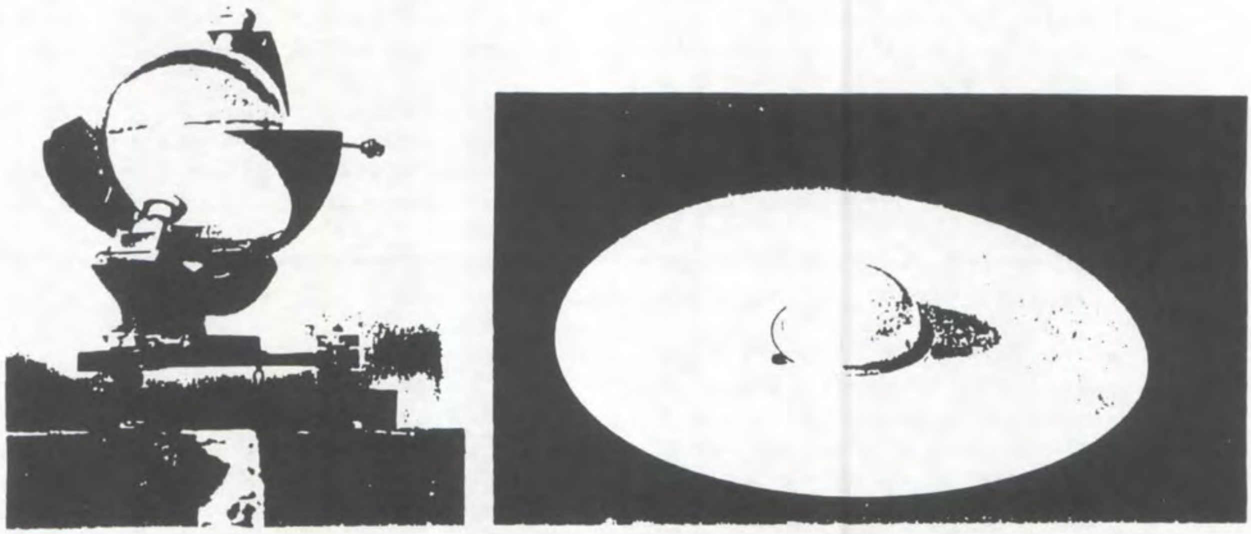

Fig. 7.8: Left A Campbell-Stokes sunshine recorder. The glass ball focuses the sunlight on the recording card on the polar side of the mounting. The image of the bright sun chars a trace from left to right (in the northern hemisphere) across the printed hour scale. A new card is inserted daily. *Right* a solarimeter. Sunlight diffuses through the small glass dome and warms the blackened top end of a thermopile whose shielded lower end stays at ambient temperature. The white collar provides a radiatively uniform surround.

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BOX 7.4

Examples of the use of weather criteria for prognosis

*1. **BLITECAST** for prediction outbreaks of **Phytophthora infestans** in potato (Mackenzie, 1981; eastern USA): Temp. and RH data must be monitored with a thermohygrograph placed between the rows in the still green canopy of a potato field. A late blite warning is given when the following conditions are met: 10 consecutive days with cumulative rainfall > 30mm and 5-day average daily temp. < 25.5 °C. The computer analyzes the data rapidly and reports the spray recommendations back to the farmer immediately. The central BLITECAST can serve 15-20 farmers within 1 hour. This forecast does not include, however, data on the presence of disease inoculum.*

*2. Rain was utilized as an indicator or predictor by Calpouzous et al., for the **SIGATOKA** disease of bananas in Puerto Rico: They found that the number of sprays which usually amounts to 25 could be reduced to 13 when based on rainfall data. According to their evaluation, 3 inches or more rain during the previous 3 weeks when exceeding the rainfall data gathered 2 weeks earlier prompt a new spray round with mineral oil.*

*3. Lim in Malaysia working on Hevea rubber issued the following forecasting rule for powdery mildew, **Oidium hevea**,: With a temperature of 32°C or less and 13 hours of continuous RH > 90% in the developing canopy of the trees, powdery mildew will appear within 7-10 days.*

*4. Temperature sums or degree days are used for many insect pests to predict their first appearance in the season (chapt. 9), like for instance, for cotton bollworm (**Heliothis zea**), pink bollworm (**Pectnophora gossypiella**) and the lygus bag (**Lygus hesperus**) in cotton in California, or for the San Jose scale (**Quadraspidiotus perniciosus**) in orchards. Usually, the development thresholds for each specific insect pest, can be calculated in day degrees.*

Attention:
*The significance of degree-day values may vary with the insect pests' biology in various regions: The alfalfa weevil (**Hypera brunneipennis**) in some regions of Illinois (USA) lays eggs in autumn and winter, and there accumulation of 200 degree-days indicates the time when sampling has to begin; however, in regions in which the weevil does not lay eggs in these seasons, sampling can be delayed until 400 degree-days have accumulated.*

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8. CROP LOSS ASSESSMENT AND THRESHOLDS

8.1 Introduction

In decision making in crop protection it is necessary to know what is the effect of the various biotic factors which threaten the yield of a crop. The evaluation of the influence of each factor, and certainly the combined effects of various factors, can be a complicated puzzle which is called crop loss assessment.

Speaking about crop losses we mean in fact the difference between the yield we could obtain in the absence of the pest or disease involved (the attainable yield) and the yield which we get as a consequence of the presence of this pest or disease. Crop losses, in general, can be observed and estimated in farmers' fields. The yield depressing effects of factors like pests and diseases are the object of study and experimentation in crop loss assessment. Regional and national crop loss figures can be determined by means of surveys.

Pests and diseases are not the only factors which may cause a lower yield. Abiotic factors like the weather, soil type, the lack of modern technology etc. may also cause lower yield than would be possible if these factors were optimal. However, in the context of crop protection we usually consider only biotic factors like insect and mite pests, fungal and virus diseases, nematodes, rodents and sometimes birds as the main factors which cause crop losses. That this is not always correct is demonstrated by the fact that for instance water management or fertilization may increase or decrease the effects of biotic factors on the yield of crops.

Crop losses may occur regularly (every year or season) or incidentally (only once over a longer period). Crop losses can be hidden (in a superficially healthy crop) or can be very much recognizable and the causes well known. Furthermore, crop losses can be transitional (temporary losses) or structural (unavoidable in a certain situation).

Definitions

Crop loss is the difference between actual yield and attainable yield (Zadoks and Schein, 1979). The terminology as well as the classification of types of losses caused by noxious organism has been described already in an earlier hand-out of this course (Introduction in Plant Production and Protection: Injury, damage and loss). Further information on the terminology of crop loss assessment and the many approaches to a quantification of the relation between pests/diseases and crop loss can be found in Chiarappa (1981).

8.2 Types of experiments for crop loss assessment (CLA)

To have an idea to what extent pest populations in various crops under different local conditions can be tolerated it is necessary to find out the relation between the presence of the pest (in numbers, in percentage infested plants, in severity or otherwise) and the resulting damage. This relation is expressed as the "damage coefficient" in for instance kg/ha less produce per added unit of pests or 0.5 ton/ha for each caterpillar/plant on average more. Pest-damage relationships are usually complex. The earlier mentioned tolerance of crops plays a role, but also the moment of

Table 8.1

Crop	Dimension of plot Width (rows)	Length (metres)	Distance between rows (centimetres)
Barley and wheat	6	6	30
Cotton	4	9	102
Maize	4	9	102
Millet	6	6	30
Potatoes	4	9	91
Rice	10	6	20
Sugar cane	6	17	183

attack during the growing season, the variety (tolerant, resistant, susceptible or somewhere in between), weather conditions, water management etc. Therefore, in trials factors are kept constant as much as possible to reveal the effect of changing pest populations.
Types of trials used for this purpose are:

* **paired treatments**, in which various population densities are compared to very low populations, obtained by persistent chemical control. In such cases correlations are made between the different population density levels and the corresponding yields (in quantity and quality). The more different population density levels can be compared in the total range of possible values against very low populations, the better the relationship between infestation level and expected damage can be assessed.
* **cage experiments**, in which accurately determined pest populations are compared as to their effects on the plants and their yield. A common problem is that caged plants under greenhouse conditions are not comparable to field plants in physiology and yield. For glasshouse crops this is not a problem.
* **field cage experiments**, the same but under more realistic (nearly) field conditions.
* **single plant experiments**, in which individual plants (or hills) are recorded and followed up to the harvest. This is usually time consuming and problems may arise with analysis when there is a large individual variability in yield among untreated plants.

8.2.1 The plot method

This applies especially for experiments to study the relationship between pest severity and injury or damage. In those cases a comparison is made between plots with different degrees of pest/disease attack and the control plot free of pest/disease. It is a paired treatment experiment in which the yields of two plots, one plot with a specific density of the pest or disease is compared with another plot protected from these pests/diseases. The experiments are replicated several times.

The plots must be:

a. Representative of the conditions in which the experiment is interested;
b. homogeneous with respect to soil conditions, crop planting and growth. This is also important to make comparisons possible with other years and other locations. Recommended specifications to size and shape of plots for eight major crops are presented in Table 8.1.

Important factors for the experimental set-up are:

1. Crop variety.

2. Type of planting (distance between rows, plants or hills).

3. Dimension of plots harvested and number of harvested units (rows, trees). The size of the plots depends strongly on the type of crop, type of planting and the mobility of pest/disease.

4. Number of replications. Each experiment should comprise a minimum of four (preferably five or six) replications.

5. Pest/disease species must be present. The density of these may be manipulated.

6. Use guard rows. It is often necessary to reduce the effect of pest movement between plots. This effect, and also the drift of pesticides used for control, can be minimized by inclusion of guard rows between the plots of each replication.

7. Allocation of treatments to plots. The allocation of the protected and non-protected plot in each replication must be random.

8. Presence and intensity of other pests and diseases. Occasionally, both protected and non-protected plots must be sprayed with a chemical to prevent or control outbreaks of other pest/diseases. These must be applied uniformly to all plots and should not affect the pest/disease under study.

9. Harvest procedure. In all experiments only the centre rows of each plot should be harvested for determination of yield and quality. Lodging of the crop, difficulty in harvesting, increased labour requirements for removal of pest-infested plant or crop, etc. may complicate the harvest and influence the ultimate results.

10. Replicate the experiments a few years. Climatological conditions vary from year to year and they exert a strong influence on the effect of pests on crop growth and yield.

