between 4-5°C (Harvey and Beresford, 1982). This discrepancy with Zadoks (1971) may be due to temperature variations found in New Zealand.

The next stage of the life cycle is sporulation. Pustules (uredinia) are a bright yellow-orange color and occur on leaves and glumes (Wiese, 1977; Harvey and Beresford, 1982). The size range is 0.3-0.5 x 0.5-1mm (Wiese, 1977) and may be oriented linearly along veins or may be found in random patterns (Wiese, 1977; Rapilly, 1979). The linear orientation of pustules is usually seen on leaves of older plants while random patterns are found on the leaves of younger plants (Harvey and Beresford, 1982). Pustule color, size and arrangement are keys to P. striiformis identification in the field but may differ slightly in appearance with cultivars and environmental conditions (Harvey and Beresford, 1982). Before sporulation a faint chlorotic area may be observed where pustules will eventually erupt through the leaf epidermis (Mares and Cousen, 1977). Sporulation requires a minimum relative humidity of 50% and increases as the percent relative humidity increases (Rapilly, 1979). P. striiformis grows systemically through infected leaves, which can cause a continuous enlargement of the sporulating zone and may produce 200 urediniospores/mm²/day (Emge et al., 1975). This systemic characteristic of stripe rust allows for an increase in inoculum, governed by urediniospore production and pustule enlargement, which leads to disease intensification in the absence of conditions suitable for new infections (Emge et al., 1975; Rapilly, 1979).

Epidemic development is influenced by a wide assortment of wheat cultivars and P. striiformis races, which produce a variety of resistance reactions (Volin and Sharp, 1973; Johnson and Bowyer, 1974). Cultivar and P. striiformis reactions may not be consistent, and can be influenced by light intensity and duration (Manners, 1950; Sharp, 1965), temperature (Llewellen et al., 1967; Brown and Sharp, 1969; Line et al., 1976) and plant age with some cultivars exhibiting adult plant resistance (Russell, 1976; Mares and Cousen, 1977). Of the more than sixty races of P. striiformis which have been identified throughout the world, two races are predominant in New Zealand (104 E137 and 106 E139) which are also widespread in Australia (Harvey and Beresford, 1982; Symons, 1982).

1.3 STRIPE RUST MANAGEMENT

A clear understanding of available control options is needed to develop a pest management program (Watson et al., 1975; Grainger, 1979; Metcalf and Luckman, 1982). Several control options have been used to manage wheat disease and generally include resistant varieties, cultural practices and fungicides (Wilcoxson, 1981). Crop rotation would have a limited effect on stripe rust development because P. striiformis is mobile and can be wind dispersed over long distances (Hermansen and Stapel, 1973). Dispersal would ensure that there would always be a source of inoculum for infection in any season provided that some infected crops or volunteer plants were present in the vicinity. Crop sanitation could be employed to break the disease cycle or slow down the rate of disease development by destroying volunteer wheat plants and reducing the level of inoculum for initial infection (Shaner and Powelson, 1972; Harvey and Beresford, 1982). Unfortunately, it may be difficult to destroy all volunteer plants and it has been observed that only a few infected volunteer wheat plants can provide enough inoculum to initiate an epidemic (Shaner and Powelson, 1972). This method may be difficult to implement on a large field scale.

Stripe rust resistant cultivars may provide the ultimate control option (Doling and Doodson, 1968) in an overall wheat pest management and production system. Many stripe rust resistant cultivars are based on the inheritance of race specific (single) genes (Mares and Cousen, 1977). Their use has led to the dramatic breakdown of the effectiveness of these resistant cultivars with pathogen adaptation and increased proportion of new races of stripe rust (Macer and Doling,1969;

Chamberlain *et al.*, 1970; Russell *et al.*, 1976). To avoid this problem, cultivars which exhibit non-race specific, durable resistance have been bred (Lupton and Johnson, 1970; Johnson and Law, 1975). Durable resistance does not usually prevent infection completely, like many of the single gene, race specific, resistance, but slows the rate of disease development (Mares and Cousen, 1977). The use of wheat cultivars with durable resistance can be complicated by the fact that the actionsof many durable resistant genes are triggered by warm (24°C) temperatures (Sharp *et al.*, 1965; Llewellen *et al.*, 1967; Mares and Cousen, 1977) and under New Zealand conditions, stripe rust epidemics may occur on such cultivars before the temperature becomes high in the summer months (Wright and Sanderson, 1982). Other strategies which employ cultivar resistance are the use of multilines, species diversification and mixtures to reduce the infection rates of epidemics (Browning *et al.*, 1977; Priestley and Byford,1980; Rapilly, 1979; Wolfe and Barratt, 1980). Gaunt (1982) recommended the phasing out of highly susceptible varieties grown in New Zealand and the establishment of a standard level of lower susceptibility for cultivars released for commercial use. This would reduce the overall level of inoculum in the agroecosystem. Cultivar introduction and acceptance may be delayed by problems associated with quality factors, market preference, unavailability of seed and lack of knowledge of cultivar performance (Hedley and McCloy, 1982).

Fungicidal control is another important stripe rust control strategy used extensively in Europe (Jenkins and Lescar, 1980) and New Zealand (Hedley and McCloy, 1982). Many foliar fungicides have been used for stripe rust control including triadimefon, propiconazole, benodanil, and oxycarboxin (Jenkins and Lescar, 1980; McCullough, 1982; Patterson, 1982). In New Zealand the only recommended fungicides for stripe rust control are triadimefon and propiconazole. Both fungicides are from the triazole group and are systemic, with both therapeutic and protective qualities. Fungicidal control can also include seed treatment fungicides, and triadimenol plus fuberidazole is recommended for wheat seed treatment in New Zealand (Hedley and McCloy, 1982; Risk and Beresford, 1982). Fungicide use on wheat has increased in crops both overseas (Jenkins and Lescar, 1980) and in New Zealand (Noonan and Close pers. comm., 1984). The pervasive and unrestrained use of some fungicides has led to the dramatic decline of fungicide efficacy and the build up of fungicide resistant sub-populations of some non-rust plant pathogens (Dekker, 1976; Holloman 1978; Delp, 1980; Edgington et al., 1980). Scheduled spray programs attempt to eradicate diseases and maintain disease-free crops. However, diseases are a natural component of an agro-ecosystem and as such, attempts to maintain a disease-free crop have often led to a failure to do so (Zadoks and Schein, 1979; Jenkins and Lescar, 1980). Many wheat growers do not inspect crops regularly in New Zealand and the need to spray at short notice may cause logistic problems when utilizing contract spray companies. Both these factors predispose the grower to adopt either no treatment or to use scheduled fungicide sprays on susceptible or resistant cultivars which may not optimize fungicide use.

The current recommendations for stripe rust control in New Zealand are to treat seed with triadimenol plus fuberidazole, to spray at the "first sign" of disease with triadimefon or propiconazole and to spray again if reinfection occurs up to anthesis (Ministry of Agriculture and Fisheries, 1983). This is vague and difficult to implement because it lacks definition. Some growers carry out scheduled sprays every four weeks after first sign, while others automatically apply fungicide when applying herbicides at early growth stages. "First sign" is not well defined and can mean something different to each grower, especially since there is no recommended sampling technique.

1.4 OBJECTIVES

Rongotea, a stripe rust susceptible wheat cultivar, is the most widely grown cultivar in New Zealand because it has high yields and acceptable bread making quality. Since this cultivar is popular with growers, the focus of this study was to develop a stripe rust management program to optimize fungicide usage.

The objectives of this study were as outlined below.

1. To develop a quick and reliable sampling plan to be used in a stripe rust research program.

2. To define stripe rust severity-incidence relationships.

3. To define the spatial pattern of stripe rust infections in the field.

4. To analyze the stripe rust severity-yield relationship and establish action levels to be used in stripe rust management.

5. To develop and validate a sequential sampling plan for the implementation of a stripe rust management program.

In Chapter 2, a comparison of sampling techniques and the selection of a reliable sample unit, sample unit pattern and sample number for stripe rust are reported. The relationship between severity and incidence is also described quantitatively.

Chapter 3 reports the investigation of spatial patterns of stripe rust both in field and field plot situations. The spatial patterns of stripe rust infections are analyzed and quantified through the use of frequency distributions and dispersion indices at different density levels through the season.

In Chapter 4, the severity-yield loss relationships of stripe rust are analyzed from field trials in three seasons, and action levels are defined.

In Chapter 5, the sampling technique, spatial pattern, incidence-severity relationship and action level for stripe rust are integrated to develop and validate a sequential sampling plan for the implementation of a stripe rust management program.

CHAPTER 2

SAMPLING AND ASSESSMENT OF STRIPE RUST

2.1 INTRODUCTION

Sampling may be used as a procedure to estimate a population size or density as an alternative to taking a census or examining every individual in a population. With large populations, a census approach is often impractical (Pielou, 1974). A sample is a relatively small proportion of individuals drawn from a population and therefore samples are examined to estimate the population size. The physical form or size of the sample is the sample unit while the manner in which sample units are examined throughout a field is the sample pattern (Southwood,1966; Ruesink,1981). The magnitude of the difference between the true population density or size, and that estimated from sampling, is the measure of reliability of the method chosen (Karandinos, 1976).

Sampling techniques include random or stratified sampling programs (Southwood,1966; Pielou,1974; Kuno, 1976). Random sampling assumes homogeneity in the field and hence every sample unit has an equal probability of containing an individual. However, natural habitats are rarely homogeneous,making random sampling invalid in those situations where there are differences in the habitat sampled. Stratified sampling divides a field into a number of subdivisions, with samples taken randomly in each subdivision, thus minimizing the effect of heterogeneity. Stratified sampling may be carried out at different levels. Two stage sampling divides an area into a number of sub-divisions which in turn can be divided into smaller sample units. Multistage sampling is an expansion of two stage sampling. Two stage and multistage sampling are particularly useful for monitoring orchard pest populations where samples can be easily divided into trees, twigs and leaves (Kuno, 1976; Zahner and Baumagaertner, 1984).

Systematic sampling is another stratified sampling technique in which sample units are examined systematically on a predetermined path through the field. The use of systematic sampling has become one of the most widely accepted sampling techniques for diseases of field crops (Aube, 1967; James, 1969; Berkenkamp, 1971; Basu et al., 1977). Stratified sampling is usually more reliable than random sampling (Southwood, 1978). Sampling reliability is influenced by the selection of sample unit and pattern, which should be based on a knowledge of the spatial pattern (Southwood, 1966; Church, 1971; Basu et al., 1977), and the methods of assessment of an organism (Teng, 1983).

Sampling is a major component of pest management programs and an integral part of studies on pesticide efficacy, severity-yield loss relationships and the biology and ecology of pests (James, 1974; Watson et al., 1975; Walker, 1981; Teng, 1983). To construct a pest management sampling program the following requirements should be met (Morris, 1960; Church, 1971; James, 1974; Walker, 1981; Teng, 1983): a clearly defined sample unit, sample pattern and sampling frequency, a quick and simple sampling procedure, a method to measure pest severity or density, a standardized degree of reliability in the use of the sampling program and a defined relationship between pest population sample estimates and crop yields.

The choice of the sample unit may influence the estimation of severity or incidence and the description of the spatial pattern of a pest population (Grieg-Smith, 1952; Kuel and Fye, 1972; Pielou, 1974; Hopkins et al., 1981; Teng, 1983; Seem, 1984). Sample units must include the location of organisms studied (eg. leaves, stems, roots, soil etc.) and should be large enough to detect the organism with an acceptable level of reliability, depending on the sample purpose (Pielou, 1974; Pedigo, 1981). Morris, (1960) recommended several factors to consider when selecting a sample unit, including: stability or a measurable change between samples, a constant proportion of the population utilizing the sample unit, ease of identification and an acceptable balance between sampling time and reliability. Sample units used for foliar diseases of cereals include all green leaves, upper four, three, two or uppermost leaves only on single tillers (James _et_ _al_., 1971; Anon, 1972; James and Shih, 1973; Jenkins and Storey, 1975; Cook, 1980) or ten consecutive tillers along a drill row (Rouse _et_ _al_., 1981).

Once a sample unit has been selected, the locations where sample units are examined in the field (sampling pattern) must be determined. Selecting random samples is difficult and impractical in a large field situation (Church, 1971). Systematic sampling patterns used in foliar disease sampling include a diagonal pattern (James, 1969; Berkenkamp, 1971; King, 1972), a "V" (Harper and Piening, 1974), an "X" (Aube, 1967) and a "W" pattern (James, 1971; Basu _et_ _al_., 1977). Selection of arbitrary paths for field sampling can lead to unreliable results, especially if the organism studied occurs in clusters (Basu _et_ _al_., 1977). Studies of sampling programs by Basu _et_ _al_., (1977), Lin _et_ _al_., (1979), Hau _et_ _al_., (1982) and Poushinsky and Basu, (1984) showed that, in populations which were aggregated, sampling patterns which had a wider field coverage, of which a "W" pattern was the most reliable, were more reliable than lower field coverage patterns such as diagonals.

Disease assessment is necessary to establish disease-yield relationships, test fungicide efficacy and screen for resistance in plant breeding programs (Large, 1966; James, 1974). Assessment methods should be standardized so that similar results may be obtained by several sampling personnel (James, 1974) and to compare crop performance at different growth stages and locations (Preece, 1971). They should also accurately assess the actual diseased area and be quick and simple to use (James, 1974; James, 1977). Disease assessment may be divided into direct and indirect methods.

Direct disease assessment methods measure disease as severity (James, 1974). Severity is defined as the area of plant tissue affected by a disease, often expressed as a percentage. Direct disease assessment may be aided by descriptive keys, standard area diagrams and automated measurement systems. Descriptive keys categorize severity by a class, number, index or grade (James, 1974). Several descriptive keys have been used, including those developed for potato blight (Anon., 1947), powdery mildew on cereals (Large and Doling, 1962) and stripe rust on wheat (Zadoks, 1961; Emge and Shrum, 1976). Standard area diagrams are pictorial representations of disease on specific plant parts or on whole plants (Large, 1966; James, 1974). Many standard area diagrams have been developed for a wide range of diseases and host plants, including foliar diseases of cereals (James, 1971; Anon., 1972; Saari and Prescott, 1975). Standard area diagrams improve consistency by reducing some sampler subjectivity (James, 1971). James (1971) suggested that percentage standard area diagrams have several advantages over descriptive keys. Visual assessment may vary among observers as a result of observer subjectivity and visual limitations of the human eye to discriminate the intensity of visual stimulus as described by the Webber - Feckner Law (Horsfall and Barratt, 1945). Percentage scales are recommended for use rather than scales such as the modified Cobb Scale (Melchers and Parker, 1922), which pre-sets the maximum possible amount of rust as 100%, but where the actual area occupied by disease is only 37%. Although the human eye detects disease severity logarithmically (Horsfall and Barratt, 1945), interpolation between depicted levels on a percentage linear scale gives an accurate estimation of severity (James, 1974). Both severity and incidence can be recorded in the process of determining the percent severity through the use of standard area diagrams, while this is not always possible with descriptive keys (James, 1974).

Severity may be assessed by more objective techniques which reduce observer error. Planimeters have been used by James (1971) and Lindow and Webb (1983); however, the procedure is much more time consuming than using standard area diagrams and may be practical only for the calibration of other methods. Lindow and Webb (1983) recently developed a microcomputer-based video image analysis technique which offers an extremely accurate method of disease assessment and may be used in future disease assessment studies. At present the technique is not rapid enough for routine analyses.

Indirect disease assessment involves measuring a factor which can be related to the disease. Indirect assessment methods include remote sensing of factors such as temperature, by infra-red thermography (Pinter *et al.*, 1979), infra-red aerial photography (Wallen and Jackson, 1971; Toler *et al.*, 1981) or reflectance (Cardenas *et al.*, 1970). Spore counts have also been used to characterize epidemics of cereal rust (Burleigh *et al.*, 1969; Dirks and Romig, 1970; Eversmeyer and Burleigh, 1970). Disease severity may be estimated by measuring disease incidence, and has been used for estimating the severity of coffee rust (Rayner, 1961), powdery mildew on wheat (James and Shih, 1973), barley leaf rust (Teng, 1978) and bean rust (Imhoff *et al.*, 1982). Incidence is the number of infected units, often expressed as a percentage of the total number of units examined (James and Shih, 1973). In the early stages of some disease epidemics there is a good relationship between the increase in severity and incidence. Incidence increases proportionally with severity up to a point at which a shortage of uninfected plants occurs and incidence changes little while the severity increases (Gregory, 1948; Seem, 1984). The severity-incidence relationship for some diseases at the upper incidence range may not be valid due to a high level of variance (Seem, 1984) and, for this reason, this method is best used for the earlier stages of epidemics when disease progress is the result of increases in both incidence and severity (James and Teng, 1979). An incidence range of 0-65% was used to describe the linear relationship between severity and incidence on the flag leaf and the first leaf below the flag leaf for barley leaf rust caused by Puccinia hordei (Teng, 1978) and leaf rust of wheat caused by Puccinia recondita (James and Shih, 1973). Similar relationships were shown for disease on the flag leaf and the first, second and third leaf down from the flag leaf for powdery mildew on wheat caused by Erysiphe graminis tritici (James and Shih, 1973). Studies of E. graminis tritici by Rouse et al. (1981) indicated that severity-incidence relationships were not constant between leaf positions, sites or seasons due to changes in environmental factors. A consistent severity-yield relationship, or an adjustment for variations in season and location, is required to estimate severity by measuring incidence in a disease management program. Incidence sampling, although it may not be as reliable as direct severity assessments, greatly reduces sampling time and in practice may be the only assessment in a field situation which is adequately standardized to be used by several sampling personnel (James, 1974; Horsfall and Cowling, 1978).

Information on the host plant growth stage should be included in sampling programs to provide meaningful comparisons of samples and the analysis of severity-yield loss relationships (Church, 1971; James, 1974). The Feekes scale, revised by Large, (1954) is used to identify cereal growth stages, but has been criticized for its vagueness, particularly in the early growth stages (Tottman et al., 1979). Zadoks et al. (1974) developed a more accurate and detailed method which divides cereal growth into more categories throughout the life cycle and labels each growth stage with a decimal code. Because of the added detail, accuracy and the ease of computation, the decimal growth code is now widely used and accepted.

The work described in this section had the following objectives.

1. to select a sampling method (sample unit and pattern)

for the study of stripe rust spatial patterns in the field and for use in a stripe rust management sampling program,

2. to describe stripe rust severity-incidence relationships for the development of a quick and reliable assessment method to be used in a stripe rust management sampling program.

2.2 MATERIALS AND METHODS

2.2.1 An Investigation of Sampling Methods

During the 1982 season, four fields sown with wheat cv. Rongotea were sampled using four sampling methods. All fields were located at Lincoln College, and ranged in size from 3.5 to 12.0 ha. Seed was treated with triadimenol + fuberidazole (15g + 2g a.i./100kg seed) and was sown in the autumn (May 25 to June 22).

Sample patterns and sample units were selected to provide maximum contrast between sample size, number and field coverage, based on studies by Basu *et al*. (1977) and Rouse *et al*. (1981). At each sampling time one thousand tillers were sampled using each of the following methods.

Method A. One hundred sample units of 10 consecutive tillers along a drill row, dispersed evenly along a W-shaped pattern in the field.

Method B. Ten sample units of 100 consecutive tillers along a drill row, dispersed evenly along a W-shaped pattern in the field.

Method C. One hundred sample units of 10 consecutive tillers along a drill row, dispersed evenly along a diagonal pattern in the field.

Method D. Ten sample units of 100 consecutive tillers along a drill row, dispersed evenly along a diagonal pattern in the field.

