20

ASSESSMENT OF DISEASE AND EFFECTS ON YIELD

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20.1 Introduction

Assessment or measurement of disease is the basis of epidemiology which is the study of disease at the level of populations of pathogens and hosts. It is also the basis of the study of the effects of disease on crop yield and of disease forecasting (Chapter 19), which involves the prediction of the amount of disease that is likely to occur at some time in the future.

It is usually not sufficient to determine whether a disease is present or absent. The critical information required is the **amount** of disease that is present. Disease often has to exceed a certain threshold before it reduces the yield of a crop. Small amounts have little effect on yield and the disease may not be worth controlling. The amount of disease is measured as the proportion of the crop population (counted as individual plants or branches or leaves etc.) that is infected (**disease incidence**) or the proportion of the area of a plant or plant organ (e.g. leaf area) that is affected (**disease severity**). In some cases, the proportion of leaves or branches infected may provide a measure of disease severity.

Although it is known that plant diseases reduce crop yields compared to yields that could be expected in the absence of disease, it is usually difficult to obtain accurate quantitative estimates of yield reductions caused by specific diseases. Many diseases occur on senescing tissue which may not have been contributing much to yield. Plants are capable of compensating for loss of a certain amount of leaf area, especially in crowded crop populations. The only diseases where the effect on yield is relatively easy to measure are those that kill entire trees in orchards or plantations (e.g. phytophthora root or collar rot of citrus or apple), and those that destroy the actual harvested product, either just before harvest (e.g. the smuts, which destroy cereal grain, and fruit rots such as cocoa pod rot caused by *Phytophthora palmivora*) or after harvest (all postharvest rots of fruits and vegetables).

Reduced yields caused by pests and diseases are commonly referred to as 'crop losses', although some pathologists prefer to think of disease as a 'yield

limiting' factor or a 'constraint on yield' rather than as a cause of 'crop loss', contending that you cannot lose what you never had in the first place. Viewed in this way, the impact of disease is expressed more directly as the increase in yield when it is controlled rather than as the prevention of a 'crop loss'. However, 'crop loss' is a useful shorthand way of expressing the impact of a disease and it is certainly one that farmers understand when they compare their yields in one year in the presence of disease with their yields in previous years in the absence of disease.

Disease and crop loss assessments are necessary before the economic impact of a disease and the benefit of particular control strategies can be determined. Ideally, this knowledge is required before much effort is expended on studying a particular disease. In reality, most diseases have been studied because people sensed that they were causing yield losses and therefore required study and the development of control measures. The economic advantage of any control method has to be determined. It is no use implementing a control measure that costs the farmer more than it returns in increased yield. Often in the past the economic value of control measures was based on vague qualitative assessments, but for a more accurate measurement of economic advantage, disease assessments have to be quantitative. The growth of the crop, its yield potential, the development of the disease and its impact on yield all have to be measured as a basis for predicting the impact on yield of particular levels of disease. This information can be combined with predictions of likely disease levels in deciding whether implementation of control measures is warranted.

The economic advantage of any control strategy can be estimated by applying the following formula:

$$
\begin{array}{c}
\text{Economic} \\
\text{advantage of} \\
\text{disease control (\$)}
\end{array}
=
\begin{array}{c}
\text{Expected return if} \\
\text{disease is} \\
\text{controlled (\$)}
\end{array}
-
\left(
\begin{array}{cc}
\text{Expected return if} & \text{Cost of} \\
\text{the disease is left} \; + & \text{control} \\
\text{uncontrolled (\$)} & \text{treatment (\$)}
\end{array}
\right)
$$

The economic advantage of control is clearly affected by the difference between the economic return if the disease is controlled and the return if it is not, which is determined by the 'crop loss' caused by the disease, the measurement of which is the main concern of this chapter. However, this is also determined by the economic value of the crop. A crop like coffee, cocoa, macadamia nuts or a vegetable with a very high value per unit weight of harvested product, will be able to sustain a greater expenditure on disease control than a relatively low value production system such as a pasture. The yield potential of a crop and hence the economic return if disease is controlled also determines the amount of expenditure on disease control that can be sustained. Australian wheat farmers producing an average of about 2 tonnes per hectare under conditions of water and nutrient deficit can spend less to control stripe rust (*Puccinia striiformis*) than European farmers who produce an average of about 8 tonnes per hectare under more favourable environmental conditions.

