Estimating and Interpreting Disease Intensity and Loss in Commercial Fields

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A commercial field is the spatial unit commonly used in surveys to provide information for integrated pest management, crop loss assessment, and pest detection. Each of these objectives requires its own level of precision in assessments of disease and loss, and plant pathologists often must develop methods to meet two or more of these objectives with the same survey. In integrated pest management, we are concerned with issuing warnings to growers based on economic and action thresholds of disease. In crop loss assessment, data must be precise enough for economic decision-making and for identifying research and extension priorities for the allocation of scarce resources. Detection of exotic pathogens and quantification of endemics through field observations may also provide important information for regulatory agencies. When disease and loss data from individual commercial fields have been aggregated to a regional level and accumulated over several seasons, they have proven very useful for evaluating effects of changing technology on agricultural production (13).

Estimation of disease intensity or loss for a field may involve any one of a number of methods (25). Disease intensity is a general term used to denote amount of disease, commonly expressed as either disease incidence (proportion of the total number of plants that are infected) or disease severity (proportion of total plant area that is infected) (11). Loss is any measurable reduction in the productivity of a food, fiber, or feed crop (4). Methods of estimation affect how the data are generated and the quality of the data. Interpretation,

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which must be distinguished from estimation, deals with how the disease or loss data are used, and with scalar and representational errors (24).

When estimating and interpreting disease or loss, it is important to consider what constitutes disease and how we perceive it. Quantification of disease is affected by the biological level of organization addressed (ie, plant parts, whole plants, samples of a number of plants, fields, or total fields per spatial unit such as county, district, state, region, or country). What is obvious at one level may be insignificant at the next; this affects both estimation and aggregation before results may be interpreted. Bateman's (3) definition of disease—"the injurious alteration of one or more ordered processes of energy utilization in a living system caused by the continued irritation of a primary factor of factors"—implies both transient and permanent effects of pathogens on plant growth and development. When deriving a measure for disease, it is necessary to ask whether the symptoms/signs of disease being measured in any way reflect the effect of disease on the plant. For example, Zadoks and Schein (26) distinguish between percent disease and percent attack; percent disease includes area of lesions plus area of direct chlorosis, while percent attack is area of lesions plus area of direct chlorosis plus any other plant area showing symptoms attributable to the pathogen. In field estimation of disease it may be difficult to decide what symptoms should be included in a measure for disease and whether increased host senescence in uninfected parts of a plant should be included in an estimate.

PROPERTIES OF A CROP PATHOSYSTEM THAT INFLUENCE ESTIMATION OF DISEASE SEVERITY AND CROP LOSS

Spatial distribution of diseased units in a pathosystem is the most important factor that influences field estimation of disease and crop loss. Spatial distribution includes the way in which disease lesions are distributed among healthy units and the way in which diseased host units are distributed among healthy units. Distribution of diseased units may be random, aggregated, or regular (19,26). With randomly distributed disease, the variance is theoretically equal to the mean. In aggregated patterns, the variance in the number of lesions per leaf is greater than the mean number of lesions per leaf, but in a regular pattern the variance is smaller than the mean.

When large numbers of host units are sampled for disease, a frequency distribution showing the number of diseased units in each severity category may be determined. The sample frequency distribution, an empirical distribution, can be compared with theoretical distributions (12) using goodness-of-fit tests, and the parameters of the empirical distributions defined. Theoretical distributions that have been applied to biological systems are the normal, lognormal, Poisson, Weibull, Gamma, and bionomial.

It is often possible to predict the theoretical distribution from the spatial pattern of the diseased units. When the distribution of lesions on leaves is completely random, the Poisson model is adequate for its description. With an aggregated pattern, a negative binomial suffices, while a regular pattern may be described by the positive binomial (6). Knowledge of the frequency distribution is essential for designing sound sampling procedures. Further, many classical statistical methods assume that the raw data have a normal distribution, and that the distribution remains the same over time. With some diseases (eg, barley leaf rust) the distribution may change within several weeks from negative binomial to Poisson to normal (23). This change affects the ability to estimate average disease severity from incidence, a method proposed for pest management (20).

DISEASE ESTIMATION METHODS FOR FIELD USE

Laboratory methods for measuring disease are usually applied to lower levels of biological organization (eg, a leaf). Although methods like video image analysis (15) greatly reduce subjectivity, research must also be done to compare the more crude field methods with the more precise laboratory-based methods, because of the inherent variability in disease severity per host unit in the field. Field estimation methods may include visual disease assessment, remote sensing, incidence-severity relationship, and spore trapping or lesion counts (11).