Each sampling unit consisted of the top three fully expanded green leaves on either ten or one hundred consecutive tillers along a drill row. Only leaves one, two and three were assessed (leaf one being the uppermost leaf) because of time constraints and the fact that leaf four was often senesced. The number of tillers with stripe rust infection on any of the top three leaves was recorded for each sample unit. The distance between sampling units varied with field size, based on the length of the paths which composed the "W" or diagonal pattern. Sample units were chosen directly in front of the right foot at each site. Sampling was initiated at growth stage (G.S.) 14 (Zadoks _et al_., 1974) and ceased after the first fungicide application to control stripe rust.

For each sample method, the mean percent incidence per sample unit, variance and relative variability was calculated from data at each sample time. Percent relative variability (% R.V.) is a measure of the sample variability relative to the sample mean and is calculated using the equation: $\%RV = SE/\bar{X}\ (100)$ (Hopkins _et al_., 1981) where SE = standard error and $\bar{X}$ = mean sample incidence. Relative variability measures the reliability of a sampling method (Zar, 1974; Ruesink, 1981) and may be used to compare sampling methods (Hillhouse and Pitre, 1974; Hopkins _et al_., 1981; Ruesink, 1981; Huber pers. comm., 1984). Mean percent incidence per sample unit and %RV values on each sampling method for each sampling time were arc-sine transformed before analysis by ANOVA of a 2 X 2 factorial design.

2.2.2 Severity - Incidence Relationships

In the 1981, 1982 and 1983 seasons, field plots 32 x 16m, 15 x 5m and 12 x 12m respectively were sown with wheat cv. Rongotea on Lincoln College Farms and sampled in conjunction with severity-yield experiments (Chapter 4). The wheat seed was treated with triadimenol + fuberidazole (15g + 2g a.i./100kg seed), sown in the autumn (May 25 to June 12) and sprayed with triadimefon (125g a.i./ha) several times for stripe rust control. For a detailed description of crop management and history see Chapter 4. In each field plot five plants were removed at equal intervals down each side of the plots, approximately 1.5m from the plot edge to avoid the influence of neighboring plots. Stripe rust severity was assessed visually, using standard area diagrams (Anon., 1973), based on the leaf area covered with stripe rust pustules and any directly related chlorosis. All green, fully expanded leaves on the main stems were assessed. Stripe rust incidence, defined as the percent of stripe rust infected leaf units per plot, was recorded at the same time as severity assessment. Growth stages were recorded using the decimal scale (Zadoks <u>et al</u>., 1974) and sampling was initiated at G.S. 14 and continued once every two weeks in 1982 and weekly in 1981 and 1983 until leaves senesced.

During the 1982 and 1983 seasons, four and ten commercial fields, respectively, of autumn sown (May 25 to June 22) wheat cv. Rongotea were sampled. In both seasons all seed was treated with triadimenol + fuberidazole (15g + 2g a.i./100kg seed). All fields were located within a 10km radius of Lincoln College. Triadimefon (125g a.i./ha) was applied for stripe rust control at times based on the growers' judgement. Sampling Method A (Section 2.2.1) was used, with a "W" sampling pattern and a sample unit of the top three leaves on ten consecutive tillers along a drill row. Stripe rust severity was assessed on the top three and top two leaves, leaf one, leaf two and leaf three, using standard area diagrams (Anon., 1973), for each ten tiller sample unit.

Mean stripe rust incidence per sample unit, i.e. the number of infected leaf units per ten tiller sample unit, was calculated. Fields in 1982 were sampled every two weeks, starting at G.S. 14 and ending at G.S. 59. In 1983, the fields were sampled weekly, starting at G.S. 14, ceasing after each triadimefon application and resuming after a three week period, up to G.S. 59 (anthesis). The three week period was based on the predicted fungicidal activity of triadimefon (O'Connor, 1984). Severity on the top three and top two leaves was the mean of the values on leaves one, two, three or one and two, respectively. Incidence on the top three or top two leaves was the presence or absence of stripe rust on any of the leaves which made up the top three or top two leaves, respectively. Stripe rust severity was linearly regressed on incidence for the top three and top two leaves, leaf one, leaf two and leaf three for each seasons field and field plot data individually. Slope values from regression equations were analyzed for significant differences ($P \geq 0.10$) using F-tests (Zar, 1974; Jones and Parrella,1984). If there were no significant differences between slope values, the data were pooled and linear regression was performed on the pooled data.

2.3 RESULTS AND DISCUSSION

2.3.1 Investigations of Sampling Methods

The percent stripe rust incidence and percent relative variability values were calculated for each sampling method at each sampling time and mean values were calculated over all sampling times (Table 2.1). Method A (one hundred, 10 tiller sample units taken on a "W" pattern) had the lowest %RV values consistently, with a mean %RV of 11.26% ($\pm$ 1.10%). A %RV value of 25 is the recommended limit for a sampling method to be acceptable for use in a pest management program (Southwood, 1966; Hopkins *et al.*, 1981; Huber pers. comm.(1984).

The other sampling methods had %RV values greater than 25, indicating that these methods may be too variable to provide a reliable sample method. Sampling Method A had the highest sensitivity for detecting stripe rust, as measured by incidence, with a mean incidence value from all samples of 13.00% ($\pm$ 6.10%) compared with 4.39%, 4.15% and 4.42%. Method B, C and D respectively (Table 2.1).

The main effect of sample pattern on %RV values was significant but the main effect of sample unit size and the interaction of sample unit size and sample pattern were not significant (Table 2.2). Sample methods which utilized a "W" pattern had a mean value of 5.0% RV greater than the mean %RV value for sampling methods which utilized a diagonal pattern. The main effect of sample pattern on the percent incidence was also significant (Table 2.2), with the mean value of methods utilizing a "W" pattern yielding a 5.8% incidence increase compared to methods which utilized a diagonal pattern; however, the main effect of sample size and interactions of sample pattern and sample unit size were not significant (Table 2.2).

The higher degree of reliability (as measured by lower %RV values) and higher degree of sensitivity (as measured by higher percentage incidences) of sampling Method A could be attributed to the increased field coverage by a "W" pattern compared to a diagonal pattern. A "W" sampling pattern was found to be effective for sampling in field situations (James, 1971; Basu et al., 1977; Lin _et_ _al_., 1979; Hau _et_ _al_., 1982; Poushinsky and Basu _et_ _al_., 1984). In aggregated disease spatial patterns a "W" pattern has been found to be superior to sampling patterns with less field coverage (Basu _et_ _al_., 1977). The fact that the "W" pattern was superior in the study may indicate that stripe rust infections were aggregated. Increased sample number may also increase reliability (Pielou, 1974). Increased sample unit size has been shown to influence sample reliability (Grieg-Smith, 1952; Kuel and Fye, 1972; Pielou, 1974); however, in this experiment a larger sample unit size did not decrease %RV

Table 2.1: The sensitivity of stripe rust detection as measured by incidence (%) and reliability as measured by RV(%) of four sampling methods in commercial fields during the 1982 - 83 season.

	Sampling Methods							
Pattern	W		W		/		/	
Unit	100 x 10 tillers		10 x 100 tillers		100 x 10 tillers		10 x 100 tillers	
Sample Number	Inc.[+]	RV[++]	Inc.	RV	Inc.	RV	Inc.	RV
1.	0.00	-	0.00	-	0.00	-	0.00	-
2.	1.30	8.46	0.60	27.43	2.00	40.00	0.20	66.46
3.	22.60	13.89	6.20	29.86	6.19	5.94	6.19	30.78
4.	79.20	2.78	20.10	10.00	17.20	7.36	17.20	7.36
5.	0.00	-	0.00	-	0.00	-	0.00	-
6.	0.90	8.89	0.49	44.30	0.10	41.67	0.10	101.27
7.	16.30	13.87	16.81	18.27	25.00	11.64	25.00	12.25
8.	0.30	10.00	0.02	67.08	0.00	-	0.00	-
9.	1.30	13.85	0.27	55.90	0.10	100.00	0.00	-
10.	22.90	13.36	6.80	24.90	1.68	6.71	6.78	24.23
11.	0.30	10.00	0.02	67.08	0.00	-	0.00	-
12.	1.80	15.00	0.50	68.35	0.10	36.00	0.40	55.38
13.	22.70	13.79	5.30	23.41	1.62	5.99	1.60	18.95
$\bar{X}$	13.00	11.26	4.39	39.69	4.15	28.40	4.42	39.56
SEM	6.10	1.10	1.88	6.50	2.12	10.30	1.95	11.40

[+]Percent of tillers examined with stripe rust infection on the top 3 leaves

[++]Percent relative variability

Table 2.2: Factorial analysis of the effects of sample unit size (10 vs. 100 tillers) and sample pattern (W vs./) on the sensitivity of detecting stripe rust on the top 3 leaves, as measured by incidence, and reliability, as measured by relative variability (RV).

	% sum of squares accounted for	
Source of variation	RV#	Inc.#
Sample unit size	2.05	1.83
Sample pattern	23.91 ***	3.77 **
Sample unit size X Sample pattern	0.07	1.40
Residual mean square (D.F.)	138.2 (21)	37.32 (36)

** Significant F-test at P ≧ 0.05

*** Significant F-test at P ≧ 0.01

Percentage values from top three leaves arc-sine transformed for analysis

D.F. Degrees of freedom

values nor increase sensitivity, possibly because of the low range of sizes (10 to 100 tillers) sampled. Systematic stratified sampling plans which use numerous small sample units and a sampling pattern with a wide field coverage have been generally recommended for use in pest management sampling programs (Morris, 1960; Pedigo, 1981). Method A offers a reliable and sensitive sampling plan for stripe rust.

2.3.2 Severity-Incidence Relationships

The severity-incidence regressions for leaf one, two, three, top two and top three leaves are summarized in Table 2.3. Only incidences below 40% were included in the regressions, since it was assumed that 40% would be near the upper limits of stripe rust encountered in commercial fields where a stripe rust management plan was used. There was a high degree of variation above 40% incidence, as seen for the top three leaf composite (Figure 2.1). A similar result was found for individual leaves and the top two leaf composite. No attempt was made to fit a regression to data for the 0-100% incidence range because of the observed large variation in the upper incidence ranges, as found in other foliar cereal diseases (James and Shih, 1973; Teng, 1978; Rouse et al.,1981).

The top three leaf composite had the highest r^2 values for both field plot and field data (Table 2.3), indicating that a sample unit composed of the top three leaf composite would yield the best estimate of severity from incidence measurements. The relationship remained consistent from season to season, site to site and sample to sample as seen in the non-significant ($P \geq 0.10$) differences between slope values of regression equations (Zar, 1974; Jones and Parrella, 1984) for all data sets. Different fungicide applications from season to season did not alter the severity-incidence relationship. Top three leaf data were pooled for all seasons and for field and field plots and a regression was performed which yielded the equation: % Severity = -0.01 + 0.02 (% Incidence) with an r^2 value of 0.75 (Figure 2.2). Leaf three and leaf two data were also pooled since there were no

Table 2.3: The relationship between incidence (%) and severity (%) of stripe rust on several sample units in field and field plot surveys of wheat cv. Rongotea from trials in 1981, 1982 and 1983.

Sample Unit	Regression Parameters and Coefficients *			
	No. obs.	Intercept	Slope	r^2
Top Three Leaves				
1981 Field Plots	10	-0.06	0.03	0.86
1982 Fields	10	0.02	0.01	0.95
1982 Field Plots	13	0.00	0.01	0.89
1983 Fields	45	-0.01	0.02	0.87
1983 Field Plots	31	-0.01	0.02	0.75
Pooled data +	109	-0.01	0.02	0.75
Top Two Leaves				
1981 Field Plots	8	0.02	0.01	0.88
1982 Fields	10	-0.05	0.04	0.57
1982 Field Plots	31	-0.04	0.04	0.52
1983 Fields	25	-0.07	0.04	0.67
1983 Field Plots	54	-0.05	0.02	0.59
Leaf Three				
1981 Field Plots	13	0.21	0.05	0.26
1982 Fields	10	-0.06	0.05	0.75
1982 Field Plots	19	0.17	0.04	0.79
1983 Fields	41	0.11	0.06	0.38
1983 Field Plots	36	-0.37	0.08	0.72
Pooled data +	119	-0.11	0.05	0.54
Leaf Two				
1981 Field Plots	8	-0.06	0.02	0.83
1982 Fields	10	-0.10	0.08	0.57
1982 Field Plots	15	-0.09	0.04	0.59
1983 Fields	27	-0.14	0.06	0.48
1983 Field Plots	54	-0.10	0.04	0.52
Pooled data +	114	-0.07	0.04	0.59
Leaf One				
1983 Field Plots	54	-0.01	0.04	0.36
1983 Fields	25	-0.07	0.06	0.89

* All linear regressions were significant, based on F-tests at $P \geq 0.10$ (Zar, 1974).

\+ Severity and incidence data from all samples combined and a common regression performed since slope values were not significantly ($P \geq 0.10$) different (Zar, 1974)

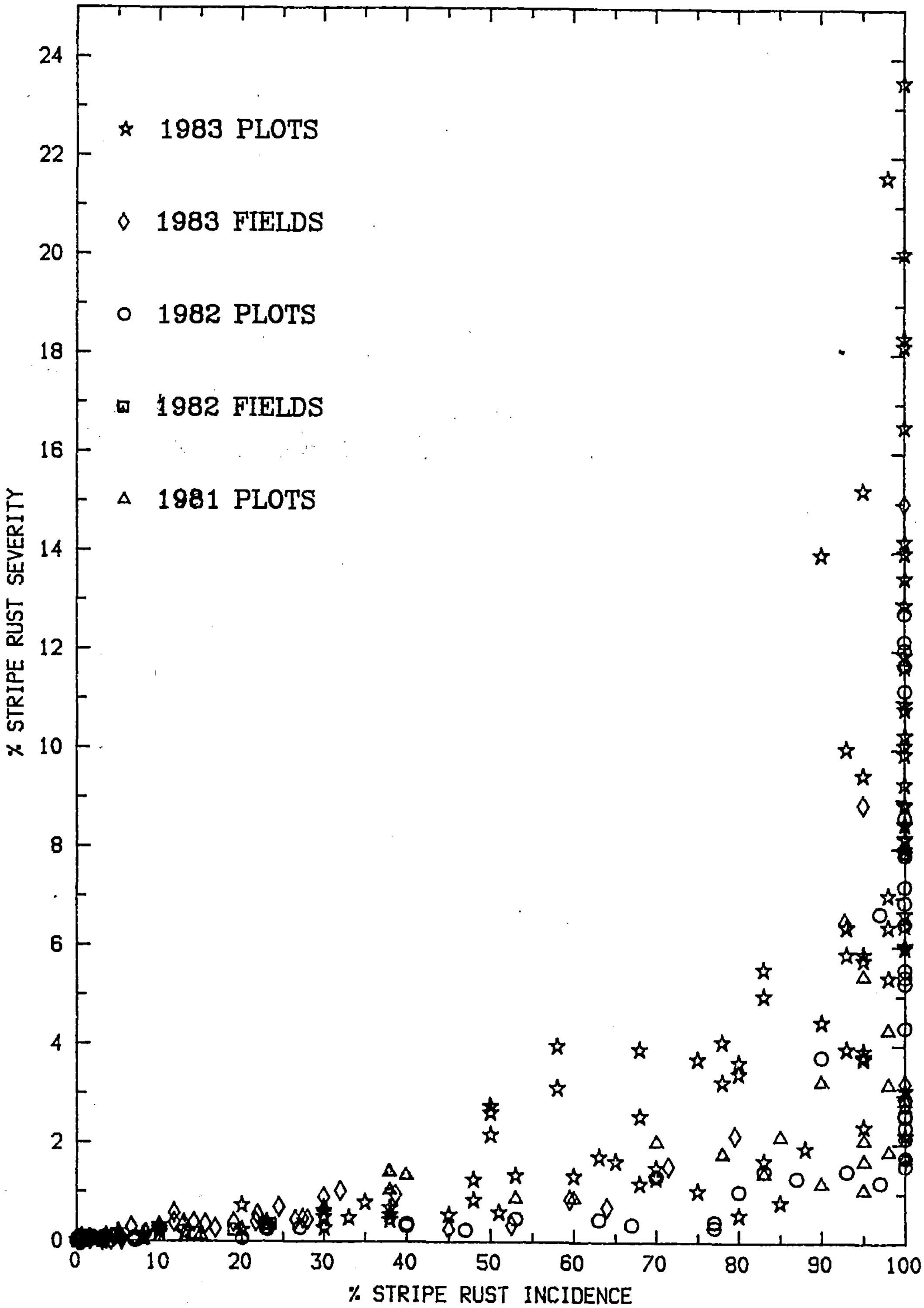

Figure 2.1: Distribution of severity-incidence data from the top three leaves over a 0-100% incidence range.

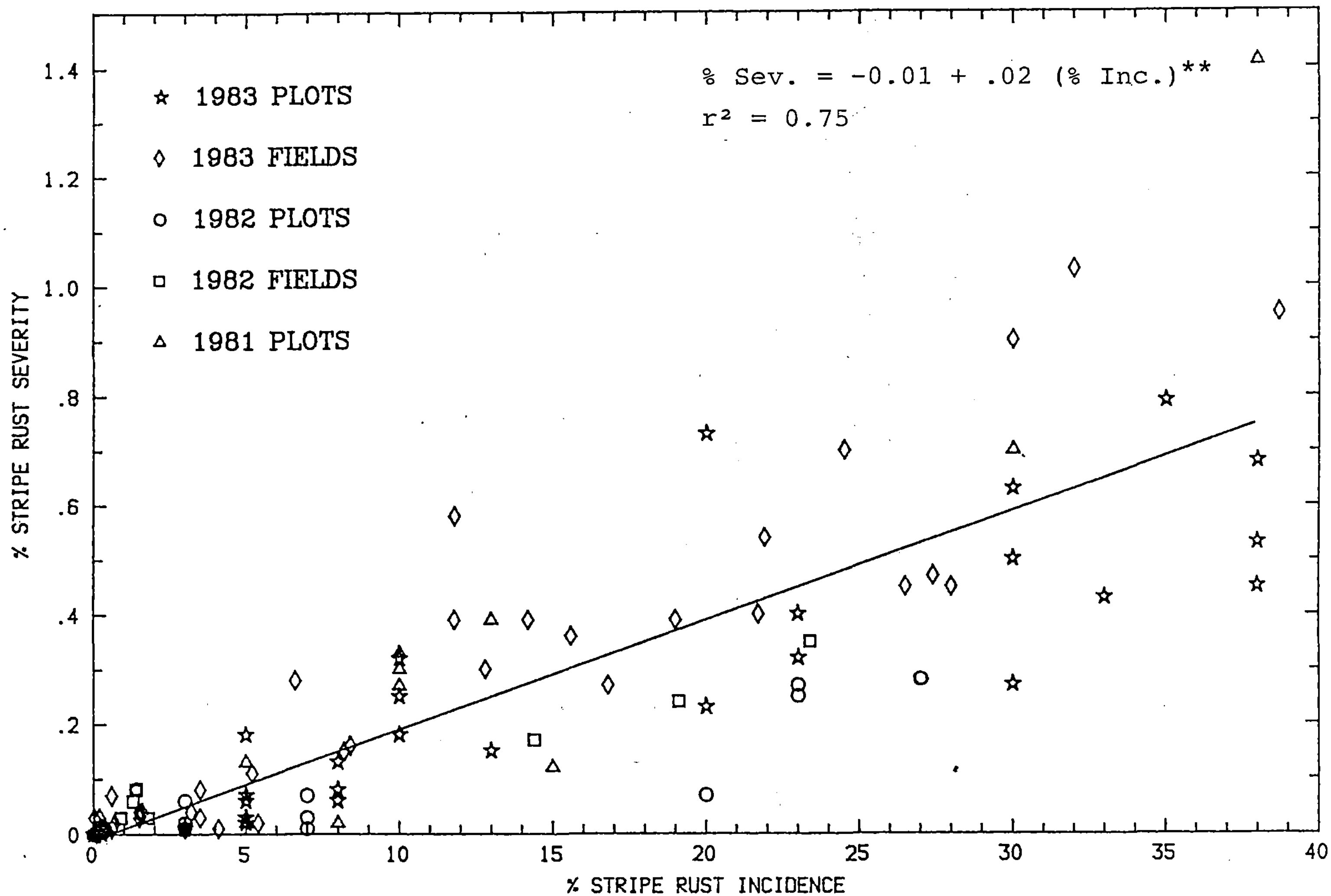

Figure 2.2: Relationship between stripe rust severity (%) and incidence (%) for stripe rust infections on the top three leaves below 40% incidence.

significant differences among slope values; however, the r^2 values were 0.54 and 0.59, indicating that these relationships may not be as good as the top three leaf composite. Leaf one and top two leaf regression were not pooled due to significant difference between slope values. Increased consistency of severity-incidence relationships through the use of leaf composites was reported by Rouse et al. (1981). The use of leaf composites as the basis for estimating severity from incidence may have an averaging effect for differences throughout the canopy. Influences of microclimate in the wheat canopy, such as differences in relative humidity (Begg et al., 1964; Denmead, 1969) and changes in host plant factors such as nitrogen levels and differences between leaf positions, may cause variable spore germination, thus leading to different severity-incidence relationships for different leaves (James and Shih, 1973). Increasing the number of leaves sampled per sample unit may also reduce variability for that sample unit.

