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Zadoks

INTERNATIONAL COURSE ON PLANT PROTECTION

CROP LOSSES

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0. CROP LOSSES - Introduction

The science of crop protection has the task to protect crops from damage, and farmers from economic losses. Unfortunately, little was known about the methods of how to assess damage and loss so accurately, that the information obtained could serve as a solid base for an optimal allocation of the ever scarce research funds.

The UN Food and Agricultural Organization greatly stimulated interest in crop loss assessment by organizing a symposium on this theme in 1967, and by editing subsequently a Crop Loss Assessment Handbook.

For the present purpose, the following terms are proposed:

Injury - Any deviation from the "normal" plant or crop as seen by an observer. Injuring may lead to damage.

Damage - Any decrease in quantity or quality of a product as a result of injury. Damage may lead to loss.

Loss - Any decrease in economic returns of agricultural activities as a result of damage. Losses can occur in the private-economic as well as in the public-economic sector.

1. CROP LOSSES - TYPES OF LOSSES

1.1. INTRODUCTION

A typology of the losses caused by plant diseases has been only rarely attempted. There is no dichotomous key to identify a loss with an element in a rigid taxonomy. In botany, for example, the name of a plant can be found with the help of a flora.

The usual solution of the typological problem is to think up a number of antitheses like: "white" versus "black" or "good" versus "bad". This method has been followed here but, since many of these antitheses have been formulated previously by other writers (CHESTER, 1950; KLEMM, 1940; LECLERG, 1964), a choice has to be made.

1.2. ACTUAL AND POTENTIAL LOSSES

The first antithesis is "actual" versus "potential" loss (KLEMM, 1940). The actual loss consists of some or all of the following elements:

a. loss of quantity and / or quality of produce;
b. extra costs of harvesting and grading;
c. costs of disease control.

These elements lead to:

d. decrease in monetary return of labour and investment;
e. decrease in economic activity of rural population; and
f. increase of prices paid by consumers.

Potential losses are the losses which may occur in the absence of control measures. The importance of potential losses can be evaluated by studying the history of catastrophes caused by plant diseases (CHESTER, 1950; LARGE, 1950; ORDISH, 1952, STEVENS, 1934; VALLEGA & CHIARAPPA, 1964, ZADOKS, 1967).

The discussion of potential losses has to be postponed because some antitheses within the category of actual losses have to be reviewed first.

1.2.1 INCIDENTAL AND REGULAR LOSSES

A second antithesis is "incidental" versus "regular" loss (CHESTER, 1950). Incidental losses occur only once or at irregular intervals. In the latter case, they are due to exceptional weather conditions over a prolonged period favouring the build-up of an epidemic (e.g. the devastating 1932 epidemic of black stem rust, Puccinia graminis, on wheat in Eastern Europe), or to the appearance of new races of the pathogen (e.g. the 1950 epidemic of black stem rust race 15 B on wheat in Northern America).
One-time losses are often due to the introduction of new diseases (e.g. tobacco blue mould, Peronospora tabacina, in Europe and the Mediterranean area).

Regular losses occur each season in more or less equal amounts. In many countries, brown leaf rust of wheat (Puccinia recondita) is the cause of regular losses. Observers may be so much used to regular losses that these are no longer recognized. Nevertheless, the long term average of regular losses may be at least as high as that of the incidental losses.

The economic aspect of regular loss is about the same for annual anr perennial crops (late blight of potatoes caused by Phytophthora infestans and black pod rot of cocoa caused by Phytophthora palmivora): it is a loss of income. With incidental loss, the economic aspect can be different in annual and perennial crops. In annual crops incidental loss causes a temporary loss of income. In perennial crops, where incidental loss often implies the loss of trees (canker disease of cypress caused by Rhynchosphaeria cupressi (Monochaetia unicornis) in East Africa), the econmic aspect is a loss of invested capital (WATTS PADWICK, 1956).

The economy of a farm and of a country is usually adapted to regular losses, whereas it can be thrown off balance by an incidental loss. Heavy incidental loss makes a deep impression on people concerned and often gives the impetus towards a new research effort. The allocation of funds can be biased in favour of resolving problems of incidental loss.

1.2.2 TRANSITIONAL AND STRUCTUAL LOSSES

The third antithesis, "transitional" versus "structural" loss, is related to the one just named. Transitional losses occur when growers change over from one farming system to another. This type of loss is of a temporary nature. Transitional loss will disappear, rapidly or after many years, when a new equilibrium has been established, sometimes at the expense of great research costs.

There are many examples of transitional losses (BARNES, 1964). Introduction of Victoria resistance in commercial oat varieties of the U.S.A. produced severe losses caused by the hitrerto unknown fungus Cochliobolus (Helminthosporium) victoriae (MEEHAN & MURPHY, 1946). Circumstantial evidence suggests that the intensive copper treatments of coffee against coffee rust (Hemileia vastatrix) in East Africa paved the way for the outbreak of coffee berry disease caused by Glomerella cingulata (Colletotrichum coffeanum) (MULDER & HOCKING, i.p.; NUTMAN & ROBERTS, 1966). In the wheat crops of the United States' North West, the hazard of snow mould (mainly Typhula idahoense) was avoided by early sowing, thus increasing the risk of yellow stripe rust (Puccinia striiformis) and mildew (Erisyphe graminis) (BRUEHL, 1966; PURDY, 1967). In Greece, an attempt was made to control the olive fly (Dacus aleae) by water-soluble organophosphorous esters. The insect Lecanium oleae escaped the treatment.