Data analysis

T-test:
The analysis of these paired treatment experiments can often be done by the use of the "paired t-test" (*see also chapter* 4).

The formula is: $t = \frac{\bar{d}}{S_{\bar{d}}} = \frac{\bar{d}}{S_d/\sqrt{n}}$

where $\bar{d}$ = mean difference between yields of treated and untreated plots

$S_{\bar{d}}$ = estimated standard error of the mean difference

S_d = estimated standard deviation of the differences

n = number of pairs

Correlation

If extensive data on pest/disease intensity and their effect on yield reduction are available, the relationship or degree of association of these two variables, may be expressed as a coefficient of correlation (r) (varying from +1 to -1). The reliability of r depends on the quantity and quality of the observations.

Regression

Regression analysis is a way of expressing pest-loss relationships. It permits the estimation of the amount of yield loss at a given pest/disease intensity. It is only as valid as the data from which it is derived. Pest/disease - loss relationship may vary with growth stage, variety of the crop, strain of pest/disease, and environment in which the pest develops. Many other conditions may influence this relationship.

8.2.2 The non-plot method

The paired-plant method

Often a pest outbreak occurs in such a way that parts of a crop are affected but others remain pest-free or a gradation of pest intensity is noted. Such occasions can be used to obtain yield-loss information with other than plot methods. One of these methods is the paired-plant method. This method has been used for measuring pest/disease versus yield-loss relationships in cereals, potatoes and beans.

Method:
- Individual affected and unaffected neighbours are marked.
- Adjacent pairs of unaffected plants are also marked to allow quantification of any compensation achieved by the unaffected plant adjacent to an incompletely competitive affected neighbour.
- Marking is done with labels or by mapping (if the plant density is low).
- Record the intensity of the pest/disease on the affected plant throughout the growing season.
- At harvest all marked plants are recovered and processed individually:
  - dry weight per plant
  - dry weight of seeds/tubers/pods etc.
  - quality criteria
- The number of plants depends on the degrees of intensity of the pest/disease. To get a firm relationship one should aim at 1000 plants.

Disadvantage: The effect of competition may be increased if a single plant is attacked by a pest/disease, resulting in stronger reduction.

Small area comparison

If the pest/disease occurs aggregated in a field and this aggregation is not due to predisposing factors (soil type, windbreak effect etc.) instead of individual plants small areas may be sampled in a paired way. The same procedure as in the paired plant method. In this case the effects on individual plants are levelled out by taking a small group of similarly infested plants. Care must be taken that the observation units are representative for the nature, biological properties and distribution of the infestation in the entire field.

On-farm "half field" comparisons

This is especially useful for rapid tests on a large scale.
Farmers who intent to spray a field against a specific pest/disease are asked to omit spraying for a representative part of the field. Samples can be taken from the sprayed and unsprayed parts of the fields until harvest.

Yields can be compared after harvest. The problem is to get a satisfactory number of replicates. Fields on a regional scale can be compared for several years.

Data analysis

For the single plant, paired plant and the paired small area-method regression analysis is very suitable. If pest/disease is recorded on presence or absence basis, performance of affected and unaffected plants can be compared by the use of a t-test.

For small-area comparison with two treatments a paired t-test is appropriate.

For half-field analysis:

1. t-test for single comparison;
2. paired t-test of mean values from all comparisons within the series;
3. analysis of variance although not in the normal way, since there is no true replication of treated and untreated plots in a field.

8.3 Manipulation of pest densities

To obtain different pest densities for the establishment of the pest yield loss relationship several methods are available.
Pest densities in the different plots (plot method) may be manipulated with:

1. Chemicals

   Pesticides can be applied at different concentrations, specific times or by using different types (selective chemicals) to control specific insects. Preliminary trials may be needed to find the most effective or selective chemical.

   Advantages: easy to apply and not laborious or time consuming.

   Disadvantages:
   - stimulation of yield (extra nitrogen by killing soil organisms);
   - reduction of yield by phytotoxic effect on the crop;
   - interaction with other pests (resurgence, killing beneficial insects, giving raise to secondary pests);
   - interaction with remaining pest individuals (weakening, aberrant behaviour, etc.);
   - interplot interference:
     . repellency in treated plots: pests are concentrated in untreated plots;
     . sprayed plot acts as a sink: pests in untreated plots decrease;
     . slow acting pesticides may not prevent damage from invading pests.

2. Caging the crop or plants to keep pests out

- Eliminate all pests in the cages with broad working insecticides, or start with a clean crop in the cage;

- (Re)infest cages with different densities of pest (do not forget control).

Disadvantages: the cages may affect the yield as the light intensity is lower and the microclimate different. The mesh size is important.

3. Artificial removal of pests

Pest can be removed by hand, mass trapping by light of pheromones (adults). Attractive crops can be sowed in between the test crop, thus lowering the pest on the test crop.

Disadvantages:
- removing the pest may damage the crop;
- intercropping may change the plant space (which increases or decreases competition) making the results incomparable with other experiments.
- removal will be temporary at best in case of attractive host plant.

4. Artificial infestation

Most often used in cages or within walls. Especially suited for non-flying insects (aphids, caterpillars).

Disadvantages:
- collection or breeding of pest is necessary, which is laborious, expensive and mostly difficult;
- timing of infestation is critical and must be parallel with field situation.

5. Resistant varieties

If susceptible and resistant varieties can be found which have similar yields when not infested, exposure to natural infestations will result in different infestation rates and different yields.

Disadvantages: - often different yield at the same infestation level.

6. Artificial damage

If the amount of damage caused by different degrees of pest attack is known, the effect of this amount of damage can be measured by causing it artificially.

The mechanical effect of insect attack can be simulated at specific places and in different degrees:
- plants can be removed from the crop
- leaves cut
- stems damaged
- roots cut.

Disadvantages:
- it is difficult to translate the results to a relationship of pest damage to infestation level because of the effects of the stage of pest, temperature, duration of attack, etc.;
- the amount of damage depends on the growth stage of the crop attacked, and on where damage is located, above or below the growing point, whether on the flag leaf or not, or whether on roots as well;
- simulation of damage may be difficult, damaging leaves is easy, but damage to growing points and roots is

difficult and uncertain. The degree of damage should be carefully measured.

A study of crop and plant physiology is important as it may elucidate the effect of damage on yield.

8.4 The threshold concept

The concept of the *economic injury level* (EIL) and *thresholds* was developed by entomologists as a reaction to excessive and inappropriate uses of insecticides (Stern et al., 1959). Although this concept has its limitations it is used now by all disciplines in crop protection and crop production. Within IPM thresholds are tools that allow decision making: whether and when to control pests. The strategy of pest management is to tolerate them at sub-economic levels in order to avoid economically non-paying control methods and to minimize environmental contamination and health problems.

The "*Economic Injury Level*" (*damage threshold*) is the pest population density at which the cost of control is equal to the value of the potential damage.

Thresholds are expressed as population densities or infestation levels: They indicate what level of pest or disease infestation is acceptable at a given moment during the development of the crop.

The meaning of the various thresholds has been expressed already earlier (see hand-out "Introduction in Plant Production and Protection. Injury, damage and loss").

8.5 Determination of thresholds

The *damage threshold* is the pest population density which would cause a loss equivalent to the costs of control. The original definition has been modified into "the level of pest attack at which the benefit of control just exceeds its costs" (Mumford and Norton, 1984). It will be clear that the damage threshold is a theoretical concept which is very useful in thinking about the decision making process. The farmer cannot do very much with the damage threshold because so many variables are determining its numerical value:

* the relation between pest population density and the expected damage,
* the expected yield level,
* the future price of the product,
* the costs of control, and
* the efficiency of the control method.

From the definition of the damage threshold it is clear that a control method applied at that moment is too late to prevent any damage. Therefore, another threshold is necessary to trigger action in time to prevent future damage.

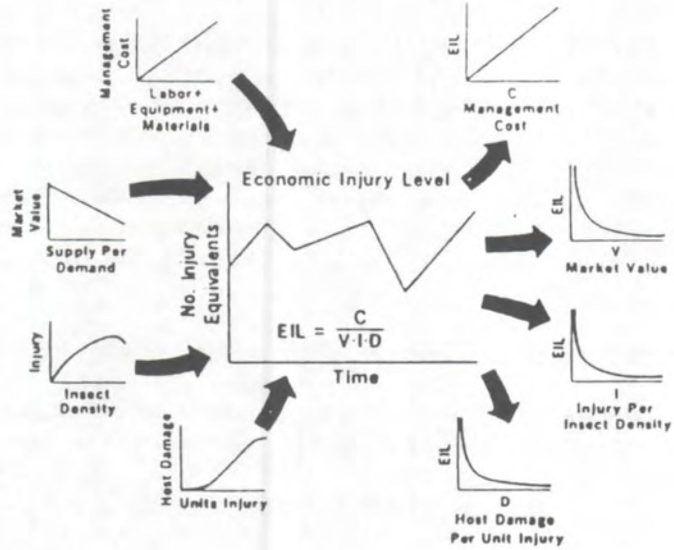

Fig. 8.1: Relationship of economic injury level components and their variables (Pedigo et al., 1986).

The *control threshold* is the pest population density which must be controlled to prevent the increasing pest population from reaching the damage threshold. Compared with the damage threshold, this control threshold is reached at lower pest levels.
The control threshold is determined by the rate of population increase; however, a good deal of speculation on future population development is often added.

The control threshold is a theoretical value and equally not very useful to farmers, because most if not all variables are not known to the farmer or grower at the moment when he or she has to take a crucial decision about the economical feasibility of applying a control treatment or not. Therefore, practical approximations like the "*tolerance level*" or "*action threshold*" are used by farmers and extensionists in combination with monitoring and sampling for supervised control.

Since the relation between the pest population density and the expected damage depends, among others, on the growth stage of the crop, a control threshold is valid for specific growth stages only. Here, by the development of "sliding, fluctuating or *dynamic*" thresholds depending on the development stage of the crop one tries to reduce the problems of over- or underestimations of damage.

8.6 Threshold calculation

Following Mumford and Norton (1984), the break-even point of the economic threshold lies where:

$$\underset{\text{(benefit of control)}}{PDKL} = \underset{\text{(cost of control)}}{C},$$

or:

$$L = \frac{C}{P * D * K}$$

where :

- P = price of product (e.g. monetary units/ton)
- D = the damage (or loss in yield) (e.g. ton/each added unit of infestation)
- K = the killing efficiency of the control method (% or fraction)
- L = the level of pest attack (e.g. number of pests/sampling unit)
- C = the costs of control (mon. units/ha).