It is obvious therefore, that decisions based on disease assessment data are critical in the economy of any farm. Furthermore, from the national standpoint, disease assessment information is fundamental for the prediction of crop yields as a basis for the smooth running of markets and financial planning. It also enables problem areas to be recognised and permits priorities for future research and development to be placed on a sound economic basis.

Much of the published work on disease assessment and crop losses has been qualitative rather than quantitative. This has led to disease incidence being described in vague terms such as 'severe', 'debilitating', 'mild' or 'of little

consequence'. Qualitative assessment of disease provides inaccurate and often misleading data. It does not enable comparisons to be made between the results of different workers or between results obtained from different seasons or locations.

Quantitative assessments of disease are based largely on comparisons between the yields obtained from diseased or damaged crops and those obtained from healthy or undamaged crops. Comparisons can be made between diseased and disease-free plants in the same crop or between diseased and disease-free plants or crops grown in different locations, provided that the locations have similar environmental conditions.

One major difficulty associated with disease assessment is the rarity in nature of a 'one cause—one disease' situation. Under field conditions, plant growth and yield are influenced by many factors including nutrients, rainfall, insects, weeds and pathogens. It is difficult, therefore, to determine the relative importance of different factors in limiting yield. There are often complex interactions between the constraints on yield. For example, the impact of a root rotting pathogen will be much greater in a drought year than a wet year, or in an infertile soil than a fertile one. The impact of foliar pathogens (e.g. rusts and powdery mildews) that disrupt the plant cuticle and so affect the water relations of a plant, will be greater in a dry than in a wet year.

The assessment of plant diseases and their effects on yield normally involves five distinct processes: (i) developing a descriptive growth stage key for the particular crop species in question, (ii) developing methods to assess the incidence and severity of disease, (iii) developing statistically sound methods of sampling crop populations for assessment of the amount of disease, (iv) estimating the negative impact of particular levels of the disease on crop yield and quality and (v) evaluating the economic benefit from various methods available for reducing the amount of disease.

20.2 Assessment of crop growth and development

While plant pathology tends to concentrate on the diseased plant, it should be realised that to understand the impact of a disease fully it is necessary to understand the growth, development and physiology of the healthy plant.

One of the first steps in quantitative disease assessment is to obtain or develop a key that describes the growth and development of disease-free plants during the growing season. In annual plants, the keys describe development from the time of sowing or planting until harvest. In perennial species such as tree crops, variations in growth patterns between seasons are described, often beginning with bud burst in spring. In tropical perennial crops the starting point is more difficult to determine since growth often occurs throughout the year. It is therefore often necessary to nominate a more arbitrary starting point (e.g. a particular growth flush at the beginning of the wet season).

Detailed drawings or photographs are needed to show such characteristics as the structure of the canopy at various stages of crop growth, the formation of new leaves and the senescence of older leaves, the development of reproductive structures and different stages in the formation of grain or other harvested products. Detailed information on the development of healthy plants is needed before the effects of disease on crop growth and development can be assessed. For example, it is important to distinguish between normal senescence of leaves and damage caused by parasites. Some parasitic fungi develop mainly on senescing leaves and so their impact on yield is probably small. They may just be speeding up the process of decay of senescent leaves.