In visual disease assessment an estimate of disease is made relative to a defined standard. Some degree of subjectivity will be associated with these estimates, but it can be minimized if the method is simple and has been tested for reproducible results among assessors (10). Visual disease assessment methods are based on standards that fall into two broad categories—descriptive keys and standard area diagrams. The British Mycological Society (1) key for assessing potato late blight is an example of a field key that has retained its usefulness over many years because of its simplicity and the detailed epidemiological studies upon which it is based. Comparison with standard area diagrams such as those of James (8) is probably the currently most used method for field estimation of disease (9). These diagrams depict defined proportions of disease severity that may reflect those proposed in the Horsfall-Barratt Scale (7). Some workers feel that the percentage scale should form the basis for all standard area diagrams, and even that arithmetic interpolations may give increased precision when used on a logarithmic scale (11). Visual disease assessment methods are convenient for field use and will continue to play an important role in field surveys.

Remote sensing of diseased fields depends on the ability to measure differences in the spectral reflectances of healthy versus diseased host units. Aerial photography is not a recent tool in plant pathology, and spectroradiometers are continually being improved to increase their versatility and portability (18). Incidence-severity relationships have been determined for several diseases but are useful only for estimation of low levels of disease (20). Other field methods that have been used for special studies include spore trapping and counting lesions. In the future, ELISA and chemical methods may provide reliable quantitative measurements of pathogen material in hosts.

There have been few studies comparing different methods of field disease estimation. In one such study, visual estimates of severity were consistently lower than the actual area of tomato leaf mold lesions calculated from leaf tracings (21). However, it is possible to correct the estimated severity by determining the relationship between estimated and actual severity at different levels of severity. The variability inherent in field estimation methods and the variability due to spatial properties of the population suggest that less precise terms may be adequate for describing disease and loss in commercial fields. For example, in the pilot program of the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA, APHIS, and PPQ, respectively) national cooperative pest survey and detection system, which was implemented in 13 states during 1982, disease was described by using grades 1–5 to denote incidence (none to extreme) and severity (none to heavy). While these grades appear broad for individual fields, they have served to convey a meaningful estimate for a state, especially in view of the scalar problems associated with calculating a mean statewide severity value.

ESTIMATING AND INTERPRETING MEAN DISEASE INTENSITY PER FIELD

In estimating disease intensity per field using one of the above methods, the sampling unit, sample size, sample point, sampling fraction, and sampling method must be considered. The way data are recorded in the field is another aspect that needs careful thought if a short turnaround time is important in processing survey data.

In most disease-loss surveys, the sampling unit is a plant, or with cereals, a tiller (22). Often, only selected parts such as the flag leaf in wheat may be assessed for disease to provide data for use in a regression model for estimating disease loss. For each field, a predetermined number of sampling units is selected to give a mean value representative of that field; this is the sample size. Sample size is determined by the cost of sampling, the precision required, and the available time, as well as by the spatial distribution of disease; the sample size should be empirically defined. The sample point is the spatial unit for which disease is estimated. In plant disease surveys, the sample point is commonly a field within some range of area. Where a farm is the sample point, some workers have designed randomization procedures for selecting one field within each farm (10).

Many sampling methods have been reported for plant disease surveys. Samples may be taken at intervals along predetermined lines in a field; these may be either one diagonal, both diagonals (forming a big letter X), or (if a more representative sampling is required) a big W, or Z pattern. Simulation and field studies can provide guidance on the best sampling method to use (2,14). With a disease that is randomly distributed all the above methods will give comparable results, and reducing the variance of the sample mean may be better achieved by increasing sample size. If the diseased units are aggregated, the sampling method will be more important than sample size, and the big X or W sampling pattern would be preferable to the single diagonal. Sampling is one of the weakest aspects of disease surveys and it deserves greater attention by pathologists working in conjunction with statisticians. For example, approaches for conducting multipest sampling in the field have received little attention and need to be developed with a better statistical basis.

The selection of number of sample points is often determined by the sampling fraction stipulated before the actual survey; sampling fraction is the proportion of sample points to total number of units in the population (22). This is dictated by criteria that may not have any biological rationale, as when the objective is to estimate mean disease per field for a county. In plant disease surveys, three methods have been used to select sample points—simple random, stratified random, and multistage (11). Estimating the disease intensities of commercial fields is expensive, which has led to attempts to determine optimum numbers of fields to give acceptable estimates. Hence, on theoretical and practical grounds, stratification appears to be preferable for minimizing the variance in a population disease mean (5). A simple equation for optimum allocation in sampling is:

$$\text{Cost} = C_o + C_h \cdot n_h$$

in which C_o = overhead cost, C = cost per unit in stratum h, and n = size of sample in stratum h.

Main and Proctor (17) studied methods for within-field stratification with respect to both statistical and economic considerations. The stratified mean disease estimate is almost always more precise than the simple random mean estimate.