Its honey-dew fed the non-parasitic sooty *Capnodium elaeophilum*, which covered both sides of the olive leaves with a tough black crust thus preventing photosynthesis. The olive trees suffered badly (ZAMBETTAKIS, 1963). In the U.S.A., changes in the practice of weed control using herbicides resulted in increased damping-off of sugarbeet and cotton seedlings, caused by *Rhizoctonia* species (ALTMAN & ROSS, 1967; PINCKARD & STANDIFER, 1966).

In contrast to the foregoing examples, which were examples of "shifting risks", structural losses are unavoidable in a given agricultural situation. An example is the loss of bananas caused by Sigatoka leaf spot (*Mycosphaerella musicola*) in the humid tropics. Whether the loss is acceptable or not is a matter of economics. The loss, though unavoidable, can be decreased by research as was demonstrated by the change-over from Bordeaux mixture to mineral oil as a means of controlling the banana leaf spot disease.

Transitional losses are restricted to annual crops and to the products of perennial crops and, usually, they don't affect production means: the trees. Transitional loss is a loss of income or interest, not of capital.

1.2.3 RECOGNIZED AND HIDDEN LOSSES

The fourth antithesis is one between "recognized" and "hidden" losses (CHESTER, 1950). The term "recognized" needs no elucidation. The hidden loss is the extent to which a "normal" crop falls short of its potential yield. The great problem is how to recognize a hidden loss in the absence of unaffected controls.

Some chemicals used for control of diseases can cause losses by damaging the plants. Under U.S.A. conditions, Bordeaux mixture controls potato late blight effectively and, in addition, it helps to avoid insect attacks. Nevertheless, the damage caused by Bordeaux has been estimated at over ten per cent (HORSFALL & TURNER, 1943). In The Netherlands, dithiocarbamates and organic tin compounds are partially replacing copper treatments for similar reasons.

The hidden losses caused by some viruses are a completely different matter. At one time many potatoes were infected by potato-X virus but the plants did not show symptoms. When the virus was recognized and X-virus free potato clones were selected, the loss caused by the hidden virus was estimated at some ten per cent (CHICK & KLINKOWSKI, 1962). A similar story can be told for the potato-S virus. In both cases, control by clonal selection is effective. Great hidden losses may occur in trees due to unregnized viruses.

1.2.4 BACKWARD AND FORWARD VIEWS ON POTENTIAL LOSSES

The antitheses 2, 3 and 4 named various aspects of actual loss. The counterpart of actual loss is potential loss: the first antithesis. There is a backward and a forward view to potential loss.

The backward view discloses what could have happened without the control measures actually taken. At one time, black-arm or angular leaf spot (Xanthomonas malvacearum)of cotton in Uganda took half of the potential yield. The potential yield was realized after the combined use of the resistant cultivar S 47 and the seed-treatment with Perenox (POTTY, 1953). In Surinam, the interruption of chemical control of banana leaf spot disease, even for a short period, is punished by total loss of the crop. Here, the potential loss is one hunderd per cent. The backward view on potential loss presents the arguments for the persuasion of farmers to use resistant varieties or chemical control and for the defence of expensive and unpopular measures like seed certification or eradication campaigns.

The forward view on potential loss is the consideration of what will happen if a new disease surprises us. These surprises happen time and time again: the grape vine mildew (Uncinula necator) from America brought ruin to European grape vines. The East Asiatic fungus Endothia parasitica annihilated the beautiful American chestnut forests. What will happen when coffee rust crosses the Atlantic to visit South America, or when American leaf disease of coffee caused by Omphalia flavida (Mycena citricolor) goes the other way to Africa?

1.3. DIRECT AND INDIRECT LOSSES

The fifth and last antithesis is one between "direct" and "indirect" losses (KLEMM, 1940). Direct losses are losses of quantity or quality of the product and, in addition, losses of yielding capacity. Indirect losses are actual losses in the economic and social field occuring as a consequence of plant diseases.
Direct losses can be divided into two groups: primary and secondary losses.

1.3.1 PRIMARY LOSSES

The primary losses are pre- or post-harvest losses of plant products due to plant diseases. They occur all along the line from seed storage through germination, growing and harvesting to handling and storage of the harvested product. The sequence ends with transport, wholesale trade, retail trade and, finally, the consumer's kitchen.

Primary losses can be losses in quantity or in quality. Loss of quantity alone is exemplified by loose smut (*Ustilago tritici*)of wheat. Loss of quality without loss of yield occurs in some fruit crops: a mild infection of scab (*Venturia inaequalis*) on apples leads to down-grading and serious loss of income. Usually, loss of quantity and quality go together.

Economically, the primary loss consists of some of the following elements:

a. Reduction of quantity of marketable product per ha
b. Reduction of market value per unit of product
c. Costs of disease control
d. Extra costs of harvesting
e. Extra costs of grading
f. Costs of replanting
g. Loss due to the necessity of growing substitute crops yielding smaller monetary returns than the customary one.

All these elements result in a loss of income or an increase of expenditure at the farm, during storage, shipment and retailing, or in the consumer's kitchen.

1.3.2 SECONDARY LOSSES

Secondary losses are losses to the yielding capacity of future crops. They occur in various forms.

The cumulative effect of soil, seed or tuber-borne diseases in annual crops is well known. The eye-spot disease (*Cercosporella herpotrichoides*) of wheat is soil-borne and its accumulation can be interrupted only by a wide rotation. The seed-borne *Alternaria porri* on leek escapes control without seed treatment. Wide-spread disease due to potato viruses can only be avoided by a rigid programme of clonal selection in seed-potato production.