Descriptive and pictorial growth stage keys have been developed for a number of crops including wheat, oats, barley and rye (Fig. 20.1), maize, rice, tobacco, cotton, legumes, broad beans (*Vicia faba*), black currants and *Narcissus* and *Chrysanthemum* flowers. With some species, such as wheat, several different growth stage keys are in use. It is helpful if standardised growth stage keys are used around the world, enabling ready comparison of results from different countries. However, with many crops that have been little studied, it may be necessary for investigators to construct their own keys.
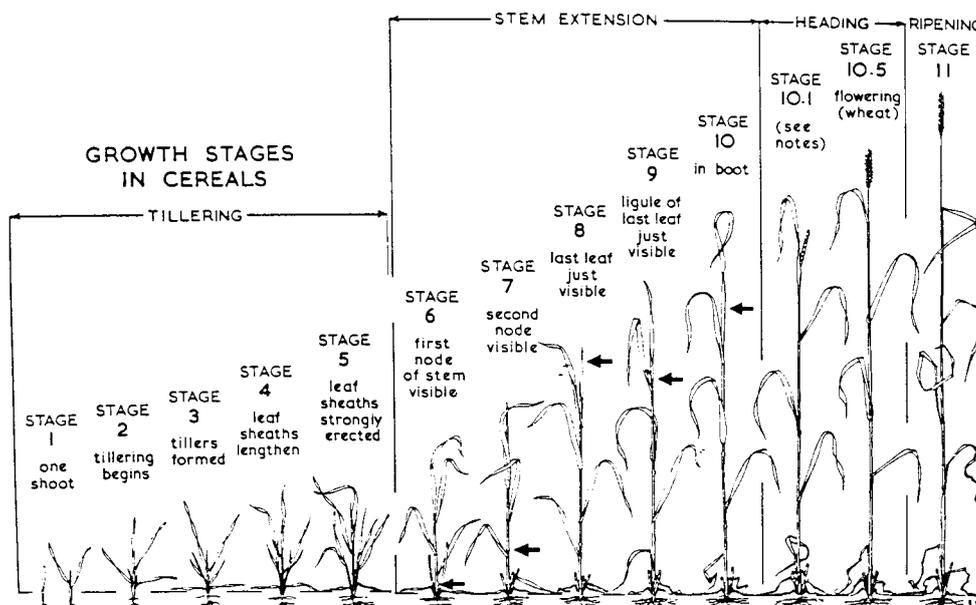
Growth Stage

1	One shoot (number of leaves can be added).
2	Beginning of tillering.
3	Tillers formed, leaves often twisted spirally. In some varieties of winter wheats, plants may be 'creeping' or prostrate.
4	Beginning of the erection of the pseudo-stem, leaf sheaths beginning to lengthen.
5	Pseudo-stem (formed by sheaths of leaves) strongly erected.
6	First node of stem visible at base of shoot.
7	Second node of stem formed, next-to-last leaf just visible.
8	Last leaf visible, but still rolled up, spike beginning to swell.
9	Ligule of last leaf just visible.
10	Sheath of last leaf completely grown out, spike swollen but not yet visible.
10.1	First spikes just visible (awns just showing in barley, spike escaping through split of sheath in wheat or oats).
10.2	Quarter of heading process completed.
10.4	Three-quarters of heading process completed.
10.5	All spikes out of sheath.
10.5.1	Beginning of flowering (wheat).
10.5.2	Flowering complete to top of spike.
10.5.3	Flowering over at base of spike.
10.5.4	Flowering over, kernel watery ripe.
11.1	Milky ripe.
11.2	Mealy ripe, contents of kernel soft but dry.
11.3	Kernel hard (difficult to divide by thumb-nail).
11.4	Ripe for cutting. straw dead.

Figure 20.1 The Feekes scale for describing growth stages of cereals. (From Large, 1954. Crown copyright is reproduced with the permission of the Controller of Her Majesty's Stationary Office.)

20.3 Methods for assessing disease incidence and severity

Disease assessment methods should (i) provide objective measurements so that results obtained by different workers, from different locations and from different seasons are comparable, (ii) be simple and quick to use, (iii) be related to an identifiable growth stage of the crop and (iv) provide an adequate sample of the entire area of crop to which the assessment refers.

Thus, disease assessment of a crop encompasses two main aspects— assessment of disease in samples from the crop and adequate sampling from the whole crop.

Measurement of disease incidence and severity

Whether or not disease incidence or severity or both should be measured will depend on the disease, the particular epidemiological circumstances and the reason for undertaking the disease assessment. With systemic diseases (e.g. many virus diseases) or root diseases (e.g. phytophthora root rots) that infect and kill whole plants or when the disease causes similar amounts of damage on plants within a crop, the disease incidence, expressed as the percentage of plants showing symptoms or damage, may suffice. At low levels of disease there is often a linear relationship between incidence and severity, and so it is sufficient to measure incidence. However, at high levels of disease there is often not a simple, consistent relationship between incidence and severity. Many diseases cause different levels of damage on different plants within a crop. In such situations it is necessary to assess disease severity. The impact of a disease on yield is often determined by the extent of disease on the nearly mature plant (e.g. on the flag leaf and head of cereals). At this stage, disease severity is usually a better predictor of crop loss than disease incidence. Thus, for most crop loss assessments, severity is required.