Pedigo et al. (1986) suggest slight modifications in the Norton model for use in practical insect pest management:

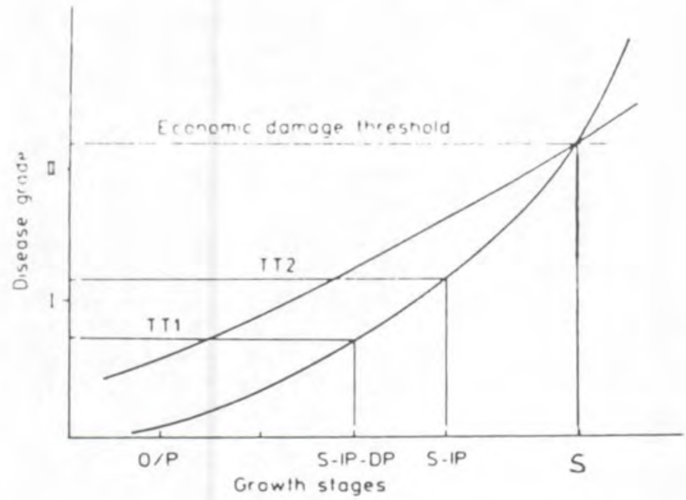

Fig. 8.2: Determination of treatment threshold according to grade of disease and stage of growth. **S** growth stage; **IP** incubation period; **DP** decision period, i.e. period elapsing between the time the decision to treat is taken and the actual application; **TT1** treatment threshold at growth stage **S**, minus incubation period **IP** and decision period **DP**; **TT2** treatment threshold at growth stage **S**, minus incubation period **IP** (Kranz and Hau, 1981).

$$EIL = C/VID$$

where:

EIL = number of injury equivalents per production unit (e.g. insects/ha), all of which live to attain their full injury potential),
C = costs of the management activity per unit of production (e.g. $/ha),
V = market value (utility) per unit of the produce ($/kg),
I = injury units per insect per production unit [e.g. proportion defoliated/(insect/ha)], and
D = damage per unit injury [e.g. (kg reduction/ha)/ proportion defoliated].

As shown in this basic model there are 4 primary components affecting EIL: (a) market value, (b) management costs, (c) injury per insect density, and (d) host damage per unit of injury. Although the mathematical relationship of these components is quite simple, complexity arises when the variables that comprise the components are also taken into account (Fig. 8.1).
The killing efficiency of the control method is obviously included in the costs of management.

When any of the variables or parameters in the equation change, such as the price of the product or the costs or efficacy of the control, then the threshold will also change. The required information, for instance, on the damage function, the effectiveness of control, crop price etc., is for some pests not easy to obtain. For instance, to estimate the benefit of treatment at a particular pest population level, the efficacy of the treatment and changes in the untreated population need to be assessed. Where natural enemy activity is important, this requires a more complex form of economic threshold determination (Stern, 1973).
Another complication arises when more than one treatment may be applied during the crop season. Although the number and timing of these treatments will be determined by the control threshold, the question remains whether thresholds are the best tools for decision making in crop protection.

8.7 Determination of thresholds in the case of plant diseases

As the concept of the EIL was originally developed for insect pests, problems can arise when the EIL concept is used for pathogens, because the control methods for most of the pathogens are, up to now, still **preventive** and not curative. Therefore, determining whether or not a pathogen population is at the EIL after infection may not be of significance, if the only control options available are methods that have to be applied **before** infection.

Thus, in the case of fungal diseases, the incubation period (the time from infection of the host plant until the manifestation of symptoms) has to be taken into account when determining control or treatment thresholds. Kranz and Hau (1981) describe procedures for this purpose (Fig. 8.2): The damage threshold at *growth stage* S is assumed to lie above grade II of disease incidence. The growers' aim is to prevent disease from reaching or exceeding this grade. The time at which he then has to initiate control operations depends on the disease's *incubation period* (IP) and the time span he needs to translate his decision to act into actual application, *decision period* (DP). If this span is likely to be long, the decision to spray or otherwise control the disease must be taken at a correspondingly lower grade of disease (TT 1) than when treatments can be applied promptly (TT 2).

8.8 Control thresholds for peasant farmers

Increasing attention has recently been paid to the development of control thresholds for peasant farmers by techniques that take into account limitations in literacy, counting and calculation.

The dominant consideration, where peasant farmers have to decide whether to control pests/diseases or not, is often not the potential loss in revenue, but the extent to which the yield obtained will feed his family until the next crop ripens. Not maximizing the profit is the goal of many farmers, but minimizing the risks.

Where crops are grown in polyculture or mixed cropping systems, it is unlikely that valid treatment thresholds can be determined. Mixed cropping systems tend to limit damage by most pests and diseases on the crops and pesticide treatments beneficial to one crop may have direct or indirect adverse effects on other crops present, e.g. by reducing their fauna of natural enemies.

On crops grown in more or less pure stands, thresholds can be established more readily, but only if considerations peculiar to farmers' thinking are taken into account. An instructive example is that of cotton pest control in Malawi (Farrington, 1977), where treatment thresholds based on field experiments were suggested to the farmers. However, farmers eventually adopted thresholds at considerably *higher* levels because (a) the suggested thresholds involved extra labour for spraying, harvesting and grading the increased yield; (b) the yield potential, and therefore the amount of preventable damage, was lower than assumed, due to inferior management on most farms; and (c) the risk of poor harvests (which would not repay the cost of treatment) in years of low rainfall, was an important consideration.

8.9 Limitations of the threshold concept

The limitations in the use of thresholds relate to the types of pests or injury that can be addressed, the control tactics used, the research requirements or the use of multiple criteria (e.g. many pest species and variable environments).
Many vectors and pathogens do not show a quantitative relationship between damage and injury and are therefore not amenable to calculation of EILs.

Numerous factors slow the progress in the use of economic thresholds, according to Bottrell (1979) the following are most important:

* Lack of knowledge of the population dynamics of the pest species, viz. interactions, reactions and co-actions of the pests with the host plants, natural enemies and other environmental factors.

* Inadequate information on the host plants' endurance to loss of vegetative parts at various stages of growth.

* Lack of information about the additive, synergistic and antagonistic effects of infestations of complexes of pest species that attack the crop simultaneously.

* Lack of experimental procedures to accurately assign values to yield losses attributed to pests, weather and other factors.

* Inadequate pest sampling and monitoring techniques and crop loss assessment methods.

* Lack of reliable information on crop production and market economics and the real costs of pest control (economic, sociological and environmental).

Another problem with thresholds is their relative unsuitability for multiple pests. To make appropriate management decisions with many pests or a pest complex is one important goal of integrated pest management. If injuries from different pests produce the same host response and all injuries can be placed on a common basis, or if effects of different injuries are additive and not interactive, then only one threshold level might be applicable. In other cases *multiple thresholds* are necessary. However, examples of the latter are scarce.

The control thresholds must be constantly revised to account for changes in crop growth, crop varieties, natural enemy populations, management practices, marketing standards, and commodity prices, for example. Thus, establishing and using control thresholds involve first of all, much research work, work in the field and often considerable expenses (Glass, 1975).

However, even crude thresholds are better than none, especially for sporadic pests and those to which the host plants have a reasonably high tolerance, to avoid unnecessary pre-emptive control treatments. Learning the characteristics of plant growth and crop development and making regular observations of the pests for several generations are important first steps. Initially, IPM programmes can be based on approximations of control thresholds. Most threshold values used are based on empirical information and experience. But all thresholds should be constantly examined and refined as additional information and experience become available.

9. DATA ACQUISITION AND DATABASES FOR IPM

9.1 Introduction

We know by now that an essential part of IPM is the proper recording and monitoring of the constraints and factors which affect the growth and productivity of a crop. When planning field trials attention should be given to adequate data acquisition. This applies to surveillance work also:

1. First define your purpose and problem before collecting field data, because both determine their nature and extent.

2. If your purpose is to identify a possible pest or disease, see to it that the material you take out of the field is properly conserved (see other parts of this course).

3. If your purpose is to carry out field trials be sure that the results, whatever they may be, can be analyzed statistically, e.g. work with replicates and a proper experimental lay-out of the trial.

4. For all field data it is necessary to record the following items:
   - short phrased purpose of data collection,
   - the date,
   - the exact location of the field,
   - in some cases to identify plants: number of the row, number of the plant in the row,
   - the name of the person taking the data,
   - the crop and variety, the growth stage of the crop,
   - the season, e.g. wet season,
   - short and clear explanation of the nature of the data (e.g. caterpillars, infested plants or pupae/...g of soil).

5. Consult textbooks or statistician if problems arise with the statistical analysis of the data. Do not assume data to be independent but find out first.

6. If you want to find out what is the main cause of crop losses or what are the major agents inflicting damage in a crop, work out a crop loss profile (=life table) for the individual plants in the field.

In general, it is essential to record regular quantitative estimates of the occurrence and abundance (incidence) of noxious organism in space (field, district, region) and time (week, month, season, years). These informations are necessary to predict future pest and crop events.

Without some systematic form of information gathering, storing and retrieval (posterior use) of the data, the role of the factors which affect the dynamics of pests in agricultural systems will not be clearly understood. Besides, if we record the actions taken and document the subsequent results, then we will know whether the strategy/tactics we applied had been positive or negative.

In many cases the lack of complete quantitative data on biological events (disease/pest progress) has been a major obstacle for developing good

reliable forecasting methods and crop loss assessments. Sporadic observations, in this case, are not enough.
A crop surveillance system which means regular data acquisition, can provide such information. The information gained may be very valuable for

* the agricultural extensionist who has to solve immediate problems,
* the researcher, because a lot of information is provided for interpretation/ analysis of situations,
* government agencies concerned with future planning and strategies.

9.2 **Acquisition of actual field data**

The method of data acquisition is an important item when planning field experiments. It is largely determined by the objective of the experiment, the most appropriate way of data evaluation and the number and nature of variables deemed essential for satisfactory answers from the results. Certain variables can only be worked out on the basis of some pre-emptive knowledge or pilot studies, the latter are sometimes needed to ascertain the relevance of variables.

