DISEASE ASSESSMENT AND YIELD LOSS

Assessment of yield loss

Confounding factors

Relating the yield of crops to varying levels of plant disease has remained a complex task both in theory and practice. The difficulty of interpreting disease-yield loss relationships was recognized by James (1983), who is one of the pioneers in this field of research. The failure to measure disease intensity (severity and incidence) accurately was a major factor contributing to this difficulty. There may be several confounding factors that weaken the statistical relationship between the independent variable (assessment) and the corresponding dependent variable (yield loss). Such factors have been identified as: interactions between diseases and between the pathogen and an environmental factor; the self-limiting effect of local lesions; overcapacity of the host plant (within-plant compensation); and between-plant compensation and lesion position effects. For example, lesions of equal size always had equal effects on yield and crop loss, and cited the example of *Phytophthora infestans* (cause of potato late blight) in which a stem lesion can kill a haulm (stem) with 10 leaves and 50 leaflets whereas the same-sized lesion on a leaflet kills only one leaflet at most. The same caution would apply to the effects of axil and leaf blade lesions of equal size caused by *Rhynchosporium secalis* on barley.

Another identifiable confounding factor is the often poor correlation between visible symptoms and amount of tissue colonization. Precise techniques can now measure fungal biomass using chitin or ergosterol as biomarkers. In *Fusarium* ear blight of wheat, kernels in asymptomatic spikelets may be infected and mycotoxin content may not be correlated with visible symptoms. Mycotoxin produced in grain can have serious consequences for the food chain; assays for mycotoxins may be more important for the milling and baking industries than estimates of disease symptom incidence and severity. Furthermore, additional factors such as the relevance of healthy leaf area duration, radiation interception, spatial pattern of disease intensity and time of infection might change our understanding of the disease-yield loss relationship.

A simple model relating loss of green area within a winter wheat crop canopy to changes in light interception might be useful in predicting disease-induced yield losses by yellow rust (caused by *Puccinia striiformis*); such a yield loss model is thus based on crop function rather than measurements of disease severity and related area under the disease progress curve (AUDPC) values which have no mechanistic link to the productivity of the host plant. A significantly better relationship between area under leaf green area index progress curve (AULGAIPC-synonymous with healthy area duration, HAD) and yield compared with disease severity assessments was also useful assessment to measure the losses. Based on this, it is been suggested that a logical adaptation of HAD (or AULGAIPC) would be to integrate radiation by green tissue to give healthy area absorption (HAA). Here, yield loss was related not just to disease intensity but also to crop physiological variables. Traditional single-point, multiple point and integral models such as AUDPC based on disease intensity do not give a complete description of the disease-yield loss relationship, as crop yield is determined by the magnitude of photosynthesis, a function of HAD (or AULGAIPC) and HAA. Finally, it should be remembered that a complete disease-yield loss relationship should also take account of economic thresholds for crop loss due to disease and the assessment of any loss in crop quality.

Reference points, terms and concepts

In describing crop-yield loss relationships, it is important to establish reference points, terms and concepts in order to standardize communication between workers. Researchers were reviewed concepts and terminology for crop losses and differentiated between potential losses (in the absence of control measures) and actual losses in crops, the latter being sub-divided into direct (loss in quantity or quality of yield) and indirect (the economic or social impact of losses). Similarly, yield was divided into attainable yield (when crops were grown under optimum conditions), primitive yield (when no disease control was applied), economic yield (highest net return on expenditure), actual yield (obtained using disease management programmes) and theoretical yield (obtained using calculations based on crop physiology or crop growth simulation models). The difference between actual and attainable yield was the method used by the Food and Agriculture Organization (FAO) to report crop losses; most disease management programmes aim to close the gap between these two yield concepts.