Measurement of disease severity is more difficult and error-prone than measurement of disease incidence. Disease incidence is based on counting infected and uninfected units of the crop (whole plants for systemic diseases, inflorescences for smuts, leaves for leaf spots and rusts etc.). From these counts the proportion of units infected is calculated. An example was given in Chapter 19 of the measurement of the incidence of blister blight of tea as a basis for forecasting the amount of disease likely to occur 2–3 weeks later. The main problem in determining disease incidence is establishing the extent of sampling that is required to adequately represent the crop.

Determining disease severity often requires estimating the proportion of the total photosynthetic area of the crop that is diseased which is often called the 'proportion of leaf area affected'. This measurement is much less precise and less controllable than measurements based on counting individual plants. Disease severity assessment relies on visual judgments which tend to be deceptive and to vary greatly from person to person. The human eye tends to detect grades of disease severity in logarithmic steps (5%, 10%, 20%, 40%, 80%) rather than in the uniform, arithmetic steps (5%, 10%, 15%, 20%, 25% etc.) by which we like to express quantities. Accordingly, various modifications of percentage scales have been proposed to take into account this fact and allow more accurate measurement of disease severity. Moreover, when less than 50% of the tissue is diseased or damaged, the eye tends to focus on or estimate the proportion of diseased area, but when more than 50% of tissue is damaged the eye tends to focus on or estimate the proportion of healthy tissue.

The most common method of estimating disease severity is the use of a set of diagrams (**disease assessment keys**) of a crop (commonly leaves, but it could

involve inflorescences, fruits or whole plants) showing different disease severities as blackened areas. Severity scales are adjusted to take into account the above concepts of visual perception. Samples of the crop are then compared with these diagrams to allow an assessment of severity. A **disease index** for a crop can be obtained by summing the individual disease assessments and then dividing this by the number of plants assessed.

For common diseases it is helpful to use published keys to standardise measurements around the world. However, in some cases such as for new diseases or in particular circumstances it may be necessary to develop one's own key. To produce a disease assessment key, the development of disease over the whole disease cycle and at different stages of plant growth must be studied. Drawings and measurements of the diseased plant at various stages of development are required and the various parts of the plant that are damaged must be analysed. This information is used to develop prototype standard diagrams which may involve photographing or tracing symptoms onto paper and accurately measuring the proportion of the tissue diseased. Alternatively, the area of leaves and the area of disease can be measured using an electronic 'leaf area meter' or a video camera and image analysing equipment connected to a computer. Eventually, the key is simplified to enable rapid and accurate measurement of the disease under field conditions. For crop loss assessments, the key has to be set so that it measures the disease at the stages of crop development that are critical for yield. The scale then has to be tested in the field in an objective way. For example, a researcher may assess a range of diseased samples with the key and then compare the results with objective measurements in the laboratory of the same samples. Some examples of descriptive and pictorial disease assessment keys are shown in Tables 20.1 and 20.2 and in Figure 20.2.

Table 20.1 Key for the assessment of leaf mould of tomato caused by *Fulvia fulva*. (From Beaumont, 1954.)

% Severity	Symptoms
0.1	Lesions found with difficulty, and on less than one plant in fifty.
1	Lesions on most plants, but only on a few leaves.
5	Lesions on every plant, and on most leaves except the young ones, but only about two to ten spots per leaf.
10	All except the youngest leaves affected, with ten to fifty spots per leaf.
25	All except the youngest leaves affected, but with about three-quarters of the leaf area green, although lowest leaves may be severely attacked.
50	All leaves affected. Most of the middle leaves showing only half their area green.
75	All leaves affected. Most of the middle leaves show only one-quarter of the leaf green, giving a grey appearance to the crop as a whole.
90	Very little green visible on middle and lower leaves, but youngest leaves show green.
100	All leaves completely covered with the lesions.

