# CROP LOSS ASSESSMENT IN RICE

International Rice Research Institute

# Crop Loss Assessment in Rice

papers given at the
International Workshop on Crop Loss Assessment
to Improve Pest Management in Rice
and Rice-based Cropping Systems
in South and Southeast Asia
11-17 October 1987

sponsored by
International Rice Research Institute
Food and Agriculture Organization
Deutsche Gesellschaft fur Technische Zusammenarbeit
(German Agency for Technical Cooperation)
Consortium for International Crop Protection

1990
International Rice Research Institute
P.O. Box 933, 1099 Manila, Philipppines

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of the 13 nonprofit international research and training centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). The CGIAR consists of 50 donor countries, international and regional organizations, and private foundations.

IRRI receives support, through the CGIAR, from a number of donors including the Asian Development Bank, the European Economic Community, the Ford Foundation, the International Development Research Centre, the International Fund for Agricultural Development, the OPEC Special Fund, the Rockefeller Foundation, UNDP, the World Bank, and the international aid agencies of the following governments: Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Federal Republic of Germany, India, Iran, Italy, Japan, Republic of Korea, Mexico, The Netherlands, New Zealand, Norway, the Philippines, Saudi Arabia, Spain, Sweden, Switzerland, United Kingdom, and United States.

The responsibility for this publication rests with the International Rice Research Institute.

ISBN 971-22-0001-9

# Contents

CROP LOSS ASSESSMENT: BACKGROUND, RATIONALE, AND CONCEPTS

COMPONENT TECHNOLOGY FOR CROP LOSS ASSESSMENT

APPLICATIONS OF PEST AND LOSS ASSESSMENT TECHNOLOGY TO PEST MANAGEMENT

# Foreword

Each year, a large proportion of potential rice yield is lost because of insect and weed infestations and diseases. In 1987, the value of losses just from diseases was about US$12.5 billion, not counting the costs of disease control chemicals and their application. To achieve adequate and stable supplies of rice, it is important, and indeed necessary, that losses be accurately measured and potential losses predicted. That will enable techniques to be developed to manage the losses. Knowledge on crop losses caused by specific pests also is needed to formulate strategies for the rational use of pesticides. This is particularly important now, given the growing awareness about the relationship between the quality of our environment and the quality of life.

IRRI is embarking on a bold new course, outlined in its strategic plan *IRRI toward 2000 and beyond,* that is placing greater emphasis on sustainable production practices and environmentally sound technology. Part of the strategy positions the concept of Integrated Pest Management (IPM) as a central theme in generating acceptable pest management knowledge.

The International Workshop on Crop Loss Assessment to Improve Pest Management in Rice and Rice-based Farming Systems in South and Southeast Asia, held 11-17 October 1987 at IRRI, was particularly relevant in helping to shape IRRI's future research direction. Crop loss assessment will provide the basis for determining which pests are causing economic damage and when pesticides are required or justified. Over a longer time frame, crop loss data collected in different ecosystems by national programs also will enable evaluation of changing pest situations as other forms of production technology are adopted by farmers. This more strategic look at rice-based farming systems will lead to improved pest management, especially of migratory pests that do not recognize political boundaries.

The workshop also demonstrated the manner in which IRRI would like to cooperate with other interested agencies, to convene meetings that address crucial issues of common concern. This undertaking is just one activity in a series of joint efforts in which IRRI is able to play the role of initiator, convenor, and research partner.

In a world that has become more vulnerable and fragile, only such cooperative approaches will be able to help us find viable solutions in time.

The workshop was supported jointly by the United States Agency for International Development (USAID), through a grant to the Consortium for International Crop Protection pest and pesticide management project. Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ), the Food and Agriculture Organization intercountry program on rice in South and Southeast Asia, and IRRI. In all, about 160 participants from 21 countries attended. The organizing committee included Dr. Paul S. Teng, workshop coordinator, Dr. J. Michael Bonman, Dr. Kwanchai A. Gomez, Dr. Peter E. Kenmore, Dr. James E. Litsinger, Dr. Edwin D. Magallona, Dr. T. W. Mew, Dr. Keith Moody, Dr. Prabhu L. Pingali, and Dr. B. Merle Shepard. The book was edited by Dr. LaRue Pollard and Ms. Emy Cervantes.

Klaus Lampe
Director General

# Preface

This book contains papers given at the International Workshop on Crop Loss Assessment to Improve Pest Management in Rice and Rice-based Farming Systems in South and Southeast Asia held at IRRI in October 1987. Such a workshop had been recommended by participants in a February 1987 meeting on Pesticide Management and Integrated Pest Management for Southeast Asia in Pattaya, Thailand. They felt that this timely topic could assist countries in the region to better justify and rationalize their Integrated Pest Management (IPM) programs.

Crop loss assessment is a scientific activity in pest management that is aimed at increased understanding and improved quantification of the effects of pests on crop growth and development. The activity ranges across different levels of scale, from plant processes involving single plants to an ecosystem.

Few reliable estimates of the magnitude of crop losses caused by the major pests of rice and other crops grown in rice-based farming systems are available. Much of the data commonly quoted for rice are at least 20 years old. For crop loss data to be reliable, they must be collected using scientifically acceptable techniques. But many of the techniques needed for tropical Asian conditions have yet to be developed. Furthermore, fundamental knowledge on how individual pests affect the rice plant or rice crop often is not available. This assumes even greater importance when IPM is the accepted strategy for pest management: IPM stresses rational use of inputs to control pests. That rationalization must be based on an objective evaluation of potential benefits and costs. Crop loss assessment techniques are the only means of providing this needed information, whether the assessment is done at the farm level or for a region.

The papers in this book are organized in three sections. Those in the first section provide background on crop loss assessment as well as a review of current knowledge on approaches and loss estimates for rice pests. Papers in the second section discuss component technologies in crop loss assessment. They deal with important phases of any loss assessment project: quantification of the pest, sampling, and experiments to develop pest-loss relationships. Most of the papers concern single pests, because little is known so far of techniques to quantify the effects on yield of multiple pests. The one paper on the effects of multiple pests is based on some pioneering work on potato; it serves as a model for potential research in rice. The role of the physical environment and of plant physiology in developing pest and loss models also is discussed, with suggestions on how to incorporate these into pest-loss models. The third section contains papers on applications of crop loss assessment technology, with emphasis on its use to improve decisionmaking in pest management. One paper uses a systems approach to provide a holistic view of pest management and shows where pest-loss relationships and crop loss data could fit. Several papers discuss large area surveys and surveillance systems, and how they may be used to better define pest problem areas. This topic is further addressed by the paper on pest zoning using historical weather and pest data. The paper on multiple-pest thresholds is also a pioneering one: it reports research on a new approach for dealing with a real-world problem that many workers have tended to put aside. The role of genetics and economics in devising pest management strategies is dealt with in two papers.

In addition to presentations, the workshop provided its participants opportunity for small group discussions on different aspects of crop loss assessment. What resulted was a set of recommendations for follow-up activities. We believe these will be especially useful in assisting researchers and research managers in national rice programs to develop future activities.

Crop loss assessment is a relatively new activity in the tropics. We sincerely hope that the 1987 workshop and this book will accelerate the generation of knowledge on losses in the region, thereby leading to improved pest management.

Paul S. Teng
Workshop Coordinator

# Crop loss assessment: a historical perspective and rationale

J. C. Zadoks

Three periods can be distinguished in the history of concerns about crop loss assessment—exploratory, emergency, and implementation. Here, I review developments in each period, describe recent crop loss research, and outline objectives of crop loss studies.

## The exploratory period

Crop loss assessment as a motive for human endeavor can be traced back 300 yr (Duhamel 1728 in Zadoks 1981a, Tozzetti 1767 in Tehon 1952). The German Korn, however, is said to have been the first (in 1880) to stress the importance of using crop loss assessments for scientific and managerial purposes (Zadoks and Koster 1976). State authorities could not be convinced of its importance, but in 1890 the German Agricultural Society began to collect some data. Eriksson and Henning (1896) did a regional crop loss survey in Sweden. Leading pathologists of the time (the Swede J. Eriksson and the German P. Sorauer) were aware of the importance of the subject and assisted the 1890 International Congress of Agriculture and Forestry in Vienna in passing a resolution on disease assessment. In 1895, the Prussian Government began to assess losses.

The Government of the Netherlands, disgusted by rumors of severe damage by San Jose Scale on citrus in California, sent its top specialist, J. Ritzema Bos, to the United States to investigate. He reported that “potential loss” (as interpreted by Zadoks 1967) was severe, and recommended installing a “plant protection service” to prevent losses due to imported pests. The world’s first Plant Protection Service began its work in the Netherlands in 1899.

The 1903 International Agricultural Congress in Rome initiated the International Phytopathological Committee, a nongovernmental organization precursor of the International Society of Plant Pathology. The International Agricultural Institute founded in Rome in 1905 had a Bureau of Agricultural Intelligence and Plant Diseases to produce agricultural statistics, including those on crop loss. The exploratory period came to an end with the 1914 International Phytopathological Conference in Rome.

## The emergency period

The World Wars of 1914-19 and 1940-45 and the years between are seen as the emergency period. The war situation hampered international exchange of commodities. Males were called to military service, causing serious shortages of rural labor. Priority was given to feeding the troops, and civilians suffered from food shortages. During World War I, famines occurred in Germany. The heavy death toll during the Bengal Famine in 1943 was due as much to political and infrastructural chaos caused by World War II (Sen 1981) as to crop failure (Padmanabhan 1973).

In the face of war emergencies, the U.S. initiated a Plant Disease Survey in 1917 (Lyman 1918). Other countries' responses are not available.

The time between the wars was a period of little activity in the specialized area of crop loss studies.

## The implementation period

The primary initiator of the implementation period was the phytopathologist E. C. Large (1950) in the United Kingdom. Quietly and systematically, he developed a sound crop loss methodology (Large 1966). The entomologist E. Judenko (1983) pioneered many concepts and A. H. Strickland (1961) implemented methods.

International interest was stimulated by the 1967 Food and Agriculture Organization (FAO) Symposium on Crop Losses in Rome, organized by plant pathologists L. Chiarappa and J. Vallega (FAO 1967). Development of crop loss methodology was furthered by two publications produced under the aegis of FAO (Chiarappa 1971, 1981). Curiously, the U.S., with the world's highest agricultural overproduction, was most interested. Plant pathologists of the U.S. Department of Agriculture became promoters of the crop loss assessment theme.

Until 1973, university science and university departments had looked down on the crop loss theme as unscientific and too field-oriented. At the Second International Congress of Plant Pathology in Minneapolis, I had the opportunity to show the range of academic interest in crop loss studies (Zadoks 1973). The crop loss theme became a natural part of epidemiology, with crop loss the end result of an epidemic. Epidemiological studies provided means of preventing crop loss (Zadoks 1987, Zadoks and Schein 1979).