Automatic and regular collection of data:
Until now only meteorological data can be recorded automatically. All the other variables of the pest tetrahedron have to be collected by means of the eyes and hands of research workers or specially trained people like scouts. This is also true for the visual evaluation of insect and spore traps, as somebody in the laboratory has either to evaluate slides from spore traps or insect catches. Although the trapping is automatically, there are not yet means to read them automatically.

For the disease and insect pest observations standard field recording forms should be specially designed for each type of observation or experiment. The advantage lies in the fact that with the standardization of the information obtained the completeness is assured, and it remains the people in the field what they have to look for.
Sometimes more than one field recording form is needed, for instance in the case where certain observations or measurements are made at different time intervals, or additional descriptions of observations at different locations are needed.

Field recording sheets should be properly filed in the office according to some system which facilitates future evaluation, that means with information on:

* purpose of experiment or survey,
* dates,
* origin of data set (farmers' name and address),
* keys used for data collection,
* description of experimental lay-out or sampling plan.

Other additional valuable information may also be entered in the recording sheet if it can be coded (identifiable through an assigned number), namely information like field number, variety, crop husbandry practices, preceding crops, region, other diseases or insect pests or mineral deficiency observed, etc.

Other information like missing data, other irregular damages, obvious differences in plant growth etc., which cannot be coded and notified in a recording sheet, should be recorded in separate file.

9.3 Data processing and reduction

Automatic data processing starts by definition with the simplest types of record-keeping and handling of information. Basically, that means nothing else than filing the information gained under a certain system according to precise rules of procedure: Sorting, classifying, tabulating, calculating and summarizing items of information is a convenience for all further methods of analysis. The second step is generally termed data description and reduction. In this step only basic statistical methods are involved, if any at all.

Sorting and tabulating of data are closely connected processes. The presentation of sorted data in tables makes them more concise and self-explanatory; a first interpretation is possible, depending only on the logical arrangements of items.In the process of analysis, data must be classified into useful and logical categories. Generally there are four important bases of classification of statistical data: qualitative, quantitative, chronological and geographical. These classifications already imply the subsequent methods of data analysis. The quantitative data are put into classes and thus form frequency distributions. The chronological arrangement of data, for example, may lead to the analysis of time series. With geographical distributions, which are treated in most cases as a form of distinct classification, populations of different localities are made comparable.

A method equivalent to the presentation of reference tables is the graphic presentation of original data (so-called scatter diagrams or scatter plots), which is effective for a limited amount of information.

A summary table is invariably the result of comprising the information contained in one or more reference tables. Here, one of the most frequently used methods of data reduction is employed: One method of summarizing statistical data consists in the formation of a frequency distribution and the calculation of its parameters. In this device the various items of a series of measurements are classified into groups and the number of items falling into each group is stated. The computer printer can provide a graphical output of the results in form of a histogram or a curve diagram of frequencies.

With the kind of raw data that we normally obtain from field observations a considerable amount of editing and screening of the basic information is required before the more elaborate analysis can be carried out. Most of the generally applicable, but more complicated statistical programmes, require further prerequisites: Some programmes can only be applied on condition that no observations are missing. This is rarely the case with biological data. Various assumptions are made also about the data in the statistical models associated with these analyses.

9.4 Use of historical data

Historical data are data in records or files often obtained for another purpose. These records may come from either survey and surveillance activities, from weather records, experimental data from national yield or variety trials (or similar), or specific crop protection trials, whether already evaluated for a different objective, or not.

The question is here how can such data be used for the development of forecasting methods. Though specifically designed experiments would be recommendable (like growth chamber experiments, CLA-experiments), such information, if available, can nevertheless be useful: Historical data can be used for testing models (growth models, forecasting rules), thus probing a certain hypothesis.

Example: A surveillance system in Canada recorded 32 years long grasshopper populations as well as data on weather and crop production. From this information forecasts on infestation probabilities and economic impact of grasshoppers were developed.

That shows that without regular and consistent (not changing) field observations and standard observation methods comparisons and analyses of historical data (but also actual data) are not possible.

Data from files can be utilized as long as they fulfil, besides the statistical requirements, also other prerequisites for the method of evaluation, like:

- they must be reliable (not biased),
- they must be consistent and complete: the same methodology used, field keys, varieties, crop husbandry; changes in staff who did the estimations, should be notified,
- they must be quantitative, not descriptive,
- pest assessment should be uniform and comparable throughout the records,
- all criteria should have been measured more than once per season,
- they should be comprehensive: several years of recording, possibly at various sites,
- information on critical growth stages of the host plant must be available, especially for crop loss assessment models, also
- information on yields from the same plots where the disease/insect pest-recordings originate from.

9.5 Databases and computers

Database facilitate decision-making:

The decision-making for IPM is based on both surveillance (monitoring in the field) and a high input of advice and information. If the data are collected regularly and over a longer period, they signify valuable databases. In this respect, the follow-up of trends in pest development by means of a computerized database is very useful in IPM.

Databases mean the complete collection of all relevant data of pest development over a longer period, at least several years. From the previous years it may be known what effects on yields etc. can be expected from a particular state of a given disease or pest progress.

Regional or national supervisors of surveillance activities can thus compare a given pest situation with the consequences observed in similar

situations before and may give a warning. Or they check for apparent irregularities, etc.
Databases are also very useful for forecasting, especially when the reliability of a forecast can be improved by the information accumulated in the database.

Database for research and training:

Databases can provide excellent material for research on crop loss relationships, thresholds, forecasts, pest dynamics, pest/host interaction, efficiency of control measures etc.
But they also can be used to check the utility of models, their validity and their scope for generalization.

Training has a high priority within IPM. Databases provide the stored experience on interactions of plant growth, weather, pest development, effect of chemical treatment or cultural practices etc. These may even be useful case studies for training programmes. Pest management games simulate pest development and control decisions in relation to costs and returns, and economic objectives. A number of computer programmes are available now to train disease assessment (for instance DISTRAIN) or to assist in the determination of appropriate sampling methods.

Computer usage in crop protection advisory is almost indispensable. The individual advice is already widely practised in some countries by means of personal computer (PC). Weather and, if available, other information too can be inquired by means of a terminal or a PC. Only computers permit the handling and use of interlocking forecasting and information systems. The extension officer, consultant or farmer will have to interpret it in relation to a pest situation, state of plant growth and pest treatment and decide for each field whether to treat or not. The Dutch EPIPRE does this in a special organized form with a computer in the center. Essentially, participating farmers are trained to do the monitoring and communication through the computer. The latter, in turn, prints advises and requirements from the information stored for each participating field. The decision, whether to treat or not when being advised to do so, rests however with the farmer.

10. SET-UP OF IPM SYSTEMS

10.1 Synthesis of an IPM system

As we recall, integrated pest management was defined by Smith & Reynolds (1966) as "a pest population management system that utilises all suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury". That means that control measures are only taken above the economic injury level or damage threshold.

Integrated pest management deals on the farmers' side with the determination of the right moment of control and the selection of suitable control methods out of a variety of possibilities; on the extensionists' and researchers' side it has to do with the study of specific problems (e.g. pest behaviour, epidemics, crop losses, etc.) and the formulation of advice/recommendations. Advice must be based on facts, e.g. knowledge of the actual and real situation in the field(s) where a control measure is being considered.

In the previous chapters we got acquainted with the systematics of obtaining relevant information from the field and thus the tools necessary to reach the decision making level in IPM (see also IPM-toolbox scheme, fig. 1.1):

1. What is ailing the crop and how to quantify it (pest assessment),
2. how much damage/loss does it cause (crop loss assessment, thresholds),
3. how to obtain reliable information on the pest situation (sampling),
4. how to measure influences coming from outside the crop/pest system (monitoring the environment),
5. how to appraise development and progress of the pest (epidemiology and population dynamics),
6. how to assess the influence of the crop on pest development (evaluation of host plant populations),
7. how to use the knowledge on the actual pest situation for decision making (forecasting), and
8. how to progress and interpret the recorded field observations (data analysis).

The whole fact finding process, from the start of the identification of a constraint to the moment when a control decision has to be taken, is considered a surveillance system and as such embedded in an integrated pest management system.

When planning and implementing IPM programmes we have to consider (a) the objective (or objectives) of the IPM programme which has to be set up and (b) the target group for which the IPM system is meant for and its local requirements.
The final target groups of an IPM programme are, of course, the farmers or users of the IPM programme; the final objective is the management of a given crop/pest-system which has its own developmental dynamics, depending on a variety of factors (environmental, economic, social, etc.). This implies, that, although a basic IPM technology exists, it has to be adapted to local or regional situations according to the local crop/pest conditions and dynamics. This means also that some pre-studies have to be conducted for which the objectives and target group may lay on a different level

(for instance, the objective can be crop loss assessment instead of decision making; the target group may be the researchers instead of the farmers).
As we have seen, the development, adaptation and implementation of IPM technology requires an interdisciplinary approach (this in difference to simple chemical control). Furthermore, a close cooperation between research scientists, farmers and extension workers is necessary for the development and adaptation of IPM programmes to local or regional conditions. In addition to matching farmers' requirements, IPM programmes will have to be modified to meet local circumstances such as climate, marketing strategies for the crop, grower organizations, social conditions, politics, etc.

Regarding the scope of IPM surveillance systems, much depends on the national circumstances, e.g. geography, size of the country, etc. However, as local factors determine to a high degree the pest/crop relation, regional programmes or programmes covering a smaller geographic area will be more effective. Decisions may be taken also in a national centre to enhance internal coordination and technical planning, but always based on data which are regionally collected and assessed. An internal coordination should be maintained regarding:
- the various tools and methods in the decision making process,
- the scientific feedback and evaluation of these methods,
- specialized research,
- the technical and logistic support,
- budgeting the activities of extension services,
- the planning of long term goals and means.

10.2 Organization and implementation

As we know by now there is no world wide recognized blue print or recipe for an IPM system; however, a number of guidelines may have applicability for the organization and implementation of IPM systems on national and regional level (Table 10.1).