Statistical and experimental methods

The assessment of yield loss is carried out using statistical and experimental methods. Briefly, statistical methods involve the following: analysis of yields in relation to estimated disease incidence over many seasons (but other factors such as weather, pests, farming practice and plant varieties must be taken into account); comparisons of expected and actual yields when it is known that a pathogen is the major cause of yield loss; yield analysis before and after control measures are applied; and the use of holistic synoptic methodology which involves grower questionnaires or national disease surveys by agricultural officers to gather information on particular diseases (e.g. severity, date of appearance, weather conditions, varietal susceptibility, estimated crop loss). Experimental methods are mainly based on yield comparisons between infected and healthy plants or between plants with different disease severities using field experiplots, microplots (hill plots), single plants or tillers; between resistant and susceptible varieties; between infected plants and plants treated with fungicides; or between healthy plants and plants where disease damage has been simulated by the removal of essential plant organs, such as the flag leaf on a cereal plant. In all of these methods, it is important that experiments are properly designed so that results can be analyzed statistically and, if possible, they should be repeated over a number of seasons and in different areas.

Empirical yield loss models

Each experimental method, such as those described above, will always have advantages and disadvantages but conventional field experiments will probably continue to provide most information for the mathematical modelling of disease-yield loss relationships. Most models describe losses at the field level; the type and complexity depend on the pathosystem and the disease descriptor employed as the independent variable using least-squares regression analysis. Such models do not directly use information on crop physiology and are, therefore, empirical or descriptive rather than mechanistic in nature. However, they can be consistent with known physiological processes or can be expanded to accommodate such processes. Teng (1985) classified empirical loss models into six categories: (1) single-point (critical-point) models, (2) multiple-point (multiple regression) models, (3) response-surface models, (4) integral models, (5) generalized or non-linear models, and (6) synoptic models. The first five models describe losses in yield due to one disease, whereas synoptic models include variables for several diseases and non-disease factors. Another approach to classifying such models is to consider whether the model uses one or more independent variables or how many estimates of disease are made over time.

Single-point or critical-point models

In single-point or critical-point models, yield loss is related to disease measurement at one specific time during the growing season or at a specific growth stage. Models using time to a certain disease severity are also considered as critical point models. It should be remembered that a critical-point model does not imply that a host plant responds to a disease at only one time or growth stage, but rather that a good statistical relationship is found at one specific time. This type of model is probably the most commonly used because of the small amount of data required and has been heavily employed for grain crops where epidemics with a reasonably stable infection rate occur near to grain-filling. Single-point models may be linear or nonlinear in their parameters and can be written in the form:

% loss (L) = $a + bX$

in which a and b are parameters and X is the disease measurement or a transformation of disease measurement at a given time.

Examples of critical-point models are those developed for cereal diseases (Table 2.6) and that of Large (1952) for late blight of potato (Fig. 2.11). The models shown for cereal foliar diseases were developed to estimate yield loss from corresponding disease severity estimates at particular growth stages, whereas those for cereal stem-base diseases (eyespot and sharp eyespot) were developed for use with disease incidence values. Large's critical point model for estimating yield losses from late blight of potato uses time to a critical disease severity: the model assumes bulking up of potato tubers ceases when 75% blight severity on the haulm is reached. A major problem with critical-point models is that they fail to accommodate variables in infection rates and shape of the disease progress curve.

Table 2.6. Examples of critical-point yield loss models for cereal diseases (Cook and King, 1984)

Disease	*Relationship*
Spring barley	
Mildew	$y = 2.5\sqrt{x_i}$
Brown rust	$y = 0.4x_{ii}$
Rhynchosporium	$y = 0.5x_{ii}$
Winter wheat	
Mildew	$y = 2.0\sqrt{x_i}$
Septoria	$y = x_{iii}$
Yellow rust	$y = 0.4x_{iii}$
Eyespot	$y = 0.1x_m + 0.36x_s$
Sharp eyespot	$y = 0.05x_m + 0.26x_s$

y = % loss in grain yield,
x_i = % disease on leaf 3 at GS 58,
x_{ii} = % disease on leaf 2 at GS 75,
x_{iii} = % disease on flag leaf at GS 75,
x_m = % tillers with moderate symptoms at GS 75,
x_s = % tillers with severe symptoms at GS 75.