A reliable estimate of stripe rust incidence was accomplished by sampling the top three green, fully expanded leaves on a sample unit of ten consecutive tillers along a drill row, taken systematically along a "W" pattern in the field. Incidence sampling may be used effectively by a wide range of sampling personnel and under various conditions encountered in commercial fields. Severity, which is used to relate disease directly to yield, can be reliably estimated from incidence sampling using the regression equation % Severity = -0.01 + 0.02 (% Incidence). This information on sampling is incorporated with the study of stripe rust spatial patterns (Chapter 3) and action levels (Chapter 4) to form the basis for a sequential sampling plan for stripe rust management (Chapter 5).

CHAPTER 3

SPATIAL PATTERN ANALYSIS OF STRIPE RUST INFECTIONS

3.1 INTRODUCTION

Analysis of the spatial pattern of a disease is an essential component in developing a disease management program and provides a basis for the selection of a sampling program which reliably estimates disease in the field (Teng, 1983). A spatial pattern is the arrangement of diseased host units among healthy ones (Pielou, 1974; Teng, 1983). Information gained from spatial pattern analysis may also be used to gain a better understanding of the ecology, reproduction and dispersal of an organism (Bliss and Fisher, 1953; Waters, 1959; Gitaitis et al., 1978; Rouse et al., 1981; Taylor et al., 1981). Spatial pattern analysis can be influenced by the selection of sample units, patterns and size (Pielou, 1974; Lin et al., 1979; Hau et al., 1982; Teng, 1983) and must be defined to construct a sequential sampling program for disease management (Onsager, 1976; Iwao, 1975). Spatial patterns can be classified into three basic models; random, aggregated and uniform (Pielou, 1974) as illustrated in Figure 3.1. A random spatial pattern is one in which all sample units have equal probabilities of being infected, and is characterized by having a sample mean equal to the sample variance. With aggregated patterns, the presence of disease in a particular sample unit increases the chance of detecting disease in an adjacent or nearby sample unit, and is characterized by having a sample mean less than the sample variance. Uniform spatial patterns are rigidly structured and are characterized by having a sample mean greater than the sample variance. Populations are seldom truly random or uniform since field conditions are rarely homogeneous and reproductive and dispersal characteristics are often contrary to the basic assumptions required for the formation of these two spatial patterns (Pielou, 1974; Southwood, 1978).

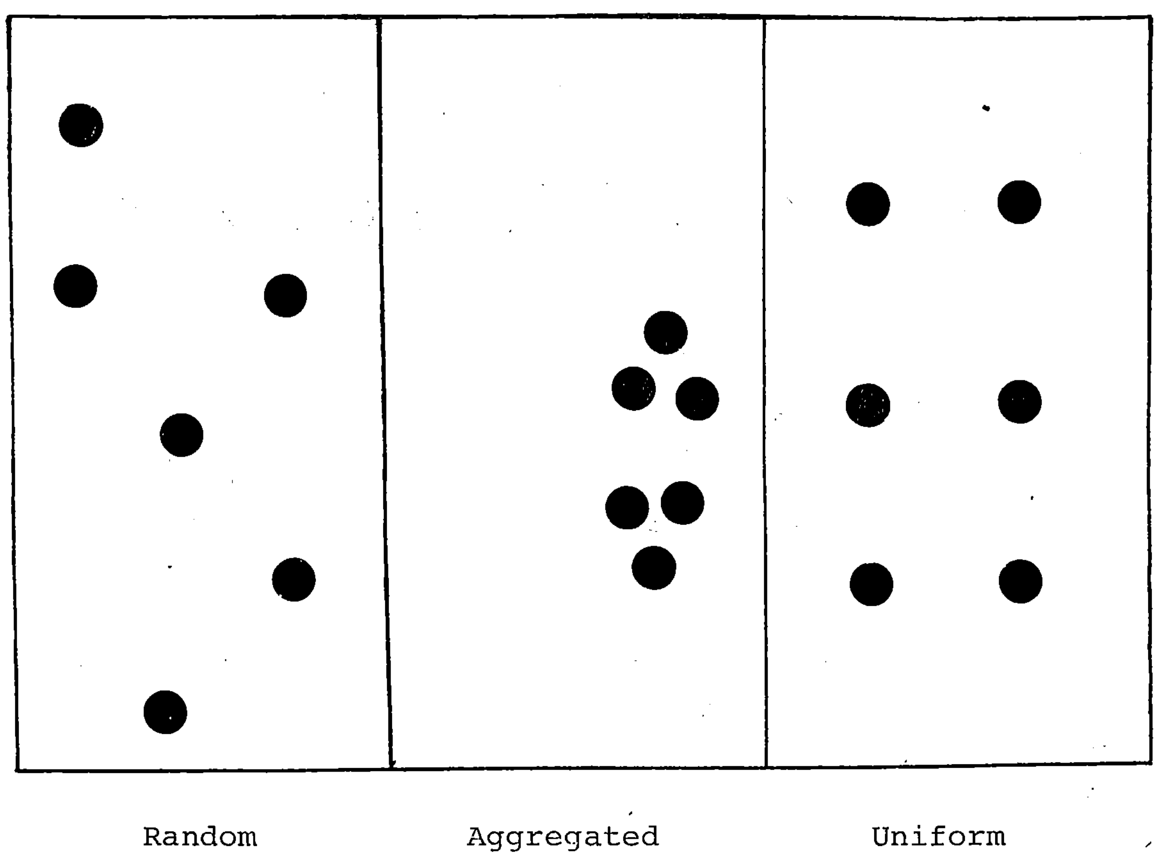

Figure 3.1: Diagramatic examples of random, aggregated and uniform spatial patterns.

Statistical methods of fitting observed frequency distributions to theoretical distribution models, dispersion indices, and methods which take account of location and distance between infections, can be used to define spatial patterns. A frequency distribution is the number of sample units examined which contain a specific number of infected units, i.e. the number of sample units with one or two or three etc. infections on the top three leaves or tillers. Observed frequency distributions can be fitted to theoretical frequency distribution models which represent random, aggregated and uniform spatial patterns. This type of spatial pattern analysis has been used to define the spatial pattern of various plant pathogens (Strandberg, 1973; Brewer *et al*., 1981; Rouse *et al*., 1981; Taylor, 1981; Hau *et al*., 1982; Shew *et al*., 1984).

Random spatial patterns can be defined by a Poisson model, which has the assumptions that every organism unit has the same probability of occurring in any sample unit, all sample units have the same probability of having an infection present, and the presence of one infection in a sample unit does not affect the probability of there being another infection present in the same sample unit (Pieters and Sterling, 1973). There are few examples in which only the Poisson model fits the observed population, because most biological populations contradict one of the basic assumptions of the model (Pielou, 1974; Southwood, 1978). Low density populations have been defined by a Poisson model, as seen in studies of cotton insect pests, *Heliothis* spp., (Kuel and Fye, 1972) and bacterial black rot (*Xanthomonas campestris*) of cabbage (Strandberg, 1973).

The remaining frequency distribution models discussed define aggregated spatial patterns. The negative binomial model is a widely applicable model to many biological populations and is characterized by the mean and the positive exponent K, which is a measure of aggregation (Bliss and Fisher, 1953). The model fits situations where heterogeneiety of field conditions exist, such as physical or host plant factors, where the reproductive and dispersal characteristics increase the probability of finding infections in adjacent sample units and where infections occur in foci which are randomly distributed and the number of infected units in each focus follows a logarithmic distribution (Waters and Henson, 1959). Spatial patterns of several plant pathogens have been defined by a negative binomial model, including bacterial black rot of cabbage (Strandberg, 1973), powdery mildew (E. graminis) of wheat (Rouse et al., 1981) and cylindrocladium black rot (Cylindrocladium crotaloriae) of peanuts (Hau et al., 1982).

The Neyman type A model (Neyman, 1939) describes a spatial pattern formed by randomly dispersed aggregates and was originally used to define the spatial pattern of European corn borer larvae (Ostrinia nubilalis). The model can account for situations where propagules are deposited in clusters, organisms disperse equally in all directions after an initial Poisson distribution, and dispersal distance is limited from the original sites of deposition. Neyman type A models have been used to define the spatial patterns of E. graminis on wheat tillers (Rouse et al., 1981) and peanut stem rot caused by Sclerotium rolfsii (Brewer et al., 1981).

Other frequency distribution models have not been utilized as much as the negative binomial or Neyman type A models to define plant pathogen spatial patterns. The Poisson binomial model (McGuire et al., 1957) defines similar spatial patterns as those defined by Neyman type A model, except that organisms arising from propagule clusters follow a binomial distribution. Other frequency distribution models similar to the Neyman type A model are Poisson with zeroes (Cohen, 1960) and Logarithmic with zeroes (Nielsen, 1964). The Thomas double Poisson model (Thomas, 1949) was developed to define aggregated plant population spatial patterns in which a plant species is randomly dispersed throughout an area with a number of other species associated with them, and is almost exclusively used for plant ecological studies.

There are several difficulties and limitations to the interpretation and use of frequency distributions to define spatial patterns. The form and size of a sample unit may affect the apparent distribution (Grieg-Smith, 1952; Waters and Henson, 1959; Pielou, 1974). The model that fitted the observed frequency distribution of *Heliothis* spp. larvae on cotton changed from Poisson to a negative binomial model with an increase in sample size (Hopkins *et al.*, 1981). The Neyman type A model fitted the observed frequency distribution of *E. graminis* on wheat tillers, but on individual leaves the negative binomial model fit the observed frequency distributions better than the Neyman A (Rouse *et al.*, 1981). Field populations rarely remain constant and frequency distribution models may be density dependent (Pielou, 1974). Thus the frequency distribution model fitted to observed distributions may change throughout a season, as in the case of leaf rust of barley (Teng, 1983) and powdery mildew of wheat (Rouse *et al.*, 1981). In these examples, early season populations were aggregated and defined by a negative binomial model, but the late season, higher density populations tended towards randomness and fit the Poisson model. Similarly, in the case of bacterial black rot of cabbages (Strandberg, 1973), early season, low density populations were defined by a negative binomial model but late season, high density populations were defined by a Poisson model. Such density dependent changes could make the spatial pattern analysis difficult. Distribution models would have to be fitted continuously and this would make the development of a sequential sampling plan difficult since the population density and fit to a model would have to be known prior to each sampling. Another difficulty in the interpretation of spatial patterns using frequency distributions is that the observed frequency distribution may be defined by more than one model (Feller, 1943; Waters and Henson, 1959; Strandberg, 1973; Pieters and Sterling, 1973; Brewer *et al.*, 1981; Nicot *et al.*, 1984), because of the related derivation of some models and the inability to distinguish between all processes of dispersion (Patil and Stiteler, 1974). It is recommended that frequency distributions should not be used as the sole description of a spatial pattern because of the problems of interpretation, but should be used in conjunction with other methods of dispersion analysis. Models must be consistent with biological observations and the fit of a particular model is only a mathematical description of a single or complex series of biological processes (Waters, 1959; Pielou, 1974).

Dispersion indices can be used to describe spatial patterns, and they differ from frequency distributions in that they quantify the degree of aggregation, rather than simply determine the presence or absence of aggregation in a population (Patil and Stiteler, 1974; Pielou, 1974). Dispersion indices are often based on the ratio of the variance to mean (Patil and Stiteler, 1974; Myers, 1978; Shew et al., 1984) and are calculated using the sample variance (s^2) and sample mean ($\bar{X}$). Variance to mean ratio values less than one, equal to one or greater than one indicate uniform, random and aggregated spatial patterns, respectively. The greater the variance to mean ratio value the greater the degree of aggregation (Taylor, 1961; Southwood, 1966; Pielou, 1974). In general, dispersion indices reduce the effect of population density and sample size (Shew et al., 1984; Myers, 1978) compared to frequency distribution models, since there is no requirement to fit the observed data to a discrete model. Spatial pattern analysis using the $s^2/\bar{X}$ dispersion index has been employed in the study of plant pathogen spatial patterns, including powdery mildew of wheat (Rouse et al., 1981) and cylindrocladium black rot of peanuts (Taylor, 1981).

Another dispersion index which has been used widely is the index of patchiness (Lloyd, 1967). This index is defined in terms of another index, mean crowding ($\overset{*}{X}$), defined by the following equation:

$$\overset{*}{X} = \overset{\bar{x}}{\cancel{1}} + (s^2/\bar{X} - 1)$$

?

where $\bar{X}$ and s^2 are the sample mean and variance, respectively (Lloyd, 1967). Mean crowding measures the number of other individuals associated with an individual in a sample unit, and increases as the population density increases (Pielou, 1974). Patchiness is defined as the ratio of mean crowding to the population mean ($\overset{*}{X}/\bar{X}$). Again with this index, values less than, equal to or greater than one indicate uniform, random and aggregated spatial patterns respectively. The analysis of spatial patterns by the index of patchiness was used in studies of Egyptian alfalfa weevil larvae, (*Hypera bruneipennis*), on alfalfa (Christensen *et al.*, 1977), several aphids species on alfalfa (Gutierrez *et al.*, 1980), cylindrocladium black rot of peanuts (Taylor *et al.*, 1981; Hau *et al.*, 1982) and *Verticillium dahliae* on potatoes (Smith and Rowe, 1984).

The K value derived from the negative binomial frequency distribution model (Bliss, 1953) and Morista's Index (Morista, 1962) are further examples of dispersion indices related to the $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ indices and yield similar measures of aggregation (Iwao and Kuno, 1971). The K values have been used extensively in entomology (Bliss, 1953; Morris, 1954; Ellenberger and Cameron, 1977) and plant pathology (Strandberg, 1973; Rouse *et al.*, 1981; Taylor, 1981; Hau *et al.*, 1982). A major drawback to the use of K values as a dispersion index is the requirement that the negative binomial distribution model must fit the observed frequency distribution. Also K values are density dependent and can change between samples (Myers, 1978), which necessitates the calculation of a common K value from several samples to use K values in developing a sequential sampling plan (Bliss and Owen, 1958). Common K values cannot always be calculated (Sylvester and Cox, 1961; Coggin and Dively, 1982). Morista's Index has not been used extensively but has been used in the study of the spatial patterns of ant lions, *Glenuroides japoneius*, (Morista, 1971) and Japanese beetles, *Popilla japonica*, (Ng *et al.*, 1983).

Taylor's power law is a dispersion index which is density independent and can be used to describe a spatial pattern of a species over a range of densities. It is defined as the regression of the log sample variance on log sample mean, and the slope of the regression line is a measure of aggregation (Taylor, 1961, 1971). Taylor's power law has been used to study the spatial pattern of citrus redmite, Panonychus citri (Jones and Parrella,1984) and several cotton insects (Wilson and Room, 1984). Other dispersion indices which have been used less extensively include Green's Coefficient (Green, 1966) and the standardized Morista's Coefficient (Smith-Gill, 1975).

Spatial patterns are characterized by two distinct factors; whether an individual or an aggregate forms the basic unit of dispersion and whether those basic units are arranged in a random or aggregated spatial pattern in the field (Iwao, 1968; Iwao and Kuno, 1971). The basic unit of dispersion is the result of the reproductive, dispersive and interactive characteristics of a species, while arrangement of the basic units of dispersion reflect more the heterogeneity of field conditions (Iwao and Kuno, 1971). The dispersion indices and frequency distribution models discussed previously do not distinguish between the two factors of spatial patterns (Iwao and Kuno, 1971). Iwao, (1968) developed a method to study this duality, based on a regression of mean crowding on mean density from several samples over a range of densities. The linear equation which results is:

$$\overset{*}{X} = \alpha + \beta\ (\bar{X})$$

where the intercept value (α) is the "Index of Basic Contagion" and is a measure of aggregation (i.e. whether it occurs in aggregates or singly). The slope value (β) is the "Density-Contagiousness Coefficient" and is a measure of how the basic units of dispersion defined by α are arranged in the field with changes in mean density ($\bar{X}$). Values of α equal to zero indicate that the basic unit of dispersion is a single individual, or in the case of plant disease a single infected unit such as a plant, whereas values greater than zero indicate that the basic unit of dispersion is an aggregate. Values of β less than, equal to or greater than one indicate uniform, random or aggregated arrangements of the basic units borne pathogen simulations (Nicot *et al.*, 1984). Spatial pattern analysis techniques which take into account location of individuals are labor intensive and may not always be suitable for the extensive sampling required for pest management. In this study the main objective was to define the spatial pattern of stripe rust as a basis for a sequential sampling plan for disease management. Disease management sampling does not require as intensive a sampling program as do ecological studies, as the major goal is to classify a population with respect to an economic threshold or action level (Iwao, 1975; Zahner and Baumgaertner, 1984). To date only frequency distribution models (Onsager, 1976), dispersion indices based on the regression of mean crowding on mean density (Iwao, 1975), and to a much lesser extent Taylor's power law (Green, 1970), have been used to develop sequential sampling plans. Spatial analysis techniques which take into account sample location were not used in this study because of the lack of applicability to the development of a sequential sampling plan and a constraint of time and labor. It is recommended that at least three different spatial analysis techniques should be used to describe spatial patterns and that the results should be consistent before a spatial pattern is accepted as being reliably defined (Pielou, 1974; Myers, 1978). Results from such studies should also conform to field observations and existing biological and ecological data of the organism studied. In this study frequency distribution models, the dispersion indices of $s^2/\bar{X}$, $\overset{*}{X}/\bar{X}$, and $\overset{*}{X}$, $\bar{X}$ regressions were used to study stripe rust spatial patterns.

3.1.1 Stripe Rust Dispersion

It has been suggested that frequency distribution models and dispersion indices fitted to field data should conform to existing knowledge of the biology and ecology of the species (Southwood, 1966; Pielou, 1974). Short range, inter-field dispersal of *P. striiformis* may occur by rain impact, splashing urediniospores up to a distance of four meters (Rapilly, 1979), and by direct leaf to leaf contact of dispersion in the field, respectively. The higher the α and β values the larger the aggregate, or focus in the case of plant diseases, and the higher the degree of aggregation. The linear relationship between $\overset{*}{X}$ and $\bar{X}$ is valid in a wide variety of theoretical and real field situations, making it a versatile and accurate method of studying spatial patterns (Iwao and Kuno, 1971). The method is not density dependent and therefore can be used to study the spatial pattern of populations that vary with time. This dispersion index is not measured for one discrete population, as is the case for frequency distribution models and other dispersion indices except Taylor's power law (Iwao and Kuno, 1971). The method has been used to study the spatial patterns of several aphids on alfalfa (Gutierrez _et al._, 1980) pear psylla, _Psylla pyricola_ (Burts and Brunner, 1981), armyworm larvae on cereals, _Pseudaletia unipuncta_ (Coggin and Dively, 1982), the entomopathogenic fungus _Nomuraea rileyi_ (Fuxa, 1984) and leaf blight of onions caused by _Botrytis squamosa_ (Boivin and Sauriol,1984).