In perennials, premature defoliation by leaf parasites weakens the trees. Loss of vigour leads to decreased production in later years. Death of the tree may follow, either caused by the parasite itself or by an unrelated cause which selectively affects the weakened tree. This happens after defoliation in apples by the scab fungus (WOOD, 1953), in peaches by the leaf curl fungus (*Taphrina deformans*) and in coffee by rust (*Hemileia vastatrix*) (LARGE, 1950).

From the economic point of view such losses are losses of capital invested in soil, seed or tree, sustained at farm level.

1.3.3 INDIRECT LOSSES

Indirect losses are the economical and social implications of plant diseases beyond their immediate agricultural effects. They occur in various sections of society and they can be classified accordingly.

1.3.3.1 FARMER'S LOSSES

At the farm level, loss of income or capital impoverishes the farmer and, eventually, forces him to give up farming. Such an abandonment can be the indirect effect of plant disease but abandonment as a direct effect is also known, e.g. in banana plantations affected by the Panama disease caused by Fusarium oxysporum f. cubense. Abandonment is always associated with depreciation of land value and great losses of capital invested in buildings, equipment, and know-how.

1.3.3.2 LOSSES TO THE RURAL COMMUNITY

When farmers suffer as a group. the whole economic life of the rural community and of its dependant industries is retarded. Returns on invested capital decrease and unemployment may occur.

In agricultural societies with low purchasing power extreme conditions lead to calamities. Nearly a century ago, coffee rust (Hemileia vastatrix) ruined coffee planters in Ceylon and caused compulsory liquidation of a bank. In the meantime coffee rust has appeared in Brasil. Somewhat earlier, potato late blight cuased the Great Famine in Western Europe and particularly in Ireland, where one million people died and one and a half million emigrated to North America.

Nowadays, coffee berry disease threatens the economy of at least one African country, causing a U.S. $ 10.000.000,- loss to Kenya in the 1965-66 season (DAVIES, 1966). Swollen shoot disease of cacao swallows up many millions of dollars and, moreover, the cutting-out programme has led to serious political repercussions (WATTS PADWICK, 1956)

1.3.3.3 CONSUMER'S LOSSES

Somebody has to pay for the losses and this is, usually, not only the farmer. The consumer also pays his share though he is often not aware of it. The consumer pays part of the losses at farm level, most of the losses incurred during storage, transport, wholesale and retail trade, and all of the kitchen losses. These losses are quite variable, according to commodity and conditions but often exceed ten per cent (MILLER, 1935)

1.3.3.4 EXPORTER'S LOSSES

Some specific losses to the agricultural community and, indirectly, to society as a whole have to be mentioned. The appearance of a new disease may endanger the export trade of a country, because the importing countries refuse to run the risk of infection by importing goods from the infected country.

The Netherlands export seeds, planting materials, and ornamentals. Its export can be endangered by the mere presence of pathogen. Export of bulk products can be endangered when the product is infected by poisonous fungi, as sometimes happens with groundnuts infected by Aspergillus flavus producing aflatoxin.

1.3.3.5 STATE LOSSES

Finally, the state has to pay its share with the help of all tax payers. Subsidies are given to ensure a fair income to the farmer and funds are created to stabilize food prices. Plant protection services, education and research institutes, and advisory services are established and maintained.

A less tangible loss of the pollution of the environment of plants animals, and men by chemicals used in disease control. The danger of fungicides is decidedly smaller than that of insecticides and herbicides. Although proof is lacking, it is usually accepted that fungicide pollution is relatively innocuous. However, too many copper sprays in orchards may reduce the number of earthworms. Little is known about long term effects of pollution of soil, water and air by fungicides on human well-being and wildlife. A socio-economic evaluation of pollution problems seems to be feasible (compare OGDEN, 1966).

1.3.3.6 LOSS EVALUATION: A SUGGESTED APPROACH

There are no standardized terms for all types of indirect losses. Their unlimited variation dictated by crop, parasite, region and historical period makes terminology a difficult affair. Nevertheless, a classification according to the social groups affected seems to be a promising approach when the typology of losses is to be used as a basis for their assessment.

These social groups are operational units of measurable dimension. Information can be obtained from them by the methods of modern sociology and the data thus obtained can be evaluated by appropriate economic techniques. But, having arrived at this point, the knowledge of the plant pathologist is exhausted, and men of other crafts have to take over.

1.4 THE THEORETICAL LOSS

When photosynthesis is the only limiting factor, a crop with a closed canopy can produce over 200 kg. ha^{-1}. day^{-1} of dry matter (DE WIT, 1965). Considering that a closed canopy of an annual crop exists during some months only and that not more than part of the dry matter is stored in marketable produce, the theoretical maximum yield of marketable produce by an annual crop is from 10 to 20 tons of dry matter per ha. Experimental top yields confirm this estimate (BODLAENDER & ALGRA, 1966) obtained nearly 20 tons per ha of potato tuber dry weight.
Actual average yields fall far behind the incidental top yields, being for many countries about 1 ton of dry matter per ha. The gap between theoretical and actual yield is called here the "theoretical" loss.

Among the causes of the theoretical loss are lack of water, fertilizer, suitable cultivars, and agricultural knowledge. The importance of knowledge and its extension is demonstrated by GRILICHES, (1964), who computed the return of marginal investment in agricultural knowledge and its extension at one thousand per cent.