The development of a key and its field testing is actually a way of training a researcher's eye to recognise the various disease severity categories. Eventually a highly trained observer will conduct the whole assessment by eye. However, even highly trained observers need to standardise or calibrate their visual assessments by regular comparison with objective measurements. For example, people differ greatly in their ability to accurately assess percent leaf area diseased. Some people tend to overestimate, others to underestimate, and others

to overestimate at low disease levels and underestimate at high levels. Regular objective testing allows statistical confidence intervals to be established for a particular observer under particular conditions. Programs have been developed for computer-assisted training of observers in disease severity assessment. The computer program develops diagrams of a diseased leaf with different severity levels. The observer estimates the severities, the program then compares their performance with the known severity and gives them feedback on the extent of their errors, allowing further training of their visual perception.

Table 20.2 Key for the assessment of late blight of potato caused by *Phytophthora infestans*. (After British Mycological Society, 1948.)

% Severity	Symptoms
0	Disease not seen in field.
0.1	Only a few plants affected here and there. Up to one or two spots in 10.8 m radius.
1	Up to ten spots per plant or general light spotting.
5	About fifty spots per plant, or up to one leaflet in ten attacked.
25	Nearly every plant with lesions; plants still retaining normal form; fields may smell of blight but look green although every plant affected.
50	Every plant affected and about half of the leaf area destroyed by blight; field looks green flecked with brown.
75	About three-quarters of the leaf area destroyed by blight; field looks neither predominantly brown or green. In some varieties the youngest leaves escape infection so that the green is more conspicuous.
95	Only a few leaves left green, but stems green.
100	All leaves dead, stems dead or dying.

Because different assessors vary in their assessments, if two people are required to carry out a disease assessment each observer should do half the number of replicates so that any error due to the different observers appears in the error mean square of the analysis of variance.

Assessment of severity of leaf disease on eucalypt saplings has involved use of diagrams to represent the whole tree. The diagrams show the extent of disease on middle and upper branches and the extent of abnormal leaf loss on lower branches. They have been used to measure the degree of resistance of various provenances of eucalypts, but assessments of disease on whole plants are more prone to error than assessments on samples of single branches or single leaves. For example, assessments of whole trees can be greatly affected by the quality of the light and the degree of shading of one tree by another. Bright sunlight can obscure the extent of disease and result in a different assessment from one done on an overcast day.

Root diseases are often assessed using an arbitrary scale such as the 0 to 5 scale of Greenhalgh and Lucas (1984) for root rot of subterranean clover, where:

0= healthy roots (no visible lesions on roots)

1= slight lateral root rot (less than 10% of lateral root tips necrotic)

2= moderately severe lateral root rot (10–50% of lateral root tips necrotic) or slight tap root rot (tip of tap root rotted) or both

3= severe lateral root rot (greater than 50% of lateral root tips necrotic) or moderately severe tap root rot (5–30% of tap root rotten from tip) or both

4= severe tap root rot (greater than 30% of tap root necrotic with healthy laterals above lesion or lesion girdling tap root immediately below hypocotyl)