The implementation period was characterized by a sequence of meetings, often under the auspices of FAO, centered on crop loss (Table 1). These aroused considerable interest but had relatively little effect. The worldwide encompassing data set produced by Cramer (1967) is now obsolete, and more recent surveys are not available.

## Crop loss research in the 1970s and 1980s

Crop loss research is no longer oriented toward its original goal: nationwide and worldwide surveys. It is geared toward crop and pest management. The great international movement toward integrated pest management has contributed to the new orientation. The linkage between epidemiology and crop physiology, to explain losses on a quantitative physiological base, has itself become a scientific challenge.

**Table 1. Partial international meetings devoted to crop loss studies.**

| Year | Symposium or meeting |
|---|---|
| 1967 | FAO symposium on crop losses, Rome (FAO 1967). |
| 1973 | Symposium on developing models for measuring crop losses. 2nd International Congress of Plant Pathology, Minneapolis, USA (Zadoks 1973). |
| 1977 | Workshop assessment of crop losses due to pests and diseases. University of Agricultural Sciences, Bangalore, India (Govindu et al 1980). |
| 1977 | Epidemiology and crop loss assessment. Australian Plant Pathology Society Workshop. Lincoln, New Zealand (Close et al 1978). |
| 1980 | Crop loss assessment. E.C. Stakman Commemorative symposium. St. Paul, Minnesota, USA (Teng and Krupa 1980). |
| 1982 | Plant diseases: infection, damage, and loss. BSPP Symposium, University of Surrey, UK (Wood and Jellis 1984). |
| 1984 | International training course on crop loss assessment as a means to improve crop production and pest management. St. Paul, Minnesota, USA (Teng 1987). |
| 1987 | International workshop on crop loss assessment to improve pest management in rice and rice-based farming systems in South and Southeast Asia, Los Baños, Philippines. |
| 1988 | International symposium on crop losses due to disease outbreaks in the tropics and countermeasures. Tropical Agriculture Research Center. 5th International Congress of Plant Pathology, Kyoto, Japan. |

**Table 2. Basic crop loss terminology (after Zadoks 1985).**

Yield = a crop's measurable economic production.
Injury = any visible and measurable symptom caused by a harmful agent.
The damage function translates injury into damage.
Damage = any reduction in quantity and/or quality of yield.
The loss function translates damage into loss.
Loss = the reduction in financial return per unit area due to harmful agents.

Entomologists provided an operational set of concepts blending the population dynamics of pests and farm economics (Stem et al 1959). Phytopathologists jumped on the bandwagon later (Zadoks 1985). Crop loss considerations were explicitly incorporated into such disease and pest management systems as EPIPRE, that specify recommendations in monetary terms (Zadoks 1989).

Fundamental crop loss research aiming at why, how, and how much, proceeds stepwise from injury to damage to loss. Those terms are defined in Table 2. Types of

**Table 3. Types of losses caused by harmful agents (Zadoks and Schein 1979).**

| | | | |
|---|---|---|---|
| Potential loss [a] | | | |
| Actual loss [e] | direct loss [b] | primary loss [c] | a. yield<br>b. quality<br>c. costs of control<br>d. extra costs of harvesting<br>e. extra costs of grading<br>f. costs of replanting<br>g. loss of income by less profitable replacement crops |
| | | secondary loss [d] | a. contamination of sowing and planting material<br>b. soil-borne diseases<br>c. weakening by premature defoliation of trees<br>d. costs of control |
| | indirect loss [f] | a. farm<br>b. rural community<br>c. exporters<br>d. trade<br>1. wholesale dealers<br>2. retail dealers<br>e. consumers<br>f. government<br>g. environment | |

[a] Losses occurring in absence of control. [b] Losses in quality and quantity of product and losses in production capacity sustained by the producer. [c] Losses in yield, quality, or wages as direct consequence of plant diseases appearing before or after the harvest. [d] Losses of future production capacity [e] Losses in the economic and social sphere as affected by plant diseases. [f] Losses in the social sphere, notwithstanding more or less successful disease control, sustained by various parties concerned.

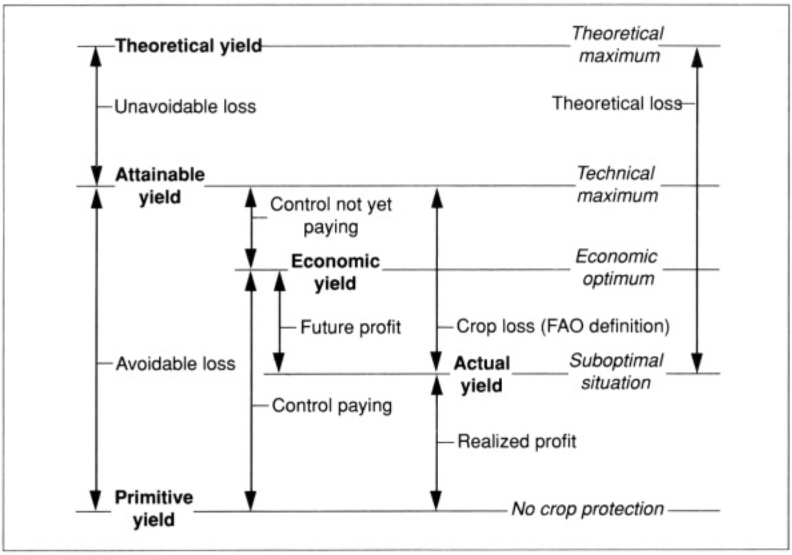
losses are defined in Table 3. Yield levels (Fig. 1) and production situations (Table 4) are described in a way that is relevant to the crop loss theme. Economic and social aspects studied by Tait (1982) and Waibel (l986) have led the way to a wider concept: production constraints.

Studies at the physiological level (Rabbinge et al 1985) are now elucidating the complex chain of events, from early infection of young plants to final yield depression. Dynamic computer simulations are one of the tools and multiple pathosystems are now being studied (He Ming and He Zhong-quan 1988, Kranz and Joerg 1988).

## Objectives of crop loss research

Putting aside the well-chosen but ambitious objectives of national and worldwide overviews of crop loss, the current objectives of crop loss research are scientific and managerial; the managerial objectives are at both individual and collective levels (Zadoks and Schein 1980).

Scientific objectives aim for the deepest possible understanding of the cause of loss due to injury in both single and multiple pathosystems. Data should be quantified at the molecular, cellular, whole-plant, and crop levels. The understanding should extend to events preceding the crop under consideration and to possible effects on following crops. It should incorporate the environment of the crop, including the crop



**1.** Yield levels distinguished in crop loss discussions (Zadoks and Schein 1979).

**Table 4. Production situations (De Wit 1982).**

| Constraints and productivity | Crop production situation | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Temporary constraints | - | Water | Nitrogen | Phosphorus |
| Complementary constraints | - | - | Water | Nitrogen |
| Cropping season, in days | >100 | | | \100 |
| Crop productivity, in kg/ha per day | 150-350 | | | 10-15 |

habitat from which inputs are received (e.g. pathogens, pests, beneficial organisms, pollutants) and to which outputs are emitted (e.g. pests, pathogens, allergens, toxins, pollutants). The understanding should include the consequences of human actions on cropping systems and vice versa, including socioeconomic implications of crop protection (Waibel 1986, Zadoks and Schein 1979). This understanding should be explanatory and action-oriented.

Managerial objectives at the collective, state level (Table 5) should be to maximize output of commodities with minimum input of pollutants (fertilizers, pesticides), to obtain stable yields with high returns to farmers, and to maintain a sustainable agriculture without exhausting natural resources (such as soil fertility, water reservoirs, and forests). Environmental, social, and health costs of pollution by pesticides are incredibly high (Loevinsohn 1987, Pimentel et al 1980). Crop loss maps can be a tool (Zadoks and Rijsdijk 1984).

**Table 5. Objectives of crop loss research in support of management at the collective level. Note that in most countries, when elementary needs are satisfied, the public will judge its government according to crisis management capacity.**

| Type of management | Objectives |
|---|---|
| Production | Maximize food production<br>Maximize rural income<br>Supervise pesticide deployment<br>Minimize polluting inputs<br>Stabilize crop yields<br>Ensure sustainable agriculture<br>Implement insurance policy |
| Research | Spend funds cost-effectively<br>Stimulate integrated crop and pest management<br>Promote rural job opportunity |
| Crisis | Preventive action<br>  Estimate risks (potential losses)<br>  Store emergency fighting materials<br>  Store emergency food<br>Immediate action<br>  Halt the emergency<br>  Distribute food<br>Follow-up action<br>  Repair damage<br>  Refund farmers |

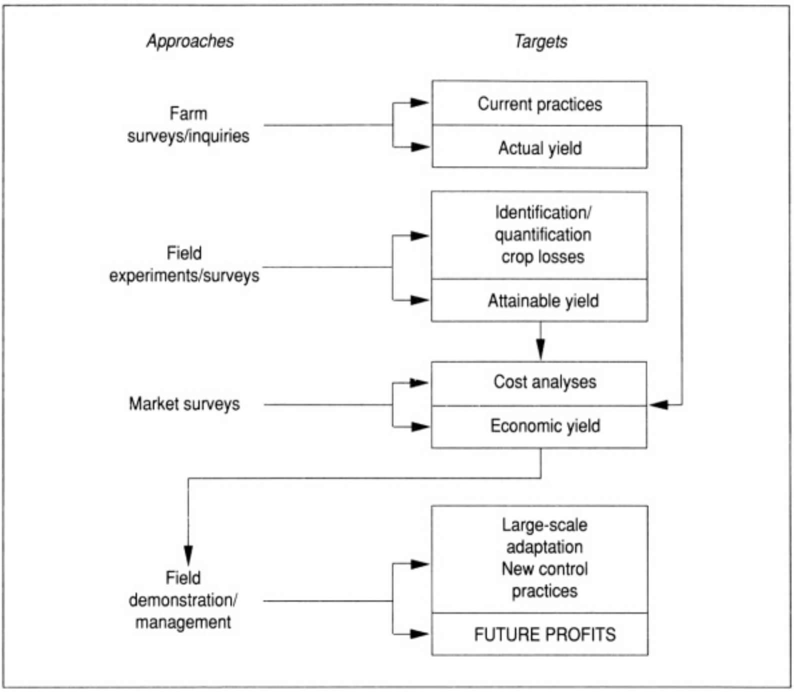
**Table 6. Objectives of crop loss research in support of management at the individual farmer level.**

Maximize farm income
Stabilize crop yields
Stabilize farm income
Reduce health hazards
Ensure future productivity of land

A second set of objectives at the collective level is for scientific management, to channel research funds where they are most cost-effective for agriculture and to give support to extension (Large 1966, Zadoks 1984).