Dispersion indices and frequency distributions are based on measuring density per sample unit, eg. the number of infected plants per ten plant sample. An alternative method of spatial pattern analysis is the use of techniques in which the distance between and location of individuals is taken into account, rather than recording the number of individuals found in a specified area (Southwood, 1966; Pielou, 1974). Such techniques include nearest-neighbor (Pielou, 1969) and spatial autocorrelation analyses (Cliff and Ord, 1981). Nearest-neighbor techniques require a knowledge of the co-ordinates of individuals throughout a study area, which requires intensive sampling and may lead to errors if the nearest individuals are not readily found (Southwood, 1966). Nearest-neighbor techniques were used to study spatial patterns of _Pseudomonas syringae_ on Soybeans (Poushinsky and Basu, 1984). Spatial autocorrelation techniques are based on the comparison of samples to neighboring samples at selected intervals and have been used in the study of southern stem rot of peanuts caused by _Sclerotium rolfsii_ (Shew _et al._, 1984) and for soil

(Zadoks, 1961; Shaner and Powelson, 1972). Longer range inter-field dispersal may occur through wind dispersal of urediniospores up to a maximum of 100m (Joshi and Palmer, 1973). Inter-field wind dispersal is limited (Shaner and Powelson, 1972) with 80-90% of urediniospores trapped by the crop within 9m of a urediniospore source (Roelfs et al., 1972). Very long range wind dispersal may also occur by urediniospores being lifted up to the upper atmosphere and travelling long distances before settling out and infecting crops far from the inoculum source (Zadoks, 1965; Hermansen and Stapel, 1973).

Stripe rust epidemics are often initiated from small disease foci of three to five leaves closely aggregated around the initial infected leaf, or from single leaf infections (Zadoks, 1961; Hendrix and Fuchs, 1970; Shaner and Powelson, 1972). The initial source of inoculum may be other infected wheat fields, volunteer wheat plants and alternative hosts either adjacent to (Shaner and Powelson, 1972; Roelfs et al., 1972) or some distance away from the crop (Joshi and Palmer, 1973). The pathogen probably spreads from initial infections primarily through leaf to leaf contact, which increases the focus size. Inter-field wind dispersal of urediniospores increases the number of foci (Zadoks, 1961), leading to repetition of the local spread cycle (Hendrix and Fuchs, 1970; Emge and Shrum, 1972; Roelfs et al., 1972; Mundy, 1973) until most plants become infected. The amount of disease development was shown to be related more to the number of initial inoculum sources or initial foci than to the infection rate (Zadoks, 1966; Rapilly, 1979).

Techniques which take into account sample unit location were used in the study of the spread of stripe rust from inoculated plants and natural infections (Kingsolver et al., 1959; Zadoks, 1961; Emge and Shrum, 1972; Joshi and Palmer, 1973), but not to quantify spatial patterns on a field basis. The objective of the present study was to analyze and quantify the spatial pattern of stripe rust on several sample units to provide a basis for the development of a reliable sampling technique and a sequential sampling plan for stripe rust management.

3.2 MATERIALS AND METHODS

In 1983 forty field plots (12 x 12m) were established in a 3.5 hectare field of wheat cv. Rongotea on a Lincoln College Farm. The crop was sown on 11 June with seed treated with triadimenol plus fuberidazole (15g and 2g a.i. per 100kg of seed) respectively. In addition commercial wheat crops were selected within a 10km radius of Lincoln College, four in 1982 and ten in 1983. All crops were autumn sown (late May to early June) with cv. Rongotea. All seed was treated with the same fungicide and rate as wheat seed in field plots.

A sample unit of ten consecutive tillers in a drill row was selected for disease assessment, on the basis of work by Rouse et al. (1981) and results from the 1982 sampling methods experiment (Section 2.3.1). In the field plots, ten sample units were sampled per plot, five evenly spaced along each side approximately 1.5m from the plot edge, at weekly intervals until G.S. 59. In fields, 100 sample units were sampled systematically along a "W" pattern, with twenty-five sample units distributed evenly along each of the four diagonals, based on studies of Basu et al. (1977) and results of the 1982 sampling methods experiment (Section 2.3.1). Distance between sample units varied according to field size, eg. for a 250m diagonal there was a 10m interval between sample units while for a 500m diagonal there was 20m between sample units. All sampling was nondestructive. Sampling began at G.S. 13 (before the first record of stripe rust) and ended at G.S. 59 (anthesis). It was assumed that disease control would not be economic after anthesis, based on work by Mundy (1973), McCullough (1982) and results of previous experiments in 1981 and 1982. Field samples were conducted weekly until the fungicide triadimefon (125g a.i./ha) was applied by the grower for the control of stripe rust. At that time sampling ceased and resumed three weeks later, assuming a minimum period of four weeks activity for triadimefon (O'Connor, 1984). Field plot samples were conducted weekly until leaf senesence. Disease incidence and severity on the top three fully expanded green leaves were assessed on sampled tillers, using standard area diagrams.

The incidence data for the top three fully expanded green leaves, top two leaves, leaf one (uppermost), leaf two and three were grouped into frequency classes (i.e. the number of sample units which had 1, 2, ...8, 9, 10 infected units). The frequency classes on each sample date were analyzed for goodness of fit to the following frequency distribution models: Poisson, negative binomial, Thomas double Poisson, Neyman type A, Poisson with zeroes, Poisson binomial, and logarithmic with zeroes, using a computer program developed by Gates and Ethridge (1972). A chi-square test for goodness of fit of observed frequency classes to the expected frequency distributions was used in the computer program at 1 and 5% significance.

All field data were classified into stripe rust incidence classes of 0-1%, 1-20%, 20-40%, 40-80% and 80-100% to test for differences in spatial patterns and density. The number of observed frequency distributions that fit, at the 5% level of significance, the distribution models for each incidence class and sample unit (top two or three leaves, leaves one, two or three) were converted to percentages, based on work by Pieters and Sterling (1973). The percentages of observed frequency distributions which did not fit any of the frequency distribution models was calculated. An observed frequency distribution was classified as aggregated if it fit any model but the Poisson. Percentage fits were transformed, using arc-sine transformation, for analysis of variance as prescribed by Riemer (1959) for cases where incidence ranges were 0-20% or 80-100%.

The dispersion indices $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ were calculated for field and field plot sample data divided into the same incidence classes described for the frequency distributions. $\overset{*}{X}$ was regressed on $\bar{X}$ for field and field plot samples for only the 0-40% incidence range. It was assumed that the incidence of stripe rust would not exceed 40% in commercial fields and that any action level determined would be below 40%. Tests were performed on all sample data to determine whether the intercept values (α) of the $\overset{*}{X}$, $\bar{X}$ regression equation were significantly different ($P \leq 0.10$) from zero or whether the slope values (β) equalled 1.00 (Zar, 1974). The slope values of the regression equations between sample data from different seasons and field or field plots were also analyzed for significant ($P \leq 0.10$) differences (Zar, 1974; Jones and Parrella,1984).

3.3 RESULTS

The frequency distribution data are summarized in Table 3.1 (top 3 leaves), Table 3.2 (top 2 leaves), Table 3.3 (leaf 3) and Table 3.4 (leaf 1), as the percentages of observed frequency distributions fitted to a series of frequency distribution models. Incidence on leaf two was the same as the top two leaf incidence since there were no situations where only leaf one was infected. The observed frequency distributions in the 0-1% incidence range were omitted from analysis for statistical reasons (Pieters and Sterling, 1973; Gates and Ethridge, 1972), and because it is difficult to distinguish between random and uniform spatial patterns in low density populations (Cassie, 1962).

The observed frequency distributions in the 1-20% incidence range fit several frequency distribution models (Tables 3.1 - 3.4). The observed frequency distributions were characterized by multiple fits to the Poisson model, representing a random spatial pattern, and to models representing aggregated spatial patterns. The Poisson model was not fit significantly more often than models representing aggregated spatial patterns, except in the 1982 field survey when infections on the top three leaves and leaf three sample units were fit significantly more to a Poisson model than aggregated models. No one specific aggregated model consistently fit the observed distributions more than other such models.

In the 20-40% incidence range the observed frequency distributions on all sample units were also characterized by multiple fits to the Poisson model and aggregated models. No aggregated model consistently fit the observed frequency distribution more than total aggregated model, although the logarithmic with zeroes model had significantly more fits than other aggregated models to the observed frequency distributions of infections on the top two leaves sample unit in the 1983 field plot survey.

The observed frequency distributions in the 40-80% incidence range of infections on the top three and two leaves fit the Poisson model significantly more than total aggregated model in the 1983 field survey. However, leaf three infections fit the Poisson model and aggregated models (Poisson binomial, Poisson with zeroes and logarithmic with zeroes) equally. There was no significant difference for the 1983 field plot survey in the fit to the Poisson and aggregated models for the observed frequency distributions of infections on the top three and two leaves. However, observed distributions of leaf three infections fit the Poisson model significantly more often than any total aggregated models.

The observed frequency distributions in the 80-100% incidence range for all sample units fit the Poisson model only or fit no model.

The dispersion indices of variance to mean ratios, $(s^2/\bar{X})$ and mean crowding to mean ratios, $(\overset{*}{X}/\bar{X})$ for a range of incidences on the top three and top two leaves, are summarized in Table 3.5, and for leaf three and leaf one in Table 3.6. Both indices were equal to 1.00 for all sample units in the 0-1% incidence range. There were no

Table 3.1: Percent fit of observed frequency distributions of incidence of stripe rust infections on the top three leaves to discrete frequency distribution models.

Distribution	Incidence Range 1-20%	20-40%	40-80%	80-100%
1982 Field Survey				
Poisson (random)	67 a	100		
Negative binomial	33 b	100		
Thomas Double Poisson	33 b	100		
Neyman Type A	41 b	100		
Poisson binomial	33 b	100		
Poisson with Zeroes	33 b	100		
Logarithmic with Zeroes	33 b	100		
Aggregated *	41 b	100		
None	33 b	0		
No. of observations	6	3		
1983 Field Survey				
Poisson (random)	40 ab	100 ab	100	100
Negative binomial	3 b	18 de	0	0
Thomas Double Poisson	3 b	18 de	0	0
Neyman Type A	3 b	18 de	0	0
Poisson binomial	3 b	35 cd	0	0
Poisson with Zeroes	8 ab	54 cd	0	0
Logarithmic with Zeroes	12 ab	12 de	0	0
Aggregated *	28 ab	75 bc	0	0
None	48 a	0 e	0	0
No. of observations	20	10	4	4
1983 Field Plot Survey				
Poisson (random)	27 b	27 ab	96 a	96 a
Negative binomial	0 c	0 c	2 bc	0 b
Thomas Double Poisson	5 bc	5 bc	8 bc	0 b
Neyman Type A	0 c	0 c	2 bc	0 b
Poisson binomial	1 c	1 c	8 bc	0 b
Poisson with Zeroes	3 bc	3 bc	2 bc	0 b
Logarithmic with Zeroes	12 bc	12 bc	30 b	0 b
Aggregated *	19 bc	19 bc	96 a	0 b
None	67 a	67 a	4 bc	4 b
No. of observations	27	13	10	27

* An observed frequency distribution was classified as aggregated to calculate the total when any distribution model was fit, other than the Poisson.

Duncan's Multiple Range Test was performed on arcsine transformed data. Within each column, means with no letter in common differ significantly at the $P \leq 0.05$ level.

Table 3.2: Percent fit of observed frequency distributions of incidence of stripe rust infections on the top two leaves to discrete frequency distribution models.

	Incidence Range			
Distribution	1-20%	20-40%	40-80%	80-100%
1982 Field Survey				
Poisson (random)	21 b			
Negative binomial	10 b			
Thomas Double Poisson	10 b			
Neyman Type A	10 b			
Poisson binomial	10 b			
Poisson with Zeroes	3 b			
Logarithmic with Zeroes	0 b			
Aggregated *	10 b			
None	79 a			
No. of observations	7			
1983 Field Survey				
Poisson (random)	50 a	37 a	100	100
Negative binomial	3 c	47 a	0	0
Thomas Double Poisson	7 bc	66 a	0	0
Neyman Type A	7 bc	31 a	0	0
Poisson binomial	7 bc	70 a	0	0
Poisson with Zeroes	17 abc	60 a	0	0
Logarithmic with Zeroes	27 ab	16 a	0	0
Aggregated *	39 a	75 a	0	0
None	100	40 a	0	0
No. of observations	21	8	5	4
1983 Field Plot Survey				
Poisson (random)	31 ab	19 bc	40 ab	50 a
Negative binomial	0 c	0 c	0 b	0 b
Thomas Double Poisson	7 bc	0 c	14 ab	0 b
Neyman Type A	1 c	0 c	14 ab	0 b
Poisson binomial	1 c	0 c	14 ab	0 b
Poisson with Zeroes	10 bc	0 c	0 b	0 b
Logarithmic with Zeroes	25 ab	70 a	1 b	0 b
Aggregated *	45 a	70 a	22 ab	0 b
None	57 a	11 bc	60 a	50 a
No. of observations	21	8	7	20

* An observed frequency distribution was classified as aggregated to calculate the total when any distribution model was fit, other than the Poisson.

Duncan's Multiple Range Test was performed on arcsine transformed data. With each column, means with no letter in common differ significantly at the $P \leq 0.05$ level.

Table 3.3: Percent fit of observed frequency distributions of incidence of stripe rust infections on leaf three to discrete frequency distribution models.

Distribution	Incidence Range 1-20%	20-40%	40-80%	80-100%
1982 Field Survey				
Poisson (random)	88 a			
Negative binomial	0 b			
Thomas Double Poisson	5 b			
Neyman Type A	0 b			
Poisson binomial	5 b			
Poisson with Zeroes	0 b			
Logarithmic with Zeroes	0 b			
Aggregated *	5 b			
None	12 b			
No. of observations	7			
1983 Field Survey				
Poisson (random)	33 a	100 a	100 a	100
Negative binomial	0 b	14 bc	0 b	0
Thomas Double Poisson	10 ab	85 ab	0 b	0
Neyman Type A	6 ab	14 bc	0 b	0
Poisson binomial	6 ab	85 ab	50 ab	0
Poisson with Zeroes	6 ab	85 ab	50 ab	0
Logarithmic with Zeroes	25 a	100 a	85 ab	0
Aggregated *	25 a	100 a	85 ab	0
None	45 a	0 c	0 b	0
No. of observations	17	4	3	3
1983 Field Plot Survey				
Poisson (random)	41 ab	50 a	99 a	98 a
Negative binomial	0 c	0 a	0 b	0 b
Thomas Double Poisson	20 abc	28 a	14 b	0 b
Neyman Type A	19 abc	18 a	0 b	0 b
Poisson binomial	21 abc	28 a	14 b	0 b
Poisson with Zeroes	15 bc	1 a	0 b	0 b
Logarithmic with Zeroes	47 ab	5 a	0 b	0 b
Aggregated *	54 a	50 a	14 b	0 b
None	36 ab	5 a	1 b	2 b
No. of observations	32	5	8	18

* An observed frequency distribution was classified as aggregated to calculate the total when any distribution model was fit, other than the Poisson.

Duncan's Multiple Range Test was performed on arcsine transformed data. With each column, means with no letter in common differ significantly at the $P \leq 0.05$ level.

Table 3.4: Percent fit of observed frequency distributions of incidence of stripe rust infections on leaf one to discrete frequency distribution models.

Distribution	Incidence Range 1-20%	20-40%
1983 Field Plot Survey		
Poisson (random)	41 a	64 a
Negative binomial	3 a	0 b
Thomas Double Poisson	12 a	7 ab
Neyman Type A	8 a	7 ab
Poisson binomial	12 a	7 ab
Poisson with Zeroes	6 a	14 ab
Logarithmic with Zeroes	28 a	14 ab
Aggregated *	28 a	14 ab
None	41 a	36 a
No. of observations	15	6

* An observed frequency distribution was classified as aggregated to calculate the total when any distribution model was fit, other than the Poisson.

Duncan's Multiple Range Test was performed on arcsine transformed data. With each column, means with no letter in common differ significantly at the $P \leq 0.05$ level.

restrictions in analysis in this incidence range as for frequency distributions. The values of both dispersion indices in the 1-20% incidence range were greater than 1.00 for all sample units. The indices $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ ranged from a minimum of 1.05 and 1.17, respectively, for the top two leaves in the 1983 field survey, to a maximum of 1.38 and 2.19, respectively, in the 1982 field survey. Both indices in the 20-40% incidence range were greater than 1.00 for all sample units, except leaf one, where both were less than 1.00. The $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ values above 1.00, ranged from 1.11 and 1.03, respectively, on the top two leaves in the 1983 field plot survey, to 1.36 and 1.55, respectively, on the top three leaves in the 1982 field survey. Index values for all sample units in the 40-80% incidence range approximated 1.00 with a range of 0.99 to 1.00. The 80-100% incidence range values of both dispersion indices were less than 1.00 for all sample units and surveys, and ranged from 0.09 and 0.89 for $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$, respectively, for infections on the top three leaves in the 1983 field plot survey, to 0.15 and 0.92, respectively, for infections on the top three leaves in the 1983 field survey and top two leaves in the 1983 field plot survey, respectively. An exception was the leaf three sample unit in the 1983 field survey which had a $s^2/\bar{X}$ value of 1.10.

The linear regression of $\overset{*}{X}$ on $\bar{X}$ in the 0-40% incidence range were significant for all sample units in all surveys except for the top two leaves in the 1982 field survey (Table 3.7). Intercept (α) and slope (β) parameters of the regression equations are summarized in Table 3.7. The α values were significantly ($P \leqq 0.10$) greater than zero on all sample units in all surveys. The β values for all top three leaf sample units in all surveys were significantly greater than one. The 1983 field survey had a β value of 1.06 for the leaf three sample unit, which was significantly greater than one. The β values for the top two leaf and leaf three sample units in the 1983 field plot and 1982 field surveys were not significantly greater than one. The β value of 0.86 for leaf one infections was significantly less than one.

Table 3.5: Dispersion indices ($s^2/\bar{X}$, $\overset{*}{X}/\bar{X}$) for observed distributions of incidence of stripe rust infections on the top three and top two leaves.

	INCIDENCE RANGE				
DISPERSION INDEX	0-1%	1-20%	20-40%	40-80%	80-100%
			TOP THREE LEAVES		
<u>1982 Field Survey</u>					
$s^2/\bar{X}$	1.00	1.30	1.36		
$\overset{*}{X}/\bar{X}$	1.00	1.68	1.55		
No. of observations	1	6	3		
<u>1983 Field Survey</u>					
$s^2/\bar{X}$	1.00	1.29	1.14	1.00	0.15
$\overset{*}{X}/\bar{X}$	1.00	1.59	1.05	1.00	0.91
No. of observations	15	20	10	4	4
<u>1983 Field Plot Survey</u>					
$s^2/\bar{X}$	1.00	1.31	1.12	0.99	0.09
$\overset{*}{X}/\bar{X}$	1.00	1.45	1.04	1.00	0.89
No. of observations	2	27	13	10	27
			TOP TWO LEAVES		
<u>1982 Field Survey</u>					
$s^2/\bar{X}$	1.00	1.38			
$\overset{*}{X}/\bar{X}$	1.00	2.19			
No. of observations	1	8			
<u>1983 Field Survey</u>					
$s^2/\bar{X}$	1.00	1.05	1.14	0.99	0.12
$\overset{*}{X}/\bar{X}$	1.00	1.17	1.07	1.00	0.90
No. of observations	4	17	4	3	3
<u>1983 Field Plot Survey</u>					
$s^2/\bar{X}$	1.00	1.37	1.11	1.00	0.07
$\overset{*}{X}/\bar{X}$	1.00	1.86	1.03	1.00	0.92
No. of observations	1	32	5	8	18

Table 3.6: Dispersion indices calculated for incidence of stripe rust infections on leaf three and leaf one.

