DISEASE ASSESSMENT AND YIELD LOSS

Disease assessment

Introduction

Disease assessment, or phytopathometry, involves the measurement and quantification of plant disease and is therefore of fundamental importance in the study and analysis of plant disease epidemics. The disease assessment being defined as the process of quantitatively measuring disease intensity while phytopathometry is the theory and practice of quantitative disease assessment. Researchers have stated that without quantification of disease no studies in epidemiology, no assessment of crop losses and no plant disease surveys and their applications would be possible. The advanced idea of disease assessment includes a number of interrelated activities, such as the future progress of the disease, disease diagnosis, forecasting and crop loss. The measurement of plant disease and its effects on crop yield, quality and value are crucial for control priorities. Traditional methods of disease assessment, such as the use of pictorial keys derived from standard area diagrams to evaluate disease severity on a 0-100% scale, have now been joined by several new approaches made possible by rapid advances in computer technology. In addition, modern assays using immunological and molecular techniques for the identification, detection and quantification of plant pathogenic organisms are used. Other new approaches to phytopathometry have evolved in which remote sensing, image analysis and the detection of crop stress caused by disease (using changes in chlorophyll fluorescence and foliage temperature) are involved.

Why assess disease and yield loss in plants?

The assessment of the amount of disease on a plant or a crop of plants is essential in any quantitative epidemiological study. Researcher identified a number of important reasons for phytopathometric and crop loss measurements, the most important of which must surely be that if we are not in a position to estimate the losses from diseases, then how can we decide rationally on how much to spend on control? Other reasons identified include the importance of disease survey data to farmers, plant breeders, fungicide manufacturers, economists and government agencies in determining the priorities for allocating resources and timing control measures. Finally, researchers and extension workers require precise methods for evaluating their experiments, particularly plant breeders where potential resistant germplasm is being screened. Yield limiting factors identified were water (the most important), genetic yield potential and adaptation, and crop losses due to plant pathogens, pests and weeds. Disease assessment and crop loss appraisal will become especially important in sustainable systems of crop protection, where critical evaluation of disease levels is required in order to assess the effectiveness of proposed low-input, environmentally friendly strategies, such as the use of cereal cultivar mixtures.

Methods used in sampling plants for disease

Any sampling method used in disease assessment must be random, representative and objective and, depending on the disease involved, can be destructive or non-destructive. Traditional sampling methods involve diagonal sampling in farmers' fields where at least 50 tillers are sampled at random along each diagonal; the pattern of disease spread, whether it is scattered or uniform, may influence the number of samples taken, which in turn is related to the standard deviation of disease incidence. In small experimental plots, sampling may not be customary as replication produces

the needed accuracy; however, a minimum of 10 samples is often used for small cereal plots. Depending on the disease, the usual emphasis in disease measurement is given to incidence or severity within the sampling unit. A number of terms used in sampling, including entity, sample size, sample point and sampling fraction, all of which need to be considered for the satisfactory measurement of disease, particularly over large field areas. Disease incidence, severity and spatial pattern depend on data obtained from field samples. The accuracy of these data, as well as the time and effort required to obtain them, are affected by the sampling technique used. In a study of three naturally occurring epidemics of leek rust (caused by *Puccinia allii*), found that in the development of a practical sampling method for detection of the disease, it was necessary to take into account a clustered distribution of diseased plants. A computer software system called Field Runner is developed to simplify the task of sampling fields. The system uses the stratified random sampling design (SRSD) with single-stage cluster sampling; this provides an unbiased sample and a lower error of disease incidence estimates than conventional diagonal, 'X' or 'W' sampling designs. A hand-held microcomputer is used to direct the operator to each sample site within a sector, each site being composed of a cluster or transect (see Fig. 2.1); fields can be assessed for severity of one disease or for incidence of one to several diseases.

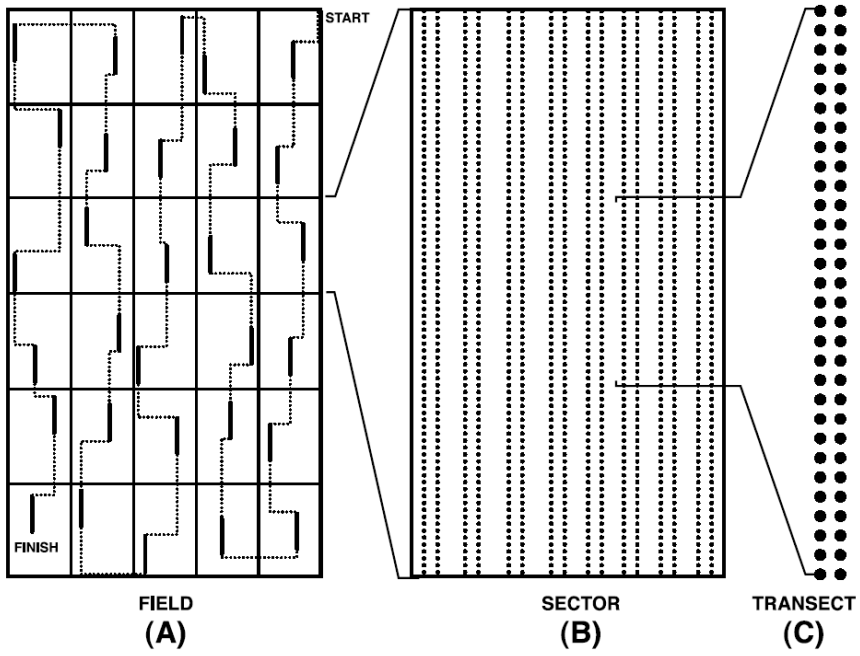


Figure 2.1. (A) Path (broken line) generated by the computer system (Field Runner) used to direct the operator to the sampling sites (solid lines) of a stratified random design. (B) One sector composed of two-row beds of individual plants (points) and a randomly located transect selected within the sector (bracketed area). (C) Two-row transect with 30 plants per row.