A third set is for crisis management, when droughts. storms, floods, radioactive fallout, or migratory pests and pathogens threaten large areas. Loss estimates are needed immediately to direct available resources to where they are most effective. Final loss assessment is needed to enable farmers to be compensated for losses incurred by catastrophes so that an impoverished and hungry rural population does no: crowd the cities. Knowledge-intensive crop protection will increase rural job opportunities.

A fourth set of objectives at the collective level is to operate various state-supported and private crop loss insurance systems (Carlson 1979).



**2.** Flow chart describing approaches to define production constraints and to ensure future profits through crop protection (Zadoks 1981b).

Managerial objectives at the individual level (Table 6) are to support decisions (Clifford and Lester 1988, Tait 1982, Zadoks 1989) in pursuit of one or more of the following goals: maximum economic return per unit of input (labor, land, energy, fertilizer, pesticide), yield stability, avoidance of hazards to man and animals, sustainability of farming, and well-being of the farm family.

Crop loss is the internationally accepted term for the theme of this volume. But the ultimate goal is not knowledge of losses, but insight into the production constraints causing the losses. Such action-oriented insights are needed to define the constraints and to ensure future profits (Fig. 2).

## References cited

Carlson G A (1979) Insurance, information, and organizational options in pest management. Annu. Rev. Phytopathol. 17:149-161.

Chiarappa L, ed. (1971) Crop loss assessment methods. FAO manual on the evaluation and prevention of losses by pests, diseases and weeds. Commonwealth Agricultural Bureaux, Famham Royal, United Kingdom.

Chiarappa L. ed. (1981) Crop loss assessment methods. Supplement 3. Commonwealth Agricultural Bureaux, Famham Royal, United Kingdom. 123 p.

Clifford B C, Lester E (1988) Control of plant diseases: costs and benefits. Oxford, Blackwell. 263 p.

Close R C, Gaunt R E, Harvey IC, McCully A J, Sanderson F R. Teng P S (1978) Epidemiology and crop loss assessment. Proceedings of a workshop held at Lincoln College, New Zealand. Canterbury, New Zealand (mimeo.)

Cramer H H (1967) Plant protection and world crop production. Pflanzenschutz Nach. 20:l-524.

De Wit C T (1982) Laproductivité des pasturages sahéliens. Pages 20-35 *in* La productivité des pasturages sahéliens. Une étude des sols, des vegetations et de I’exploitation de cette ressource naturelle. F. T. W. Penning de Vries and M. A. Djiteye, eds. Agricultural Research Report 918. Pudoc, Wageningen. 525 p.

Eriksson J, Henning E (1896) Die getreideroste. Ihre Geschichte und Natur sowie Massregeln gegen dieselben. Norstedt and Soener, Stockholm. 463 p.

FAO — Food and Agriculture Organization (1967) Papers presented at the FAO Symposium on Crop Losses. Rome, Italy.

Govindu H C, Veeresh G K, Walker P T, Jenkyn J F (1980) Assessment of crop losses due to pests and diseases. Technical Series No. 33. University of Agricultural Sciences, Hebbal, Bangalore. 300 p.

He Ming, He Zhong-quan (1988) A strategy for integrated pest control on rice. Abstracts of the Beijing intenational symposium of plant pathology. Chinese Society for Plant Pathology, Beijing.

Judenko E (1983) Glossary of terms used in the application of the analytical method for assessing yield losses caused by pests. Roczniki Nauk Rolniczych (Polish Agriculture Annual) Seria E, 10:9-25.

Kranz J, Joerg E (1988) Syn-epidemiological studies in wheat. Abstracts of the Beijing international symposium of plant pathology. Chinese Society for Plant Pathology, Beijing.

Large E C (1950) The advance of the fungi. 3d ed. Jonathan Cape, London. 488 p.

Large E C (1966) Measuring plant disease. Annu. Rev. Phytopathol. 4:9-28.

Loevinsohn M E (1987) Insecticide use and increased mortality in rural Central Luzon, Philippines. The Lancet (June 13):1359-1362.

Lyman G R (1918) The relation of phytopathologists to plant disease survey work. Phytopathology 8:219-228.

Padmanabhan S Y (1973) The great Bengal famine. Annu. Rev. Phytopathol. 11:11-26.

Pimentel D, Andow D, Dyson-Hudson R, Gallahan D, Jacobson S, Irish M, Kroop S, Moss A, Schreiner I, Shepard B M, Thompson T, Vinzant B (1980) Environmental and social costs of pesticides: a preliminary assessment. Oikos 34:125-140.

Rabbinge R, Jorritsma I T M, Schans J (1985) Damage components of powdery mildew in winter wheat. Neth. J. Plant Pathol. 91:235-247.

Sen A (1981) Poverty and famines: an essay on entitlement and deprivation. Oxford, Clarendon. 257 p.

Stem V M, Vanden Bosch R, Hagen K S (1959) The integrated control concept. Hilgardia 29:81-101.

Strickland A H (1981) Sampling crop pests and their hosts. Annu. Rev. Entomol. 6:201-220.

Tait E J (1982) Farmers’ attitudes and crop protection decision making. BCPC Monogr. 25:42-52.

Tehon L R (1952) G. Targioni Tozzetti: true nature, causes and sad effects of the rust, the bunt, the smut, and other maladies of wheat, and of oats in the field. Phytopathol. Classics 9:159.

Teng P S, ed. (1987) Crop loss assessment and pest management. APS Press, St. Paul, Minnesota. 270 p.

Teng P S, Krupa S V (1980) Crop loss assessment. Assessment of losses which constrain production and crop improvement in agriculture and forestry. *In* Proceedings of the E. C. Stakman Commemorative Symposium. Department of Plant Pathology, University of Minnesota, St. Paul. 327 p.

Waibel H (1986) The economics of integrated pest control in integrated rice: a case study from the Philippines. Springer-Verlag, Berlin. 196 p.

Wood R K S, Jellis G J (1984) Plant diseases: infection, damage and loss. Blackwell. Oxford. 327 p.

Zadoks J C (1967) Types of losses caused by plant diseases. Pages 149-158 *in* Papers presented at the FAO Symposium on Crop Losses. Food and Agriculture Organization. Rome, Italy.

Zadoks J C (1973) Modelling the models. Introduction to the Symposium 'Developing models for measuring crop losses.' 2nd International Congress of Plant Pathology. Minneapolis. Wageninpen. 4 p. (mimeo.)

Zadoks J C (1981a) Mr. Duhamel's 1928 treatise on the violet root rot of saffron crocus: Physical explanation of a disease that perishes several plants in the Gastinois, and saffron in particular. Meded. Landbouwhogesch. Wageningen 81(7):31.

Zadoks J C (1981b) Crop losses today, profit tomorrow: an approach to quantifying production constraints and to measuring progress. Pages 5-11 *in* Crop loss assessment methods. Supplement 3. L. Chiarappa, ed. Commonwealth Agricultural Bureaux. Farnham Royal. United Kingdom.

Zadoks J C (1984) Cost effectiveness of plant protection on a national basis. EPPO Bull. 14:325-335.

Zadoks J C (1985) On the conceptual basis of crop loss assessment: the threshold theory. Annu. Rev. Phytopathol. 23:455-473.

Zadoks J C (1987) Rationale and concepts of crop loss assessment for improving management and crop protection. Pages 1-5 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, St. Paul.

Zadoks J C (1989) EPIPRE, a computer-based decision support system for pest and disease control in wheat: its development and implementation in Europe. Plant Dis. Epidemiol. 2. (in press)

Zadoks J C, Koster L M (1976) A historical survey of botanical epidemiology. A sketch of the development of ideas in ecological phytopathology. Meded. Landbouwhogesch. Wageningen 76(12):56.

Zadoks J C, Rijsdijk F H (1984) Agro-ecological atlas of cereal growing in Europe. III. Atlas of cereal diseases and pests in Europe. Pudoc, Wageningen. 169 p.

Zadoks J C, Schein RD (1979) Epidemiology and plant disease management. Oxford University Press, New York. 427 p.

Zadoks J C, Schein R D (1980) Epidemiology and plant disease management, the known and the needed. Pages 1-17 *in* Comparative epidemiology. J. Palti and J. Kranz, eds. Pudoc, Wageningen. 122 p.

## Notes

J. C. Zadoks, Department of Phytopathology, Binnenhaven 9, P.O. Box 8025, 6700 EE Wageningen, The Netherlands.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Crop loss and pest and pesticide management

D. G. Bottrell

Assessing the damage potential of crop pests and differentiating losses caused by pests from other causes are the first steps toward profitable pest control. Crop protection specialists can use such assessments to establish guidelines on when pesticides or other control methods are needed (and when they are not needed). Used appropriately, such guidelines can assist farmers in decreasing pest losses; reducing unnecessary costs; and increasing yields, profits, and safety.

This discussion summarizes use of crop loss assessment information for pest and pesticide management in less developed countries. For a more complete overview, see discussions in Reichelderfer et al (1984), Teng (1987a), and Teng and Krupa (1980).

Pest management refers to any actions, used singly or in combination, that keep pests below unacceptable levels. Pesticide management refers to the correct use of chemical agents to keep pests to those levels.

## Crop loss assessment in economically less-developed countries

The potential consequences of crop losses due to pests in the less developed countries are frightening to contemplate, especially when they are compared with the consequences of crop losses to pests in industrialized countries. While crop losses and the costs of pest control can seriously lower the earnings of individual farmers in an industrialized country, the aggregate effect country- or area-wide may be relatively minor. In the USA, for example, only 3.1 % of the population are directly engaged in farming; earnings from agriculture account for only about 2.4% of national income (CEA 1984). Even when the social and environmental costs of the use of pesticides are considered, the impact of crop losses to pests probably would not exceed 1.5% of the total national economy (Reichelderfer and Bottrell 1985).

But a number of less developed country economies depend more heavily on agriculture. In Central America, agriculture accounts for 26% of the gross domestic product and employs more than 50% of the region's labor force (AID 1984). In Central America and other developing areas that have largely agrarian economies, crop losses to pests can affect not only individual producers but also the welfare of entire countries.

Accurately assessing crop losses to pests and pinpointing when steps are needed to reduce significant losses are crucial in efforts to strengthen agriculture in such regions.

## Using crop loss assessments to manage pests and pesticides

Crop loss assessments have two primary applications in pest and pesticide management.