	INCIDENCE RANGE				
DISPERSION INDEX	0-1%	1-20%	20-40%	40-80%	80-100%
		LEAF THREE			
1982 Field Survey					
$s^2/\bar{X}$	1.00	1.26			
$\overset{*}{X}/\bar{X}$	1.00	1.69			
No. of observations	5	7			
1983 Field Survey					
$s^2/\bar{X}$	1.00	1.23	1.13	0.99	1.10
$\overset{*}{X}/\bar{X}$	1.00	1.44	1.06	1.00	0.91
No. of observations	14	21	8	5	4
1983 Field Plot Survey					
$s^2/\bar{X}$	1.00	1.34	1.14	1.00	0.14
$\overset{*}{X}/\bar{X}$	1.00	1.47	1.17	1.00	0.91
No. of observations	4	21	8	7	20
		LEAF ONE			
1983 Field Plot Survey					
$s^2/\bar{X}$	1.00	1.37	0.81		
$\overset{*}{X}/\bar{X}$	1.00	1.73	0.86		
No. of observations	1	15	6		

Table 3.7: Regression equation parameters for the correlation of mean crowding ($\overset{*}{X}$) on mean density ($\bar{X}$) of the incidence of stripe rust infections on several sample units in surveys of field plots in 1982 and 1983.

Sample Unit	No. observation	α	β	r^2
Top Three Leaves				
1982 Field Survey	12	0.07	1.14	0.97
1983 Field Survey	36	0.11	1.09	0.87
1983 Field Plot Survey	38	0.06	1.12	0.80
Pooled data +	86	0.11	1.12	0.86
Top Two Leaves				
1982 Field Survey	8	0.56	0.63	0.51
1983 Field Survey	26	0.07	0.93	0.87
1983 Field Plot Survey	37	0.36	0.98	0.86
Leaf Three				
1982 Field Survey	12	0.22	0.97	0.95
1983 Field Survey	41	0.08	1.06	0.93
1983 Field Plot Survey	46	0.08	0.99	0.90
Pooled data +	99	0.10	1.00	0.91
Leaf One				
1983 Field Plot Survey	21	0.38	0.86	0.87

NB: All regressions were significant ($P \leq 0.05$) based on an F-test (Zar, 1974), except top two leaf sample unit in the 1982 field survey.

+ $\overset{*}{X}/\bar{X}$ data from all samples combined and a common regression performed since slope values were not significantly ($P \leq 0.10$) different (Zar, 1974).

The $\overset{*}{X}$ on $\bar{X}$ regression for the top two leaves in the 1982 fields could not be used for spatial pattern analysis since the linear regression was not significant (Table 3.7).

The slope values (β) of surveys for the top three leaf and leaf three sample units were not significantly different ($P \leqq 0.10$), and a common regression was therefore fitted to the $\overset{*}{X}$ and $\bar{X}$ data from all surveys for each of these sample units. The regressions of the pooled data were significant ($P \leqq 0.05$) and had r^2 values of 0.86 and 0.91 for the top three leaf and leaf three sample units, respectively (Table 3.7). The pooled regression equation for infections on leaf three had an α value of 0.10, which was significantly greater than zero, and a β value of 1.00 (Table 3.7). The top three leaf pooled regression equation had an α value of 0.11 and a β value of 1.12, which were significantly greater than zero and one, respectively (Table 3.7, Figure 3.2).

3.4 DISCUSSION AND CONCLUSION

Stripe rust infections on all sample units in the 0-1% incidence range occurred in a random spatial pattern, as indicated by dispersion indices equal to 1.00. Low population densities are often characterized by random spatial patterns (Kuel and Fye, 1972; Elliot, 1977) and this finding is consistent with other field observations of stripe rust infections (Shaner and Powelson, 1972; Rapilly, 1979).

At stripe rust incidence values up to 40%, the observed frequency distributions on all sample units fit both random and aggregated distribution models, which indicated that the spatial patterns were slightly aggregated (Pielou, 1974). The dispersion indices were greater than 1.00 on all sample units, which indicated that stripe rust infections were slightly aggregated. Stripe rust epidemics in the field

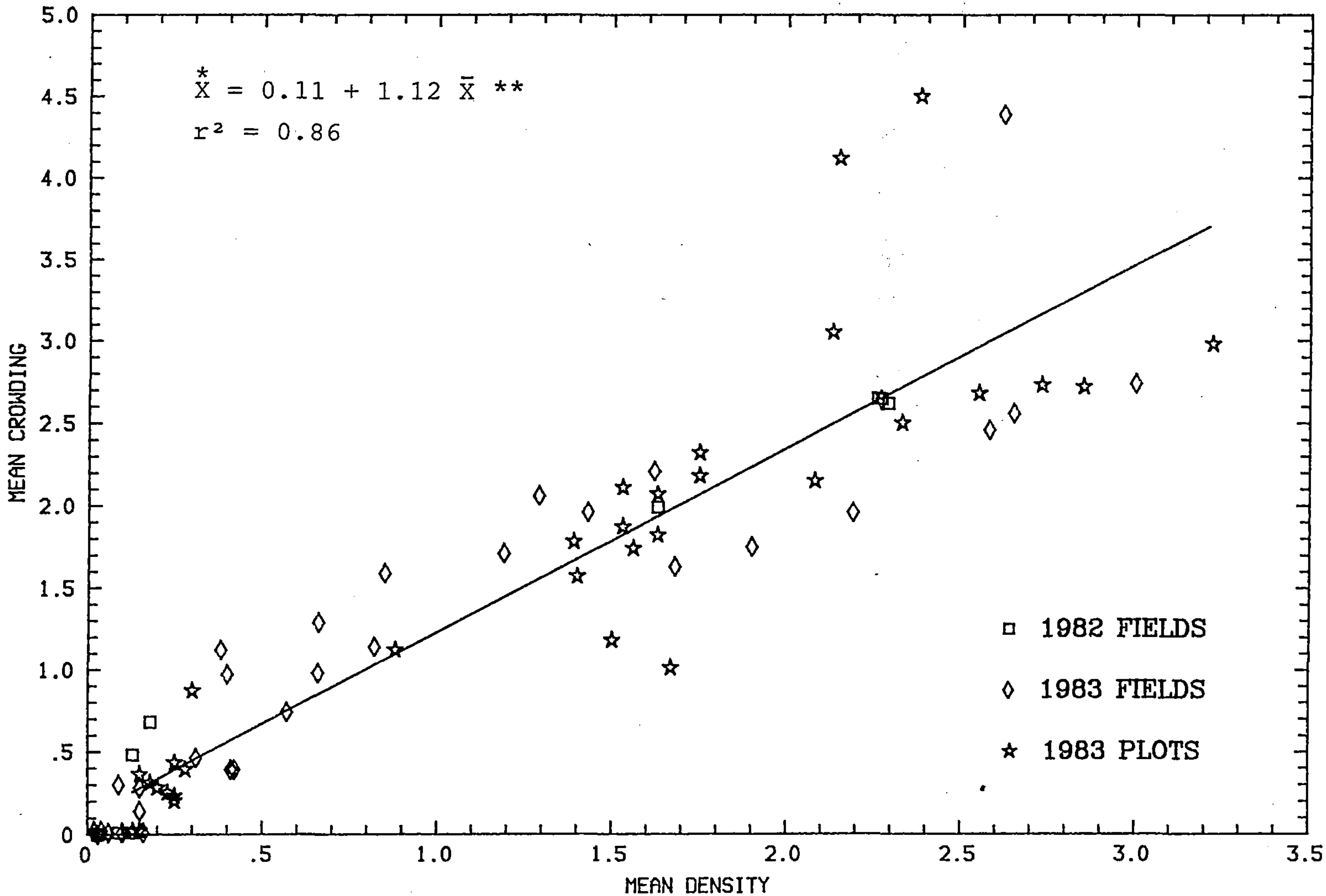

Figure 3.2: Relation of mean crowding ($\overset{*}{X}$) to mean density ($\bar{X}$) for stripe rust incidence (0-40% range) on the top three leaves.

have been described as aggregated, with disease foci in the early and middle periods of epidemic development (Hendrix and Fuchs, 1970).

At higher densities (40-80% incidence), the incidence of infections on all sample units occurred in random spatial patterns, as indicated by the fit of observed frequency distributions to the Poisson model and $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ index values equal to 1.00. Stripe rust epidemics with moderate to high incidence levels have been described as randomly dispersed in the field (Emge and Shrum, 1976; Rapilly, 1979). High density stripe rust infections (80-100% incidence) on all sample units appeared to have uniform spatial patterns, as indicated by dispersion indices below 1.00. However, observed frequency distributions of infections were best fit to the Poisson distribution model which indicated a random spatial pattern. Sample unit size for high density population sampling may greatly influence the interpretation of spatial patterns, since small sample units may yield a uniform spatial pattern as incidence nears 100% and every sample unit becomes infected while a larger sample unit may yield a random spatial pattern (Pielou, 1974). Interpretation of the spatial pattern in this incidence range is difficult. At very high densities, stripe rust epidemics (Emge and Shrum, 1976; Rapilly, 1979) and stem rust epidemics on wheat (Kingsolver _et al._, 1959) were observed to be uniformly dispersed throughout a field. Thus as density increased the spatial pattern changed from random to slightly aggregated to random or uniform. A similar progression from aggregated spatial patterns to random patterns as disease incidence increased was observed for powdery mildew on wheat (Rouse _et al._, 1981).

The frequency distributions and $s^2/\bar{X}$ and $\overset{*}{X}/\bar{X}$ dispersion indices were density dependent and did not describe the dual nature of spatial patterns. The regressions of $\overset{*}{X}$ on $\bar{X}$ were performed on data in the 0-40% incidence range, which was the range assumed to be encountered in commercially managed fields. Stripe rust infections on the top two, leaf two and leaf three sample units had spatial units of small foci which were randomly distributed, as indicated by α values significantly greater than zero but no higher than 0.56, and β values not significantly different to 1.00. The higher the α and β values the larger the foci and greater degree of aggregation of those units respectively. Infections on leaf one sample units had a spatial pattern of small foci dispersed uniformly throughout the field, as indicated by α and β values of 0.38 and 0.86, respectively. The top three leaf infections had a spatial pattern of slightly aggregated small foci as indicated by α values significantly greater than 0.00, but no higher than 0.11, and β values significantly greater than 1.00 but no higher than 1.14, respectively. Variation of spatial patterns for the top three leaf and leaf three sample units was not significant between seasons and surveys as indicated through an analysis of β values from regression equations.

The spatial pattern of infections on the top three leaf and leaf three sample units were not significantly affected by season or location, which would allow these units to be used in variable situations encountered in disease management sampling plans. The spatial pattern of infections on the top three leaves was the only sample unit to be consistently defined by all spatial analysis techniques which indicated that the aggregated nature of the spatial pattern was reliably defined.

A knowledge of the spatial pattern of stripe rust infections on the top three leaves can be used in a sampling method (Chapter 2) to detect stripe rust reliably in the field. The next step in the development of a sequential sampling plan for stripe rust management, is the establishment of an action level, through the study of severity-yield relationships, which will be reported in the next chapter.

CHAPTER 4

STRIPE RUST SEVERITY-YIELD RELATIONSHIPS AND ACTION LEVELS

4.1 INTRODUCTION

Maintaining disease free wheat crops through routine prophylatic fungicide application has proved to be an inefficient use of fungicides (Cook, 1980; Jenkins and Lescar, 1980). The study of severity-yield relationships defines criteria to optimize fungicide usage, based on the effect of disease on yield (James, 1974). Economic thresholds, the level of disease at which control should be applied to prevent the disease from reaching the economic injury level, can be used as criteria for fungicide use in disease management (Stern, 1973; Headley, 1972; Apple, 1977). Economic injury levels are defined as the amount of disease which causes a reduction in crop value greater than the cost of control. Action levels, the level of disease at which control is judged to be necessary to avoid significant yield loss, can be used as criteria for fungicide use when it is difficult to establish definite economic thresholds and economic injury levels (Lincoln, 1978; Pitre et al., 1979). Disease action levels may be identified by predictive methods to analyze the risk of a disease becoming severe enough to warrant fungicidal control or by measuring the effects of fungicide applications on yield in field trials and then identifying factors which produce significant yield responses (Jenkins and Lescar, 1980). Models which are used to define action levels or criteria to base fungicide applications on can be defined as empirical, mechanistic or a combination of both (Krause and Massie, 1975). Empirical models define a severity-yield relationship based on observed behaviour and correlations whereas mechanistic models attempt to describe the nature of the relationship (Teng and Gaunt, 1980).

Empirical severity-yield models may be derived using several techniques to develop critical-point, multiple-point, area under the curve models (James, 1974) and response surface models (Calpouzos *et al.*, 1976). Critical point models for cereal diseases and insect pests were used in studies on leaf blotch of barley caused by *Rhynchosporium secalis* (James *et al.*, 1968), stem rust of wheat caused by *Puccinia graminis* (Romig and Calpouzos, 1970), powdery mildew on barley caused by *Erysiphe graminis* (Jenkins and Storey, 1975) and the rose grain aphid, *Metopolophium dirhedum*, on wheat (Holt *et al.*, 1984). Multiple-point models estimate yield loss based on disease severities at several growth stages, using multiple regression techniques to define a severity-yield loss correlation. Multiple point models were used in studies of leaf rust of wheat caused by *Puccinia recondita* (Burleigh *et al.*, 1972) and leaf rust of barley caused by *Puccinia hordei* (Teng *et al.*, 1980). In most cases multiple point models have increased model reliability (Burleigh *et al.*, 1972; James, 1974). Area under the curve models relate the area under disease progress curves to yield and were used to define severity-yield relationships of stem rust of wheat (Line *et al.*, 1976; Buchenau, 1975). Response surface models take into account disease severity, growth stages and yield, with the severity-yield loss correlation at a specific growth stage related to every other severity-yield loss correlation at other growth stages to create a three dimensional response surface model. Response surface models have been developed for stem rust of wheat, *P. graminis* (Calpouzos *et al.*, 1976). Attaining data to generate response surface models may be difficult, since many treatments are required to develop severity-yield relationships at several growth stages (Teng and Gaunt, 1980).

Mechanistic models define and take into account factors which influence disease development, such as climatic, host plant and crop husbandry and predict damaging levels of disease based on an explanation of the effect of disease on yield. Such models, developed to time fungicide applications for disease management, include those for *Septoria nodorum* on wheat (Tyldesley and Thompson, 1980) and foliar diseases of soybean (Backman *et al.*, 1984).

Severity-yield loss relationships for stripe rust management have been analyzed through the use of empirical critical-point models, with varying results. Doling and Doodson (1968) developed yield loss models for stripe rust severity on whole plants at G.S. 69, defined by the equations:

$$\% \text{ Yield Loss} = 3.01 \times (\text{severity})^{\frac{1}{2}} - 3.6$$

and

$$\% \text{ Yield Loss} = 0.27 \times (\text{severity}) + 3.9$$

There was no explanation of the difference between the two models and r^2 values were not reported. Mundy, (1973) developed yield loss models for stripe rust severity on the flag leaf at G.S. 75, defined by the equations:

$$\% \text{ Yield Loss} = 5.06 \times (\text{severity})^{\frac{1}{2}} - 17.15$$

and

$$\% \text{ Yield Loss} = 0.44 \times (\text{severity}) + 3.15$$

with r^2 values of 0.87 and 0.86 respectively. To date there have been no multiple-point, area under the curve or response surface models developed for stripe rust management. Empirical critical-point models have been based on growth stages after G.S. 59 (anthesis), which may or may not be valid in New Zealand.

An alternative approach to developing mechanistic or empirical critical-point, multi-point, area under the curve and response surface models is to apply fungicides at predetermined action levels or times and empirically derive the action level which optimized yield. This method has been used extensively for developing action levels or economic thresholds for insect pests including soybean insect pests (Thomas et al., 1974), green peach aphids (*Myzus persicae*) on potatoes (Cancelado and Radcliffe, 1979) and *Heliothis* spp. on cotton (Wilson, 1981). Such methods have also been used to study the effect of disease on yield and to establish criteria for fungicide applications, as in the studies of downy mildew of cucurbits caused by *Pseudoperonospera cubensis*, target leaf spot of cucurbits caused by *Corynespora cassicola*, late blight of tomato caused by *Phytophthora infestans* (Jones, 1978), powdery mildew of barley (Jenkins and Storey, 1975) and root-knot nematode (*Meloidogyne incognita*) on tobacco (Kirby *et al*., 1983). Action levels derived empirically for stripe rust management in Europe were 8% mean severity on the top three leaves (Anon., 1973), 5% on the top two leaves (Mundy, 1973) and 1% on the uppermost leaf (Jenkins and Lescar, 1980).

Seed treatment fungicides are an important chemical control option in New Zealand and other areas where infections occur at early growth stages. Before the 1980 season, and the introduction of stripe rust, carboxin plus thiram was a common wheat seed fungicide treatment used in New Zealand. This effectively controlled covered smut, loose smut and seedling root rot diseases but not stripe rust. Triadimenol plus fuberidazole seed treatment controlled stripe rust in Europe (McCullough pers. comm. 1981) and triadimefon was used as a foliar spray for effective stripe rust control in Europe (Jenkins and Lescar, 1980) and in New Zealand after the introduction of the pathogen in 1980 (Chan and Gaunt, 1982; McCullough, 1982).

Three trials were conducted during the 1981-82, 1982-83 and 1983-84 seasons on autumn sown wheat cv. Rongotea with the following objectives:

Trial 1: (1981-82 season)

1. To study the efficacy of the seed treatment fungicides triadimenol plus fuberidazole and carboxin plus thiram on stripe rust.

2. To study stripe rust severity-yield relationships throughout the season as a basis for establishing action levels and defining the growth period at which fungicide applications would be most effective in preventing yield reduction.

Trial 2: (1982-83 season)

1. To study stripe rust severity-yield relationships throughout the season to gain further information on action levels to optimize fungicide applications.

2. To analyze the effect of stripe rust on yield components and provide information on the nature of yield loss.

Trial 3: (1983-84 season)

1. To establish action levels and period of crop growth at which to apply fungicides.

2. To analyze the effect of stripe rust on yield components and provide further information on the nature of yield loss.

3. To test the efficacy of management programs based on action levels or growth stage schedules.

4.2 TRIAL 1: 1981-82 SEASON

4.2.1 Materials and Methods

An eleven hectare field of Templeton silt loam on the Lincoln College Farm was sown with winter wheat cv. Rongotea (150kg/ha) on 2 July 1981. One half was sown with seed treated with triadimenol plus fuberidazole (15g + 2g a.i./100kg seed, respectively). The other half was sown with seed treated with carboxin plus thiram (5g + 50g a.i./100kg seed, respectively). The previous crops were clover in the 1979-80 season and peas in the 1980-81 season. Diammonium phosphate (100kg/ha) was applied as a pre-plant fertilizer and MCPA (1125g a.i./ha) was applied at G.S. 14 for broadleaf weed control. Spray treatments consisted of applying triadimefon (125g a.i./ha) to control stripe rust at G.S. 32

(16 October) and/or G.S. 59 (18 November) with each seed treatment in a factorial design, giving a total of eight treatments. There were four replicate blocks, with each field plot (32 x 16m) separated by a 1m buffer of unsprayed wheat. Fungicide was applied by tractor rig with a 7m boom and hollow cone nozzles (Tee Jet Tx26) which delivered 200 liters/ha.