10.2.1 Planning phase

As a first step we have to collect all information on the crop/pest system for which we want to elaborate an IPM programme:
1. Analysis of the situation: fact finding in farmer's field; involved in this activity: extensionists, researchers(?), plant protection service.
2. Additionally, we need to collect all existing information on:
   - population density and the resulting damage (crop loss assessment, economic thresholds),
   - population dynamics and epidemiology: How much is known already about the pest and its behaviour, which facts determine the multiplication, dispersion and appearance of pests? How can we measure that?
   - The geographic magnitude of the phytosanitary problem under consideration: Is it local, regional, national?
3. Planning of monitoring activities:
   a) what will be the objective of the monitoring or study:
      - incidence of a pest,
      - crop loss assessment (since forecasting and decision making in IPM is not possible without economic injury levels or damage thresh-olds, one also needs reliable data on thresholds. This in term might involve proper pest assessment trials to determine the right methodology of pest evaluation for crop loss appraisal),

- population dynamics (e.g. in case one wants to start monitoring a certain pest of which the behaviour and life cycle is not very much known yet, one has to do some studies first on the biology and population dynamics of the pest in question.

If there is only few information available on these items, then a more detailed study or surveillance has to be planned, and then consequently, the methodology for monitoring may require a higher accuracy.

b) **Who will be the immediate target group** which will be using the surveillance plan? Farmers, extensionists, researchers?
   If the objective of a surveillance plan is more research oriented, than the target group will be the researchers or extensionists.

c) **Surveillance plan**: The actual monitoring has to be described in detail in a plan:
   - what criteria have to be assessed: host plant, pest, environment, all three?
   - sampling plan, containing sample size, unit, method, etc.
   - procedure (who is going to do this), technical support, logistics, financiation,
   - feedback to researchers, other disciplines (statistician, computer specialist, etc.)

10.2.2 Implementation phase

How the implementation of a surveillance system might be organized is illustrated in fig. 10.1, in which the various steps and institutions involved are indicated.

There are 7 phases which can be distinguished:
1. identification;
2. monitoring, data collection (these can be collected by the farmer himself, the extensionist or the researcher);
3. transmission of field data to regional or national centers (by computer terminal, telephone, mail);
4. evaluation of field data in regional or national centers, data interpretation (followed by forecasting);
5. re-transmission of results, followed by immediate recommendation, advice;
6. decision (taken regionally, nationally, or individually by every farmer himself. (A decision can be to take some action or to do nothing).
7. Adequate feedback to : farmer, extensionist, researcher,
   about: * the decision which has been taken,
   * the underlying reasons,
   * possible rejection of the data,
   * request for correction of the data

The implementation of an IPM surveillance system not only requires knowledge but also technical and logistical support, for instance:
- simple meteorological stations in the various regions,
- maintenance of all technical and scientific equipment,
- means of transport (vehicles, telephone or radio connections, computer terminals),
- providing of necessary technical aids (planning board, calculators, handbooks, insect traps, etc.),

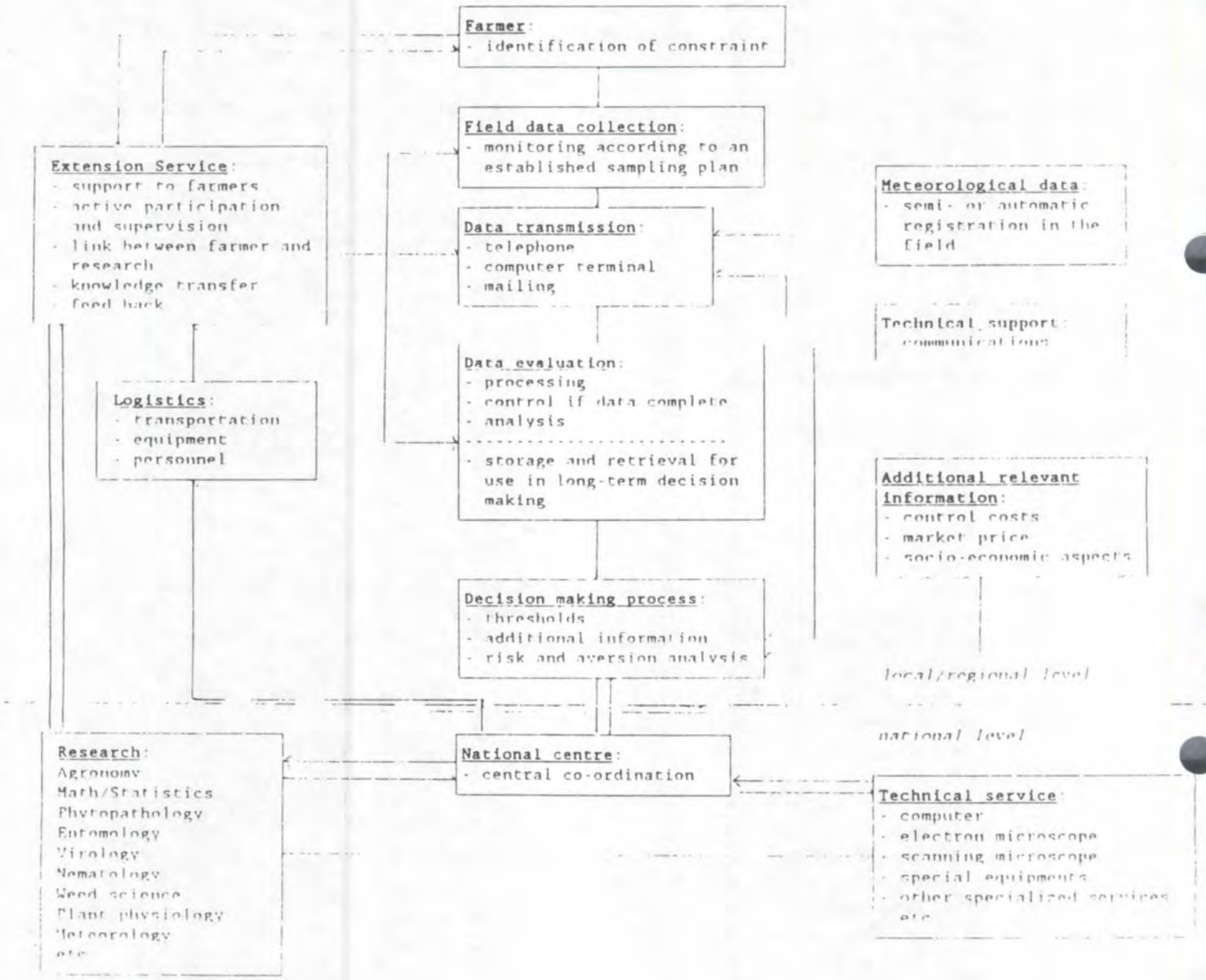

Fig. 10.1: Organization scheme of a surveillance system.
(Monitoring System + Information Network + Data transmission)

- increasing the technical abilities of the personnel.

One thing must be clear: proper implementation of an IPM system requires accompanying research and extension personnel, computer terminals and, last but not least, farmers who are willing to co-operate.

Table 10.1 Guidelines for the organization and implementation of a surveillance system

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1. Specification of the objective (or objectives) the surveillance is meant for.
2. Definition of the target group which will use the surveillance plan.
3. Information on the socio-economic situation of the target group and their possible limitations.
4. Set-up of a sampling plan.
5. Description of the monitoring techniques and equipment necessary.
6. Description of the procedure of monitoring.
7. Description of the organization of the monitoring activities on district, regional or national level.
8. Definition of the action threshold.
9. If forecasting is possible and included, description of the predictors.
10. Description of the possible control measures.
11. Information on financial requirements, necessary resources, etc.
12. Information on the training necessity for the personnel which will execute the monitoring.
13. Information on the necessary scientific backstopping and cooperation with other institutions.

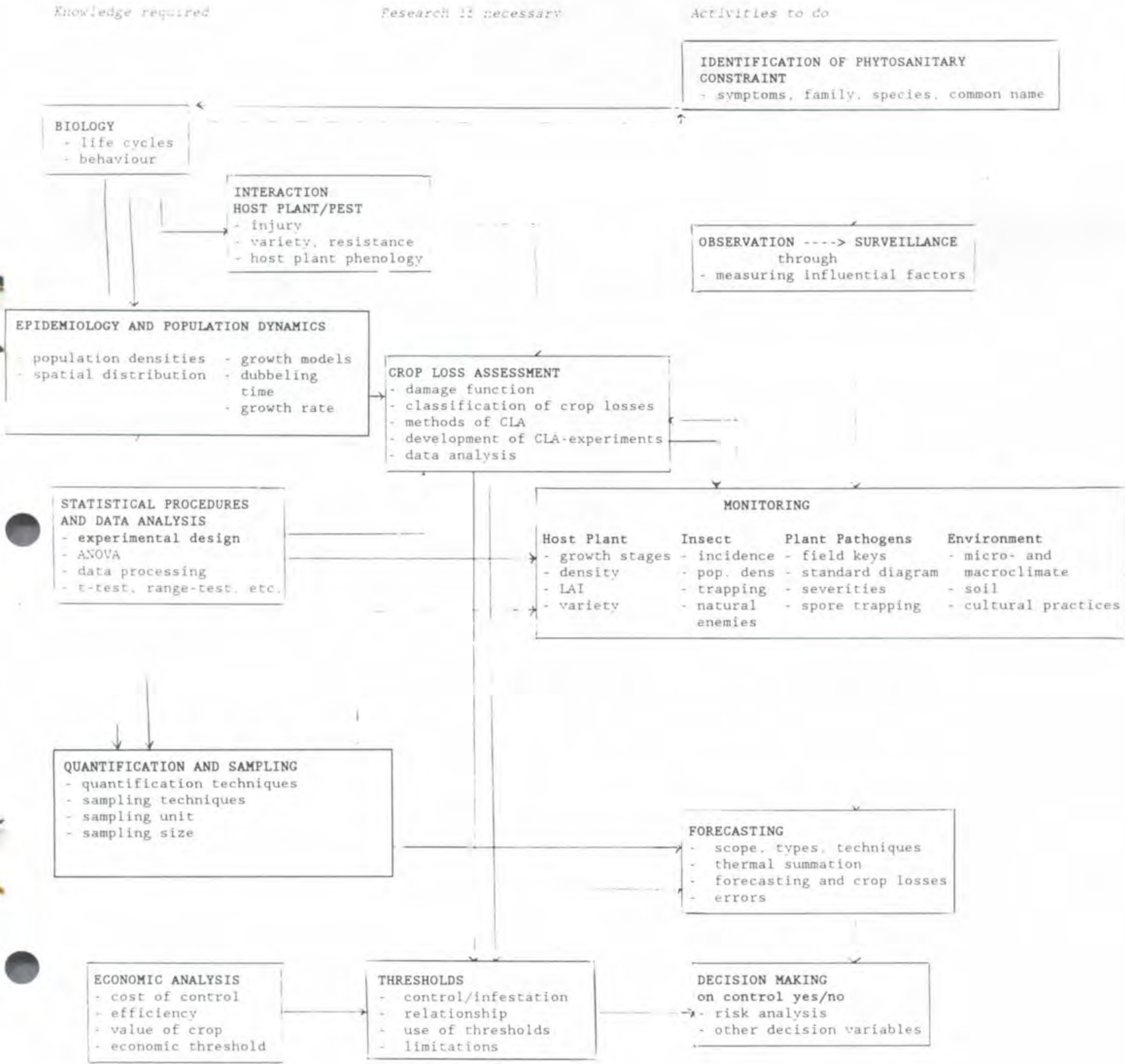

Figure 1.1 IPM-SCHEME (with the most important keywords)
(tools and steps necessary to reach the decision making level)

ipmtoolboxscheme

TABLE A 1—(*Continued*)