- The information can be used to establish economic thresholds (also called action and treatment thresholds).
- The information can provide a better understanding of the relative severity of pest species infestation. That knowledge is useful in setting priorities for research, extension, policymaking, maintenance of pesticide inventories, etc.

The most appropriate procedure to use in assessing crop losses depends on the objective of the assessment, the crop, the pest species. the available resources, and whether the assessment is at the farm or regional level (see Palti and Ausher [1986], Reichelderfer et al [1984], Teng [1987a], and Teng and Krupa [1980] forreviews). The discussion here is restricted to the use of assessments in setting economic thresholds and to their limitations.

### Establishing economic thresholds

In this paper, economic threshold (a concept introduced by Stem et al 1959) is synonymous with economic injury level (see Zadoks 1987 for a different interpretation). Economic threshold is the density of a pest population below which the cost of applying control measures exceeds the losses caused by the pest. It is the breakeven point, the zero profit level, in pest control. Below the economic threshold, the cost of pest control is not returned in crop value. Above the threshold, control may be profitable, if its costs do not exceed benefits.

Researchers have used many different procedures to determine the relationship of the level of pest damage or pest infestation and crop loss (see Pedigo et al [1986], Teng [1987a], Walker [1987 a,b,c], Zadoks [1987], various articles in this volume). Some of the common procedures are briefly reviewed here.

*Small-plot technique.* Small plots are probably the most common technique used in collecting crop loss data. Small replicated plots situated side by side are exposed to different levels of pest density. Some investigators artificially infest the plots (e.g. with laboratory-reared insects or disease inoculum) or manipulate natural infestations. Others chemically manipulate natural populations. A common procedure is to leave one plot untreated and to treat the other plots with different levels of pesticides to produce from 0 to 100% control.

For the most realistic results, the plots should be situated in farmers' fields but protected from the farmers' pest control practices. Soil fertility, crop variety and age, irrigation level, and tillage in the experimental area should be uniform. Samples should be sufficiently large and should be taken uniformly over all plots. If pests are uniformly distributed over the field and plant growing conditions are uniform, small samples may be sufficient. But uneven distribution of some pests (e.g. nematodes) creates special problems (Barker and Nusbaum 1971).

The small-plot technique has various drawbacks, especially when pesticides are used to establish pest levels. For example, use of some systemic insecticides may increase yields independently of their effect on insect infestations. Other pesticides may be phytotoxic and reduce yields. Another potential problem is pesticidal drift between plots, especially when insecticidal sprays are used. The insecticidal drift may not be sufficiently potent to kill insect pests in the untreated plots, but even low levels can devastate some species of natural enemies. That can give treated plots a yield advantage over untreated plots. Some investigators have placed barriers (plastic screening, etc.) between plots to reduce pesticidal drift.

*Cage technique.* Wire or cloth screen cages are used to confine whole plants or plant parts (cereal grain heads, plant leaves, etc.) and different levels of pest populations (insects, mites, rodents). The use of cages has obvious limitations. The cage may drastically change the microclimate around the plants, disrupting normal growth or behavior of both plant and pests. Also, cages exclude the pest's natural enemies. Economic thresholds for pests with effective natural enemies are meaningless unless they incorporate the effect of those beneficial organisms. Shepard et al (1988) showed that experiments in the Philippines to establish economic thresholds for rice planthoppers (*Nilaparvata lugens* and *Sogatella furcifera*) that ignored predators would encourage unnecessary use of insecticides.

*Simulated-damage technique.* In simulated damage studies, artificial methods are used to mimic pest injury. The technique has been used to simulate the damage caused by various pest organisms that attack plants by chewing (insects, rodents). Poche et a1 (1981) used a sharp instrument to simulate rat feeding on stems of IR8 rice in Bangladesh. Four damage levels (0, 10, 25, and 50% damaged stems) were simulated and compared at tillering, booting, and maturity of rice in the field. Damage at tillering did not significantly reduce yields, but damage to only 10% of the stems at booting or at maturity significantly reduced yields. The authors concluded that rat control need not begin before the booting stage.

This example illustrates the importance of taking plant growth stages into account in studies to establish economic threshold. Economic thresholds are rarely static; they usually change with seasonal changes.

The damage caused by some chewing pests cannot be simulated realistically. Simulation has been used successfully in only a few cases.

*Computer models.* Computer models can provide a theoretical explanation of the effect of injurious or competitive organisms on crops (see Teng [1987b] and papers in this volume). Such models have considerable potential for developing and testing economic thresholds. However, they need to be tested in real farming environments.

*The intuitive method.* Despite experimental advances, intuition and trial and error are still important aspects of crop loss assessment and setting economic thresholds. In fact, some of the most effective integrated pest management programs in the USA use economic thresholds derived largely from intuition, not hard data. As early as 1923, for example, entomologists recommended that insecticidal control of the boll weevil *Anthonomus grandis* be withheld until the insect had damaged 10-15% of the cotton squares (flower buds) (Bottrell 1979, Hunter and Coad 1923). They recommended essentially the same economic threshold being used today (Bottrell and Adkisson 1977), one they derived largely without supporting data.

Familiarity with growth characteristics of the crop and population dynamics of the pests are important first steps in setting economic thresholds. Even crude thresholds are better than none, especially for sporadic pests and those for which the crop plants have areasonably high tolerance. Crude thresholds can be refined as additional data become available and as farmers and extension personnel gain experience using economic thresholds.

## Interpreting the results

If $Y$ represents loss (e.g. percentage of crop yield) and $X$ represents pest population level (e.g. number of pests per meter of plant row, per 100 plants, or per hectare) or plant damage level (e.g. percentage of leaf area or stems damaged), then in its simplest form, the relationship would be linear: the level of loss would be directly related to the level of the pest population or pest injury.

For example, when $X$ is 1 and $Y$ is 10 (10 times greater than $X$), then when $X$ is 1.1, $Y$ is 11 (still 10 times greater than $X$), and so on. However. levels of pest damage and crop damage are rarely, if ever, perfectly correlated. The relationship of plant damage and yield reduction may not be linear.

Other factors may complicate the interpretation of data. One difficulty is separating the damage caused by pest species A from that caused by pest species B, C, or D, when all species attack the crop simultaneously. Another question is: Do unattacked plants growing next to attacked plants produce compensatory yield? These and other factors should be considered in designing crop loss experiments and in interpreting the results.

Separating crop losses caused by pests from losses to weather, soil fertility, poor management, etc. is another problem. In the Philippines, Herdt and Wickham (1978) calculated potential rice yields at about 8 t/ha, although actual yields were only about 2 t/ha. Combined losses from weeds and insects accounted for only about 20% of the difference between actual and potential yields.

Statisticians, economists, crop physiologists, and others can help design economic threshold studies and interpret the results. However, ultimately crop protection specialists must do their own “biological thinking” to decide the economic threshold levels appropriate for particular farming situations. To do this effectively, crop protection specialists must be keenly attuned to the relevant pest problems, farming techniques, and farmer behaviors.

## Translating results into practice

To a farmer or extension agent, an economic threshold is merely a gauge to determine the need for a remedial control measure (usually application of a pesticide). Monitoring of pest populations, natural enemies, crop growth and development, and weather

**Table 1. Calculating economic thresholds for controlling tomato fruitworm in Grenada.** [a]

| Fruitworms/ 100 plants | Potential tomato loss (kg/ha) | costs of control (US$/ha) | Benefits (US$/ha) (Tomatoes = US$2.5/kg) Increase | | Benefits (US$/ha) (Tomatoes = US$1.0/kg) Increase | |
|---|---|---|---|---|---|---|
| | | | Sales | Profits | Sales | Profits |
| 25 | 224 | 111 | 560 | 449 | 224 | 113 |
| 20 | 179 | 111 | 448 | 337 | 179 | 68 |
| 15 | 134 | 111 | 335 | 224 | 134 | 23 |
| 10 | 90 | 111 | 225 | 114 | 90 | -21 |
| 5 | | 111 | 113 | 452 | 45 | -66 |

[a] Data were provided by participants in a Consortium for International Crop Protection course in Grenada, 1986. Loss data were derived from participants' estimates: they are not field data. Sales increase = potential loss × market price. Profits increase = sales - control costs.

establishes the need (or lack of need) for control. When monitoring shows that a pest population is increasing to damaging levels despite the presence of natural controls or the use of a pest management technique such as a pest-resistant crop variety, pesticide application may be necessary.

Table 1 illustrates a simple way to translate crop loss data into economic threshold data. It was used in the control of tomato fruitworm *Helinthis zea* in Grenada (see Reichelderfer et al [1984] for other examples). Costs are based on 1986 market prices. The costs of control (US$lll/ha per tomato crop) are based on five insecticide applications (200 centiliters Ambush/ha per crop). Application equipment (backpack sprayer) and labor costs are not included. The cost of monitoring (inspection of tomato fruits, flowers, and terminals every 2-3 d) also is not included.

The breakeven point (economic threshold) for tomato fruitworm control in Grenada in 1986 was affected by the selling price of tomatoes. When the farmers received US$2.5 /kg, the economic threshold was about 5 fruitworms/100 plants. When they received US$l/kg, the economic threshold increased to about 15 fruitworms/ 100 plants.

An economic threshold is rarely, if ever, static. It changes with changes in crop growth, level and cost of inputs (fertilizer, pesticide, labor, etc.), and outputs (yield, selling price of product). Subsidy programs (input subsidies or price supports) also affect the threshold level. Pesticide subsidies (Repetto 1985) can allow farmers to obtain pesticides at very low costs, or even free, lowering threshold levels.

For pest species that have low economic thresholds (such as the tomato fruitworm), pest monitoring must be sufficiently sensitive and conducted frequently enough to detect slight changes in pest density, to give farmers or extension agents ample warning to control a pest before it surpasses its economic threshold. Pest species with high economic thresholds may require less sensitive and less frequent monitoring. Regardless of the monitoring technique used, it must be inexpensive, easily understood, and easily implemented. Otherwise, farmers will resist using economic thresholds as part of their pest management strategy.

Further, the use of economic thresholds must result in a substantial increase in profit or farmers will tend to resist adoption. In the Philippines, use of economic thresholds in rice insect pest control programs increased farmer net returns an estimated 2.8-5.3%. That rate of return was not high enough to entice farmers into using the thresholds (Waibel 1988).

In other cases, use of economic thresholds may not be appropriate. With some pathogens, preventive treatments must be applied before the initial inoculum (spores, etc.) colonizes. Often weed control is best achieved through preventive, preemergence soil treatments rather than through postemergence treatments. In general, economic thresholds are used only to establish the need for postemergence herbicides.

## Effect of farmer perceptions

Efforts in crop loss assessment and the setting of economic thresholds are purely academic unless farmers use the end product. The farmers will resist applying economic threshold techniques that are difficult to understand or too expensive, or that do not lead to a good net return.