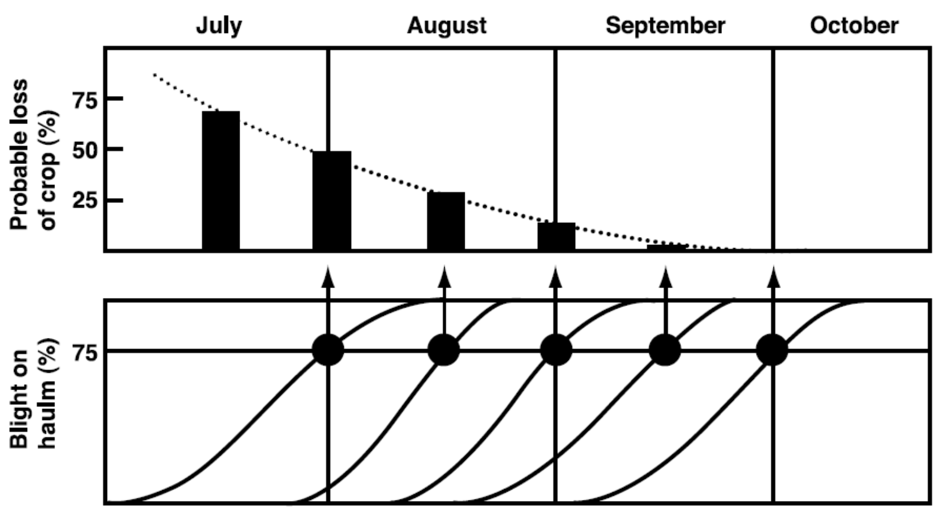

Figure 2.11. Estimated yield loss from epidemics of potato late blight in which the 75% disease level (the critical disease severity) is reached at differing times during the season. (After Large, 1952; Crown copyright, 1986).

Multiple-point models

Multiple-point models can be used for diseases with high variability in infection rates and where the disease progress curves can be markedly different. These models can be used for epidemics that develop over a long time period relative to the life of the crop and where yield accumulation is a prolonged process (e.g. potatoes). Multiple-point models relate yield loss to assessments of disease made at several times during the growth season. Assessments can be made at specific times or at specific host plant growth stages. Loss is then related to disease measured at each of these points during the epidemic or to the change in disease between assessments using a multiple regression equation, with the general form:

$$\% \text{ loss (L)} = b1X1 + b2X2 + b3X3 \ldots bnXn$$

where $b1$ … bn are partial regression coefficients for the first and nth week respectively, and $X1$ … Xn are the corresponding weekly disease increments for the first and the nth week, respectively.

Response surface (a three-dimensional graph)

Calpouzos *et al.* (1976) developed another form of multiple-point model for estimating losses due to wheat stem rust. Yield loss was plotted as a response surface (a three-dimensional graph) and was a function of the slope of the epidemic and the growth stage at the time of epidemic onset using the equation:

$$\% \text{ loss (L)} = f(X1X2)$$

where $X1$ = slope of the epidemic (infection rate) and $X2$ = growth stage at epidemic onset.

Integral models or trapezoidal integration method

Van der Plank (1963) proposed a modification of the multiple-point model in which the area under the disease progress curve (AUDPC) is used as a descriptor for the epidemic to measure crop loss. The AUDPC, an integral model, relates loss to a summing of disease measurements over a specific period of crop growth. AUDPC can be estimated using the following equation of Shaner and Finney (1977):

$$\text{AUDPC} = \sum_{i}^{n-1} \left(\frac{y_i + y_{i-1}}{2}\right)(t_{\,i+1} - t_{\,i})$$

in which *n* is the number of assessment times, *y* is the disease measurement and *t* is time (usually in days or degree days). AUDPC is simply *y* integrated between two times and can be approximated using the midpoint rule or trapezoidal integration method. As shown in Fig. 2.12 (Campbell and Madden, 1990b), the disease progress is divided into a series of rectangles, the areas of which are summed to approximate the total area under the curve. The narrower the intervals between assessments, the more accurate is the determination of AUDPC, which can be standardized by dividing its value with the total time duration (tn – $t1$) of the epidemic. This allows for comparisons between epidemics of differing durations and allows two epidemics to be distinguished which have different progress curves but the same disease severity at a critical date.