	50–54	55–59	60–64	65–69	70–74	75–79	80–84	85–89	90–94	95–99
00	59391	58030	52098	82718	87024	82848	04190	96574	90464	29065
01	99567	76364	77204	04615	27062	96621	43918	01896	83991	51141
02	10363	97518	51400	25670	98342	61891	27101	37855	06235	33316
03	86859	19558	64432	16706	99612	59798	32803	67708	15297	28612
04	11258	24591	36863	55368	31721	94335	34936	02566	80972	08188
05	95068	88628	35911	14530	33020	80428	39936	31855	34334	64865
06	54463	47237	73800	91017	36239	71824	83671	39892	60518	37092
07	16874	62677	57412	13215	31389	62233	80827	73917	82802	84420
08	92494	63157	76593	91316	03505	72389	96363	52887	01087	66091
09	15669	56689	35682	40844	53256	81872	35213	09840	34471	74441
10	99116	75486	84989	23476	52967	67104	39495	39100	17217	74073
11	15696	10703	65178	90637	63110	17622	53988	71087	84148	11670
12	97720	15369	51269	69620	03388	13699	33423	67453	43269	56720
13	11666	13841	71681	98000	35979	39719	81899	07449	47985	46967
14	71628	73130	78783	75691	41632	09847	61547	18707	85489	69944
15	40501	51089	99943	91843	41995	88931	73631	69361	05375	15417
16	22518	55576	98215	82068	10798	86211	36584	67466	69373	40054
17	75112	30485	62173	02132	14878	92879	22281	16783	86352	00077
18	80327	02671	98191	84342	90813	49268	95441	15496	20168	09271
19	60251	45548	02146	05597	48228	81366	34598	72856	66762	17002
20	57430	82270	10421	00540	43648	75888	66049	21511	47676	33444
21	73528	39559	34434	88596	54086	71693	43132	14414	79949	85193
22	25991	65959	70769	64721	86413	33475	42740	06175	82758	66248
23	78388	16638	09134	59980	63806	48472	39318	35434	24057	74739
24	12477	09965	96657	57994	59439	76330	24596	77515	09577	91871
25	83266	32883	42451	15579	38155	29793	40914	65990	16255	17777
26	76970	80876	10237	39515	79152	74798	39357	09054	73579	92359
27	37074	65198	44785	68624	98336	84481	97610	78735	46703	98265
28	83712	06514	30101	78295	54656	85417	43189	60048	72781	72606
29	20287	56862	69727	94443	64936	08366	27227	05158	50326	59566
30	74261	32592	86538	27041	65172	85532	07571	80609	39285	65340
31	64081	49863	08478	96001	18888	14810	70545	89755	59064	07210
32	05617	75818	47750	67814	29575	10526	66192	44464	27058	40467
33	26793	74951	95466	74307	13330	42664	85515	20632	05497	33625
34	65988	72850	48737	54719	52056	01596	03845	35067	03134	70322
35	27366	42271	44300	73399	21105	03280	73457	43093	05192	48657
36	56760	10909	98147	34736	33863	95256	12731	66598	50771	83665
37	72880	43338	93643	58904	59543	23943	11231	83268	65938	81581
38	77888	38100	03062	58103	47961	83841	25878	23746	55903	44115
39	28440	07819	21580	51459	47971	29882	13990	29226	23608	15873
40	63525	94441	77033	12147	51054	49955	58312	76923	96071	05813
41	47606	93410	16359	89033	89696	47231	64498	31776	05383	39902
42	52669	45030	96279	14709	52372	87832	02735	50803	72744	88208
43	16738	60159	07425	62369	07515	82721	37875	71153	21315	00132
44	59348	11695	45751	15865	74739	05572	32688	20271	65128	14551
45	12900	71775	29845	60774	94924	21810	38636	33717	67598	82521
46	75086	23537	49939	33595	13484	97588	28617	17979	70749	35234
47	99495	51434	29181	09993	38190	42553	68922	52125	91077	40197
48	26075	31671	45386	36583	93459	48599	52022	41330	60651	91321
49	13636	93596	23377	51133	95126	61496	42474	45141	46660	42338

TABLE A 4

THE DISTRIBUTION OF t* (TWO-TAILED TESTS)

Degrees of Freedom	Probability of a Larger Value, Sign Ignored								
	0.500	0.400	0.200	0.100	0.050	0.025	0.010	0.005	0.001
1	1.000	1.376	3.078	6.314	12.706	25.452	63.657		
2	0.816	1.061	1.886	2.920	4.303	6.205	9.925	14.089	31.598
3	.765	0.978	1.638	2.353	3.182	4.176	5.841	7.453	12.941
4	.741	.941	1.533	2.132	2.776	3.495	4.604	5.598	8.610
5	.727	.920	1.476	2.015	2.571	3.163	4.032	4.773	6.859
6	.718	.906	1.440	1.943	2.447	2.969	3.707	4.317	5.959
7	.711	.896	1.415	1.895	2.365	2.841	3.499	4.029	5.405
8	.706	.889	1.397	1.860	2.306	2.752	3.355	3.832	5.041
9	.703	.883	1.383	1.833	2.262	2.685	3.250	3.690	4.781
10	.700	.879	1.372	1.812	2.228	2.634	3.169	3.581	4.587
11	.697	.876	1.363	1.796	2.201	2.593	3.106	3.497	4.437
12	.695	.873	1.356	1.782	2.179	2.560	3.055	3.428	4.318
13	.694	.870	1.350	1.771	2.160	2.533	3.012	3.372	4.221
14	.692	.868	1.345	1.761	2.145	2.510	2.977	3.326	4.140
15	.691	.866	1.341	1.753	2.131	2.490	2.947	3.286	4.073
16	.690	.865	1.337	1.746	2.120	2.473	2.921	3.252	4.015
17	.689	.863	1.333	1.740	2.110	2.458	2.898	3.222	3.965
18	.688	.862	1.330	1.734	2.101	2.445	2.878	3.197	3.922
19	.688	.861	1.328	1.729	2.093	2.433	2.861	3.174	3.883
20	.687	.860	1.325	1.725	2.086	2.423	2.845	3.153	3.850
21	.686	.859	1.323	1.721	2.080	2.414	2.831	3.135	3.819
22	.686	.858	1.321	1.717	2.074	2.406	2.819	3.119	3.792
23	.685	.858	1.319	1.714	2.069	2.398	2.807	3.104	3.767
24	.685	.857	1.318	1.711	2.064	2.391	2.797	3.090	3.745
25	.684	.856	1.316	1.708	2.060	2.385	2.787	3.078	3.725
26	.684	.856	1.315	1.706	2.056	2.379	2.779	3.067	3.707
27	.684	.855	1.314	1.703	2.052	2.373	2.771	3.056	3.690
28	.683	.855	1.313	1.701	2.048	2.368	2.763	3.047	3.674
29	.683	.854	1.311	1.699	2.045	2.364	2.756	3.038	3.659
30	.683	.854	1.310	1.697	2.042	2.360	2.750	3.030	3.646
35	.682	.852	1.306	1.690	2.030	2.342	2.724	2.996	3.591
40	.681	.851	1.303	1.684	2.021	2.329	2.704	2.971	3.551
45	.680	.850	1.301	1.680	2.014	2.319	2.690	2.952	3.520
50	.680	.849	1.299	1.676	2.008	2.310	2.678	2.937	3.496
55	.679	.849	1.297	1.673	2.004	2.304	2.669	2.925	3.476
60	.679	.848	1.296	1.671	2.000	2.299	2.660	2.915	3.460
70	.678	.847	1.294	1.667	1.994	2.290	2.648	2.899	3.435
80	.678	.847	1.293	1.665	1.989	2.284	2.638	2.887	3.416
90	.678	.846	1.291	1.662	1.986	2.279	2.631	2.878	3.402
100	.677	.846	1.290	1.661	1.982	2.276	2.625	2.871	3.390
120	.677	.845	1.289	1.658	1.980	2.270	2.617	2.860	3.373
∞	.6745	.8416	1.2816	1.6448	1.9600	2.2414	2.5758	2.8070	3.2905

* Parts of this table are reprinted by permission from R. A. Fisher's *Statistical Methods for Research Workers*, published by Oliver and Boyd, Edinburgh (1925–1950); from Maxine Merrington's "Table of Percentage Points of the t-Distribution," Biometrika, 32:300 (1942); and from Bernard Ostle's *Statistics in Research*, Iowa State University Press (1954).