Farmer perceptions of pest problems and the potential benefits of controlling pests will determine whether economic thresholds are accepted or rejected (Kenmore 1987). These complex perceptions, influenced by economic background, level of education, experience, religious and cultural background, and many other factors, are especially difficult for outsiders to understand (Francis 1985).

## References cited

AID—Agency for International Development (1984) Integrated pest management (Project No. 596-0110). Project Paper, Regional Office for Central American Programs, AID/LAC/P-178. Washington, D.C.

Barker K R, Nusbaum C J (1971) Diagnostic and advisory services. Pages 281-301 *in* Plant parasitic nematodes. Vol. 1. B. M. Zuckerman, W. F. Mai, and R. A. Rhode, eds. Academic Press, New York.

Bottrell D G (1979) Integrated pest management. Council on Environment Quality, U.S. Government Printing Office, Washington, D.C. 120 p.

Bottrell D G, Adkisson P L (1977) Cotton insect pest management. Annu. Rev. Entomol. 22:451-481.

CEA—Council of Economic Advisors (1984) Economic report of the president. [Transmitted to the Congress, February 1984, together with the Annual Report of the Council of Economic Advisors.] U.S. Government Printing Office, Washington, D.C.

Francis C A (1985) Rationality of new technology for small farmers in the tropics. Agric. Human Values 2:54-59.

Herdt R W, Wickham T H (1978) Exploring the gap between potential and actual rice yields: the Philippines case. Pages 3-29 *in* Economic consequences of the new rice technology. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Hunter W D, Coad B R (1923) The boll weevil problem. Farmers' Bull. 1329. US. Department of Agriculture. Washington, D.C. 30 p.

IRRI—International Rice Research Institute (1989) Crop loss assessment. P.O. Box 933, Manila, Philippines.

Kenmore P E (1987) Crop loss assessment in a practical integrated pest control program for tropical Asian rice. Pages 225-241 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Palti J, Ausher R, eds. (1986) Advisory work in crop pest and disease management. Springer-Verlag, New York. 284 p.

Pedigo L P, Hutchins S H, Higley L G (1986) Economic injury levels in theory and practice. Annu. Rev. Entomol. 31:341-368.

Poche R M, Haque M E, Mian M Y, Sultana P, Karim M A (1981) Rice yield reduction by simulated rat damage in Bangladesh. Trop. Pest Manage. 27:242-246.

Reichelderfer K H, Bottrell D G (1985) Evaluating the economic and sociological implications of agricultural pests and their control. Crop Prot. 4:281-297.

Reichelderfer K H, Carlson G A, Norton G A (1984) Economic guidelines for crop pest control. Plant Production and Protection Paper 58. Food and Agriculture Organization, Rome. 93 p.

Repetto R (1985) Paying the price: pesticide subsidies in developing countries. Research Report 2. World Resources Institute, Washington. D.C. 27 p.

Shepard B M, Ferrer ER, Kenmore PE (1988) Sequential sampling of planthoppers and predators in rice. J. Plant Prot. Trop. 5:39-44.

Stem V M, Smith R F, van den Bosch R, Hagen K S (1959) The integrated control concept. Hilgardia 29:81-101.

Teng P S, ed. (1987a) Crop loss assessment and pest management. APS Press, The American Phytopathological Society, St. Paul, Minnesota. 270 p.

Teng P S (1987b) Quantifying the relationship between disease intensity and yield loss. Pages 105-113 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Teng P S, Krupa S V (1980) Assessment of losses which constrain production and crop improvement in agriculture and forestry. Proceedings of the E. C. Stakman commemorative symposium. University of Minnesota, Agricultural Experiment Station Miscellaneous Publication 7. St. Paul, Minnesota. 327 p.

Waibel H (1988) Some new aspects on economic thresholds in rice. J. Plant Prot. Trop. 5:31-37.

Walker P T (1987a) Measurement of insect pest populations and injury. Pages 19-29 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Walker PT (1987b) Methods of studying the relation between different insect population levels, damage and yield in experiments and surveys. Pages 97-104 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Walker PT (1987c) Quantifying therelationship between insect populations, damage, yield and economic thresholds. Pages 114-125 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Zadoks J C (1987) The concept of thresholds: warning, action and damage thresholds. Pages 168-175 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

## Notes

*Acknowledgments.* This is scientific article No. H-168, contribution No. 7948, of the Maryland Agricultural Experiment Station. Participation in the workshop was sponsored by the Consortium for International Crop Protection, Integrated Pest Management and Environmental Protection project, AID Contract No. DAN-4142-C-00-5122-00, Project No. 936-4142.

*Author's address:* D. G. Bottrell, University of Maryland/Consortium for International Crop Protection, Department of Entomology, College Park, Maryland 70749/USA.

*Citation information:* International Rice Research institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Crop loss assessment: a review of representative approaches and current technology

P.S.Teng

Crop loss information is generated by different groups in response to the needs of different clientele. This makes it important to define the operational environment for loss assessment. To help in decisionmaking, the type and quality of information generated must use methodology acceptable to both the end-user and those collecting the information. End-users of crop loss information include

- Researchers, who usually are interested in understanding the pest-loss relationship and being able to predict losses for formulating action thresholds.
- Public-sector extension and crop protection services technical support personnel and private-sector consultants, who usually are interested in where losses are occurring, their magnitude and significance, and how pests can be managed to make losses acceptable.
- Farmers, who basically are interested in the qualitative or quantitative effect of pests on yields of their crops; especially if they have been sensitized to needs-based control measures.
- Planners and legislators, who usually are interested in knowing if losses will affect the supply-demand situation of major commodities, their prices, etc., and whether they need to consider taking action to avert adverse public reaction.

Crop loss data can be generated using different methods; each method is dependent on the resolution of data required for decisionmaking. No single method for data collection has been generally accepted so far. For convenience, data collection methods are considered to be “direct” or “indirect.”

The methodology for crop loss assessment in temperate and tropical crops was reviewed recently (Teng 1986, 1987). Here I discuss the practical aspects of this methodology.

## Direct methods for data collection

The experiment/survey approach is perhaps the most direct and empirical approach for data collection in crop loss assessment. Van der Graaff (1981) has suggested that indirect methods be used to improve the reliability of direct methods and to provide data for cross-validation. The experiment/survey approach contains many elements of the scientific method as we know it today. The general strategy for using this approach requires

- Quantification of pathogen or disease.
- Collection of data to measure the disease-loss relationship.
- Modeling of the disease-loss relationship.
- Development and use of regional crop loss databases.

The following discussion of each element emphasizes the current situation and future needs.

## Quantifying pathogens and diseases

Fungal, bacterial, and viral pathogens commonly cause identifiable symptoms on plants which can be used to design a method of disease measurement. Nematodes usually have been quantified in terms of numbers per soil or plant unit.

In the context of loss assessment, quantification is essential for providing the pathogen or disease “descriptor” to be used in estimating the relationship between the pathogen or disease and yield or loss. Pathogen numbers may be related to the intensity of plant symptoms, which in turn is a visual indication of the stress imposed on the plant that results in measurable loss. The choice of a descriptor, therefore, should be made with some knowledge of yield physiology, to reflect the interaction between pathogen and yield. With nematodes, preplant nematode density is the descriptor most commonly used in describing the quantitative relationships of pathogen-yield loss (Barker and Olthof 1976).

Disease incidence is the proportion of plants infected in a population (usually is expressed as a percentage). Disease severity is the proportion of plant tissue infected. The Food and Agriculture Organization (FAO) has used disease intensity to mean either disease incidence or disease severity (Chiarappa 1981). Disease assessment is using an acceptable method to determine disease intensity in a population of plants. The methods used by plant pathologists for field disease assessment are disease keys, standard area diagrams, remote sensing, and population counts. Disease keys and standard area diagrams rely on comparing the severity found with a predefined key or series of diagrams depicting different degrees of severity. The severity assessment for a plant part, such as a leaf, includes infected area as well as any accompanying chlorosis or necrosis. Remote sensing has been successfully used in assessing with pests that cause total plant loss but has been only marginally successful with pests that affect only plant parts. Population counts, with the exception of nematodes, are not widely used to quantify plant diseases. The methodology for making nematode counts is well-established. However, with other types of pathogens, methods for pathogen or disease quantification have not achieved the same degree of standardization as methods for diagnosis (James and Teng 1979).

A problem in loss assessment is determining a representative mean value of the pathogen or disease in a cropping unit using the designated method of assessment. Recently it has been recognized that sampling for diseased populations is relatively less researched than sampling for pest incidence (Teng 1983). The distribution of a pathogen or disease in any spatial unit may be described mathematically as a frequency distribution with estimated parameters (e.g. normal or negative binomial). Preliminary indications of the type of distribution are obtained by examining the mean-variance ratio of the sample mean of disease intensity. Knowledge of the type of distribution in a field enables an economical sampling protocol to be designed that will result in a representative mean. Nematode populations commonly occur as clusters, suggesting that the pattern of taking samples from a field is important.

Recent use of microprocessor technology for disease measurements suggest that we may soon see more reliable methods used in the field. Pedersen (1985) has designed a portable, low-cost data acquisition system for measuring canopy reflectances. It can be used in determining the mean effect of a pest in terms of reduced crop vigor. IRRI is testing the use of this instrument in assessing the severity of rice tungro virus and leaf blast.

Lindow and Webb (1983) used a laboratory-based video image analysis unit to measure the area of infected leaf tissue and proportion of infection. They also have begun using portable video-cameras to tape images of diseased leaves in the field. The images are analyzed in the laboratory. Image analysis is routinely used to measure the root area of plants. It is conceivable that there will be developments allowing its use for counting nematodes in a sample.

## Collecting data to measure the disease-loss relationship

In the experimental phase of a disease-loss program, data are collected either from fields with natural epidemics or from experimental treatment plots established with different disease intensities (Teng 1985b).

*The single-tiller/single-plant method.* In any cropping area, fields can commonly be found with varying disease intensities within one season. Richardson et al (1975) used a single-tiller method to collect data for modeling the disease-loss relationship. Hundreds of tillers (shoots) are tagged, with care taken to select tillers reflecting a wide range of disease severities, including zero and maximum disease. Using a predefined survey procedure, disease intensity is assessed and tillers harvested in each field. Each tiller is a single datum point for regression analysis.

The single-tiller method is a derivation of the paired-plant method, in which pairs of healthy and diseased plants are tagged and observations made on both throughout the growing season. Advantages of the single-tiller and paired-plant methods are that both use natural epidemics and both are economical in labor, space, and time. However, the methods have mathematical limitations: models developed have only been able to explain a small proportion of the variation in yield due to disease (Richardson 1980).