Timing and frequency of disease assessment

Disease assessment data must be qualified by the growth stage of the crop or plant at the time of the assessment. This is because the effects of a given level of disease on plant growth and yield and the importance of that disease level in relation to the progress of an epidemic will vary at different plant growth stages. Consequently, it is important to be familiar with the keys currently available and other methods, for determining stages of plant growth. It is also pertinent here to briefly consider the frequency with which disease assessments should be carried out, as this will obviously relate to the type of disease being assessed.

Simple interest diseases (monocyclic or polyetic) may well require fewer assessments than compound interest or polycyclic diseases. With monocyclic pathogens the amount of disease at the end of the season should be proportional to the initial inoculum but, with polycyclic pathogens, the relationship is less direct. Factors such as temperature, moisture and crop plant resistance will influence the final disease level more than initial inoculum. Indeed, with some polycyclic pathogens (e.g. *Phytophthora infestans*, cause of late blight of potato), increase through secondary inoculum production is so rapid that different levels of initial inoculum can still result in the total destruction of a potato field. Clearly then, several disease assessments would be necessary to effectively monitor the progress of a potato blight epidemic in order to implement appropriate control methods using disease threshold values. It should be remembered, however, that some polycyclic pathogens might not always cause as much damage as those monocyclic pathogens that reach critical levels over a relatively short number of years.

Disease assessments should be related to a stage of plant development that determines an important physiological function - for example grain filling in cereals. For many years, growth stages in cereals were scored on the Feekes scale from 1-11 (Fig. 2.2) or Zadoks scale for growth stages of cereals. that facilitates computerized data processing (Table 2.1); this key is essentially a further development of the Feekes scale and provides better descriptions of the earlier stages of cereal growth for all small-grain species growing in a wide range of climatic conditions. The decimalized key of Zadoks *et al.* (1974) was illustrated by Tottman *et al.* (1979) and Tottman and Broad (1987) (Fig. 2.3), and differs from the Feekes scale in describing individual plants rather than classifying crop growth stages.