Data collection, handling, and retrieval may be bottlenecks in converting disease estimates into useful field information. Plant pathologists have traditionally used the paper-and-pencil method for field recording in which the field survey form is the frontline record of raw data. Increasingly, portable microprocessor-based units are being used; commercially available units vary in sophistication and price. Mark-sense cards or paper which require special readers are another option. The main advantage of using electronic devices is that they circumvent the need to enter written data through a keyboard. However, the lack of a permanent record of a field observation can be a problem if the device malfunctions. Ideally, a field scout should be able to transmit from remote sites by telephone the data on all the fields he has surveyed.

In spite of the best efforts to ensure objectivity in estimating disease intensities of commercial fields, errors do occur in diagnosis of symptoms and in assessment and sampling. Some survey programs, eg, the Minnesota Cooperative Pest and Disease Surveillance Information System, are researching nonparametric methods for quantifying scout quality as it relates to any field estimate.

ESTIMATING AND INTERPRETING MEAN LOSS PER FIELD

Estimates of crop losses in commercial fields may be made using indirect (expert testimony, inquiries, and literature reviews) or direct (survey and remote sensing) methods (25). Little research has been conducted to compare all these methods under the same conditions, but James and Teng (11) suggested that the survey approach gives the most objective estimates of disease and loss.

When data from many fields are used to derive a county estimate of crop loss, the estimates may be based on either disease incidence or severity. Field estimates of disease incidence from sampling may be directly converted to a loss figure for individual fields and the county mean calculated from these. With severity, two methods have been used. In the first, severity per plant is assessed for a sample size, the mean plant severity per field calculated and used to estimate mean loss per field, then mean county loss is calculated from the field means. In the second method, severity per plant is used to estimate loss per plant; linear averaging will then give mean loss per field, from which mean county loss is calculated. Both methods usually employ regression models relating disease intensity to loss. The regression models are based on the assumptions that there are equal or no effects of other variables that may alter the basic disease-loss relationship in each field, and that linear averaging of loss is valid. These assumptions are not always realistic, because loss due to one factor may not be independent of that caused by other factors. This lack of independence of losses due to several factors may account for published examples of greater than 100% loss (16).

Most disease-loss regression models are intended for estimating the proportionate loss per sample. It is often desirable to estimate production losses at the county level; however, the yield data commonly available for a county are usually for actual yield estimated by some crop reporting service, ie, yield in the presence of stress. To convert mean percent yield loss to mean loss in production, the following equation can be used (24):

$$\text{Production loss} = [\text{Actual county yield}/(1.0 - \text{Loss proportion})] - \text{Actual county yield.}$$

The actual yield of a crop is usually produced by plants subjected to multiple stresses. Estimating loss caused by a single stress is complicated by the problem of linear aggregation and averaging of losses for multiple stresses. Furthermore, no realistic method for validating a county loss estimate is available.

When loss estimates are needed for larger spatial units, additional problems of representing the loss estimate are encountered. In Minnesota, the mean severity of eyespot of corn during the tassel stage for 12 counties with eyespot was 2.3% in 1981, giving a corresponding yield loss of 1.2% per county (*unpublished*). Values of mean severities/loss per county ranged from 0.1%/0.07% to 13.5%/10.3% for those 12 counties. However, 49 counties were surveyed in the program, and the mean severity and loss per county for these 49 counties was 0.5 and 0.38%, respectively. Minnesota has 87 counties, so the mean loss per county in Minnesota is even lower if the divisor is 87. Interpretation and use of loss data in management decisions requires explicit knowledge of how the estimates were calculated from raw field data. In the above example, losses due to only one disease were calculated. Surveys in England and Wales (13) in 1976 showed that barley losses caused by mildew, net blotch, and leaf rust were 8.7, 0.2, and 0.3%, respectively; in 1977 the corresponding losses were 3.6, 0.3, and 0.4%. King (13) calculated losses using a separate model for each disease with the assumption of no interaction between diseases in causing loss. Recent evidence indicates that this assumption may not be valid (16).

Yield losses may be estimated for the following units, in increasing size: plant, plot, field, county, district, state, region, or country. Almost without exception, models for estimating losses are developed by using data generated at the plant or plot level. At these lower levels, plant populations are relatively uniform for many attributes including development stage. For larger units, variation in population attributes may require the use of different models, each with its own error of estimation, for different fields. It is impossible to sample all fields at an equivalent development stage.

Crop loss assessment requires a holistic and interdisciplinary approach because, under field conditions, the losses are rarely caused by a single pest. Furthermore, any errors in sampling fields for disease and loss will be magnified as the field estimates are aggregated and averaged over larger areas. More objective methods for estimating multiple disease effects on crops are urgently needed. Until such methods are available, we will continue to be concerned about the validity of our disease and loss estimates.

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