The contribution of plant diseases to the theoretical loss cannot be estimated at present. But one point is certain: the more man asks from the production capacity of his crops, the greater the losses from plant diseases can be, unless there is a continuous and ever increasing effort to keep plant diseases down. In the past we have been moderately successful since procentual losses steadily decreased (BARNES, 1964). In the future we may be even more successful if we help each other by an intensified exchange of materials, results and views, all over the world.

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Table 1.1

CLASSIFICATION OF LOSSES CAUSED BY INJURIOUS AGENTS

- Potential loss [1)]
- Actual loss [5)]
  - direct l. [2)]
    - primary l. [3)]
      - a. yield
      - b. quality
      - c. costs of control
      - d. extra costs of harvesting
      - e. extra costs of grading
      - f. costs of replanting
      - g. loss of income by less profitable replacement crops
    - secondary l. [4)]
      - a. contamination of sowing- and plant material
      - b. soil born diseases
      - c. weakening by premature defolation of trees
      - d. costs of control
  - indirect l. [6)]
    - a. farm
    - b. rural municipality
    - c. exporters
    - d. trade
      - 1. whole sale dealers
      - 2. retail dealers
    - e. consumers
    - f. government
    - g. environment

1) losses occurring in absence of control

2) losses in quality and quantity of product and losses in production capacity sustained by the producer

3) losses of yield, quality or wages as direct consequence of plant diseases appearing before or after the harvest

4) losses of future production capacity

5) losses in the economic and social sphere as affected by plant diseases

6) losses in the social sphere notwithstanding the more or less successful disease control, sustained by various parties concerned

2. CROP LOSSES - PHYSIOLOGY OF CROP LOSSES

2.1. DAMAGE TO THE INDIVIDUAL PLANT

This chapter deals with the study of the reactions of the individual plant to infection. The approaches of the epidemiologist (study of the development of populations of pathologenic fungi) and of the plant physiologist (study of the development of healthy plants or crops) are complementary with respect to injury and damage. This is not surprising if one considers the dependance of both plant host and pathogen of physical factors in the environment like radiation (energy source), temperature (potential velocity level for metabolic processes), or water (liquid or vapour in atmosphere of soil). From the environment the growing and developing organism obtains the necessary information and the energy to perform optimal growth and development.

2.1.1 THE FUNCTIONAL EQUILIBRIUM

The concept of functional equilibrium was developed by plant physiologists. A good example is the tendency of plants to keep the sprout/root ratio almost constant during the vegetative phase (BROUWER, 1963). The actual value of the sprout/root ratio appears to be highly influenced by environmental factors, but reproducable under the same set of factors, e.g. in controlled environments.
Injury by cutting away leaves or roots retards the growth of the plant considerably. After the original sprout/root ratio has been restored, the growth speed is brought back to its original level and the plant develops "normal". Time seems to be the only "thing" the growing and developing plant has lost. Although this is of little importance in experiments under controlled conditions, it may be vital for plants growing in a seasonal rythm.

2.1.2 MUTILATION EXPERIMENTS

Mutilation experiments have given some idea about the possible effect of infections causing leave or root inactivity. However, the relevance of mutilation experiments to the problem of injury by infections may be small, when the reaction to infection is different from the reaction to removal of a plant part. ARNY (1969) experimenting in a growth chamber with maize and *Helminthosporium maydis*, found that at high intensity a good correlation existed between damage caused by the pathogen and leaf mutilation. At low light intensity, damage by *H. maydis* appeared relatively greater than by leave mutilation. If this effect is real, it confirms the general approach for this type of problems. The infection causes changes in the capacity of the photosynthesis apparatus, changes in the internal transport of the assimilates through the plant, changes in the water requirements of the plant, and changes in the temperature control.

Infection experiments with individual plants for the study of the relation between injury and damage are scarce. It is useful to consider the following relations:

a. environmental factors growth and development of healthy plants
b. nature of injury extent of damage
c. amount of injury extent of damage
d. time of injury extent of damage
e. development of injury extent of damage

2.1.3 TRANSLOCATION OF ASSIMILATES

A new, developing leaf is fed with assimilates from other plant parts (from reserves or photosynthesis products) to build up its structures. After a while, the production of assimilates by the new leaf can compensate the leaf's own needs, and later on the leaf itself is exporting assimilates to other plant parts. The transport of assimilates in the plant is called translocation. Most of the assimilates are translocated towards the youngest leaves; a certain amount is transported to the roots.

If a wheat leaf becomes infected with yellow rust (Puccinia striiformis), the physiology of the leaf changes within a few days. The CO_2-assimilation slows down in 4 days to 75% and later on to 25% of the CO_2-assimilation of the uninfected control leaf. Whereas the latent period of the yellow rust is at least 10 days, the "mutilation" or shadow-effect starts already a week before the macroscopically visible rust symptoms become visible (DOODSON e.a. 1964). Within 4 days after inoculation the translocation from the infected leaf is reduced by 50% of the original value. 14 days after inoculation the translocation is negligable. The distribution pattern of the exported assimilates is hardly influenced by yellow rust, roots excepted. The roots are short of support.

Little is known about the influence of pathogens on the translocation of assimilates. There is some evidence that perthotrophic leaf-invading fungi do not affect the translocation (PIENING & KAUFMANN, 1969; ARNY, 1969). Biotrophic leaf pathogens can probably reduce the export of assimilates from the infected leaves to various extents, and they may even "turn the switch", so that the infected leaf imports assimilates.