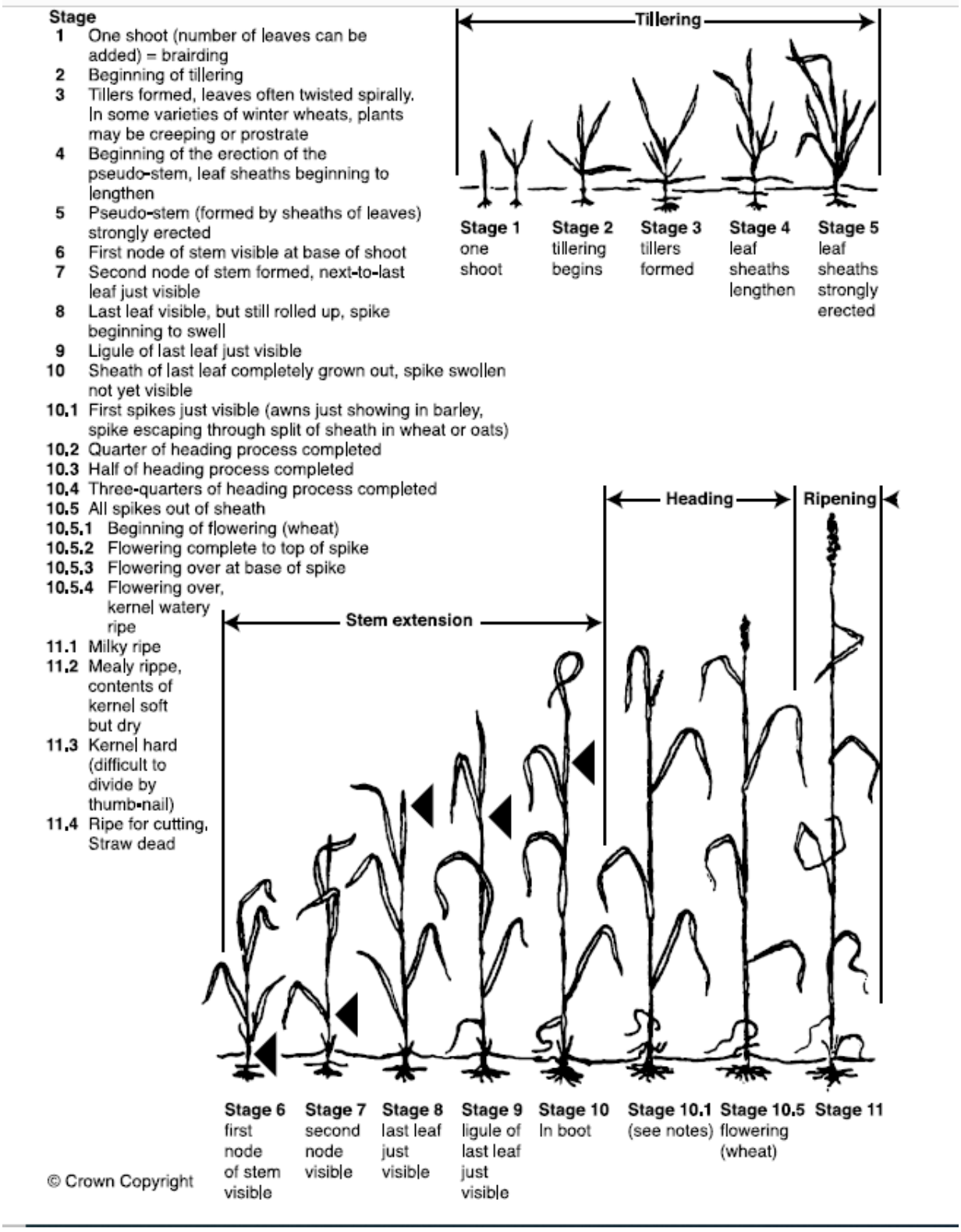


Figure 2.2. The Feekes growth stage scale for cereals, illustrated by Large (1954).

Methods of disease assessment

In any disease assessment or phytopathometric method, two criteria must be satisfied as consistency between observers and simplicity for speed of operation. These criteria, therefore, dictate that all assessment methods should be well defined and standardized at the earliest possible stage of their development. A successful system for the assessment of disease gives results that are accurate, precise and reproducible and presented the analogy of the target used by an archer where the objective was to shoot all arrows into the centre circle of the target (Fig. 2.4): obviously, option A would be the most desirable for any assessment method.

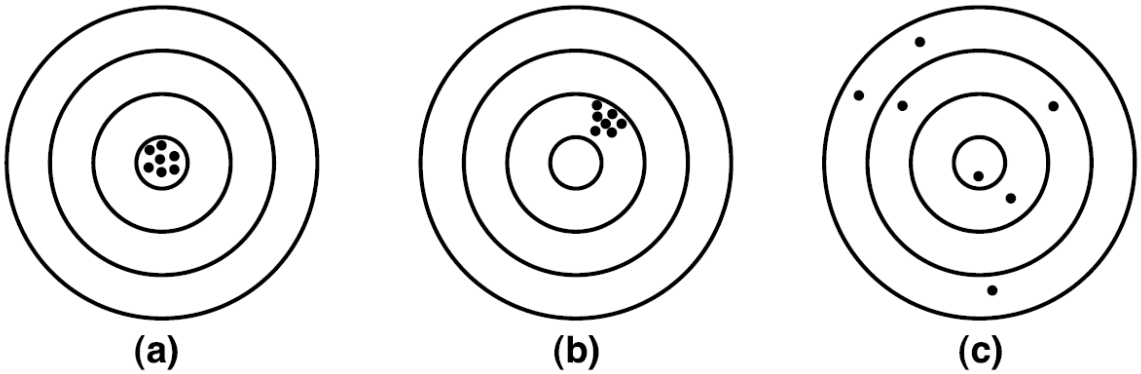


Figure 2.4. Accuracy and precision of an archer when the objective is to place all arrows in the central circle: (a) accurate and precise; (b) not accurate, but precise; (c) not accurate and not precise. (From Campbell and Madden, 1990a).

Disease can be measured using direct methods (i.e. assessing disease in or on plant material) or indirect methods (e.g. monitoring the spore population using spore traps). Obviously direct methods are likely to be more strongly correlated with yield losses in the crop and are therefore to be preferred. However, recent methods involving remote sensing and detection of crop stress due to disease are likely to increase the accuracy of indirect disease measurements. Direct methods are concerned with both the quantitative and qualitative estimations of disease.

Direct quantitative methods

Direct quantitative methods are largely concerned with measurements of incidence or severity, defined as follows:

Disease incidence (*I*) = (number of infected plant units / total number of plant units assessed) x 100

Disease severity (*S*) = (area of diseased tissue / total tissue area) x 100

Although assessment of disease incidence is traditionally based on visual disease symptoms, the definition can easily accommodate other more modern methods such as the enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR); disease incidence is a binary variable, that is, a plant unit is either (visibly) diseased or not. Disease incidence would be suitable for assessing systemic infections which may result in total plant loss (e.g. viruses or cereal smuts) as well as many root diseases, or where a single lesion causes leaf death (e.g. axil lesions in barley caused by *Rhynchosporium secalis*) but may also be useful in the early stages of an epidemic caused by a cereal foliar pathogen when both incidence (number of tillers affected) and severity (leaf area affected) are related and increase simultaneously. In general, incidence is easier and quicker to assess than severity and is therefore more convenient to use in disease surveys where many observations are needed or when non-experts are used to collect data; however, severity may be a more important and useful measurement for many diseases and is sometimes measured as the number of colonies (or lesions) per plant unit (disease density).