5= tap and lateral roots completely rotted or plant dead.
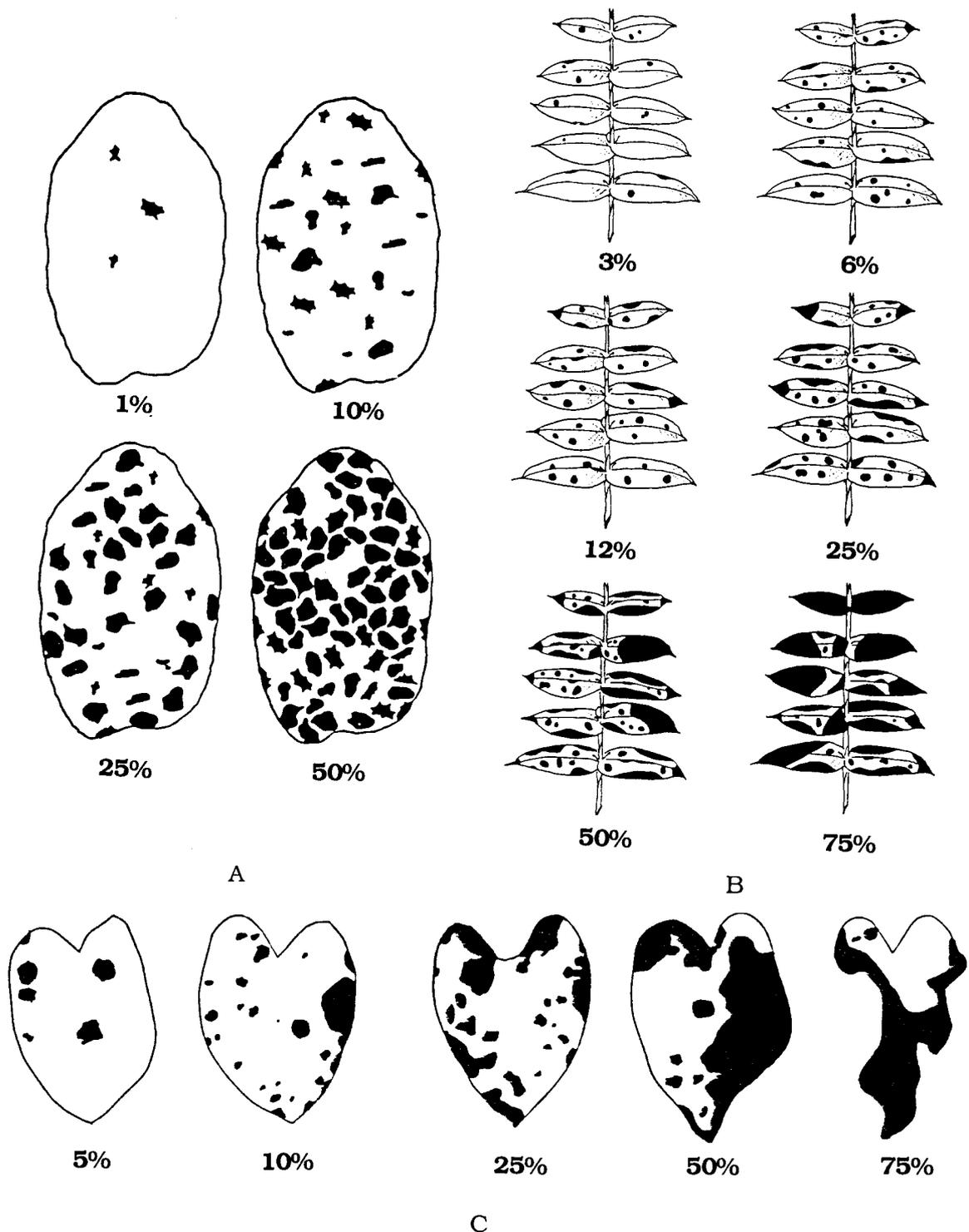
Figure 20.2 Disease assessment keys. (A) Common scab of potatoes caused by *Streptomyces scabies.* (From James 1971.) (B) Mycosphaerella leaf diseases of eucalypts. (From Carnegie et al. 1994.) (C) Phytophthora blight (*P. colocasiae*) of taro (*Colocasia esculenta*). (From Gollifer and Brown, 1974.)

Infected root systems can be surface sterilised and plated onto selective media, which allow the pathogen to grow out of the region of the root that is infected. The proportion of the root system infected can then be measured.

Some workers have used electronic root length measuring devices to determine the extent of root loss in infected, compared with uninfected, root systems.

Disease incidence can be also assessed using remote sensing techniques. For example, the incidence of rusts such as *Puccinia graminis* in cereal crops has been measured using spore traps to determine the quantity of spores arising from the diseased crop. This method assumes that spore production is directly related to the amount of disease in the crop. This is not always so (see the example of tea blister blight in Chapter 19). It has the advantage that the disease assessment is made without actually walking into the crop, a practice that may alter the rate of spread of disease due to the disturbance resulting from intrusion into the crop. Other remote sensing techniques include the use of electronic scanners and other instruments to produce quantitative estimates of disease incidence from data on infrared (IR) aerial photographs. Such IR photographs can be taken from either aircraft or satellites. Methods have even been developed to take disease assessment photographs from radio-controlled, model aircraft.

Video cameras and image analysis can be used to objectively measure disease severity in the field, but to date these methods are too cumbersome and time consuming to replace the trained human eye in all except experimental assessments.

Finer measurements of disease severity not only enable more accurate assessment of the impact of disease on yield but also enable better assessment of the effect of quantitative resistance and other control measures. It is likely that in the past much useful resistance was discarded from breeding programs because the small amount of resistance it contributed was not assessable using broad-brush assessment methods. It is now appreciated that even small amounts of resistance may be important in disease control in combination with other control measures and that even small amounts of partial resistance may be useful in combination with other sources of resistance in breeding programs.