Time and position of the infection together with the distribution pattern explain the nature of the damage, at least qualitatively. Suppose that all parts of a wheat plant are equally susceptible. An early infection will reduce the size of the root system and the number of flowers. A middle late infection will enhance abortion and retard the grain filling. A late infection causes shriveling of the grain.
In the field, growth conditions for wheat are seldom optimal. When a yellow rust epidemic comes to a stop and when the following weather conditions are near-optimal for wheat, the plants (or the crops recover. The stems become deep green. The relatively small number of grains are well filled, so that the result is a low yield of good quality. This phenomenon is called "compensation".

2.1.4 INDIRECT EFFECTS

Wheat plants, early infected by yellow rust (striiformis) suffer from a heavily reduced root growth (DOODSON, 1965). The same effect can a.o. be generated by leaf rust of wheat (recondita). This had been dramatically demonstrated by MARTIN & HENDRIX (1966,1967), METHA & ZADOKS (1970) got similar evidence for recondita (leaf rust of wheat); ARNY (1969) for Helminthosporium maydis of maize.

Table Effect of yellow rust (Puccinia striiformis) on the root growth of cv Baart spring wheat in a mistculture

treatment	root volume ml	reduction %
untreated control	26	--
inoculated from the first leaf onwards	4	83
inoculated from the 3rd leaf onwards	9	63
inoculated from the 5th leaf onwards	10	63
flaf leaf only inoculated	17	32

This phenomenon has practical implications, especially in semi-arid regions with a heavy infection in the autumn (e.g. North-West Pacific Area of the U.S.A.). The weakened plants are more susceptible to root rot diseases, growth in spring is retarded, plants are more susceptible to drought, and often show unexpected yield reductions, unexpected in terms of visible injury on the leaves (HENDRIX p.c.).

2.1.5 THE WATER BALANCE OF THE PLANT

The water requirement of the plant is usually covered by water uptake via the roots and incidentally via the leaves. The plant looses water via the leaf surfaces by evapo-transpiration. The water uptake by the roots is affected by aeration and water potential of the root environment. Roots take up water along most of their surface. At lower water potentials the water uptake is highly reduced, the uptake of ions relatively little. The leaf growth, especially the water consuming elongation growth of the leaves, decreases. If the water potential in the roots decreases below a certain threshold value the stomata will be closed. This causes a reduction in photosynthesis, at least when enough light is available (BROUWER, 1963).

Wheat plants inoculated with leaf rust (recondita) show a higher water uptake and transpiration rate than healthy plants under the same conditions. The transpiration is greater than the absorption, causing a evapo-transpiration deficit in the light, and in the dark (!) (PARODI & BITZER, 1969). A part of the extra transpiration can be ascribed to water leakage through the uredosori.

The combined effects of a weakened root system and a higher water requirement under dry conditions may be disastrous. Evidence is available for restistance against water leakage in the stem rust-wheat combination. Fortunately, pathogens causing open wounds are scarce: the rusts are typical examples.

2.1.6 THEORETICAL CONSIDERATIONS ON THE EFFECTS OF INFECTION

Some theoretical considerations have been developed about the relation between the number of lesions and their position on the plant, and the resulting damage. These considerations are derived from the mathematics of bombing developed in military science.
Starting points are:

a. A lesions on the leaf has a local effect, described by destruction of an assimilating area of the size of the lesion (no "metabolic sink", no compensation).
b. Two leaf lesions can overlap, but the destruction of tissue is possible only once.
c. A root lesions causes inactivation of the distal root part.
d. If 2 root lesions occur on 1 root, only the proximal lesion is effective.
e. All lesions arise at the same time.

JUSTESEN & TAMMES (1960) developed mathematical models for a number of cases, e.g. for root lesions by a fungus, nematode or insect, or seeds attacked by beetle larvae (Calandra spp.), and for leaf lesions caused by fungi. Although the equations differ in details, all the resulting damage curves share the effect, that the percentage intact plant tissue decreases with increasing number of lesions, but the progress of damage is increasingly retarded. The damage effect per injury spot is decreasing with increasing number of injuries. Injuries of the same type on an individual plant are self limiting.

2.2. DAMAGE TO THE CROP

The physiological relations found in individual plants give some idea about the reaction of the plant in a well defined environment (radiation, temperature, humidity, nutrients, etc.). When more plants of the same cultivar are placed close to each other, as in a crop situation, the reaction possibilities are increased, because the individual plants mutually influence each other. Basic in the approach of crops are the concepts of sharing a limited amount of water, nutrients and light, the latter by mutual shadow of the lower leaf levels. The crop makes its own microclimate. In a crop, the upper leaf layers catch more of the light; lower leaf layers assimilate below their capacity. When parts in the upper leaf layers are removed, more light is caught by the lower layers, and therefore the damage is less than expected from single plant experiments: "compensation". The frequently observed dense growth of fungi on the lower leaves does damage in single plant experiments, but little or no damage can be demonstrated in a crop.

A large number of mutilation experiments has been carried out in small plot experiments. The hail damage insurance companies have probably the best information about damage in the world (HEUVER e.a., 1966; KALTON e.a., 1949).

In these mutilation experiments two aspects are usually checked:

a. the amount of injury and its relation to damage, and
b. the time of the injury and its relation to damage

The following generalizations can be drawn:

a. little injury does no damage
b. at maximum of injury some yield is always obtained
c. the magnitude of the damage is closely related to the time (in the physiological sense) of the injury and the weather conditions later on
d. when generative parts are injured the damage in crops with an undetermined growth is relatively smaller than in crops with a determined growth

The first question that arises when one looks through the results of these mutilation experiments is, whether these experiments have any similarity to what happens after injury by biotic agents. Extrapolation from mutilation experiments to damage after injury by biotic agents is usually unjustified, because of differences in the time of the injury and the development of the injury later on, and because of differences in nature of most mutilations compared with biotic injurers especially to growth and development control systems in the plants.