Relationships between incidence and severity (*I*-*S* relationships) are examples of data comprising a spatial hierarchy and are an epidemiologically significant concept; any quantifiable relationship between the two parameters may permit more precise measurements of severity. Three types of analysis have been used to describe the *I*-

S relationship: these are correlation and regression, multiple infection models and the measurement of aggregation. Disease incidence at the higher scale was shown to be an asymptotic function of incidence at the lower scale, the degree of aggregation at that scale, and the size of the sampling unit. For example, in light leaf spot (caused by *Pyrenopeziza brassicae*) on winter oilseed rape, the *I-S* relationship by assessing the disease as % plants, % leaves or % leaf area (severity); regression analyses showed good relationships between % leaves (incidence at the leaf scale and severity at the plant scale) and % plants (incidence) until % plants approached 100%.

Other direct methods of quantifying disease may involve estimations of disease intensity or prevalence. Intensity is often used to denote measures of the number of fungal colonies on leaves; it is also measured as both incidence and severity. For instance, in powdery mildew calculation at low disease intensities (<5 pustules per leaf) and small sample sizes (<12 leaves) it was more efficient to sample the upper surface only than both surfaces. Prevalence is an ambiguous term and usually refers to disease incidence within a geographical area. For example, ten fields in an area are inspected for disease and six are found to be infected; the disease prevalence for that area is 60%.

Most assessment keys have been designed to measure disease severity using either descriptive or pictorial (picture) keys. With either type of key, it is essential that standardization is maintained and the use of arbitrary categories such as slight, moderate or severe should be avoided. Such broad categories take no account of the fact that the eye apparently assesses diseased areas in logarithmic steps, as stated by the Weber-Fechner law for visual acuity (for appropriate stimuli, visual response is proportional to the logarithm of the stimulus). Thus up to 50% disease severity, the eye reads diseased tissue but above this value healthy tissue is judged. A logarithmic scale for the measurement of plant disease severity have been suggested by Horsfall

and Bratt, in which grades were allotted according to the leaf area diseased: 1 = nil, 2 = 0-3%, 3 = 3-6% and so on to 11 = 97-100% and 12 = 100%. This scale reads the diseased tissues in logarithmic units below 50% and healthy tissue in the same units above 50%. Thus, if the Horsfall-Barratt hypothesis is correct, the least reliable estimates of severity should occur at the 50% level. Founding the greatest overestimation of severity which occur at levels below 25%, suggest that the Horsfall-Barratt hypothesis over-simplifies the stimulus response relationship of visual disease severity assessment. Furthermore, the relationship between actual disease severity and estimated severity was found to be linear rather than logarithmic as proposed by Horsfall and Barratt. There is, therefore, no single accepted method of making visual estimates of disease severity, and a linear percentage scale is often used.

The advantages of the percentage scale are: the upper and lower limits are always uniquely defined; the scale is flexible and can be divided and subdivided; it is universally known and can be used to measure incidence and severity by a foliar or root pathogen; and it can easily be transformed for epidemiological analysis, e.g. transformation to logits for calculation of *r*, the apparent infection rate. The best-known descriptive key to utilize the percentage scale was that published by the British Mycological Society for measuring potato late blight (Table 2.3).

The pictorial disease assessment key uses standard area diagrams that illustrate the developmental stages of a disease on small simple units (leaves, fruits) or on large composite units such as branches or whole plants. Such standard diagrams are derived from a series of disease symptom pictures that may be in the form of line drawings, photographs or even preserved specimens. There are many examples and suggestions of pictorial keys for diseases assessments (figure 2.5).

Table 2.3. Descriptive key for assessment of late blight of potatoes caused by Phytophthora infestans (*Anon., 1947)*

Blight (%)	*Disease severity description*
0	Not seen on field
0.1	Only a few plants affected here and there; up to 1 or 2 spots in 12 yards radius
1	Up to 10 spots per plant, or general light spotting
5	About 50 spots per plant or up to 1 leaflet in 10 attacked
25	Nearly every leaflet with lesions, plants still retaining normal form: field may smell of blight, but looks green although every plant is affected
50	Every plant affected and about half of leaf area destroyed by blight; field looks green flecked with brown
75	About $^{3}/_{4}$ of leaf area destroyed by blight: field looks neither predominantly brown nor green. In some varieties the youngest leaves escape infection so that green is more conspicuous than in varieties like King Edward, which commonly shows severe shoot infection
95	Only a few leaves left green, but stems green
100	All leaves dead, stems dead or dying

Since the ultimate aim is to relate disease to yield loss, the plant units assessed should ideally be important contributors to yield, for example, the top two leaves of a cereal plant. Standard area diagrams were traditionally and painstakingly prepared using graph paper outlines but the use of planimeters, electronic scanners and image analyzers have improved and quickened their production.

Despite the above measures to standardize assessment keys and to eliminate as far as possible operator error (subjectivity), the visual assessment of disease severity suffers from fundamental errors. Standard area diagrams do not display the variegated patterns of disease so commonly caused by a plant pathogen, especially on a leaf. Thus an observer is compelled to visualize the total area that the various lesion shapes would cover if they could be combined and then expressed as a percentage of the total area of the leaf.