Stripe rust severity was assessed weekly after the first spray application in each treatment until senesence. Ten plants per plot were removed randomly from rows 1.5-2.0m from the plot edge. Stripe rust severity on all fully expanded green leaves was assessed using a standard area diagram (Anon., 1973) which included pustules and directly associated chlorosis.

Plots were mechanically harvested, when grain moisture was approximately 14%, with a Walter and Winterstieger Seedmaster harvester. Two 10 x 1.5m strips were cut from the middle of each plot to measure yield (t/ha adjusted to 14% moisture). Grain weight was determined from a sample of one thousand grains dried at 80°C for 48 hours. Data were analyzed by analysis of variance of treatments, main effects and interactions using F-tests (Snedecor and Cochran, 1967). Stripe rust severity data from the top three leaves at several growth stages were regressed with header harvest yields using both quadratic and linear regression models, with significance of fit ($P \leq 0.05$) analyzed by F-tests (Zar, 1974).

4.2.2 Results

The triadimenol plus fuberidazole seed treatment (T+F) controlled stripe rust for thirty days, up to G.S. 34, as shown by significantly lower stripe rust severities than carboxin plus thiram (C+T) seed treatment (Table 4.1). A C+T seed treatment without foliar sprays resulted in the highest severities (Table 4.1).

Table 4.1: The effect of seed treatments and foliar sprays on the development of stripe rust on wheat, cv. Rongotea, in field plots in 1981 - 82.

		Mean % stripe rust severity on top 3 leaves						
Seed* Treatment	Foliar+ Spray	G.S.32	33	34	39	49	59	61
C+T	Nil	0.1	1.7	0.3	1.0	2.0	3.3	5.4
C+T	G.S.32	0.1	0.3	0.1	0.3	0.9	1.5	5.0
C+T	G.S.59	0.1	1.7	0.3	1.0	2.0	3.3	3.2
C+T	G.S.32+59	0.1	0.3	0.1	0.3	0.9	1.7	2.1
T+F	Nil	0.0	0.4	0.1	1.4	1.8	1.7	2.8
T+F	G.S.32	0.0	0.3	0.0	0.0	0.3	1.8	1.9
T+F	G.S.59	0.0	0.4	0.1	1.4	0.9	1.7	1.4
T+F	G.S.32+59	0.0	0.3	0.0	0.0	0.3	1.0	0.9
LSD ($P = 0.05$)		-	1.1	0.2	0.7	1.0	1.1	1.8
SEM		-	0.4	0.1	0.2	0.3	0.4	0.8

* C+T = carboxin + thiram (50g + 50g a.i./100kg seed)
T+F = triadiminol + fubridazole (15g+2g a.i./100kg seed)

+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

The greatest yield resulted from the T+F seed treatment with fungicide sprays at G.S. 32 and 59 (Table 4.2). The lowest yields resulted from T+F or C+T seed treatments alone or with a spray at G.S. 32 (Table 4.2). The heaviest individual grain weights resulted from C+T or T+F with sprays at G.S. 32 + 59, or T+F with a spray at G.S. 59. A C+T or T+F seed treatment alone had the lowest individual grain weight (Table 4.2). The main effects of applying a T+F seed treatment, fungicide at G.S. 32 or G.S. 59 on yield were significant although interactions were not (Table 4.3). There were mean yield increases of 0.28, 0.31 and 0.37 t/ha, respectively, over treatments which did not include the main effect. Mean yield increases of the main effects were derived by calculating the difference between the mean of all treatments which included a specific main effect and those which did not, using treatment values from Table 4.2. Individual grain weight was increased significantly by the main effects of fungicide applications at G.S. 32 or G.S. 59 (Table 4.3) with mean increases of 1.6 and 2.8mg, respectively, as calculated for yield increases.

The regressions of stripe rust severity on the top three leaves at several growth stages are summarized in Table 4.4. Neither quadratic nor linear models were fit significantly to severity-yield regressions before G.S. 39. A quadratic model at G.S. 39 was the only model fit with a high r^2 value (0.92). Models which fit significantly at G.S. 59 and 61 had r^2 values less than 0.60.

Stripe rust severity on the top three leaves at the time of fungicide application in the highest yielding treatment of T+F plus sprays at G.S. 32 + 59, was 0.0 and 1.0%, respectively (Table 4.1).

Table 4.2: The effect of seed treatments and foliar sprays on header yields and individual grain weights during the 1981 - 82 season.

Seed* Treatment	Foliar+ Spray	Header Yield (t/ha)#	Individual Grain Wt. (mg)
C+T	Nil	2.90	37.5
C+T	G.S.32	3.07	39.0
C+T	G.S.59	3.37	39.6
C+T	G.S.32+59	3.41	41.8
T+F	Nil	3.01	38.0
T+F	G.S.32	2.87	39.5
T+F	G.S.59	3.35	41.9
T+F	G.S.32+59	3.75	41.5
LSD (P = 0.05)		0.24	1.6

* C+T = carboxin + thiram (50g + 50g a.i./100kg seed)
T+F = triadimenol + fuberidazole (15g+2g a.i./100kg seed)

\+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

\# Adjusted to 14% moisture content

Table 4.3: Factorial analysis of the effects of seed and foliar fungicide applications on header yield and individual grain weight for the 1981 - 82 season.

		% Sum of Squares Accounted For	
Source of Variation	D.F.	Header Yield	Individual Grain Wt.
S.T.°	1	19.13*	2.36
G.S.32+	1	23.91*	17.20*
G.S.59+	1	33.43*	49.29*
S.T.xG.S.32	1	1.96	1.26
S.T.xG.S.59	1	1.79	2.09
G.S.32xG.S.59	1	0.04	0.12
S.T.xG.S.32xG.S.59	1	1.26	0.01
Residual Mean Square	21	0.11	1.22

* Significant F-test (P $\leq$ 0.05)

° Triadimenol + fuberidazole (15g+2g/100kg seed), seed treatment for stripe rust control vs. carboxin + thiram (50g + 50g a.i./kg seed)

\+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

Table 4.4: Regression models of header yields (14% moisture) on % stripe rust severity on the top three leaves of wheat, cv. Rongotea, during the 1981 - 82 season.

	Regression Models			
	Linear		Quadratic	
Growth Stage	Equation	r^2	Equation	r^2
32	Yield=3.25-0.24(sev)	0.00	Yield=6.08-10.3(sev)+5.05(sev)^2	0.35
33	Yield=3.37-0.40(sev)	0.43	Yield=3.53-1.64(sev)+0.88(sev)^2	0.64
34	Yield=3.18-0.66(sev)	0.00	Yield=2.90+4.81(sev)-0.30(sev)^2	0.00
39	Yield=3.56-0.37(sev)	0.66	Yield=4.04-1.57(sev)+0.50(sev)^2	0.92**
49	Yield=3.79-0.28(sev)	0.39	Yield=4.00-0.51(sev)+0.05(sev)^2	0.27
59	Yield=3.72-0.17(sev)	0.57*	Yield=3.90-0.32(sev)+0.02(sev)^2	0.52*
61	Yield=3.75-0.14(sev)	0.48*	Yield=3.84-0.19(sev)+0.01(sev)^2	0.38

* Significant F-test at $P \leq 0.05$ (Zar, 1974)

** Significant F-test at $P \leq 0.01$ (Zar, 1974)

NB There were four observations for growth stages 32 to 39 and eight observations for growth stages 49 to 61.

4.3 TRIAL 2: 1982-1983 SEASON

4.3.1 Materials and Methods

A four hectare field on the Lincoln College Farm was sown with winter wheat cv. Rongotea (150kg seed/ha) in a Temuka silt loam soil on 25 May 1982. In the previous season the field was in ryegrass pasture, and diammonium phosphate (100kg/ha) was incorporated in the soil before sowing. Seed was treated with triadimenol plus fuberidazole (15g + 2g a.i./100kg of seed respectively). Chlorsulfuron (15g a.i./ha) was applied at G.S. 15 for broad leaf weed control. Triadimefon (125g a.i./ha) was applied for stripe rust control at G.S. 24, 32, 59 and/or 75 to give sixteen treatments in a full factorial design. Treatment plots (15 x 5m), separated by buffer zones (3m wide) of unsprayed Rongotea wheat, were randomized in three replicate blocks. Stripe rust severity was assessed every two weeks on all green fully expanded leaves until senesence, using standard area diagrams, as in the 1981-82 season.

At harvest, when the grain moisture was approximately 14%, two 10 x 1.5m strips were mechanically harvested as in the 1981-82 season. Ten $0.1m^2$ quadrats of whole plants were also sampled randomly from each plot before mechanical harvest, 1.5m from each side. The number of ears/m^2 were counted, threshed mechanically and the yield/m^2 and grains/head measured. Sub-samples were taken from both quadrat and header harvests and individual grain weight determined as in the 1981-82 season. Yield data were analyzed by analysis of variance of treatments, main effects and interactions using F-tests and significant differences ($P \leq 0.05$) between treatments were determined using least significant differences (Snedecor and Cochran, 1967). Values for stripe rust severity on the top three leaves were regressed with header harvest yields, and defined by linear and quadratic models as in the 1981-82 season.

4.3.2 Results

Treatments resulted in a range of disease severities throughout the season (Table 4.5). A nil spray program resulted in the highest disease severities throughout the season, with a maximum of 18.0% on the top three leaves at G.S. 75. A one spray program for early season control, in which fungicide was applied at G.S. 24 when severity was 0.0%, controlled disease completely until G.S. 43. A full season program with fungicide applications at G.S. 24, 32, 59 and 75 maintained low severities throughout the season, with maximum values of 1.0% (G.S. 59) and 1.6% (G.S. 75).

The header yield in untreated plots was 5.57 t/ha (Table 4.6). Treatments which included a fungicide application at G.S. 32 resulted in the greatest yields. For example, when an application was combined with an application at G.S. 59 or 75, the yields were 6.57 and 6.15 t/ha, respectively (Table 4.6). The yield of a full season spray treatment (G.S. 24, 32, 59 + 75) was not significantly greater than any other treatment with an application at G.S. 32.

A quadrat yield of 566.4g/m² resulted from a nil spray treatment (Table 4.6). The greatest quadrat yields resulted from treatments with applications at G.S. 24 + 32, G.S. 32 + 59, G.S. 24 + 32 + 59, G.S. 24 + 32 + 75, G.S. 24 + 59 + 75 and a full spray program with a range of 736.2mg to 675.2mg (Table 4.6). A header harvest individual grain weight of 35.4mg resulted from a nil spray treatment. The heaviest header harvest individual grain weights ranged from 39.7mg to 37.9mg, resulting from sprays applied at G.S. 24 + 32 and G.S. 32 + 59 + 75, respectively (Table 4.6). A quadrat individual grain weight of 36.2mg resulted from a nil spray treatment. The heaviest quadrat individual grain weight ranged from 39.5mg to 37.9mg, resulting from sprays at G.S. 32 + 59 and G.S. 32 + 75, respectively. The greatest grain number per head ranged from 33.1 to 31.1 grains, respectively from sprays at G.S. 24, 32, 59 + 75 or

Table 4.5: The effect of foliar sprays on the development of stripe rust on wheat, cv. Rongotea, in field plots for the 1982 - 83 season.

	Mean % stripe rust severity on top 3 leaves				
Treatment+ G.S.	24	32	43	59	75
Nil	0.0	0.4	0.4	11.7	18.0
G.S. 24	0.0	0.0	0.3	5.6	11.2
G.S. 32	0.0	0.4	0.3	1.3	2.9
G.S. 59	0.0	0.4	0.4	6.5	8.6
G.S. 75	0.0	0.4	0.4	6.7	12.8
G.S. 24+32	0.0	0.0	0.0	0.6	2.6
G.S. 24+59	0.0	0.0	0.5	2.4	5.4
G.S. 24+75	0.0	0.0	0.5	6.7	7.9
G.S. 32+59	0.0	0.4	0.3	1.5	1.7
G.S. 32+75	0.0	0.4	0.3	1.5	2.6
G.S. 59+75	0.0	0.4	0.4	6.7	12.8
G.S. 24+32+59	0.0	0.1	0.1	0.6	2.6
G.S. 24+32+75	0.0	0.1	0.0	1.3	2.1
G.S. 24+59+75	0.0	0.0	0.4	1.2	7.2
G.S. 32+59+75	0.0	0.0	0.2	1.0	5.3
G.S. 24+32+59+75	0.0	0.0	0.0	1.0	1.6
LSD ($P \leq 0.05$)	-	0.3	0.3	2.3	5.4
SEM	-	0.1	0.1	0.8	1.9

+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

G.S. 24 + 32 and G.S. 32 + 59 + 75, respectively. A nil spray treatment resulted in 26.6 grains per head (Table 4.6). There were no significant differences between the ears/m² of treatments.

The main effects of fungicide applications at G.S. 24 or 32 on header yield were significant (Table 4.7) with a mean increase of 0.20 t/ha and 0.44 t/ha, respectively, compared to those treatments which did not include these applications. Mean increases were derived by calculating the difference between the mean of yields with and without the main effect from Table 4.6. There were no significant interactions for the effects of fungicide applications at different growth stages on header yield (Table 4.7). Quadrat yields followed the same trends as header yields, and fungicide applications at G.S. 24 or 32 significantly increased quadrat yield. Significant interactions occurred between spray applications at G.S. 32 x 59, G.S. 32 x 75 and G.S. 24 x 59 x 75 (Table 4.7). This indicated that efficacy of fungicide applications at G.S. 75 or 59 was dependent on an application at G.S. 32 or 24.

The main effects of fungicide applications at G.S. 32 or 59 on header harvest individual grain weight were significant (Table 4.7). An application at G.S. 32 resulted in a mean individual grain weight increase of 1.3mg while an application at G.S. 59 resulted in an increase of 0.9mg as calculated in the same manner as the mean main effect on header harvest yield increases. Similar effects were seen for quadrat harvest data with significant main effects of fungicide applied at G.S. 32 or 59. There were no significant interactions between fungicide applications and either harvest or quadrat individual grain weights (Table 4.7).

The main effects on grain number/ear of applying fungicide at G.S. 24 or 32 were both significant (Table 4.7), with an increase of 2.9 and 2.2 grains, respectively, compared with the mean of treatments without fungicides applied at these growth stages. The number of ears/m² was not influenced by fungicide applications (Table 4.7).

Table 4.6: Mean header and quadrat yield and yield components for treatments during the 1982 - 83 season.

Treatment+	Spray No.	Header Harvest Yield (t/ha)#	Header Harvest Ind.Grain Wt. (mg)	Quadrat Harvest Yield (g/m²)#	Quadrat Harvest Ind.Grain Wt. (mg)	Quadrat Harvest Grains/ Ear	Quadrat Harvest Ears/ m²
G.S. 24	1	6.02	35.7	625.2	36.3	32.0	519.7
G.S. 32	1	6.20	39.0	651.2	39.2	29.0	541.3
G.S. 59	1	5.92	39.2	629.0	37.5	28.1	533.7
G.S. 75	1	5.48	35.8	605.4	36.9	27.1	541.3
G.S. 24+32	2	6.42	39.7	703.2	38.4	33.1	499.7
G.S. 24+59	2	5.88	38.5	571.3	39.3	30.8	498.3
G.S. 24+75	2	5.96	35.6	642.0	37.4	32.2	521.3
G.S. 32+59	2	6.57	38.6	689.8	39.5	31.5	507.7
G.S. 32+75	2	6.15	37.3	611.0	37.9	30.9	541.3
G.S. 59+75	2	5.97	38.8	588.4	38.6	27.8	540.3
G.S. 24+32+59	3	6.44	38.4	736.2	38.8	32.7	540.7
G.S. 24+32+75	3	6.44	39.2	700.5	38.1	31.5	531.0
G.S. 24+59+75	3	6.21	38.2	675.2	38.0	30.5	542.3
G.S. 32+59+75	3	6.27	37.9	643.1	38.9	31.1	498.0
G.S. 24+32+59+75	4	6.27	39.5	733.9	38.9	33.1	551.7
Nil	0	5.57	35.4	566.4	36.2	26.6	528.0
LSD ($P \leq 0.05$)		0.44	2.1	52.1	1.8	2.0	58.0

Adjusted to 14% moisture content

+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

Table 4.7: Factorial analysis of effects of foliar fungicide application timing on header and quadrat yield and yield components for the 1982 - 83 season.

		% sum of squares accounted for					
		Header Harvest		Quadrat Harvest			
Treatment+	D.F.	Yield#	Ind.Grain Wt. (mg)	Yield#	Ind.Grain Wt. (mg)	Grains/ Ear	Ears/ m²
G.S. 24	1	6.04*	1.70	17.87**	0.03	40.00**	0.01
G.S. 32	1	28.18**	18.45**	35.88**	15.96**	23.19**	1.92
G.S. 59	1	2.51	8.19*	2.60	16.25**	0.71	0.52
G.S. 75	1	0.58	0.08	0.20	0.05	0.02	1.98
G.S. 24x32	1	0.83	0.22	2.32	1.12	4.57	1.40
G.S. 24x59	1	3.48	0.17	0.83	0.02	3.10	3.48
G.S. 24x75	1	1.55	4.35	1.14	4.61	1.58	0.07
G.S. 32x59	1	0.97	6.61	5.57*	0.01	0.65	3.22
G.S. 32x75	1	2.03	2.11	4.60*	3.91	0.00	1.31
G.S. 59x75	1	0.03	0.79	0.03	0.18	0.16	0.20
G.S. 24x32x59	1	0.12	0.55	0.28	0.00	1.05	0.91
G.S. 24x32x75	1	0.00	0.19	0.09	4.26	0.47	0.70
G.S. 24x59x75	1	0.45	3.91	4.12*	1.96	1.63	0.09
G.S. 32x59x75	1	3.23	2.25	0.00	1.04	0.04	0.55
G.S. 24x32x59x75	1	0.01	6.75	2.53	2.34	1.01	3.51
Residual Mean Square	30	0.07	98.25	21.03	46.00	20.76	73.25

+ Growth stage(s) at which triadimefon (125g a.i./ha) was applied

* Significant F-test ($P \leqq 0.05$)

** Significant F-test ($P \leqq 0.01$)

NB % sum of squares without * or ** not significant at $P \leqq 0.05$

Adjusted to 14% moisture content

The relationship between stripe rust severity on the top three leaves at G.S. 32 and header yield was described (r^2 = .84) by a quadratic regression model (Table 4.8). At G.S. 43 and 75 the relationship was defined by both linear and quadratic regression models (Table 4.8) with r^2 values ranging from .41 to .60.

Disease severity on the top three leaves at the time of spray application, for treatments with the greatest header yields were 0.4% (G.S. 32), 0.4% and 1.5% (G.S. 32 + 59), 0.0%, 0.1% and 0.6% (G.S. 24 + 32 + 59) or a full spray treatment (G.S. 24, 32, 59 + 75) when severities were 0.0%, 0.0%, 1.0% and 1.6% respectively (Table 4.5). Maintaining a severity of less than 1.5% on the top three leaves until G.S. 59, resulted in the greatest yields, compared to treatments which had severities above this level.

4.4 TRIAL 3: 1983-84 SEASON

4.4.1 Materials and Methods

A six hectare field of Temuka silt loam soil on the Lincoln College Farm was sown with winter wheat cv. Rongotea (150kg/ha) in the 1983-84 season. In the previous season, the field was ryegrass pasture, and glyphosate (2160g a.i./ha) was applied before cultivation to eliminate existing pasture and weeds. Diammonium phosphate fertilizer (100kg/ha) was incorporated in the soil before sowing. All seed was treated with the fungicides triadimenol plus fuberidazole (15g + 2g a.i./100kg seed, respectively). Action levels of either 0.1, 0.5 or 1.0% stripe rust severity on the top three leaves, based on the results of the 1981-82 and 1982-83 seasons, were used as criteria for applying one, two or three triadimefon sprays (125g a.i./ha) during the season. Five additional treatments were based on scheduled triadimefon sprays (125g a.i./ha) at

Table 4.8: Regression models of header yields (14% moisture) on % stripe rust severity on the top three leaves of wheat, cv. Rongotea, during the 1982 - 83 season.