2.3. RELATION BETWEEN INJURY AND DAMAGE

Damage is a function of the injury. The most simple function is a straight line, and for reasons of simplicity a straight line relation would be very useful. A general equation for the linear relation can be presented as:

$YL = L_y . I$

YL = Yield loss or damage

I = injury

and L_y being a constant, the loss factor ($0 \leq L_y \leq 1$)

GRAINGER (1967) presents a number of values for L_y without compensation. LE CLERQ (1967) supposed a linear relation, and he gave examples in barley, rice, sugarbeet and wheat.

Non-linear functions are presented by KINGSOLVER e.a. (1959): Logarithmic (rust on wheat); DOLING & DOODSON (1968): exponential (rust on wheat); LARGE & DOLING (1962); exponential (mildew/barley).

2.4. INTERACTIONS BETWEEN INJURIOUS AGENTS

It is hard to separate in field experiments the effect of one agent from that of another one. When chemical control experiments are analysed in more detail, the control effe·: is often significant, although the pathogen to control was just absent. Interactions between pathogens and environmental factors, like drought, high temperatures,lack of sunshine, wind, nutrients (N-fertilizers) or soil characteristics are considered as the rule, not as a exception (W. FEEKES; J.W. HENDRIX, p.c.).
The concept of interaction in the sense mentioned above is not new, but it is difficult to prove the interactions in clinical experiments, and a high level of technology is required to perform this type of work under controlled conditions. An attempt was done by VAN DER WAL, SHEARER and ZADOKS (1970) for the interaction of recondita and Septoria nodorum. The results were conform the interpretation of field data. The damage done to the plant by either of the pathogens separately was low, when measured in yield of kernels. But both pathogens together on one plant caused a damage far higher than the sum of the damages done by either of the two pathogens alone.

3. CROP LOSSES - METHODOLOGY OF FIELD EXPERIMENTS ON CROP DAMAGE

3.1. THE STATEMENT OF THE AUTHORITY

The present situation in thinking about crop losses is that relatively little experience is stored in the traditional scientific way: very little is published, but experts have built up enough experience to have some feeling for the effects of injuries and the resulting damages to the crop. The discussion at the 35th annual meeting of the Associate Committee on Plant Diseases, National Research Council of Canada, Saskatoon, 1967, may illustrate this clearly:

D.J. SAMBORSKI: Would you agree that many of the loss estimates are   For example, I might say with little justification that last year there was 10% loss due to leaf rust. How credible are these estimates?

D.W. CREELMAN: Well, if you said it Dr. Samborski, it becomes authoritative. This situation is true for both of us. For example, in my position with the Plant Disease Survey, if I were to say that annual losses from plant diseases were a quarter of a billion dollars, this too becomes authoritative and no one can dispute me until work is done on the subject (D.W. CREELMAN (1968) can. Plant. Dis. Surv. 48: 58-60. Surveys to assess plant disease losses).

The sources of information on crop losses are:

The enquiry, the experiment, and the survey. Basic to the assessment of crop losses is the experiment, more specifically the field experiment.

3.2. FIELD EXPERIMENTS

For a good interpretation it is necessary to select and determine which variables should be measured of the crop and the injurious agent.
The second important step is to design an experiment in such a way that the results of the measurements can be analysed statistically, in order to reduce subjectivity in the interpretation. Theoretically, the field experiment should represent an infinite area, and a long series of years. This is impossible; so one has to perform the experiments in small plots during a small number of seasons. But usually, the results are extrapolated to large areas and a long series of years. "The shot must therefore be in the right direction".

In statistical terminology the foregoing implies that one deals with estimators of values. A better estimate of the true value is achieved as plot size increases.
In the limit situation the experiment embraces the whole area and all the years, the limit value of the estimator equalling the value to be determined.

The expectation of the estimator should be equal to the value of interest; or in other words, there should not be any systematic error. The conclusions derived from small plots should be representative for large areas: this is the requirement of representativity or relevance. The estimator should be as accurate as possible, having a minimum of variance. This character of estimators reduces the width of confidence intervals, which is important in testing the significance of differences and in extrapolating. The variance of the estimator has an impact on size of a sample or the number of replications in an experiment. The choice of size or number is determined in part by the magnitude of the smallest significant difference desired. Replication and randomisation are prerequisites for estimation and testing. In some experiments, there may be good arguments against randomisation; the experiments apts for improvement of estimation at the expense of testing.

1 BORDER- AND SEPARATION STRIPS

An experimental field should be surrounded by wide border strips to assure enough homogenicity of the microclimate in all the plots. Separation strips are used to prevent the mutual influence of neighbouring plots with different treatments (to avoid drift of chemicals, or cross-infection by fungi, insects e.d.) The separation strips can very well consist of a neutral crop, e.g. oats in a wheat experiment. The wider the strips are, the better the separation but the worse the "noise" or additional variance caused by variance in soil characteristsics.

When wind-borne diseases or pests are studied, interaction between plots by cross-infection is inevitable. The effects of severe attacks are underestimated due to loss of inoculum. The effect of the non-injured healthy control is underestimated, due to the influx of inoculum. VAN DER PLANK (1963) advises to omit the untreated control in experiments for testing chemical control compounds. In general, the consequences of differences in treatments tend to be underestimated in small plot experiments.