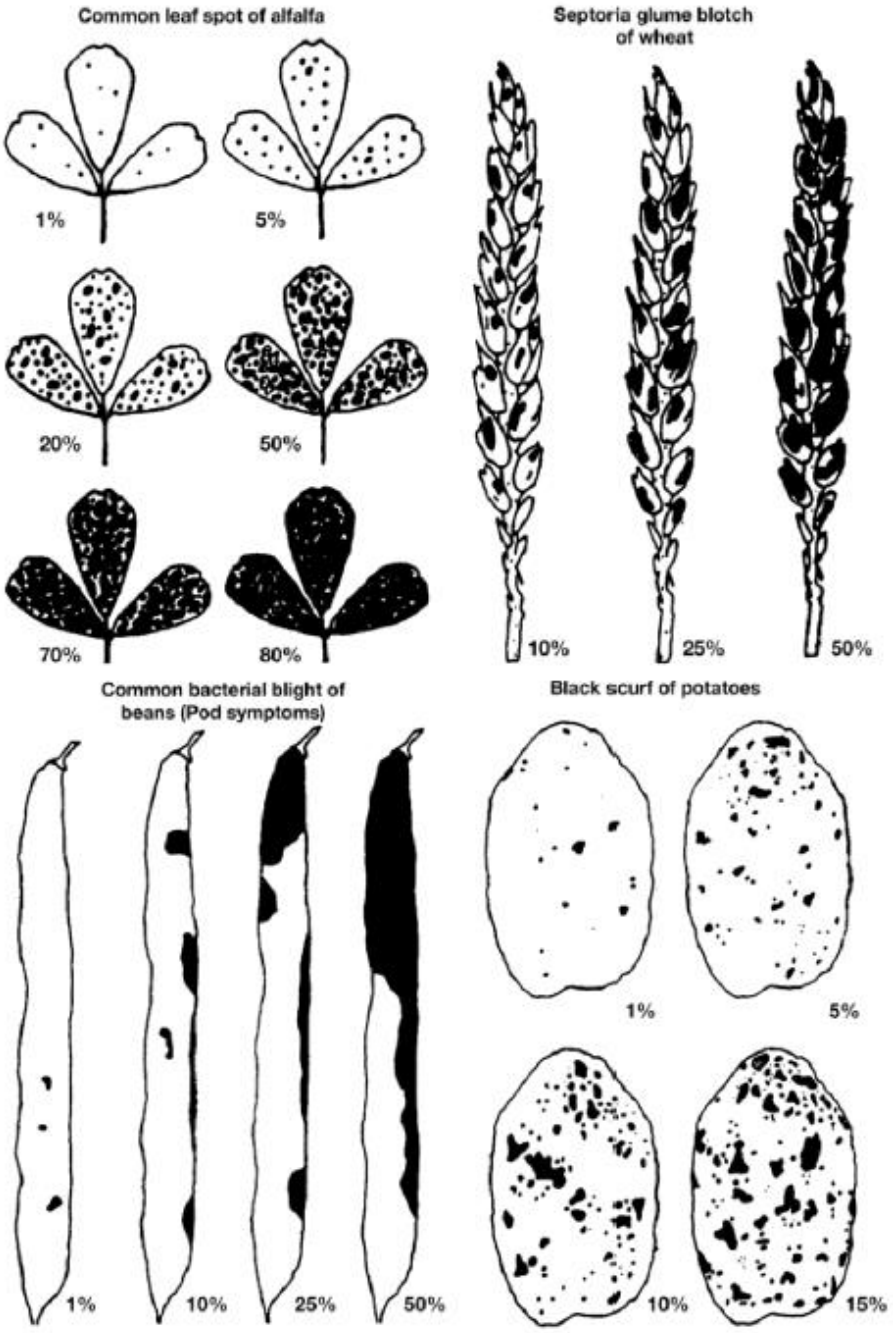
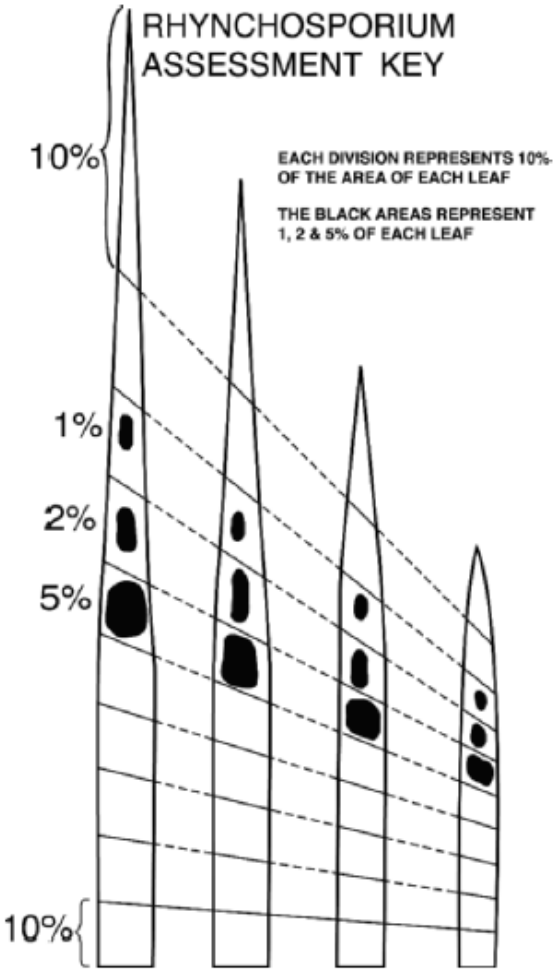


Figure 2.5. Examples of pictorial assessment keys for estimating disease severity (after James, 1971).

A second problem relates to variation in leaf size and how this affects the observer's assessment of severity. The key, devised for the assessment of barley leaf blotch disease caused by *Rhynchosporium secalis* (Fig. 2.6), usefully attempted to relate comparable percentage areas of disease on four standard area leaf diagrams of barley of differing size classes divided into 10% divisions.