		Regression Models			
		Linear		Quadratic	
Growth Stage	No. obs.	Equation	r^2	Equation	r^2
32	9	Yield=6.17-1.11(sev)	0.00	Yield=6.01+12.50(sev)-66.1(sev)^2	0.84*
43	13	Yield=6.43-1.10(sev)	0.41*	Yield=6.34+0.40(sev)-3.28(sev)^2	0.44*
59	15	Yield=6.26-0.05(sev)	0.19	Yield=6.43-0.22(sev)+0.02(sev)^2	0.19
75	16	Yield=6.46-0.06(sev)	0.60*	Yield=6.41-0.04(sev)+0.00(sev)^2	0.58*

* Significant F-test at $P \leq 0.05$ (Zar, 1974)

predetermined growth stages from G.S. 16/24 to G.S. 59. All fungicide sprays were applied by tractor as in the previous season. Growth stage 59 was selected as a terminating point for fungicide applications based on the 1982-83 experiment and work by McCullough (1982). Action levels were detected and severity assessed on ten plants from each plot every week, using standard area diagrams as in the 1981-82 and 1982-83 seasons. A waiting period of three weeks was imposed after every fungicide application before a subsequent spray decision was made, based on previous experience and information on the longevity of triadimefon activity (Anon., 1983). Treatments were arranged in a randomized block design with four replicates of fifteen plots (12 x 12m) with 6m of unsprayed Rongotea wheat between plots.

Plots were harvested and yield and yield components measured as in the 1982-83 season. Yield data was analyzed by using least significant difference tests to detect significant differences ($P \leq 0.05$) between treatment means (Snedecor and Cochran, 1967). Stripe rust severity on the top three leaves at several growth stages throughout the season were regressed with header harvest yields and defined by linear and quadratic models as in the previous season's experiments.

4.4.2 <u>Results</u>

Stripe rust severities on the top three leaves ranged from 0 to 23.5% during the season as seen in Table 4.9 which summarizes severities from treatments of action levels used for early, mid and full season control up to G.S. 16/24, 37 or 59, respectively, and growth stage schedules. Treatments with three fungicide applications had the greatest header yields, compared to treatments with nil, one or two fungicide applications, regardless of whether the treatments were based on growth stage schedules or action levels (Table 4.10). The use of 0.1 or 1.0% severity action levels resulted in significantly greater header harvest yields than a 0.5%

Table 4.9: The effect of foliar sprays on the development of stripe rust on wheat, cv. Rongotea, in field plots during the 1983 - 84 season.

	Mean % stripe rust on the top three leaves												
Treatment G.S.	15/23	15/24	16/24	16/24	17/31	17/31	32	37	41	47	55	59	61
ACTION LEVELS (% Inc.)													
Up to G.S. 16·24													
0.1	0.0	0.2°	0.4	2.3	1.0	1.3	5.5	13.3	9.9	6.0	7.6	11.0	15.0
0.5	0.0	0.0	0.7°	5.0	6.4	0.3	0.5	9.3	10.3	3.2	8.5	7.9	9.3
1.0	0.1	0.1	1.3	3.7°	9.0	2.7	0.7	2.4	7.9	3.5	3.7	12.3	5.3
Up to G.S. 37													
0.1	0.0	0.2°	0.6	3.1	2.5	0.5°	1.5	0.8	0.4	1.4	6.0	8.7	8.4
0.5	0.0	0.0	0.8°	3.7	5.9	0.1	0.7°	5.4	0.6	0.6	3.1	6.4	4.5
1.0	0.0	0.0	0.6	3.9°	10.0	3.1	0.2	1.3°	8.2	0.1	0.8	2.9	6.9
Up to G.S. 59													
0.1	0.0	0.2°	0.5	3.1	2.5	0.5°	1.5	0.8	0.4	1.4°	6.0	3.4	6.1
0.5	0.0	0.0	0.8°	3.7	5.9	0.1	0.7°	5.4	0.6	0.6	3.1	6.4°	4.5
1.0	0.0	0.0	0.6	3.9°	10.0	3.1	3.1	1.7°	8.2	0.1	0.8	2.9°	6.9
G.S. SCHEDULE													
G.S. 16/24	0.1	0.0	1.2	3.9°	10.8	2.6	0.3	2.2	8.3	5.6	9.1	11.9	12.8
G.S. 41	0.0	0.0	1.3	4.1	12.9	13.9	18.2	20.1	8.6°	8.2	11.3	11.7	7.7
G.S. 16/24+41	0.0	0.2	1.3	4.0°	8.9	1.7	0.5	5.9	6.0°	6.4	8.9	8.0	3.2
G.S. 41+59	0.0	0.0	1.3	4.1	10.8	13.9	18.2	20.1	8.6°	8.2	11.3	11.7°	7.7
G.S. 16/24+41+59	0.0	0.0	1.3	4.0°	8.9	1.7	0.5	5.9	6.0°	6.4	8.9	8.0°	3.2
NIL	0.1	0.2	1.6	3.6	10.0	14.0	21.6	23.5	16.8	8.5	14.2	18.3	15.7
LSD ($P \leq 0.05$)	0.1	0.2	1.4	3.4	5.2	2.8	6.5	4.8	2.5	1.9	2.7	1.8	3.3
SEM	0.0	0.1	0.5	1.2	1.8	1.0	2.2	1.7	0.9	0.7	0.9	0.6	1.1

° Growth stage(s) at which triadimefon (125g a.i./ha) was applied.

action level (Table 4.10). However, a delay in a fungicide application was incurred, because of high winds and the risk of drift to adjacent plots, for a 0.5% action level treatment at G.S. 55. The use of action levels, regardless of the severity, resulted in a mean header yield of 6.69 t/ha which was not significantly different to the use of growth stages, with a header yield of 6.66 t/ha.

Application of fungicides up to G.S. 59, based on a 0.1 or 1.0% severity on the top three leaves, resulted in the greatest header yields of 6.45 and 6.35 t/ha, while a nil treatment yielded 4.98 t/ha (Table 4.11). The greatest quadrat yields resulted from the use of 0.1%, 0.5%, 1.0% action levels up to G.S. 59, a 1.0% action level up to G.S.37, or scheduled fungicide applications at G.S. 16/24 + 41, G.S. 41 + 59 and G.S. 16/24, 41 + 59, with a range between 694.6 to 635.3g/m². The nil treatment resulted in a quadrat yield of 552.6g/m² (Table 4.11). The heaviest individual grain weights for both header and quadrat harvests were associated with fungicide applications between G.S. 37 and 59, regardless of whether the spray decision was based on action levels or growth stage schedules (Table 4.11). Treatments which included a fungicide application at or before G.S. 41, except the G.S. 41 + 59 treatment, had the greatest grain number per head, which ranged from 29.1 to 28.5 whereas a nil treatment had 26.1 grains per head (Table 4.11). There were no significant differences in ears/m² (Table 4.11).

The only severity-yield relationship defined significantly ($P \leq 0.05$) by linear or quadratic regression models was for disease severity on the top three leaves at G.S. 59, with r^2 values of 0.62 and 0.64, respectively. The use of 0.1% or 1.0% severity action levels as criteria for three fungicide applications, up to G.S. 59, resulted in applications when severities on the top three leaves were 0.2%, 0.5% and 1.4% or 3.9%, 1.7% and 2.9%, respectively (Table 4.9). Fungicide was applied when severity surpassed the action level and therefore severities at the time of fungicide application were greater than the action level.

Table 4.10: Mean header yields for treatments based on action levels, different numbers of fungicide applications and action level or G.S. schedule management programs on wheat, cv. Rongotea, for the 1983 - 84 season.

Treatments	Header Yield (t/ha)#
Spray No. +	
0	4.98 d
1	5.29 c
2	5.78 b
3	6.14 a
Action Level ++	
0.1%	5.77 a
0.5%	5.47 b
1.0%	5.84 a
Management Program +++	
Action level	6.69
G.S. Schedule	6.66

Adjusted to 14% moisture content

Values without any letter in common are significantly different at $P \leq 0.05$ as analyzed by Duncan's Multiple Range Test for action level treatments and spray number treatments respectively.

+ Number of triadimefon (125g a.i./ha) applications in action level and growth stage schedule treatments.

++ Triadimefon (125g a.i./ha) was applied when mean severity on the top 3 leaves surpassed 0.1%, 0.5% or 1.0%, respectively.

+++ Management programs based on action levels or G.S. schedule.

Table 4.11: Mean header and quadrat yield and yield components for treatments during the 1983 - 84 season.

Treatment +	Spray No.	Header Harvest: Yield# (t/ha)	Header Harvest: Ind.Grain Wt. (mg)	Quadrat Harvest: Yield# (g/m^2)	Quadrat Harvest: Ind.Grain Wt. (mg)	Quadrat Harvest: Grains/ Ear	Quadrat Harvest: Ears/ m^2
ACTION LEVELS (% Inc.)							
Up to G.S. 16·24							
0.1	1	5.19	34.8	550.7	36.5	29.5	595
0.5	1	5.21	33.5	584.6	37.1	28.5	558
1.0	1	5.24	32.7	590.2	37.0	28.7	525
Up to G.S. 37							
0.1	2	5.44	35.0	614.2	39.4	29.3	577
0.5	2	5.67	34.6	610.5	37.9	29.4	551
1.0	2	5.95	37.7	645.6	37.9	29.3	563
Up to G.S. 59							
0.1	3	6.45	36.7	694.0	39.8	29.1	548
0.5	3	5.77	36.5	660.2	40.2	29.4	521
1.0	3	6.35	37.1	694.6	40.2	29.2	527
SCHEDULE							
G.S. 16·24	1	5.35	31.7	613.6	37.6	28.5	551
G.S. 41	1	5.45	38.8	606.4	41.9	28.5	516
G.S. 16·24+41	2	5.80	36.7	663.4	41.1	29.1	540
G.S. 41+59	2	5.77	38.6	635.3	41.8	27.4	566
G.S. 16·24+41+59	3	5.93	39.0	660.3	41.7	29.8	519
Nil	0	4.98	32.1	552.6	37.4	26.1	531
LSD ($P \leq 0.05$)		0.43	2.9	60.7	1.8	1.4	80

Adjusted to 14% moisture content

+ Triadimefon (125g a.i./ha) applied

Table 4.12: Regression models of header yields (14% moisture) on % stripe rust severity on the top three leaves of wheat, cv. Rongotea, during the 1983 - 84 season.

Growth Stage	Regression Models: Linear Equation	Linear r^2	Quadratic Equation	Quadratic r^2
23	Yield=5.54-3.59(sev)	0.19	Yield=5.50+1.31(sev)-4.23(sev)^2	0.14
23	Yield=5.41+0.15(sev)	0.00	Yield=5.63+1.16(sev)+6.41(sev)^2	0.08
23	Yield=5.55+0.14(sev)	0.00	Yield=4.86+1.79(sev)-1.04(sev)^2	0.15
24	Yield=5.55+0.03(sev)	0.00	Yield=3.94+0.81(sev)-0.11(sev)^2	0.00
24	Yield=5.42+0.00(sev)	0.00	Yield=5.26-0.07(sev)-0.01(sev)^2	0.00
31	Yield=5.50-0.02(sev)	0.00	Yield=5.39-0.07(sev)-0.01(sev)^2	0.00
31	Yield=5.51-0.02(sev)	0.12	Yield=5.52-0.03(sev)-0.01(sev)^2	0.00
32	Yield=5.61-0.02(sev)	0.24	Yield=5.63-0.03(sev)-0.00(sev)^2	0.13
37	Yield=5.71-0.04(sev)	0.25	Yield=5.59+0.01(sev)-0.00(sev)^2	0.24
41	Yield=5.64-0.05(sev)	0.15	Yield=5.73-0.13(sev)-0.01(sev)^2	0.09
47	Yield=5.72-0.04(sev)	0.20	Yield=5.71-0.04(sev)-0.00(sev)^2	0.08
59	Yield=6.24-0.08(sev)	0.62*	Yield=6.57-0.16(sev)+0.00(sev)^2	0.64*
61	Yield=6.02-0.06(sev)	0.26	Yield=5.69+0.02(sev)+0.00(sev)^2	0.19

* Significant F-test at $P \leq 0.05$ (Zar, 1974)

NB There were ten observations for growth stages 23 to 47 and eleven observations for growth stages 59 and 61.

4.5 DISCUSSION

Stripe rust infections were not observed before the five leaf stage, G.S. 15, when a triadimenol plus fuberidazole seed treatment was used, as also reported by Chan and Gaunt (1982) and McCullough (1982). Fungicides applied when stripe rust severity on the top three leaves was zero did not increase yield significantly (Section 4.3.2). The greatest header and quadrat yields resulted from fungicide applications up to G.S. 59 (immediately before anthesis). Fungicides applied after anthesis did not increase yield significantly, as seen in Trial 2 in the 1982-83 season (Section 4.3.2), and reported in other studies in New Zealand (McCullough, 1982). Thus the important period for stripe rust monitoring and control in New Zealand is between G.S. 15 and 59 for winter wheat cv. Rongotea, assuming seed treatment with triadimenol plus fuberidazole. A 49 day withholding period between the last application of triadimefon and harvest also limits the use of chemical control beyond G.S. 59.

The effects of stripe rust on yield can be interpreted by measuring the yield components ear number/m^2, grain number/ear and individual grain weight. The number of ears/m^2 was not affected by stripe rust infection, as shown by Chan and Gaunt (1982) and McCloy (1982). Studies in the U.S.A. (Hendrix and Fuchs, 1970) and Britain (Doling and Doodson, 1968; Mundy, 1973) showed that stripe rust infections during the seedling stage in crops which were not treated with an effective seed treatment reduced tillering and the ear number at harvest. Grain number per ear was reduced by stripe rust infections before G.S. 41-43 (booting), as reported in the U.S.A. (Hendrix and Fuchs, 1970), Britain (Doodson et al., 1964) and New Zealand (McCloy, 1982; Chan, 1984). The potential grain number per ear is determined approximately between G.S. 15 and 68, during ear development and grain set (Doodson et al., 1964; Dougherty and Langer, 1974) and stripe rust infections may reduce photosythetic area and assimilate supply for primordia formation, floret development and grain set. Applications of fungicides at

G.S. 32 to 59 increased individual grain weight compared to wheat which did not receive fungicide applications at those times. Reduction in individual grain weight occurs as a result of a reduction in photosythetic leaf area and subsequent reduction of assimilates available for translocation to developing grains (Mains, 1930; Stoy, 1965; King and Polley, 1976). Fungicides applied at G.S. 32 and/or 59 would reduce stripe rust severity during the later part of the season from G.S. 65. Stripe rust infections at early growth stages caused reductions in individual grain weight in the U.S.A. (Hendrix and Fuchs, 1970), Britain (Doodson et al., 1964; King, 1976) and New Zealand (McCloy, 1982; Chan, 1984).

Critical point models of the relationship between stripe rust severity and yield loss developed in Britain for late season epidemics were significant for G.S. 67 and 75 (Doodson and Doling, 1968; Mundy, 1973). In this study, linear and quadratic critical point models were fit at early growth stages, but the growth stages at which severity was best correlated to yield loss were not consistent. Stripe rust infections appeared to reduce yield because of effects before G.S. 59, as seen in the reduced grain number and the significant yield increases which resulted from applying fungicides between G.S. 24 and 32. Therefore the regression models were not relevant to decisions for stripe rust management in New Zealand, since control would be required before G.S. 59. Regression models were unique to each season and could be a reflection of seasonal and locational effects on wheat growth and stripe rust development. Such variation in cereal foliar disease models was observed by Romig and Calpouzos (1970), James (1971) and Brooks (1972). Interpretation of critical-point models may be difficult when data used to develop such models are derived from artificially manipulated epidemics through the use of fungicides and because such models are empirical in nature and do not explain the severity-yield relationship. Significant empirical models reflect periods during the season when the distribution of severity-yield co-ordinates may not be variable as at other periods, but this may be a statistical artifact or a true severity-yield correlation. Only critical-point models were analyzed in the study, although multiple-point severity-yield models have been shown to increase model accuracy in some situations (Burleigh et al., 1972; James, 1974). Implementation of multiple-point models would be difficult in disease management programs since severity at a particular growth stage in a model may not directly affect yield, but may affect subsequent disease development at a later growth stage which would affect yield (Teng and Gaunt, 1980). Mechanistic models were not developed because of the complexity and resources required for such development.

Applying fungicides for stripe rust control using an action level, or the level of stripe rust at which action is judged necessary to avoid subsequent yield loss, was a valid alternative since no model was developed which consistently defined severity-yield loss relationships during the monitoring period between G.S. 15 and 59. Fungicide applied before stripe rust infections occurred on the top three leaves did not increase yield compared to fungicide applications when severities were between 0.1% and 0.4% in 1982 (Section 4.3.2) and between 0.2% and 3.0% in 1983 (Section 4.4.2). The use of a 0.1% and 1.0% severity, on the top three leaves, as action levels for fungicide application up to G.S. 59 resulted in heavier header yields compared to treatments which used growth stage schedules or treatments which were based on action levels but did not control stripe rust between G.S. 16.24 and 59 (Section 4.4.2). The existence of a wide severity range, 0.1% to 3.0%, at which fungicides should be applied to control stripe rust up to G.S. 59 would make the use of action levels useful in commercial field situations, since delays in fungicide applications for logistic or climatological reasons would not necessarily mean that a significant yield loss would occur. A 0.2% mean severity on the top three leaves was selected as the action level to apply fungicides, based on observations during three seasons. The 0.2% action level was in the lower range of severities at which fungicide applications resulted in the greatest yields. However, 0.2% was selected to allow for the risk of fungicide application delays. The 0.2% action level is low compared to those which were recommended for use in Europe, such as 8% stripe rust severity on the top three leaves (Anon., 1973), 5% on the top two leaves (Mundy, 1973) and 1% on the top leaf for moderately susceptible cultivars. On the other hand, the action level is high in relation to "first sight" recommendations for susceptible cultivars in Europe (Jenkins and Lescar, 1980) and New Zealand (Hedley and McCloy, 1982). Differences between action levels recommended in Europe and a 0.2% action level for a susceptible cultivar, Rongotea, in New Zealand reflects the significant effects of stripe rust infections before G.S. 59 on yield, compared to the later season infections which occur in Europe. Further studies may enable the definition of a series of action levels throughout crop growth which would correspond to differences in crop sensitivity to stripe rust at different growth stages.

Prophylatic or scheduled fungicide applications have not always proved to be the most efficient use of fungicides for the control of foliar cereal diseases (Cook, 1980; Jenkins and Lescar, 1980) since fungicide may be applied when disease is absent or at a low risk of causing any significant yield loss. The use of a 0.2% stripe rust severity on the top three leaves as a criterion for fungicide applications up to G.S. 59 would optimize fungicide use and be valid regardless of seasonal or locational variation. Triadimefon provided effective stripe rust control for up to four weeks, which is in agreement with label recommendations. Combined with a triadimenol plus fuberidazole seed treatment, triadimefon offered effective fungicide control options to be used in a stripe rust management program. The 0.2% action level will be integrated with sampling methods and severity-incidence relationship (Chapter 2) and spatial patterns (Chapter 3) to construct a sequential sampling plan to detect the 0.2% action level reliably and quickly, as reported in the next chapter.