.2 EXPERIMENTAL DESIGN

Types of design:

Paired plot design (one variable, 2 levels)
Multiple plot design (one variable, more levels)
Factorial design
Space planted crops

In the "paired plot design" a block exists of a treated and an untreated plot. This design is common when one depends on natural infection. In incidental cases "plot" just means "plant" (paired plant sampling) or drill; "paired plant methods" can be useful in the study of systemic diseases.

In the "multiple plot design" attempts are made to obtain a gradient of injuries from none to heavy. This can be achieved by variations in dosage and timing of inoculation, and/or by chemical control. All the main effects and their interactions can be studied, but these trials become large and, consequently expensive.

In the "split plot design" the number of objects can be reduced by accepting some confounding of effects or interactions. This design is especially useful when more than one injurious agent is studied in a single experiment.

In crops with standardized spacing of plants e.g. potatoes) special methods can be used e.g. when individual plants become diseased with the planted tuber as the source of infection. The analysis is then based on a comparison between the yield of the diseased and the healthy neighbour plants.

3.2.3 DISEASE PHENOLOGY PLOTS

J. GRAINGER, West of Scotland College of Agriculture, is the protagonist of the disease phenology plots. These are standard yield trials with the same varieties each year on the same soil. In these plots regular observations are made on the growth and development of the crop (also in chemical sense), diseases and pests. Furthermore, synoptic and microclimatic observation are made. In long term arrays (20 years or more), the great amount of yield data collected may lead to valuable conclusions, although part of this is only of local signifinance.

3.2.4 In the U.S.A. single drills are often used as the experimental units. The drill length of such a experimental unit is 3 to 10 m, sown in many replicates (up to e.g. 12). in the statistical sense the results of such experiments are usually easy to test, but one should be careful. Single drills, sown at large distances, are easy to handle experimentally, but they do not necessarily represent a crop, because inter-drill competition for light, moisture or nutrient may be absent. Apply the criterium of representativity.

3.3 THE CROP

1 THE "PRELIMINARY PORTFOLIO"

One should "understand" the crop from sowing to harvest. The only way to achieve the knowledge thereto is to draw the plants and the crop periodically. On the basis of this experience characteristics phenological data can be defined and coded. Among the results should be a scale for developmental stages. In a similar way yield parameters are determined. For the diseases and injuries observation keys should be made. These tables and keys together with some experience in how to use them is the "preliminary portfolio" (LARGE, 1966).

3.3.2 DEVELOPMENT STAGES

The damage caused by an injurious agent is highly dependant on the timing of the injury. The physiological time registration is performed with scales for development stages. An of the most successful scales is the FEEKES SCALE for cereals (LARGE, 1954)

3.3.3 YIELD PARAMETERS

Important parameters are:

yield of the harvested product (kg/ha)
quality
grading, cleanliness, uniformity, financial return (market value)

Other parameters are, more interesting to the crop physiologist:

root development
length of the vegetation period
straw stiffness, harvestability, dry matter production

3.4. THE INJURIOUS AGENT

3.4.1 PHYTOPATHOMETRICS

In crop loss studies, an accurate table for the assessment of injury is essential. Variation in the degree of injury within one experiment is useful. LARGE proposed "phytopathometrics" as a name for that part of phytopathology which deals with assessment methods for the estimation of degrees of infection and injury.

3.4.2 ASSESSMENT SCALES

The simplest method of measuring the degree of injury is by counting or weighing: number of plants (e.g. Ustilago tritici in wheat)
weight of plants (e.g. diseases in potato)
The figures from these assessments are directly subject to further analysis.

In the majority of cases, the injury is to be estimated in a percentage of leaf-, fruit- or tuber-surface, with the aid of standard diagrams, also called keys or pictorial scales. This method is especially useful in the assessment of more or less uniform patterns of injury in a crop. Many scales have been developed in recent years.
If one has to make a selection out of the scale collection, the following points should be considered:

a. The purpose of the scale:
breeding: differentiating on the lower injury levels,
epidemiology: differentiation in the very high and in the very low levels (less than 1% an higher than 90%)

b. Applicability in practice for trainers and untreated observers:
   The differences between the scale values should be easy to recognize and memorize
   More refinement can be used by better trained people

c. The number of scale values:
   Scales extensive research seldom have more than 5 scale values
   For detailed reserach 10 to 12 scale values are often used.

In view of the automatic data processing by means of computers modern scales often use 9 or 10 scale values.

3.3.4 THE WEBER-FECHNER LAW

Observations are mostly done by means of the human eye, and the intervals in scale values are adapted to the peculiarities of the eye, especially that one described by the Weber-Fechner Law:

The resolution of the eye is proportional to the logarithm of the stimulus (HORSFALL, 1945).

scale	scale values											
A1			1	2	3	4	5	6	7	9	10	
A2		0	3	6	12	25	50	75	87	94	97	100
B		1	3	9	24	50	76			91	97	99
C1		1	5	10	25	50	75					100
C2		4	5	6	7	8	9					10
C1	.1	.01	.001									
C2	3	2	1									

Scale A2	Logarithmic scale with 11 values for "percentage of attack".
Scale A1	Code numbers for "degrees of attack" corresponding with the intervals of scale A2: A10-value scale; no symbol for "no observation"
Scale B	A 9- point logistic scale for percentages of attack.
Scale C	The international yellow rust scale (*Puccinia striiformis*):(ZADOKS, 1961)
Scale C1	Percentage of leaf area visibly infected by rust.
Scale C2	Corresponding code numbers for the "degree of attack"

The scales A and B are purpose-neutral, scale C is typically adapted for use in epidemiology and breeding. The oldest scale is the COBB-scale for *Puccinia recondita* on wheat (COBB, 1892). This scale, modified by PETERSON e.a. (1948), is still used all over the whole world.