Assessment key for *Rhynchosporium* leaf blotch or scald of barley. Match the leaf to one of the diagrams and use the black areas (representing 1%, 2% and 5% of each leaf) as a guide in assessing the percentage leaf (lamina) area covered by small isolated lesions, and the 10% sections for the larger lesions that have coalesced.

Figure 2.6. Pictorial assessment key for leaf blotch of barley caused by Rhynchosporium secalis *(from James* et al., *1968).*

visual estimates of wheat disease severity was compared with actual severities using image analyses of tracings of diseased leaves infected by *Septoria tritici* and *Blumeria (Erysiphe) graminis;* results showed that observer estimates were imprecise, inaccurate and varied considerably over short timescales, but that relative bias decreased with increasing disease severity, so that overestimations occurred at low (<10%) disease severity, or 30-40% leaf senescence. Such visual assessment errors could alter experimental conclusions.

The accuracy and precision of disease assessments was improved simply by selecting the most appropriate methods and by training observers to assess disease severity using computerized disease assessment training programmes such as AREAGRAM, DISTRAIN and Disease.Pro. Although

AREAGRAM graded user's performance, it generated only standard area diagrams with fixed disease patterns. DISTRAIN was developed as a training programme for disease assessment using variegated patterns of disease severity for eight common foliar diseases of cereals; the programme also allowed a comparison of estimated severity with actual severity. A more generic disease assessment programme, Severity.Pro, was developed that allowed the user to select from a menu of leaf shapes (e.g. alfalfa, apple, barley, cucumber, grape, tomato) and lesion types (e.g. anthracnose, blotch, downy mildew, target spot, powdery mildew) so mimicking almost any foliar pathosystem.

There are many variations and modifications of the standardized pictorial disease assessment key. One of the more useful of these is the Saari-Prescott 0-9 scale incorporating a double digit 00-99 scale (Fig. 2.8) for evaluating the intensity (severity and vertical disease progress) of foliar diseases (except rusts) in wheat, triticale and barley. In this system, the first digit gives the relative height of the

disease using the original 0-9 Saari-Prescott scale as a measure and the second digit shows disease severity but in terms of 0-9 (0%-90% coverage in equal divisions of 10%). So in a plant with a disease height of 5 and an average disease coverage on the upper four leaves of 10%, the numerical disease description is 51.

Figure 2.8. Saari-Prescott (0-9) scale for appraising the intensity of foliar diseases in wheat and barley.

Other direct quantitative methods of measuring disease involve computing coefficients and indices, and measuring components of partial disease resistance (PDR). Septoria Progress Coefficient (SPC) was used for septorial diseases in which plant and disease height were determined, where SPC = disease height (cm)/plant height (cm). SPC indicates the position of pycnidia relative to plant height regardless of pycnidial coverage and allows a comparison of infection placement on cultivars with different plant stature. A disease index for measuring eyespot infection on wheat caused by *Pseudocercosporella herpotrichoides* was produced in which the

tillers taken at random from the field are assigned to one of the infection categories and an index calculated from the formula (Table 2.4).

Table 2.4. Calculation of a disease index for eyespot of wheat caused by Pseudocercosporella herpotrichoides *(Scott and Hollins, 1974)*

Infection category	*Disease severity description*
0	**Uninfected**
1	**Slight eyespot** (one or more small lesions occupying less than half the circumference of the stem)
2	**Moderate eyespot** (one or more lesions occupying at least half the circumference of the stem)
3	**Severe eyespot** (stem completely girdled with lesions; tissue softened so that lodging would readily occur)

Notes on assessment

1. Examine 20 tillers per 20 m2 plot.

2. Assign each tiller to one of the infection categories above.

3. Write the number of tillers in each category on the record sheet.

4. An index will be calculated from the data as follows:

Disease index (DI) = $(0 \times a) + (1 \times b) + (2 \times c) + (3 \times d) / (a + b + c + d) \times 100/3$

where *a, b, c* and *d* are the number of tillers examined which fall into the categories 0, 1, 2, and 3, respectively.

Direct qualitative methods

Direct qualitative assessments of disease are used to differentiate host responses or interactions, ideally under controlled conditions, where resistance or susceptibility is determined by genetic systems in the host and pathogen. Thus, responses to

individual virulences (physiologic races), as required in breeding programmes or race surveys, are measured using a qualitative method of assessment as shown in Table 2.5 for *Pyrenophora teres* (cause of barley net blotch disease). Such qualitative keys clearly differentiate resistant from susceptible responses; in net blotch disease 0, 1 and 2 are resistant (no chlorosis), and 3 and 4 are susceptible (chlorosis present).

Table 2.5: Reaction-type classes for *Pyrenophora teres* on barley (Khan and Boyd, 1969).

Class	*Reaction*
0	No observable infection.
1	Pin-point brown lesions, no chlorosis.
2	Small dark brown lesions, no chlorosis.
3	Restricted long brown streaks, slight associated chlorosis.
4	Brown elongated lesions with net-like cross variations, marked chlorosis.