Interplant differences in yield are a major source of variation in single-tiller/paired-plant studies. Hauet al (1980) improved on the method by using measurements of plant parts related to potential yield, but not affected by disease, to correct for differences in observed yield. That reduced some of the variation. Earlier literature frequently reported use of a paired-plant/tiller technique that uses pairs of healthy or diseased plants (Chester 1950).

*The synoptic method.* To determine the effect of multiple factors on wheat yield, Stynes (1980) developed a “synoptic” procedure that involved intensively sampling parts of farmers’ fields throughout the season. Variables measured included disease, insects, and nematodes and soil and water properties. Models were developed in which several factors combined to explain a significant proportion of the yield variation.

A more simple procedure to determine production constraints on farmers’ fields has been used by IRRI and in Colombia.

The synoptic method allows crop-loss profiles to be developed that show the contribution of each constraint in reducing attainable yield to actual yield. In the U.S., Wiese (1980) modified the procedure for field peas, but he found that the models developed were not stable across seasons.

A limitation common to both the single-tiller and synoptic methods is that the range of a disease severity may be so narrow that its importance as a yield constraint is underestimated.

*Field plot techniques.* Plots arranged in an experimental design, such as randomized complete block, are common in crop-loss work (Shane and Teng 1987). The plots maybe paired treatment or multiple treatment, with desired levels of disease or pathogen population. In crop loss assessment, the aim of treatment is to ensure that epidemics with different characteristics are generated; treatment methods may not be economical. In the paired-plot approach, healthy (protected) and diseased (unprotected or inoculated) plots are situated near enough to each other to constitute a replication, with the pairs repeated over many locations. In the multiple-treatment experiments, treatments range from healthy (no disease) to maximum disease. Levels of disease have been generated on cultivars with different susceptibilities but comparable potential yields by varying planting date, by using fungicides, by using isogenic lines, and by differential inoculation. Different nematode populations can be produced by growing hosts and nonhosts before the experiment is established, by inoculation, or by mixing infested soil into the plots (Teng 1985b).

An important consideration is plot size. Although nematologists usually use microplots, pathologists working with airborne pathogens have had to use larger plots because of the problem of interplot interference. In practice, when plot size is increased, there is a trade-off between reducing inherent yield variation and increasing the variation due to soil factors. In general, small plot size results in higher between-plot variation and requires a larger number of replications for any difference between two treatments to be detected.

Recently, the inability of standard experimental designs with replication to provide data that can explain the full range of interaction between crop yield, disease intensity, and crop development stage has been recognized. The relationship between yield loss and disease at different growth stages may be conceptualized as a three-dimension response surface. At each growth stage, disease-loss may be represented by curves like the inverse of the Seinhorst model (Teng and Gaunt 1980). To derive a holistic model of the three-dimension surface would require data from a wide range of epidemics—more than can be obtained with replicated experiments. Teng and Oshima

(1983) have argued for the use of response surface methodology, with its emphasis on treatment number rather than replication number, to provide the data needed for modeling disease loss.

The statistical techniques for modeling disease-loss relationship are such variance-reduction techniques as least-squares regression, which assumes that there is no or minimum variation in the independent variable (disease). With standard experimental designs, this assumption is violated when data are averaged across replications. With response surface designs, treatment values without variance may be obtained.

Experiments to model nematode population-loss relationships commonly focus on the initial nematode population (Barker et al 1985). This approach is in marked contrast to that in experiments involving fungal pathogens. With fungal pathogens, repeated assessments during the season are needed to determine the crop growth stage(s) most sensitive to disease. Perhaps the precision of nematode models could be improved if data on population levels during the cropping season were available.

## Modeling the disease-loss relationship

A mathematical model is a concise way of representing any system. The usefulness of crop-loss experimental data would be limited if the data were not reduced to a simple form. The disease-loss relationship takes many forms, and no universal mathematical model fits all the forms. Teng (1985a) has postulated nine possible shapes of the disease-loss curve. Further, the mathematical description of the relationship depends on the disease descriptor used (such as disease severity at one growth stage or area-under-the-disease progress curve). With nematodes, the log of nematode density is commonly used as the independent variable.

The majority of mathematical models describing the disease-loss relationship have been derived using least-squares regression techniques, although simulation modeling has been attempted recently. With regression models, some workers have suggested using several statistical criteria (F, r, s, and t) to evaluate each model.

Assumptions made in collecting the data for modeling need to be recognized and tested. For example, regression assumes that the variables show a normal distribution. This assumption is often violated in taking samples of disease incidence.

Empirical disease-loss models may be grouped into single-point, multiple-point, integral, response-surface, nonlinear, and synoptic models (Teng 1985a).

*Single-point models.* Single-point models relate loss to disease intensity at a specific time (a critical crop growth stage or a predetermined number of days into the growing season). With wheat stem rust, loss may be estimated from percent stem rust severity at the 3/4-berry stage (X) using the model

$$\% \text{ Loss} = -25.53 + 27.17 \ln X$$

Romig and Calpouzos (1970) identified the 3/4-berry stage as a time when the crop was most sensitive to rust. James and Teng (1979) have cautioned that fitting a single-point model to a data set does not imply that no other growth stages respond to disease, but rather that a particular stage shows good statistical correlation. It is often necessary to incorporate some physiological knowledge into regression models, to ensure that the models are biologically meaningful.

Another form of single-point model is one for estimating losses in potato due to late blight from the number of blight-free days. Olofsson (1968) used the model

$$\text{Yield (t/ha)} = 234.0 - 1.706X$$

where X = blight-free days.

Single-point models are the most common type of disease-loss model, primarily because they require relatively less data todevelop. However, their application appears restricted to short-duration, late epidemics with stable infection rates. This model type assumes that disease dynamics before and after the single point resembles that encountered in the original experiments.

*Multiple-point models.* Multiple-point models relate yield loss to several disease assessments during a crop's life. The disease descriptors used have been either disease increments during a defined period or disease intensities at specified growth stages. An example is the model for estimating wheat-yield loss due to leaf rust from three growth stages.

$$\%\ \text{Loss} = 5.3788 + 5.5260X_2 - 0.3308X_5 + 0.5019X_7$$

where $X_2$ = percent rust/tiller at boot stage, $X_5$ = percent rust on flag leaf at early berry stage, and $X_7$ = percent rust on flag leaf at early dough stage.

Burleigh et al (1972) found that even though they could determine several single-point models from the same data, the multiple-point model explained the most variation in yield loss due to rust. Multiple-point models are particularly suited for epidemics that are of long duration, have unstable infection rates, and affect more than one yield component.

*Integral models.* Integral models relate loss to a disease descriptor derived from summing disease intensities over a specified period of the crop. The idea may be attributed to Van der Plank (1963), who proposed using the area-under-disease progress curve (AUDPC) to analyze wheat stem rust data. An example is the model for estimating loss in cowpea due to *Cercospora* leaf spot (Schneider et al 1976):

$$\%\ \text{Loss} = 0.43\ \text{AUDPC} - 14.95$$

In general, AUDPC models cannot distinguish between late and early epidemics, since two progress curves with very different onset times and infection rates could give the same area under the curve. AUDPC models have been applied successfully with short-duration, late epidemics. Some workers have improved the predictive ability of AUDPC models by assigning weighting factors to the disease assessments made at different growth stages.

*Other models.* Teng and Gaunt (1980) conceptualized the relationship among disease, crop growth stage, and loss as a three-dimension response surface. The response surface may be generalized as

$$\%\ \text{Loss} = f\ (\text{Disease-crop stage})$$

Loss can be estimated if disease intensity and growth stage are known. Thus, response surface models may also be considered an integrated series of single-point models. Several workers have developed models fitting this concept. With rice blast, Torres and Teng (1988) considered leaf blast (X) and panicle blast (Z) as separate variables and determined a model for estimating yield loss (Y) as

$$Y = 0.2101 + 1.0124X + 0.5102Z$$

Substantially more data are required to develop response surface models than the other models discussed. This has led to the search for alternative ways of experimentation to collect data.

The majority of disease-loss models have assumed a linear relationship, but it is generally recognized that biological relationships may be nonlinear. Madden et al (1981) modified the Weibull Distribution Function, with its very flexible curve-fitting capabilities, for use on disease-loss relationships, and obtained good fits to data. An attempt also has been made to incorporate the dynamics of yield loss at different phenological stages into a single model by using the rate of yield gain at each instant of crop development as a function of disease (Shaw and Royle 1987).

Commonly, more than one model can be found to fit a set of experimental data from any disease-loss system. Although it is usually advisable to collect more data than necessary, because of the lack of prior knowledge on the form of the model, with some diseases and crops enough is known about yield physiology to enable postulation of potential relationships. This approach can help guide the design of experiments and pinpoint growth stages where it may be useful to have more treatments.

The intended use of a model is another consideration in determining the form of a model to use, whether it be single point or multiple point. In surveys where fields may be visited only once, several different single-point models would be needed. To forecast potential yield loss may require a multiple-point or integral model that can account for fluctuating rates of disease progress in response to such factors as fungicide application.

## Indirect methods of data collection

The experiment/survey method for collecting crop loss data is expensive and requires considerable resources in organization and infrastructure. Developing countries are often reluctant to spend their scarce resources on an activity not directly related to solving a pest control problem. Direct methods of data collection are rarely used. More common is derivation of crop loss estimates using the following indirect methods (Van der Graaff 1981, Zadoks and Schein 1979):

- Expert testimony. Knowledgeable scientists are asked to make a “statement of authority” on the extent of loss, based on their experience with the crop and diseases in an area.
- Inquiries. Estimates are solicited from a broad range of people concerned with the production of a crop in an area, to develop a consensus on the extent of loss. This approach resembles the “delphi” procedure used in research management.
- Literature reviews. Publications of work not specifically designed for loss assessments are evaluated for their value in providing estimates. Examples are multilocation fungicide and cultivar evaluation trials.

- Remote sensing. Satellite imagery is used in estimating crop area, crop yield, and crop losses. This technique has worked well for diseases that result in total plant loss, as with some nematode-caused diseases.
- Field experiments designed for other purposes.

## Using secondary data

*Pesticide trials.* The main objective of pesticide trials is to assess the efficiency of pesticides, and the rate and timing of their application. Occasionally, they can give information on the relationship between yield reduction and parasite or weed intensity. To obtain such data, different levels of parasite or weed intensity must be generated and these must be related to different levels of yield. Most trials also will give general data on yield reduction through comparing treated and untreated plots. The best crop loss data are derived from trials where complete protection is included as one treatment, where pesticides are used to keep one plot pest-free.