3.4.4 REMARK

Since these injury assessment are estimations of the loss of assimilating area, the knowledge of the physiology of the non-injured plant is essential, because the activity of the leaf per unit area is not constant in time; the assessment figures are not w ighed for this fact.

3.4.5 DISEASE CLASSES

When the attack cannot be assessed quantitatively, but can be classified qualitatively, the sample units should be classified in disease classes, with the use of a descriptive and, if possible, illustrated scale. As percentage of disease of a sample one can use the weighed average of the sample units calculated from all the disease classes (e.g. by multiplying number of sampling units per class by ranking number of class, and dividing the product by the total number of sampling units involved). This method is adequate for soil born diseases as Ophiobolus graminis in wheat and Plasmodiophora brassicae in Brassica spp.

3.4.6 DIVERSITY OF SYMPTOMS

The assessment system would be watertight if the injurious agent would cause only one type of injury. This is not always true (Puccinia striiformis in barley; Phytophthora infestans in potato; Piricularia oryzae in rice). The problem has not been studied systematically. A possible solution could be the quantification of all the symptoms, based on a knowledge of the effects to the plant's physiology.

3.5 THE INJURY-FREE CONTROL

The obtainance of an injury-free control is less simple than is usually thought. There are three methods, which can not be applied always at the same agent-plant combination.

a. Separation of the healthy and diseased plants, when healthy and diseased planting material are mixed (systemic diseases).
b. Chemical control. Usually the dosage and the frequency of application is too high for economical use on a large scale.
c. Isogenic lines. Lines which differ only in one gene for susceptibility (ALLEN e.a. 1963).

The methods a and c are of the yes-no (exclusion) type, b provides the possibility of more variation. Chemical control, however, is not without risk. On one hand the applied compound can injure the crop itself. A classic example is the use of Bordeaux mixture, used for more than half a century to control Phytophthora infestans in potato. The application itself causes a damage of 10% (HORSFALL & TURNER, 1943). On the other hand the applied compound can increase the yield. This has been found with maneb on barley to control dwarf rust (Puccina hordei). The vegetation period may be extended for a few days as side-effect of the application of maneb.

A third possibility is that the control is also active against injurious agents not taken into account in the experiment. So the yield of wheat was increased by the application of maneb against leaf rust (Puccinia recondita) in the Red River Valley (Minn.) even in the absence of the rust. This was probably due to the simultaneous control of Septoria nodorum.

3.6 FIELD OBSERVATIONS IN PRACTICE

3.6.1 THE MEANING OF FIELD OBSERVATIONS

Field observations in commercial fields do usually make sense if no damage trials are available because of:

a. lacking infrastructure;
b. unexpected appearance of injuries;
c. cases where experimentation with diseases or pests is not possible or not wanted.

3.6.2 EXPERIMENTAL BLOCKS

In commercial fields experimental blocks can be designed, where injury and yield experiments can be performed. Such a method makes sense only if the injury source is not homogeneous by distributed over the crop. The position of these blocks in the field can be selected systematically or at random.

3.6.3 PAIRED PLANTS RESP. PAIRED PLANTS SAMPLES

With great variation in attack per plant one can often find healthy and injured plants close together. The degree of attack and the yield of both plants is then measured and the damage calculated. Cases where different levels of attack can be found, offer the opportunity to compare different levels of attack with the corresponding damage. Commercial fields are usually not homogeneous in yield; they form a mosaic of spots with more and with less production. The paired plant method solves this problem to a large extent when the assumption is valid, that two plants close to each other have the same production capacity.
The logical extention of the paired plant method was used by ATKINSON & GRANT, 1968, in field research on damage caused by "wheat streak mosaic virus". They harvested plots of 1 yrd sq., counted the diseased plants, measured the yields of the diseased and healthy plants, and calculated the relative yield as:

$$\%\ \text{yield} = \frac{W}{W_1 \times N} \times 100$$

with: W = total harvested weight per yrd sq.
W_1 = averaged weight of a healthy plant
N = total number of plants per yrd sq.

After the elimination of the yield level per plot a strong correlation was found between the percentage diseased plants and the yield.

	prevalence	severity	loss
Erysiphe graminis	99	11	18
Barley yellow dwarf virus	89	--	--
Rhynchosporium secalis	75	2	1
Puccinia hordei	68	4	3
Puccinia striiformis	50	1	1
Selenophoma donacis	9	1	--
Totally diseased		18	
Dead tissue		25	--
Total loss in %			23

The total loss averaged over the whole area was ca 23% of the potential yield, corresponding with a monetary value of ca. *f* 450.000.000,--.

3.9. AERIAL SURVEY TECHNIQUES

To determine the geographical size of an injury the aerial photography is sometimes useful. Aerial photograph in black-and-white is already classic. Experiments with infra-red (black-and white) and infrared colour (false colour film) are going on presently. More advanced techniques like multiband spectral scanning (MSS) are in the developing stage.But all these techniques show only the presence and the extent of injury or damage;their cause has to be determined by classical terrestrical methods (SHAY, 1970)

4. CROP LOSSES - GENERAL REFERENCES

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