A six-point qualitative assessment scale for *Septoria tritici* was developed by Rosielle (1972) in which 0 = an immune response - no pycnidia or leaf symptoms; 1 = highly resistant (HR) - occasional isolated pycnidia with hypersensitive flecking; 2 = resistant (R) – very light pycnidial formation with some lesion coalescence; 3 = intermediate (I) – light pycnidial formation with lesion coalescence; 4 = susceptible (S) – moderate pycnidial formation with considerable lesion coalescence; and 5 = very susceptible (VS) - large abundant pycnidia with extensive lesion coalescence.

Indirect methods

Indirect methods of disease assessment have increased in number with the development of new technologies. Traditional methods rely on monitoring pathogen spore populations over infected crops or trapping insect vectors of a virus to estimate the level of crop infection. Fox (1993a) identified two basic methods for air-borne fungal spores: measuring the concentration of spores in a given volume of air (concentration methods); and counting the number of spores deposited on a surface (deposition methods). The correlation between the two methods is poorly understood and will obviously depend on meteorological factors. Concentration methods involve sophisticated spore traps with a power source (e.g. the original Hirst Volumetric Spore Trap), whereas deposition methods often comprise simple sticky, horizontal or vertical surfaces exposed to the air under a rain shelter. Rain-dispersed spores can be effectively caught in funnel traps positioned within the infected crop; these are then emptied after rainfall and the spores counted on a haemacytometer slide. Methods used to trap spores in this way therefore involve estimates of spores using microscopy, or colony counts in culture or on living plants used themselves as spore traps. An extension of the latter is the use of trap nurseries and mobile nurseries, in which sets of genotypes are assembled that carry specific resistances to the target pathogen in different geographic locations. Standardized methods of sowing and disease assessment are used and samples sent to a testing centre for virulence identification, usually as part of a race survey. Other indirect methods of assessing disease include measuring the effect of the pathogen on host parameters such as (for cereals) stunting, increased or decreased tillering, root growth, premature or delayed ripening and reductions in ear number, grain number, size and quality.

It is often the case that data from the visual assessment of plant disease severity do not correlate with the amount of fungal biomass colonizing host tissue; this lack of correlation inevitably leads to inaccurate disease-yield loss relationships. Whereas diseases such as powdery mildew, which has a superficial ectotrophic growth habit on the host, may well show a close correlation between visual assessment and tissue colonization, most other diseases, where the pathogen is more invasive of the host tissue, are unlikely to show such a relationship. In order to test these assumptions, several workers developed more precise techniques of quantifying fungal biomass within host tissues, either by measuring fungal chitin or ergosterol. Chitin is not found in plant tissue but is a principal component of fungal cell walls and, similarly, ergosterol is a fungal membranespecific component. Thus, the chemical assays used for these biomarkers provide sophisticated quantitative techniques for the indirect assessment of disease severity in plant tissue.

Traditional methods, although still widely used, are rapidly being replaced by immunological and nucleic acid-based techniques. Of particular interest in the quantitative assessment of plant disease are user-friendly enzyme-linked immunosorbent assay (ELISA) kits for use in the field and the use of the polymerase chain reaction (PCR), particularly quantitative PCR (qPCR), for determining infection in plant material. Fluorescent *in situ* hybridization (FISH) is a recent technique that is used to identify and quantify soil bacteria and fungi using complementary probes to DNA or RNA sequences of the organism of interest labelled with a fluorochrome. Further development of these techniques for use by the farmer or grower as dip-sticks or dot-blots will provide more precise methods of indirectly assessing plant diseases on site.

Remote sensing

The use of aerial photography and photogrammetry using infrared film or colour filter combinations to enhance the differentiation between healthy and diseased tissue, represent a separate approach to disease assessment and were first used by Neblette (1927) and Taubenhaus *et al.* (1929) for surveying infection by cotton root rot (caused by *Phymatotrichum omnivorum)* in Texas and by Bawden (1933) in studies of virus diseases of potato and tobacco. Aerial photography was an example of remote sensing, defined by Nilsson (1995) as 'the measurement of an object without physical contact between the measuring device and the object'. Quality of results possible depends on the properties of the photographic film used, such as grain size and spectral sensitivity. Infrared film is usually used because near-infrared and infrared light are reflected deeper in leaf tissue than visible light. Remote sensing now relies on digital image processing and image analysis, including advanced nuclear magnetic resonance imaging (NMRI), for the interpretation and quantification of non-destructive disease measurements in crops.

Remote sensing uses the properties of the electromagnetic spectrum and is based on the principle that any body reflects or absorbs radiant energy as electromagnetic waves with specific properties. Such properties of plant vegetation, such as whether it is healthy or diseased, influence the amount and quality of radiation reflected or emitted from the canopy. As such, this technology provides a useful tool in phytopathometry. A distinction should be made between the more commonly used passive remote sensing which measures (via films or electronic instruments) the electromagnetic solar energy reflected from vegetation, and the newer active remote sensing, where intensive energy pulses of specific wavelengths are directed against the vegetation and the interaction is exploited and analyzed, such as in LIDAR (light detection and ranging).