TABLE A 14, Part I

5% (ROMAN TYPE) AND 1% (BOLD FACE TYPE) POINTS FOR THE DISTRIBUTION OF F

f_2	f_1 Degrees of Freedom (for greater mean square)																								f_1
	1	2	3	4	5	6	7	8	9	10	11	12	14	16	20	24	30	40	50	75	100	200	500	∞	
1	161	200	216	225	230	234	237	239	241	242	243	244	245	246	248	249	250	251	252	253	253	254	254	254	1
	4,052	**4,999**	**5,403**	**5,625**	**5,764**	**5,859**	**5,928**	**5,981**	**6,022**	**6,056**	**6,082**	**6,106**	**6,142**	**6,169**	**6,208**	**6,234**	**6,261**	**6,286**	**6,302**	**6,323**	**6,334**	**6,352**	**6,361**	**6,366**	
2	18.51	19.00	19.16	19.25	19.30	19.33	19.36	19.37	19.38	19.39	19.40	19.41	19.42	19.43	19.44	19.45	19.46	19.47	19.47	19.48	19.49	19.49	19.50	19.50	2
	98.49	**99.00**	**99.17**	**99.25**	**99.30**	**99.33**	**99.36**	**99.37**	**99.39**	**99.40**	**99.41**	**99.42**	**99.43**	**99.44**	**99.45**	**99.46**	**99.47**	**99.48**	**99.48**	**99.49**	**99.49**	**99.49**	**99.50**	**99.50**	
3	10.13	9.55	9.28	9.12	9.01	8.94	8.88	8.84	8.81	8.78	8.76	8.74	8.71	8.69	8.66	8.64	8.62	8.60	8.58	8.57	8.56	8.54	8.54	8.53	3
	34.12	**30.82**	**29.46**	**28.71**	**28.24**	**27.91**	**27.67**	**27.49**	**27.34**	**27.23**	**27.13**	**27.05**	**26.92**	**26.83**	**26.69**	**26.60**	**26.50**	**26.41**	**26.35**	**26.27**	**26.23**	**26.18**	**26.14**	**26.12**	
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.93	5.91	5.87	5.84	5.80	5.77	5.74	5.71	5.70	5.68	5.66	5.65	5.64	5.63	4
	21.20	**18.00**	**16.69**	**15.98**	**15.52**	**15.21**	**14.98**	**14.80**	**14.66**	**14.54**	**14.45**	**14.37**	**14.24**	**14.15**	**14.02**	**13.93**	**13.83**	**13.74**	**13.69**	**13.61**	**13.57**	**13.52**	**13.48**	**13.46**	
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.78	4.74	4.70	4.68	4.64	4.60	4.56	4.53	4.50	4.46	4.44	4.42	4.40	4.38	4.37	4.36	5
	16.26	**13.27**	**12.06**	**11.39**	**10.97**	**10.67**	**10.45**	**10.29**	**10.15**	**10.05**	**9.96**	**9.89**	**9.77**	**9.68**	**9.55**	**9.47**	**9.38**	**9.29**	**9.24**	**9.17**	**9.13**	**9.07**	**9.04**	**9.02**	
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.03	4.00	3.96	3.92	3.87	3.84	3.81	3.77	3.75	3.72	3.71	3.69	3.68	3.67	6
	13.74	**10.92**	**9.78**	**9.15**	**8.75**	**8.47**	**8.26**	**8.10**	**7.98**	**7.87**	**7.79**	**7.72**	**7.60**	**7.52**	**7.39**	**7.31**	**7.23**	**7.14**	**7.09**	**7.02**	**6.99**	**6.94**	**6.90**	**6.88**	
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.63	3.60	3.57	3.52	3.49	3.44	3.41	3.38	3.34	3.32	3.29	3.28	3.25	3.24	3.23	7
	12.25	**9.55**	**8.45**	**7.85**	**7.46**	**7.19**	**7.00**	**6.84**	**6.71**	**6.62**	**6.54**	**6.47**	**6.35**	**6.27**	**6.15**	**6.07**	**5.98**	**5.90**	**5.85**	**5.78**	**5.75**	**5.70**	**5.67**	**5.65**	
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.34	3.31	3.28	3.23	3.20	3.15	3.12	3.08	3.05	3.03	3.00	2.98	2.96	2.94	2.93	8
	11.26	**8.65**	**7.59**	**7.01**	**6.63**	**6.37**	**6.19**	**6.03**	**5.91**	**5.82**	**5.74**	**5.67**	**5.56**	**5.48**	**5.36**	**5.28**	**5.20**	**5.11**	**5.06**	**5.00**	**4.96**	**4.91**	**4.88**	**4.86**	
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.13	3.10	3.07	3.02	2.98	2.93	2.90	2.86	2.82	2.80	2.77	2.76	2.73	2.72	2.71	9
	10.56	**8.02**	**6.99**	**6.42**	**6.06**	**5.80**	**5.62**	**5.47**	**5.35**	**5.26**	**5.18**	**5.11**	**5.00**	**4.92**	**4.80**	**4.73**	**4.64**	**4.56**	**4.51**	**4.45**	**4.41**	**4.36**	**4.33**	**4.31**	
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.97	2.94	2.91	2.86	2.82	2.77	2.74	2.70	2.67	2.64	2.61	2.59	2.56	2.55	2.54	10
	10.04	**7.56**	**6.55**	**5.99**	**5.64**	**5.39**	**5.21**	**5.06**	**4.95**	**4.85**	**4.78**	**4.71**	**4.60**	**4.52**	**4.41**	**4.33**	**4.25**	**4.17**	**4.12**	**4.05**	**4.01**	**3.96**	**3.93**	**3.91**	
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.86	2.82	2.79	2.74	2.70	2.65	2.61	2.57	2.53	2.50	2.47	2.45	2.42	2.41	2.40	11
	9.65	**7.20**	**6.22**	**5.67**	**5.32**	**5.07**	**4.88**	**4.74**	**4.63**	**4.54**	**4.46**	**4.40**	**4.29**	**4.21**	**4.10**	**4.02**	**3.94**	**3.86**	**3.80**	**3.74**	**3.70**	**3.66**	**3.62**	**3.60**	
12	4.75	3.88	3.49	3.26	3.11	3.00	2.92	2.85	2.80	2.76	2.72	2.69	2.64	2.60	2.54	2.50	2.46	2.42	2.40	2.36	2.35	2.32	2.31	2.30	12
	9.33	**6.93**	**5.95**	**5.41**	**5.06**	**4.82**	**4.65**	**4.50**	**4.39**	**4.30**	**4.22**	**4.16**	**4.05**	**3.98**	**3.86**	**3.78**	**3.70**	**3.61**	**3.56**	**3.49**	**3.46**	**3.41**	**3.38**	**3.36**	
13	4.67	3.80	3.41	3.18	3.02	2.92	2.84	2.77	2.72	2.67	2.63	2.60	2.55	2.51	2.46	2.42	2.38	2.34	2.32	2.28	2.26	2.24	2.22	2.21	13
	9.07	**6.70**	**5.74**	**5.20**	**4.86**	**4.62**	**4.44**	**4.30**	**4.19**	**4.10**	**4.02**	**3.96**	**3.85**	**3.78**	**3.67**	**3.59**	**3.51**	**3.42**	**3.37**	**3.30**	**3.27**	**3.21**	**3.18**	**3.16**	

TABLE A 14, Part I—(*Continued*)

f_1	f_1 Degrees of Freedom (for greater mean square)																								f_2
	1	2	3	4	5	6	7	8	9	10	11	12	14	16	20	24	30	40	50	75	100	200	500	∞	
14	4.60	3.74	3.34	3.11	2.96	2.85	2.77	2.70	2.65	2.60	2.56	2.53	2.48	2.44	2.39	2.35	2.31	2.27	2.24	2.21	2.19	2.16	2.14	2.13	14
	8.86	**6.51**	**5.56**	**5.03**	**4.69**	**4.46**	**4.28**	**4.14**	**4.03**	**3.94**	**3.86**	**3.80**	**3.70**	**3.62**	**3.51**	**3.43**	**3.34**	**3.26**	**3.21**	**3.14**	**3.11**	**3.06**	**3.02**	**3.00**	
15	4.54	3.68	3.29	3.06	2.90	2.79	2.70	2.64	2.59	2.55	2.51	2.48	2.43	2.39	2.33	2.29	2.25	2.21	2.18	2.15	2.12	2.10	2.08	2.07	15
	8.68	**6.36**	**5.42**	**4.89**	**4.56**	**4.32**	**4.14**	**4.00**	**3.89**	**3.80**	**3.73**	**3.67**	**3.56**	**3.48**	**3.36**	**3.29**	**3.20**	**3.12**	**3.07**	**3.00**	**2.97**	**2.92**	**2.89**	**2.87**	
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.45	2.42	2.37	2.33	2.28	2.24	2.20	2.16	2.13	2.09	2.07	2.04	2.02	2.01	16
	8.53	**6.23**	**5.29**	**4.77**	**4.44**	**4.20**	**4.03**	**3.89**	**3.78**	**3.69**	**3.61**	**3.55**	**3.45**	**3.37**	**3.25**	**3.18**	**3.10**	**3.01**	**2.96**	**2.98**	**2.86**	**2.80**	**2.77**	**2.75**	
17	4.45	3.59	3.20	2.96	2.81	2.70	2.62	2.55	2.50	2.45	2.41	2.38	2.33	2.29	2.23	2.19	2.15	2.11	2.08	2.04	2.02	1.99	1.97	1.96	17
	8.40	**6.11**	**5.18**	**4.67**	**4.34**	**4.10**	**3.93**	**3.79**	**3.68**	**3.59**	**3.52**	**3.45**	**3.35**	**3.27**	**3.16**	**3.08**	**3.00**	**2.92**	**2.86**	**2.79**	**2.76**	**2.70**	**2.67**	**2.65**	
18	4.41	3.55	3.16	2.93	2.77	3.66	2.58	2.51	2.46	2.41	2.37	2.34	2.29	2.25	2.19	2.15	2.11	2.07	2.04	2.00	1.98	1.95	1.93	1.92	18
	8.28	**6.01**	**5.09**	**4.58**	**4.25**	**4.01**	**3.85**	**3.71**	**3.60**	**3.51**	**3.44**	**3.37**	**3.27**	**3.19**	**3.07**	**3.00**	**2.91**	**2.83**	**2.78**	**2.71**	**2.68**	**2.62**	**2.59**	**2.57**	
19	4.38	3.52	3.13	2.90	2.74	2.63	2.55	2.48	2.43	2.38	2.34	2.31	2.26	2.21	2.15	2.11	2.07	2.02	2.00	1.96	1.94	1.91	1.90	1.88	19
	8.18	**5.93**	**5.01**	**4.50**	**4.17**	**3.94**	**3.77**	**3.63**	**3.52**	**3.43**	**3.36**	**3.30**	**3.19**	**3.12**	**3.00**	**2.92**	**2.84**	**2.76**	**2.70**	**2.63**	**2.60**	**2.54**	**2.51**	**2.49**	
20	4.35	3.49	3.10	2.87	2.71	2.60	2.52	2.45	2.40	2.35	2.31	2.28	2.23	2.18	2.12	2.08	2.04	1.99	1.96	1.92	1.90	1.87	1.85	1.84	20
	8.10	**5.85**	**4.94**	**4.43**	**4.10**	**3.87**	**3.71**	**3.56**	**3.45**	**3.37**	**3.30**	**3.23**	**3.13**	**3.05**	**2.94**	**2.86**	**2.77**	**2.69**	**2.63**	**2.56**	**2.53**	**2.47**	**2.44**	**2.42**	
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.28	2.25	2.20	2.15	2.09	2.05	2.00	1.96	1.93	1.89	1.87	1.84	1.82	1.81	21
	8.02	**5.78**	**4.87**	**4.37**	**4.04**	**3.81**	**3.65**	**3.51**	**3.40**	**3.31**	**3.24**	**3.17**	**3.07**	**2.99**	**2.88**	**2.80**	**2.72**	**2.63**	**2.58**	**2.51**	**2.47**	**2.42**	**2.38**	**2.36**	
22	4.30	3.44	3.05	2.82	2.66	2.55	2.47	2.40	2.35	2.30	2.26	2.23	2.18	2.13	2.07	2.03	1.98	1.93	1.91	1.87	1.84	1.81	1.80	1.78	22
	7.94	**5.72**	**4.82**	**4.31**	**3.99**	**3.76**	**3.59**	**3.45**	**3.35**	**3.26**	**3.18**	**3.12**	**3.02**	**2.94**	**2.83**	**2.75**	**2.67**	**2.58**	**2.53**	**2.46**	**2.42**	**2.37**	**2.33**	**2.31**	
23	4.28	3.42	3.03	2.80	2.64	2.53	2.45	2.38	2.32	2.28	2.24	2.20	2.14	2.10	2.04	2.00	1.96	1.91	1.88	1.84	1.82	1.79	1.77	1.76	23
	7.88	**5.66**	**4.76**	**4.26**	**3.94**	**3.71**	**3.54**	**3.41**	**3.30**	**3.21**	**3.14**	**3.07**	**2.97**	**2.89**	**2.78**	**2.70**	**2.62**	**2.53**	**2.48**	**2.41**	**2.37**	**2.32**	**2.28**	**2.26**	
24	4.26	3.40	3.01	2.78	2.62	2.51	2.43	2.36	2.30	2.26	2.22	2.18	2.13	2.09	2.02	1.98	1.94	1.89	1.86	1.82	1.80	1.76	1.74	1.73	24
	7.82	**5.61**	**4.72**	**4.22**	**3.90**	**3.67**	**3.50**	**3.36**	**3.25**	**3.17**	**3.09**	**3.03**	**2.93**	**2.85**	**2.74**	**2.66**	**2.58**	**2.49**	**2.44**	**2.36**	**2.33**	**2.27**	**2.23**	**2.21**	
25	4.24	3.38	2.99	2.76	2.60	2.49	2.41	2.34	2.28	2.24	2.20	2.16	2.11	2.06	2.00	1.96	1.92	1.87	1.64	1.80	1.77	1.74	1.72	1.71	25
	7.77	**5.57**	**4.68**	**4.18**	**3.86**	**3.63**	**3.46**	**3.32**	**3.21**	**3.13**	**3.05**	**2.99**	**2.89**	**2.81**	**2.70**	**2.62**	**2.54**	**2.45**	**2.40**	**2.32**	**2.29**	**2.23**	**2.19**	**2.17**	
26	4.22	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.18	2.15	2.10	2.05	1.99	1.95	1.90	1.85	1.82	1.78	1.76	1.72	1.70	1.69	26
	7.72	**5.53**	**4.64**	**4.14**	**3.82**	**3.59**	**3.42**	**3.29**	**3.17**	**3.09**	**3.02**	**2.96**	**2.86**	**2.77**	**2.66**	**2.58**	**2.50**	**2.41**	**2.36**	**2.28**	**2.25**	**2.19**	**2.15**	**2.13**	