CHAPTER 5

A SEQUENTIAL SAMPLING PLAN AND STRIPE RUST MANAGEMENT PROGRAM

5.1 INTRODUCTION

Pest management sampling plans must be rapid and reliable if they are to be accepted in commercial field situations (James, 1974; Sterling and Pieters, 1979; Shepard, 1981). The goal of pest management sampling plans is the rapid classification of pest populations relative to a predetermined economic threshold or action level on which a control decision is based, rather than the precise estimation of population densities (Iwao, 1975). Sequential sampling is a rapid and reliable sampling method suitable for the classification of pest populations for pest management (Waters, 1955; Onsager, 1976). The technique does not depend on a fixed number of samples, but uses a flexible sample size based on the spatial pattern of the pest, predetermined economic thresholds or action levels, and levels of confidence in making correct decisions. Sample units are examined in sequence until a decision is made from sampling and cumulative information. Decisions are based on the classification of pest populations below a lower limit, where the pest level is judged to be too small to necessitate control action, or above an upper limit where the population is judged to be large enough to recommend control action. In both cases, once the decision is reached, no further sampling is carried out until a later occasion. At small or large population levels, few samples are required to make a management decision, but at intermediate levels, where the population is close to the economic threshold or action level, further sampling is required. Non-sequential (fixed number) sampling plans require the same number of samples irrespective of population size, whereas decisions may be made more rapidly by sequential sampling when either small or large populations are present (Waters, 1955). The use of sequential sampling plans can lead to a 50-70% saving in time and labor compared to non-sequential sampling plans (Waters, 1955; Sterling, 1975; Coggin and Dively, 1982).

Non-sequential sampling plans require preliminary estimates of sample means and variances to determine sample number (Karandinos, 1976), which may require double sampling, thus increasing the time and effort required to use such sampling plans (Kuno, 1969).

The components required to develop a sequential sampling plan are a reliable sampling technique, a quantitive description of the spatial pattern of the pest in the field, a relationship between yield and pest density or severity, and a level of confidence of making a correct decision (Shepard, 1981; Hopkins et al., 1981). Sequential sampling was initially developed by Wald (1945) and has since been used in sampling plans for the management of many pests, particularly insects (Allen et al., 1972; Sevacherian and Stern, 1972; Pieters and Sterling, 1974; Strayer et al., 1977). In the original sequential sampling plans a frequency distribution model (eg. negative binomial, Poisson), had to be fitted to the observed population. Fitting observed population data to mathematical models may be difficult and may restrict the use of such plans. The models which best fit the data may change from observation to observation (McGuire et al., 1957), or there may be more than one suitable model (Waters and Henson, 1959) as seen in this study (Chapter 3). This presents problems in the construction of the sequential sampling plan. A negative binomial distribution model has been found to fit many aggregated pest populations. To use the model, a common K value is needed for the calculation of a sequential sampling plan and this presents some difficulties for this system (Sylvester and Cox, 1961; Coggin and Dively, 1982).

Iwao (1975) developed a sequential sampling plan which avoids the restrictions of fitting frequency distribution models to pest populations. The plan is also density independent, which confers reliability over a range of pest densities encountered in the field. The use of this type of sequential sampling plan is becoming widely accepted and has been used in several pest management plans, including those for armyworm, Pseudaletia unipuncta, on small grains (Coggin and Dively, 1982) and leaf blight on onions caused by Botrytis squamosa (Boivin and Sauriol, 1984). Iwao's plan is based on describing the spatial pattern using the linear regression of mean crowding on mean density, which describes the basic unit of aggregation (i.e. single or clump) and how those units are dispersed (i.e. random or aggregated) as described in Chapter 3. In this chapter a sequential sampling plan using Iwao's method and the validation of the plan on a commercial field basis, is reported. The plan was based on studies of sampling techniques and severity-incidence relationships (Chapter 2), spatial pattern (Chapter 3), and severity-yield relationships (Chapter 4) for stripe rust over three seasons from 1981 to 1984.

5.2 MATERIALS AND METHODS

5.2.1 The Sequential Sampling Plan

A sequential sampling graph and table were constructed using the equations below, developed by Iwao, (1975) to calculate upper and lower acceptance levels:

$$T \text{ upper} = nx + t[n(\alpha + 1)x + (\beta - 1)x^2]^{\frac{1}{2}}$$

and

$$T \text{ lower} = nx - t[n(\alpha + 1)x + (\beta - 1)x^2]^{\frac{1}{2}}$$

where T = the total number of tillers sampled for stripe rust incidence, n = the number of sample units examined, x = the action level, and t = the value of the student's t test at a chosen level of significance for a two-sided test and an infinite number of degrees of freedom. The null hypothesis (Ho: density of the sampled population = the action level) was tested with a predetermined level of confidence (t). Values of β and α are the slopes and intercept values from the regression of mean crowding and mean density respectively.

The sample unit was the top three green fully expanded leaves on ten consecutive tillers examined along a "W" pattern in the field (based on studies presented in Chapter 2). The action level recommended for the management of stripe rust was 0.2% severity on the top three leaves, based on the severity-yield loss experiments during three seasons from 1981 to 1984 (presented in Chapter 4). A stripe rust severity of 0.2% can be estimated rapidly from sampling for approximately 10% incidence in the field, based on the regression equation:

$$\% \text{ severity} = -0.01 + 0.02 \ (\% \text{ incidence})$$

derived from severity-incidence studies (presented in Chapter 2). Thus the action level used in constructing the sequential sampling plan was a mean value of one tiller infected with stripe rust per ten tiller sample unit. The α and β values used in the sequential sampling equations were 0.11 and 1.12 respectively. These values were derived from the pooled regression of mean crowding on mean density from data for the top three leaves in 1982 and 1983 (for further details refer to Chapter 3). The level of confidence chosen for the plan was 90% ($t = 1.64$), which equals a 10% risk of making an error in decision making and is a recommended confidence level for pest management sampling plans (Sterling and Pieters, 1979). The equations used to generate the upper and lower acceptance limits were therefore:

$$T \text{ upper} = n(1.0) + 1.64[n\ (0.11+1)1.0 + (1.12-1)1.0^2]^{\frac{1}{2}}$$

and

$$T \text{ lower} = n(1.0) - 1.64[n\ (0.11+1)1.0 + (1.12-1)1.0^2]^{\frac{1}{2}}$$

When the pest population density is very close to the action level, the sampled pest density may continue to lie between upper and lower acceptance limits for a large number of sample units. Thus, the number of sample units required to make a decision may be too large to be practically acceptable. To avoid this problem, Iwao, (1975) devised a method to calculate the maximum number of sample units required before it can be assumed that the sampled pest population density equals the action level within a pre-set level of confidence. The following equation was used to calculate the maximum number of sample units:

$$n\ max = \frac{t^2\ [(\alpha + 1)x + (\beta - 1)x^2]}{d^2}$$

where d^2 = the confidence interval chosen for the estimation of pest density when the sample mean density equals the action level. All other variables are the same as those described for the equations to calculate the upper and lower acceptance limits. When the maximum number of samples is reached before the upper or lower acceptance limit is reached, the sampled pest density is assumed to be equal to the action level at the chosen level of confidence (d).

5.2.2 Validation of the Sequential Sampling Plan

In the 1984-85 season, four commercial fields on the Lincoln College Mixed Cropping Farm were sown with wheat cv. Rongotea in a Temuka silt loam during the third week in March. Field sizes ranged from 7.7 to 10 ha. All seed was treated with the fungicides triadimenol and fuberidazole (15g and 2g a.i. per 100kg of seed, respectively). Fields were divided in half and in one half the sequential sampling plan was used to decide when to apply the fungicide triadimefon (125g a.i./ha) by tractor rig for stripe rust control. A scheduled spray program was used in the other half of the field based on current farm practice. The first spray of the schedule was applied after the first incidence of stripe rust was observed through sampling in the same manner as the sequential sampling plan. Successive sprays were applied every four weeks up to G.S. 59. Both halves of the field were sampled weekly after G.S. 15 until the first fungicide application, and thereafter sampling recommenced three weeks after each fungicide application. A total of forty sample units (top three green, expanded leaves on ten consecutive tillers) were sampled randomly along a "W" pattern at each sample date to estimate rust severities, but spray decisions were based either on the sequential sampling plan or schedule respectively. A record of the number of samples and time required to reach a spray decision was recorded. All sampling and fungicide applications stopped at G.S. 59 - 61.

At harvest, on 8 and 9 January 1985, all plants were removed from twenty $0.1m^2$ quadrats sampled randomly in each half of each field on a "W" pattern. In two of the fields, four 10m x 5m areas in each field half were harvested to assess yield with an International Combine Harvester. In the other two fields, four 30m x 1.5m areas were harvested with a Walter and Wintersteiger Seedmaster experimental plot combine harvester. Different harvesters were used because of problems with availability. Yield and yield components were analyzed as described for the 1982-83 and 1983-84 experiments. Differences between yield and yield components from the two field halves were tested for significance ($P \leq 0.05$) using paired t tests (Snedecor and Cochran, 1967).

5.3 RESULTS

A sequential sampling graph (Figure 5.1) was constructed by plotting the upper and lower acceptance limits generated by using Iwao's (1975) sequential sampling equations. For practical use in field situations, sequential sampling decision tables were found to be easier to use by the sampler (Coggin and Dively, 1982) and therefore a decision table was constructed with instructions on the implementation of the sequential sampling plan for the management of stripe rust (Table 5.1).

The minimum sample unit number required was set at ten, as recommended for sequential sampling plans by Pieters and Sterling (1974) and Boivin and Sauriol (1984). This represents one diagonal of the "W" sampling pattern. If an

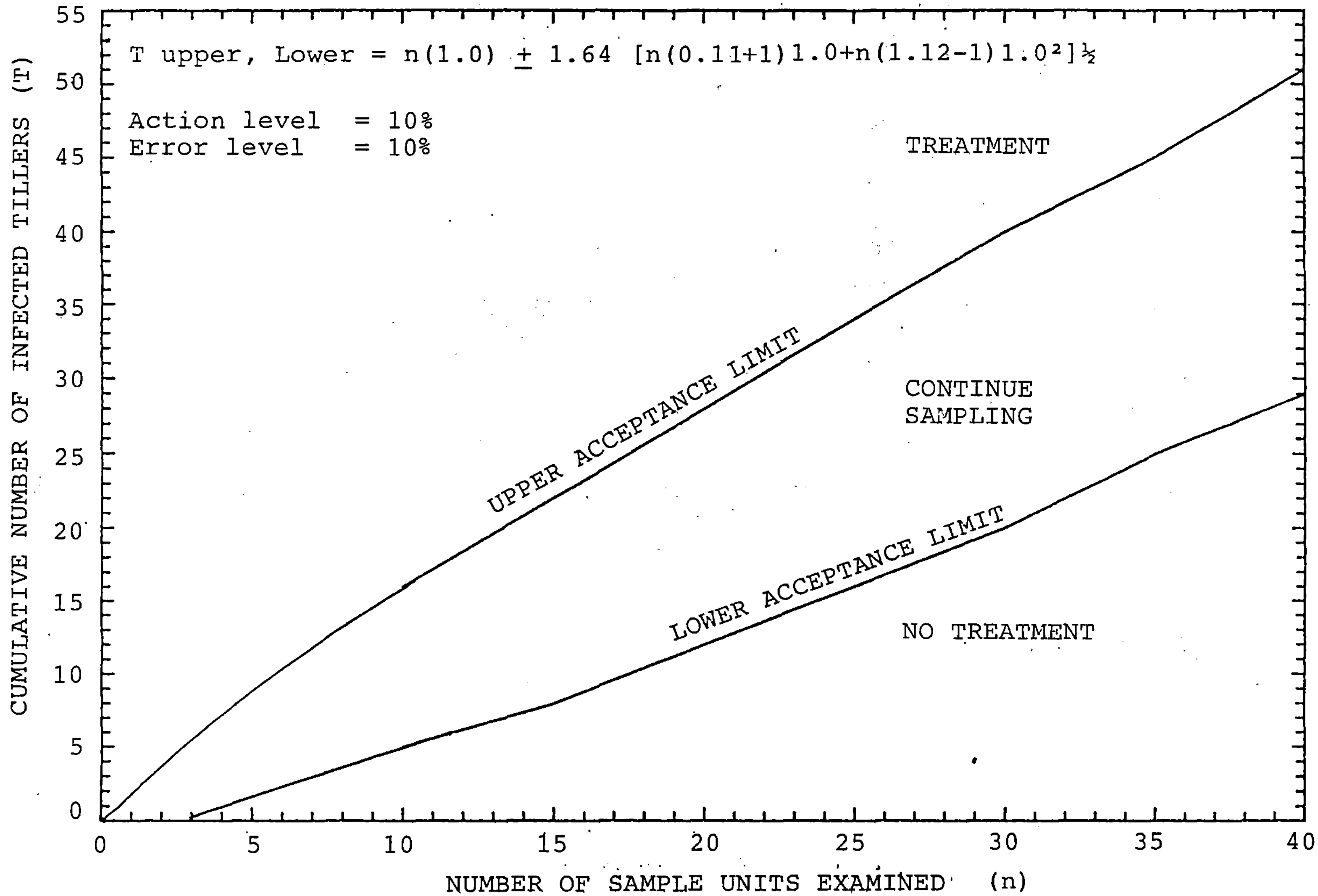

Figure 5.1: Sequential sampling graph for incidence of stripe rust infections on the top three leaves, using a 10% incidence action level and a confidence level of 90%.

Table 5.1: The sequential sampling plan for management of stripe rust.

	Cumulative number of infected tillers				
Sample Unit Number	Acceptance Limits Lower	Acceptance Limits Upper	Sample Unit Number	Acceptance Limits Lower	Acceptance Limits Upper
1	N.D.	N.D.	21	13	29
2	N.D.	N.D.	22	14	30
3	N.D.	N.D.	23	15	31
4	N.D.	N.D.	24	15	33
5	N.D.	N.D.	25	16	34
6	N.D.	N.D.	26	17	35
7	N.D.	N.D.	27	18	36
8	N.D.	N.D.	28	19	37
9	N.D.	N.D.	29	20	38
10	5	16	30	20	40
11	5	17	31	21	41
12	6	18	32	22	42
13	7	19	33	23	43
14	7	21	34	24	44
15	8	22	35	25	45
16	9	23	36	25	45
17	10	24	37	26	48
18	11	25	38	27	49
19	11	27	39	28	50
20	12	28	40	29	51

N.D. no decision is made

Operating Rules

1. Begin sampling at G.S. 15.
2. Walk approximately 20m from each border at a corner of a field, examine the top three green fully exposed leaves on ten consecutive tillers in a drill row (sample unit) and record the number which have stripe rust.
3. After examining the first sample unit, walk in a "W" pattern through the field and examine ten sample units spread evenly along each diagonal of the "W". Distance between sample units will vary with field size (i.e. 200m diagonal = 20m between sample units). Select sample units by examining the ten tillers directly in front of the right foot.
4. Keep a cumulative total of the number of tillers with stripe rust on the top three leaves.
5. After the first ten sample units refer to the decision table. If the cumulative total is less than the lower limit, stop sampling and return one week later to resample. If the total is above the upper limit, stop and spray as soon as possible and resample in three weeks. If the total is between the upper and lower limits, continue sampling and referring to decision table until a decision is reached. If the cumulative total is between the upper and lower acceptance limits after forty samples, stop sampling and spray as soon as possible and resample in three weeks.
6. Stop sampling at G.S. 61.

obvious inoculum source exists adjacent to the field, the first ten sample units should be spread evenly over the entire "W" before making a decision. If no decision is made, sample again as per Table 5.1. A maximum sample unit number was set at forty, as it was assumed that in commercial field situations it would not be practical for samplers to examine more than forty sample units. If no decision is made after forty sample units, it is assumed that the density of stripe rust infections equalled the action level of 10%. Using Iwao's equation;

$$40 = \frac{1.64^2[(0.11 + 1)1.0 + (1.12-1)1.0^20]}{.29^2}$$

the assumption has a confidence level of 0.29, which was judged to be accurate enough for stripe rust management situations. This allowed a decision to be made without examining an excessive number of sample units, or requiring an additional sample after two or three days delay to make a decision.

Use of the sequential sampling plan in four commercial fields in the 1984-85 season resulted in savings of one fungicide application without any significant ($P \leq 0.05$) loss in yield, in all fields, compared to a four week spray schedule after first sight of the disease (Table 5.2). Spray decisions using the sequential sampling plan were made in an average time of seven minutes (± one minute) and required an average of eleven (± two) sample units to make a decision. The sequential sampling decisions were always in agreement with a forty sample fixed number sampling plan which on average took thirty-two minutes (± five minutes). The use of sequential sampling plans in pest management reduced the pesticide load on some crops up to 50% (Casey et al., 1975) and in this limited study, a reduction of fungicide usage for stripe rust management was also achieved.

Table 5.2: Comparison of a sequential sampling program or schedule spray program for stripe rust management.

	Management Program	
	Sequential Sampling	Spray Schedule
Number of sprays +	2	3
Header harvest (t/ha) #	6.50	6.74*
Quadrat harvest (g/m^2)#	767.0	795.2*
Header individual grain wt. (mg)	36.9	37.9*
Grains/ear	35.4	35.7*
Ears/m^2	587.3	589.0*

+ Triadimefon (125g a.i./ha) applied

Adjusted to 14% moisture content

* Not significantly different from sequential sampling program using paired t-tests at $P \leq 0.05$.

5.4 CONCLUSION

The sequential sampling plan developed in these studies was shown, on a limited scale, to be a quick and reliable method for assessment of risk of significant yield loss attributable to stripe rust. The plan could be used by growers to optimize the use of fungicides.

Further studies on the sensitivity of wheat to stripe rust infection at different growth stages is warranted, to define action levels more accurately. This management program uses a single action level. At later growth stages, nearer anthesis, the crop may be less sensitive to stripe rust, and thus allow for the use of a higher action level. Stripe rust reaction and potential yield in different cultivars may alter the value of variables required for the generation of a sequential sampling plan. To develop a sequential sampling plan for stripe rust in other cultivars, the spatial pattern and sampling method should be analyzed. Yield potential must also be high enough to give sufficient monetary returns to make management cost effective.

This management program is disease based and relies on crop monitoring for a continuous update of the disease risk relative to the action level. Many disease management programs have avoided such methods, possibly because there was no quick and reliable sampling technique. Alternative disease management programs have been based on epidemic prediction by measuring climatic variables, such as those for wheat glume blotch (Tyldesley et al., 1980) and soybean foliar disease (Backman et al., 1984) or inoculum inputs such as for wheat stem rust (Burleigh et al. 1969).

Crop monitoring allows for a direct assessment of current disease risk situations and is therefore similar to insect pest management programs. This type of diseased based management program may not be applicable in all situations. Limitations may occur when effective fungicides are not available, when the value of the crop does not counter the cost of fungicide application and crop monitoring, or when it is difficult to assess disease before significant yield loss occurs. The latter may occur with diseases which have long latent periods, infect plant portions not readily visible or have symptoms and/or signs not readily observed and assessed. All these factors influence the level of risk a grower perceives in the use of such management programs (Chiarappa, 1974). The use of disease management programs is also influenced by the initial objectives of the grower and the perception of risk a grower associates with a particular disease (Norton, 1976). Increased information on the level of disease present and possible outcomes if not controlled adequately by a disease management program, yields greater flexibility in fungicide timing. A reduction in fungicide can be obtained through management compared to growers who must use proplylactic treatments due to a lack of information available to base decisions on. Disease management monitoring programs are more likely to be used where growers perceive a higher risk of damage of disease and where the grower is more informed on a disease and monitoring program (Carlson, 1979).

Although this study focused on stripe rust management on cv. Rongotea, it could be integrated with past, present and future studies of all wheat pests to form the basis of a New Zealand wheat pest management program. Other control options could be incorporated into disease management programs and the use of less susceptible cultivars in conjunction with crop monitoring could reduce fungicide usage further. The objectives of future disease management studies should be analyzed for the possibility of the development of sequential sampling plans through the study of disease sampling methods, spatial patterns and action levels.

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