Remote sensing for detecting and estimating severity of plant diseases is used at three altitudes or levels above the crop canopy. At the lowest altitude, within 1.5-2.0 m above crop height, hand-held multispectral radiometers or multiple waveband video cameras are used; at 75-1500 m, aerial photography is used, whereas at the highest altitude, satellite imagery is employed utilizing satellites orbiting at 650-850 km above the earth's surface. In addition, video image analysis systems, (Fig. 2.9), which uses a video camera interfaced through a digitizer to a microcomputer and display monitor, can be used under laboratory conditions for measuring diseased or damaged tissue at close quarters; systems such as the Delta-T Devices WinDIAS true-colour Windowsbased system are able to differentiate the primary colours of diseased and healthy tissue (brown, yellow and green) in order to analyze percentage diseased leaf area automatically.In 2002, image analysis software called ASSESS was made available by The American Phytopathological Society for plant disease quantification. The software was optimized for the measurement of leaf area, percent area infected, lesion/pustule count, root length and ground cover. ASSESS relies on the Hue - Saturation-Intensity colour model enabling the user to effectively extract the leaf from the background and then the lesions from the leaf.

Whereas hand-held multispectral radiometers or multiple waveband video cameras are most appropriate for disease measurements on plants or pots within fields, aerial infrared photography is most useful at field level, and satellite imagery has been used since 1972 for large areas or regions of the earth's surface devoted to agriculture and forestry. Images are transmitted to earth stations by satellites such as the American National Oceanic and Atmospheric Administration (NOAA) and LANDSAT series (1, 4 and 5), and the French SPOT satellite (which uses 10 metre resolution imagery), that feature advanced very high resolution radiometer (AVHRR) optical and thermal sensors; these have been joined by IRS, Ikonos and EROS satellites.

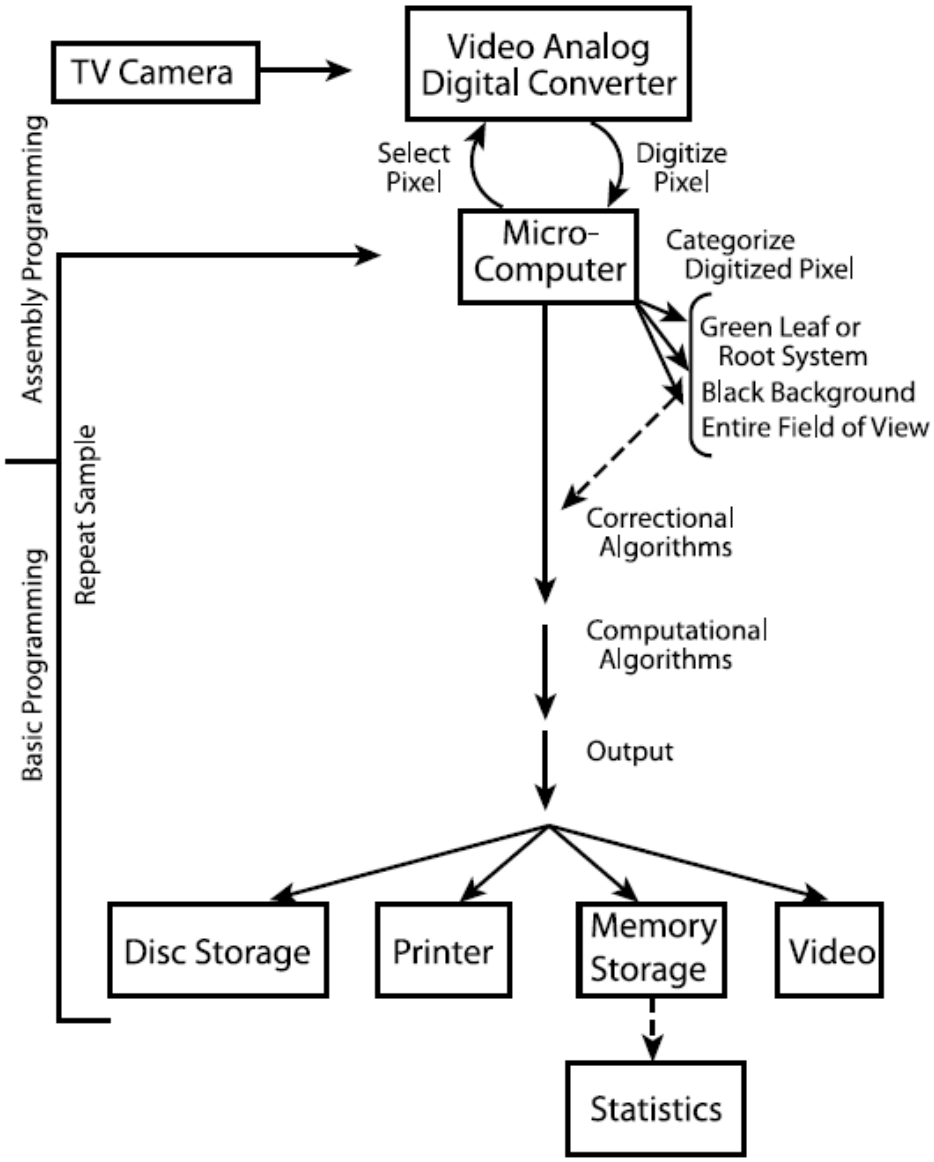


Figure 2.9. Video image analysis system for measuring diseased or damaged plant tissue (Lindow and Wenn, 1983).

However, the importance of ground truth, that is actual visits to the target crop to verify remote sensing data, is an important part of the process. The persistence of cloud cover in countries such as the UK and Brazil has been a serious impediment to the progress of this technology; however synthetic aperture radar (SAR) high-

resolution technology can overcome this problem and was used in 1991 on board the European Remote Sensing Satellite ERS-1.