Some caution needs to be taken in accepting these data as being truly representative of the real situation, for the following reasons:

- Sometimes trials are made on specially chosen, susceptible varieties.
- Differences between cultivation methods in the trials and those farmers use could be substantial.
- Pesticide trials are often conducted in sites known for their high parasite or weed intensity.

The location, variety, and pest or disease situation should be representative of the area in which the crop is grown. The meteorological conditions also need to be considered. Qualifiers are needed to evaluate whether conditions of growth are normal or abnormal.

To improve the reliability of data from pesticide trials, the following additional information should be obtained:

- identification of parasite or weed against which the treatment is applied,
- experimental layout,
- quantitative data on assessment of disease/pest/weed intensity (including growth stage at which records are taken), and,
- obviously, yield data and statistical analysis.

Possible sources of data from pesticide trials (other than those published in journals) are chemical companies, research stations, and ministries of agriculture as part of their pesticide registration procedures. Obtaining these data may be difficult, because they are often confidential.

*Variety testing trials.* Often variety testing trials will show important differences in injury and losses caused by parasites. They might be used for establishing relationships between damage and yield. If a locally grown. popular cultivar is included in the tests, the damage-yield relation derived from the other cultivars may permit calculation of the yield loss suffered by local growers.

To determine the effect of the parasite on yield, it is necessary that the majority of the varieties should yield approximately the same under disease- or pest-free conditions.

As in pesticide trials, cultivation practices should not differ from those local farmers use. Plot locations should be representative of the area. Qualifiers are needed on meteorological conditions.

Data from variety trials should also indicate field layout, disease or pest intensity score, and growth stage(s) at which observations were made. Yield records and statistical analysis of yield data should be available. The sources of these data are exclusively research stations.

## Representative systems for loss assessment

### For research

Crop and pest observations are made daily in farming areas, for many different reasons. Extension agents may be visiting a field at the farmer's request, a researcher may be collecting disease-loss data, or a private consultant may be making a scheduled visit to determine whether a disease action threshold has been reached. If these different observations were integrated into a common data set (database), an extension agent, researcher, or consultant would be able to derive a more comprehensive picture of the crop-pest status in an area than he/she could on the basis of individual observations alone.

In the United States, recognition of this fact and the need to make better use of scarce resources have led to the development of many statewide programs for pest monitoring. Examples are the Cooperative Crop Monitoring Systems (CCMS) in Michigan and the MINPEST System in Minnesota (Teng 1984). These systems have many common features: a network for acquiring field biological and environmental data, a computerized system forhandling the data, and an information delivery system. The MINPEST System can illustrate the salient features of these systems.

MINPEST is a cooperative surveillance system involving the University of Minnesota and the Minnesota Department of Agriculture. The university's functions include research, extension, and teaching: the Department of Agriculture's are mainly regulatory. The system has been operating since 1980. In 1983, it involved private consultants and manufacturers in pest data collection.

In contrast to the Michigan CCMS. which relies on voluntary data collection by its users, MINPEST has its own group of field scouts who visit the same fields regularly each season. A stratified procedure is used to select each year's fields, to reflect the area under a crop type for each county.

In 1983, university scouts made weekly visits to 360 fields ofpotato, wheat, sugar beet, and edible beans. Field data were collected using standardized survey forms with a percentage scale as the basis for quantifying pest incidence or severity. In each field, 20 plants were examined from each of five areas to provide a field average for any pest or plant injury present. Crop growth stage was recorded on a numerical scale specific to each crop. In addition to the weekly data, field history and pesticide use history were collected.

The forms recording field data were sent to the MINPEST center at the university for entry into microcomputers. Programs written to minimize human error were used.

Because large amounts of data were generated each week. a database management system called SIR (Scientific Information System) was used on a CYBER mainframe computer to handle data from each field. Field disease averages were sent from the microcomputers to the mainframe computer as needed, using a standard telephone line and the same communications programs on both computers. Using microcomputers to store raw data reduced computer costs; using the mainframe computers enabled faster data summaries.

Each week, tables summarizing the field survey data were made available to extension and private industry personnel on a county-by-county basis, to aid in making decisions on control. A MINPEST participant with access to a computer terminal could be updated on the status of key pests in one or more counties of the state. Minnesota is approximately 580 km (360 miles) long. Knowing the disease intensities in the southern parts could help northern counties prepare for infestation.

Disease distribution or intensity data are easily summarzred and presented using features available in database management systems like SIR. In addition to tables, weekly maps can be drawn, using the computer to highlight areas of high infestation. These maps, like the data presented as tables, are easily stored in the computer and transmitted to remote sites by telephone.

The data from MINPEST can be used for crop loss research. For example, data from individual fields of the same crop may be subjected to multiple regression or principal components analysis to define crop loss profiles. These techniques enable the formulation of equations to explain the contribution of key production factors or constraints to the difference between actual yield in the farmers' fields studied and attainable yield.

Crop and pest surveillance data collected over several seasons enable the development of pest calendars which detail the average onset and duration of different parts of the life cycle of insects or pathogens. Pest calendars are used in Minnesota to increase the likelihood of detecting a pest by indicating when to intensify sampling for that pest. Surveillance data also have been used in research on the influence of specific cultural practices or crop history on epidemic development. For example, previous crop and rotation patterns were shown to be significant determinants of *Cercospora* leaf spot development in sugar beet fields in Minnesota (Shane et al 1985).

An exciting area of research made possible by large-scale data is production area analysis, leading to the delineation of risk zones for certain diseases (Coakley 1988). Data on potato early blight show that, in some Minnesota counties, the progress curves of epidemics in different fields are similar; in other counties, there is no relationship between progress curves. Where progress curves are similar, the number of sample sites may be reduced and still obtain an acceptable estimate of average severity for that county. Or one “indicator field” could be identified to reflect the whole county. Statistical techniques such as cluster analysis have been used to define areas with common pest problems, and the feasibility of regional pest forecasts has been determined.

## For national plant pest control and quarantine

*The National Pest Survey and Detection System, USA.* Recognition of the importance of large-area pest surveillance led to the development of a Cooperative National Plant Pest Survey and Detection Program (CNPPSDP) in the United States. The program, supported and managed by the U.S. Department of Agriculture Animal and Plant Health Inspection Service (APHIS), began its first operational season in 1982, with 13 states participating (Wallenmaier 1986). Its major goals are to detect new and exotic plant pests, monitor endemic plant pests, and facilitate export certification of plant products. Its basic rationale is that identification and quantification of endemics are essential for detecting exotic pests, and that the involvement of state survey programs would ensure maximum effort.

To meet its goals, the program has defined the following short-term objectives: to develop a nationwide computerized communications system for sharing pest data, facilitate adoption of standardized survey methodology, encourage interdisciplinary survey effort at the state level, and develop a pest-forecasting capability. In addition, the system aims at providing crop loss estimates for different pests.

As its name implies, CNPPSDP is a cooperative effort between APHIS and individual states. The program is coordinated in Hyattsville, Maryland. Nine area survey coordinators are responsible for two to six states and maintain liaison between the agency and state programs. The APHIS program provides a central computer at Fort Collins, Colorado, to process state crop and pest data.

Through its designated area survey coordinator, each state in the program is encouraged to develop an integrated database, using a standardized data format for transmission to Fort Collins. States are provided with some support funds to facilitate integration of different continuing surveys within the state.

In 1983, pest data were transmitted weekly April to September. During the 1984 cropping season, it was envisaged that any state would be able to query the central computer for a status report over the entire country of a specific pest during a certain week. In the future, this kind of system will enable active monitoring of key pests from one part of the country to another.

The current resolution of weekly data being sent the central computer is at a county level. Data on each site and pest are assigned an identification number to enable calculation of county averages. A numerical coding system is used for all data elements. In 1983, the data elements in each record were ID number, observation date, state, county, crop, crop growth stage, pest, pest life stage, abundance/incidence, damage/severity, and sample method. Diseases were quantified using a 1-5 scale for incidence and severity (e.g. with severity, 1 = none, 2 = trace, 3 = light, 4 = moderate, 5 = heavy). The rating scale was adopted as an interim standard for conversion of data from different states into a common form.

Teng (1983) and Teng and Shane (1984) pointed out that less-specific data resolution is needed for decisionmaking at the national policy level than for state organizations or individual farmers. They have suggested that it may be possible to formulate national policy on the basis of a 1-5 scale. A more detailed scale, such as the percentage scale, would be required for disease management decisions on farms.

As part of CNPPSDP, cooperative work was begun on a Pest Surveillance Methodology Information Database (PESMID) between the University of Minnesota and APHIS. PESMID contains about 468 published maize pest surveillance methods and is documenting unpublished methods used by states participating in the program. With this computerized system, an interested person anywhere in the United States, using a standard telephone access, can determine if a method already exists for dealing with some aspect of detection or survey of a pest.

It is too early to evaluate CNPPSDP's accomplishment of its objectives, but so far the program has acted as a catalyst and provided a forum for examining critically disease detection, disease assessment, and survey methodology (Teng 1984).

*Cereal survey programs in England and Wales.* A series of surveys on barley-foliage diseases initiated by James (1969) in England and Wales in 1967 and continued by King (1972, 1977a) probably provides the most convincing evidence of the usefulness of surveys. The first survey, in 1967, demonstrated the significance of powdery mildew and the probable need for chemical control measures previously considered unnecessary. Approximately 300 fields totaling 2.125 ha of spring barley were sampled and about 7,500 tillers were assessed for diseases on the flag leaf and second leaf at growth stage 11.1 (King 1980). Average severities are given below, with their associated standard errors.

| Disease | Lamina affected (%) |
|---|---|
| Mildew | 11.0 ± 0.6 |
| Brown rust | 4.3 ± 0.4 |
| Leaf blotch | 1.7 ± 0.2 |
| Yellow rust | 1.0 ± 0.2 |
| Halo spot | 0.1 ± 0.05 |

Loss due to mildew was estimated at 13-18% and total loss due to foliage diseases at 20-25%. A similar survey in the southwest of England the same season independently confirmed the importance of mildew (Melville and Lanham 1972). The usefulness of the barley survey has ensured its repetition every year (except for 1971). It also prompted the development of a similar annual survey on wheat in 1970 (King 1977b).

Since 1967, barley mildew has consistently caused significant losses. With the exception of 1970 and 1975, it was the most severe foliage disease recorded, despite increased use of mildew fungicides. During 1967-70, mildew was estimated to cause an average 9% loss (King 1972). Analysis of survey data led King (1977b) to conclude that in 1974 and 1975, at least 60% of the crops not treated could have been treated, to economic advantage.