Sampling for disease incidence and severity assessments

Most of the disease assessment methods referred to above are applied to samples taken from the whole crop or plantation area. Therefore, a major limitation in the overall assessment of disease is the sampling method. The disease assessment will only be accurate if the sampling method enables accurate extrapolation to the entire crop.

Samples of crop units (plants, leaves, inflorescences etc.) can be taken at random from a field (e.g. by following a set of random number coordinates, or a randomly chosen number of paces across the field) or in a predetermined way (e.g. by walking across a diagonal or in a 'W' or diamond pattern across the field and taking a sample every 10 paces). Random sampling is preferred by biometricians. There are programs available for portable computers that indicate the random number of paces for sampling during a 'walk pattern' through a field.

Alternatively, standard quadrats can be placed at random in a field and all plants within each quadrat assessed. In experimental plots often a part of each plot is assessed for disease. Because of the influence of 'edge effects', taking a few samples from the edges of fields is never sufficient to accurately reflect the disease situation throughout the field. This is a problem in sampling leaf disease in eucalypt forests. Often the best view of the disease in the foliage is from roadsides where the edge of the forest is exposed. However, this may not reflect the occurrence of disease in the bulk of the forest.

The intensity of sampling should be determined for each disease situation. It will depend on the uniformity of disease in a plant population. A disease spread uniformly throughout a crop will require fewer samples for accurate assessment than one with a patchy distribution through the crop. It is possible when developing the methodology for studying a particular disease, to sample a certain number of times at each of progressively increasing levels of sampling intensity. The standard error of the mean disease incidence or severity at each sampling intensity can then be plotted against the sampling intensity. The optimum sampling intensity is determined as the one at which the standard error first falls to a low level which is maintained even at much higher sampling intensities (Figure 20.3). It is a waste of time taking a larger number of samples if they do not greatly reduce the standard error of the assessments.
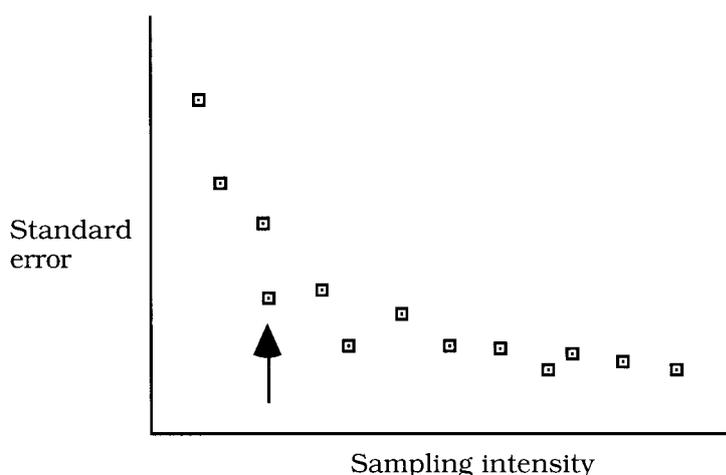
Figure 20.3 Plot of standard error of mean disease assessment measurements against sampling intensity, showing the point at which the standard error declines to a relatively stable low level (approximately the optimum sampling intensity).

20.4 Assessment of crop losses

Having determined the amount of disease in relation to the growth pattern of a crop, the next step is to determine the effect of different levels of disease on yield of the crop. The two main approaches used to relate disease intensity to crop losses are the experimental and the statistical.

The experimental approach

The experimental approach to crop loss assessment usually involves setting up experiments in which the level of disease in a crop is controlled using different levels of inoculation or treatments with biocides (fungicides, nematicides, bactericides). Often, an intensive spraying schedule is used to hold disease to a level close to zero, which allows the potential yield of the crop in the absence of disease to be determined. A reduced spray treatment may allow development of a moderate disease severity, while withholding of treatment may allow development of a severe epidemic. This allows a comparison of epidemic progress and yields in the plots. From this a relationship between disease parameters and yield can be determined, allowing prediction of crop loss based on certain disease intensities at certain periods of crop growth. The value of this