AUDPC models make two assumptions: injury to the host is proportional to the amount of tissue infected; and injury is proportional to the duration of the disease. Most AUDPC models have been used for epidemics of relatively short duration, which are late in the crop growth cycle and where yield is accumulated over a short period of time. However, integral models that use AUDPC cannot distinguish between early and late-occurring epidemics without applying weighting factors to assessments at different growth stages.

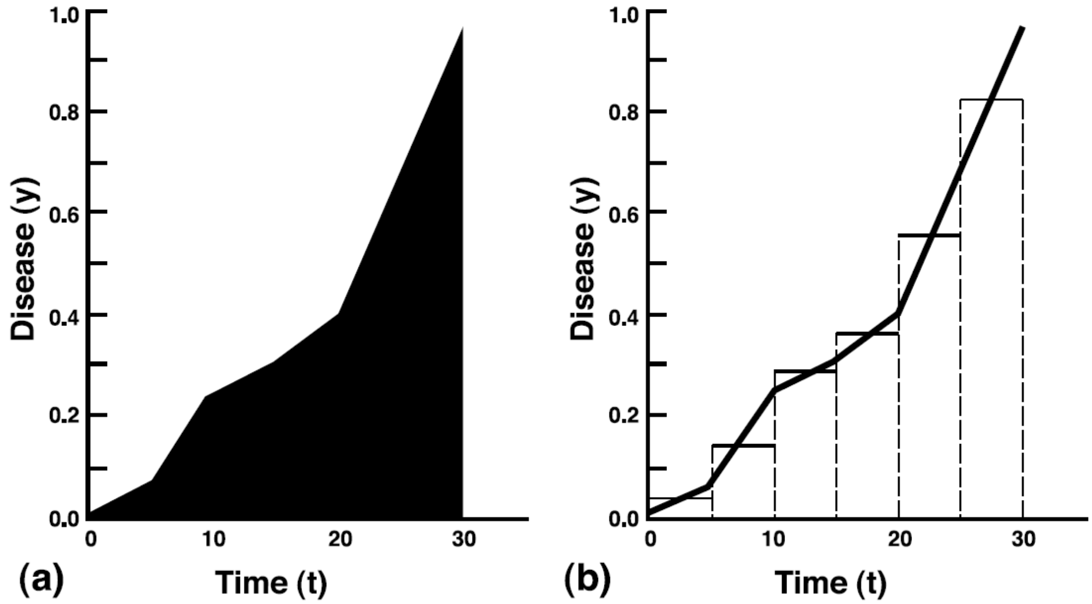

Fig. 2.12. (a) Area under the disease progress curve (AUDPC) for a hypothetical epidemic. (b) Illustration of the midpoint rule (or trapezoidal integration method) for calculating AUDPC. (Campbell and Madden, 1990b).

Generalized or non-linear models

Generalized or non-linear models are sometimes more appropriate where the shape of the loss-disease curve dictates that this approach should be used; many such models can have variability in the shape of the curve relating yield to the disease descriptor.

Synoptic or multivariate statistical models

Synoptic or multivariate statistical models are used where multiple diseases and other constraints may be determining the yield-loss relationship, a situation often encountered in actual crop production systems; data for such models often derive from surveys, in which no manipulation has been carried out to obtain specific disease levels. Complex multivariate techniques for analysis of the data, such as principal components and correspondence analyses, may be required. Models can be expanded to account for control costs and resulting economic yield, both in quantity and quality. Expert systems and geographic information systems (GIS) can also be used to provide regional estimates of losses in agricultural production.