The function, $F = e$ with exponent $2z$, is computed in part from Fisher's table VI (7). Additional entries are by interpolation, mostly graphical.

TABLE A 5
CUMULATIVE DISTRIBUTION OF CHI-SQUARE*

Degrees of Freedom	Probability of a Greater Value												
	0.995	0.990	0.975	0.950	0.900	0.750	0.500	0.250	0.100	0.050	0.025	0.010	0.005
1	....	....	....	....	0.02	0.10	0.45	1.32	2.71	3.84	5.02	6.63	7.88
2	0.01	0.02	0.05	0.10	0.21	0.58	1.39	2.77	4.61	5.99	7.38	9.21	10.60
3	0.07	0.11	0.22	0.35	0.58	1.21	2.37	4.11	6.25	7.81	9.35	11.34	12.84
4	0.21	0.30	0.48	0.71	1.06	1.92	3.36	5.39	7.78	9.49	11.14	13.28	14.86
5	0.41	0.55	0.83	1.15	1.61	2.67	4.35	6.63	9.24	11.07	12.83	15.09	16.75
6	0.68	0.87	1.24	1.64	2.20	3.45	5.35	7.84	10.64	12.59	14.45	16.81	18.55
7	0.99	1.24	1.69	2.17	2.83	4.25	6.35	9.04	12.02	14.07	16.01	18.48	20.28
8	1.34	1.65	2.18	2.73	3.49	5.07	7.34	10.22	13.36	15.51	17.53	20.09	21.96
9	1.73	2.09	2.70	3.33	4.17	5.90	8.34	11.39	14.68	16.92	19.02	21.67	23.59
10	2.16	2.56	3.25	3.94	4.87	6.74	9.34	12.55	15.99	18.31	20.48	23.21	25.19
11	2.60	3.05	3.82	4.57	5.58	7.58	10.34	13.70	17.28	19.68	21.92	24.72	26.76
12	3.07	3.57	4.40	5.23	6.30	8.44	11.34	14.85	18.55	21.03	23.34	26.22	28.30
13	3.57	4.11	5.01	5.89	7.04	9.30	12.34	15.98	19.81	22.36	24.74	27.69	29.82
14	4.07	4.66	5.63	6.57	7.79	10.17	13.34	17.12	21.06	23.68	26.12	29.14	31.32
15	4.60	5.23	6.27	7.26	8.55	11.04	14.34	18.25	22.31	25.00	27.49	30.58	32.80
16	5.14	5.81	6.91	7.96	9.31	11.91	15.34	19.37	23.54	26.30	28.85	32.00	34.27
17	5.70	6.41	7.56	8.67	10.09	12.79	16.34	20.49	24.77	27.59	30.19	33.41	35.72
18	6.26	7.01	8.23	9.39	10.86	13.68	17.34	21.60	25.99	28.87	31.53	34.81	37.16
19	6.84	7.63	8.91	10.12	11.65	14.56	18.34	22.72	27.20	30.14	32.85	36.19	38.58
20	7.43	8.26	9.59	10.85	12.44	15.45	19.34	23.83	28.41	31.41	34.17	37.57	40.00

TABLE A 5—(*Continued*)
CUMULATIVE DISTRIBUTION OF CHI-SQUARE*

Degrees of Freedom	Probability of a Greater Value												
	0.995	0.990	0.975	0.950	0.900	0.750	0.500	0.250	0.100	0.050	0.025	0.010	0.005
21	8.03	8.90	10.28	11.59	13.24	16.34	20.34	24.93	29.62	32.67	35.48	38.93	41.40
22	8.64	9.54	10.98	12.34	14.04	17.24	21.34	26.04	30.81	33.92	36.78	40.29	42.80
23	9.26	10.20	11.69	13.09	14.85	18.14	22.34	27.14	32.01	35.17	38.08	41.64	44.18
24	9.89	10.86	12.40	13.85	15.66	19.04	23.34	28.24	33.20	36.42	39.36	42.98	45.56
25	10.52	11.52	13.12	14.61	16.47	19.94	24.34	29.34	34.38	37.65	40.65	44.31	46.93
26	11.16	12.20	13.84	15.38	17.29	20.84	25.34	30.43	35.56	38.89	41.92	45.64	48.29
27	11.81	12.88	14.57	16.15	18.11	21.75	26.34	31.53	36.74	40.11	43.19	46.96	49.64
28	12.46	13.56	15.31	16.93	18.94	22.66	27.34	32.62	37.92	41.34	44.46	48.28	50.99
29	13.12	14.26	16.05	17.71	19.77	23.57	28.34	33.71	39.09	42.56	45.72	49.59	52.34
30	13.79	14.95	16.79	18.49	20.60	24.48	29.34	34.80	40.26	43.77	46.98	50.89	53.67
40	20.71	22.16	24.43	26.51	29.05	33.66	39.34	45.62	51.80	55.76	59.34	63.69	66.77
50	27.99	29.71	32.36	34.76	37.69	42.94	49.33	56.33	63.17	67.50	71.42	76.15	79.49
60	35.53	37.48	40.48	43.19	46.46	52.29	59.33	66.98	74.40	79.08	83.30	88.38	91.95
70	43.28	45.44	48.76	51.74	55.33	61.70	69.33	77.58	85.53	90.53	95.02	100.42	104.22
80	51.17	53.54	57.15	60.39	64.28	71.14	79.33	88.13	96.58	101.88	106.63	112.33	116.32
90	59.20	61.75	65.65	69.13	73.29	80.62	89.33	98.64	107.56	113.14	118.14	124.12	128.30
100	67.33	70.06	74.22	77.93	82.36	90.13	99.33	109.14	118.50	124.34	129.56	135.81	140.17

* Condensed from table with 6 significant figures by Catherine M. Thompson, by permission of the Editor of *Biometrika*.

TABLE A 7

(i) SIGNIFICANCE LEVELS OF $t_w = (\bar{X} - \mu)/w$ IN NORMAL SAMPLES. TWO-TAILED TEST. DIVIDE P BY 2 FOR A ONE-TAILED TEST*

Size of Sample	Probability P 0.10	0.05	0.02	0.01
2	3.157	6.353	15.910	31.828
3	0.885	1.304	2.111	3.008
4	.529	0.717	1.023	1.316
5	.388	.507	0.685	0.843
6	.312	.399	.523	.628
7	.263	.333	.429	.507
8	.230	.288	.366	.429
9	.205	.255	.322	.374
10	.186	.230	.288	.333
11	.170	.210	.262	.302
12	.158	.194	.241	.277
13	.147	.181	.224	.256
14	.138	.170	.209	.239
15	.131	.160	.197	.224
16	.124	.151	.186	.212
17	.118	.144	.177	.201
18	.113	.137	.168	.191
19	.108	.131	.161	.182
20	.104	.126	.154	.175

* Taken from more extensive tables by permission of E. Lord and the Editor of *Biometrika*.

(*Table A 7 continued overleaf*)