In all the surveys on spring barley in England and Wales, a stratified random sampling procedure was used to select fields, with strata based on administrative regions. The number of fields sampled in each region was proportional to the barley area in the region. On farms with more than one barley field, the field sampled was selected randomly (James 1969). This facilitated computations of the national mean, due to equal weightings in each region.

Fifty tillers were removed at random along the diagonal of a field and dispatched to a central laboratory for assessment. A subsample of 25 flag leaves and 3-5 second leaves were assessed for disease. The remaining leaves were used for virus testing or race identification.

The disease data were punched directly onto computer tape and a specially written program was used for analysis. The detailed procedure is outlined by James (1969) and revisions reported by King (1972, 1977b). In the later surveys, Wales was oversampled to provide more accurate estimates. An additional growth stage was included in some samples for better mildew-loss estimation. King has utilized the more critical decimal code of Zadoks et al (1974) in recording growth stage.

The results of the winter wheat surveys in England and Wales for 1970-75 have been reported by King (1977a). *Septoria nodorum* was found the most severe leaf disease in all years except in 1970, when mildew was most severe, and in 1975, when brown rust (*Puccinia recondita*) was most severe. Estimation of yield losses has been hampered by the lack of disease-loss information. King estimated that for 1970-75, mildew caused an average 3% annual loss; *Septoria* caused 2% loss.

Both the barley and winter wheat surveys are now conducted annually, with continuous modification to provide comprehensive information on foliage and other foot-rot diseases.

Richardson (1971) has used a survey technique that determines yield directly in survey fields. The technique attempts to partition loss in yield due to different diseases and other constraint factors at different growth stages. For each crop, the seedling population is checked and final yield as well as three yield components—ears per plant, seeds per ear, and seed weight—aredetermined from a sample of ears. Richardson reported that three yield component potentials are estimated:

- Potential ear population from the particular seedling population,
- Potential yield from the actual ear population, and
- Potential yield from the potential ear population.

These three estimates are used in conjunction with actual yield to calculate the following losses:

- The differences between potential yield from the seedling population and that from the actual ear population is considered a loss due to ear deficiency.
- The difference between potential yield from the actual ear population and actual yield is a loss due to a deficiency in seed number per ear or in seed size.
- The total loss is the difference between the potential yield from the seedling population and the actual yield, with the addition of losses due to nonfunctional ears.

An example for a particular crop is shown in Table 1 (after Richardson 1971). Richardson's method aims at estimating losses within the total production system. The approach is claimed to be successful, despite the problems of estimating potential yield.

**Table 1. Calculating wheat yield (cv. Cappelle Desprez) loss from survey data (after Richardson 1971).**

| Populations (millions per acre) | | | |
|---|---|---|---|
| Seedlings | 1.26 | | |
| Potential ear | | 2.41 | |
| Actual ear | 1.02 | | |
| Yield - cwt per acre (t/ha) | | | |
| Potential from potential ear population | | | 114 (14.3) |
| Potential from actual ear population | | 42 (5.3) | |
| Actual | 40 (5.0) | | |
| Losses (%) | | | |
| Ear deficiency | | 114 - 42 = | 63% |
| Nonfunctional ears | | = | 0.4% |
| Deficiencies of seed number and size | | 42 - 40 = | 4.4% |
| Total | 114-0.4-0.4 = 65% | | |

## For research, extension, and planning

Crop losses due to plant diseases and nematodes represent a significant constraint on crop production in North Carolina. Annual estimates of the magnitude and fluctuation of disease losses are useful to a wide range of users, including research project leaders, extension workers, administrators, granting agencies, the agricultural news media, and others. The North Carolina State University (NCSU) offers a unique system that compiles annual estimates of crop losses using data from many different sources (Main and Gurtz 1989). Loss estimates are given a confidence rating dependent on the collection method, then disseminated to end users.

The initial thrust for developing the system was through a pilot project funded by the National Crop Loss Assessment System Committee (USDA/CSRS) and the National Agricultural Pesticide Impact Assessment Program. A standing committee in the NCSU Department of Plant Pathology is charged with estimating crop losses and compiling and reporting annual crop loss estimates due to plant diseases and nematodes. The objective is to provide information on disease losses to the agricultural community. As the database accumulates over sufficient years, trend analysis and computer-assisted mapping techniques will be used to document patterns of disease loss distribution and temporal changes in disease problems.

The committee assigns a coordinator for each crop, who consults colleagues with knowledge of the disease problems on that particular crop. Together, they arrive at estimates of disease incidence in the state (percent acreage affected by the disease) and crop value reduction. Value reduction includes the potential crop not harvested in the current year, the portion of the crop harvested that must be discarded, and/or the reduction in crop value due to lower quality product because of damage by a particular disease. The estimates are based onresults from research plots and sample surveys and on professional opinions of specialists and county extension agents. Each estimate is assigned a confidence rating: 1 = confident (i.e. actual disease measurements made through surveys or research tests); 2 = reliable (i.e. estimate was based on knowledge of the crop in relation to general distribution and severity of the disease); 3 = indicative (i.e. the estimate is an educated guess).

As the harvest is completed each fall, the coordinators record their estimates on standard data forms. Both disease losses and chemical control information are requested, in writing, and coded. Necessary details of procedure and codes are provided in an instruction workbook.

The records are reviewed, edited, and processed using the North Carolina Crop Loss System computer-assisted program. A tabular output lists disease losses by crop and pathogen. Supplementary information on crop reproduction statistics and summary tables also are generated.

To avoid the problem of accounting for disease losses twice, crop production values are adjusted upward within the computer algorithm by a percentage equal to the sum of individual disease loss percentages for that crop. This provides a potential value for the crop if no diseases occurred. Losses due to pathogen damage are calculated by multiplying the potential crop value by the percent loss for each disease.

Table 2 contains the 1988 statistics for alfalfa: production, loss, and control cost estimates for each disease and estimates of total loss. The production statistics were derived from numerous sources (North Carolina Crop and Livestock Reporting

**Table 2. Disease losses in North Carolina corn fields (Main and Gurtz 1989).**

| Disease and organism | Crop yield loss | | Total control expenses (US$) | Total losses plus expenses (US$) |
|---|---|---|---|---|
| | % | Value (US$) | | |
| Aflatoxin | | | | |
| *Aspergillus flavus* | 1.00 | 2,584,144 | 0 | 2,584,144 |
| Air pollution | | | | |
| Ozone | 2.00 | 5,168,289 | 0 | 5,168,289 |
| Anthracnose | | | | |
| *Colletotrichum graminicola* | 0.40 | 1,033,658 | 0 | 1,033,658 |
| Gray leaf spot | | | | |
| *Cercospora zeae*- Maydis | 0.10 | 258,414 | 0 | 258,414 |
| Maize chlorotic dwarf | | | | |
| Maize chlorotic dwarf virus | 0.10 | 258,414 | 0 | 258,414 |
| Maize dwarf mosaic | | | | |
| Maize dwarf mosaic virus | 0.02 | 51,683 | 0 | 51,683 |
| Nematode(s) | | | | |
| No name given | 2.50 | 6,460,361 | 3,459,572 | 9,919,933 |
| Smut | | | | |
| *Ustilago zeae* | 0.10 | 258,414 | 0 | 258,414 |
| Southern leaf blight | | | | |
| *Bipolaris maydis* | 0.10 | 258,414 | 0 | 258,414 |
| Stalk rot | | | | |
| *Gibberella zeae* | 1.00 | 2,584,144 | 0 | 2,584,144 |
| Stalk rot | | | | |
| *Fusarium moniliforme* | 3.50 | 9,044,505 | 0 | 9,044,505 |
| Total | 10.82 | 27,960,440 | 3,459,572 | 31,420,012 |

**Table 3. Summary of 1988 crop losses in North Carolina (Main and Gurtz 1989).**

| Category | Estimated damage (%) | Value of loss (US$) |
|---|---|---|
| Fungus | 5.59 | 191,844,206 |
| Abiotic, pollutant | 4.76 | 96,685,690 |
| Nematode | 2.46 | 79,125,511 |
| Virus | 3.60 | 77,003,172 |
| Physiological | 8.17 | 6,925,012 |
| Bacterium | 1.83 | 24,919,351 |
| Complex | 0.89 | 1,071,864 |
| Undetermined | 0.99 | 17,508,315 |
| Abiotic, chemical | 1.94 | 2,769,553 |
| Mycoplasma | 1.00 | 150,573 |
| Total | | 498,003,247 |

Service, Agricultural Economics Extension, Horticultural Extension, Plant Pathology faculty).

The body of the table contains three categories of loss estimates: dollar loss due to disease, control costs associated with chemical pesticides, and total loss (crop losses plus control costs). For each loss estimate category, total dollar value loss, dollar loss per acre, and equivalent number of production acres lost (based on total dollar lost divided by the average income per acre) are computed. Note that the control cost per acre calculation differs from calculations used to generate disease and total dollar loss per acre. The control cost per acre is based only on those acres treated with pesticides; disease and total (disease + control cost) loss per acre are based on total acreage for the crop (total dollar losses per acre = disease loss value per acre averaged over all acres + control costs per acre averaged over all acres). The NCSU system also prepares loss estimates for different types of stress (Table 3). Each statistic is summed over all diseases to give summary loss figures for the crop. Estimates were compiled on 83 crops attacked by 189 pathogens. In 1988, losses were estimated at $498,003,246 (Table 3).

## Conclusion

Crop loss assessment is common in the temperate cropping systems of industrialized countries. In tropical rice-based systems, it is are relatively new activity. However, the need for accurate estimates of crop losses due to key pests has been expressed in many international forums in the economically less developed countries, such as the workshop on which these proceedings are based and the 1988 Southeast Asian Regional Workshop on Pesticide Management and IPM (Teng and Heong 1988). It is hoped that, with increasing interest and effort, more literature on this topic pertaining to the tropics will become available soon.

## References cited

Barker K R. Olthoff T H A (1976) Relationships between nematode population densities and crop responses. Annu. Rev. Phytopathol. 14:327-353.

Barker K R, Schmitt D P, Imbriani J L (1985) Nematode population dynamics with emphasis on determining damage potential to crops. Pages 135-148 *in* An advanced treatise on *Meloodogyne.* Vol. II. K. R. Barker, C. C. Carter, and J. N. Sasser, eds. North Carolina State University Graphics, Raleigh.

Burleigh J R, Roelfs A P, Eversmeyer M G (1972) Estimating damage to wheat caused by *Puccinia recondita tritici.* Phytopathology 62:034-946.

Chester K S (1950) Plant disease losses: their appraisal and interpretation. Plant Dis. Rep. (suppl.) 193:189-362.

Chiarappa L, ed. (1981) Crop loss assessment methods. Supplement 3. Food and Agriculture Organization/Commonwealth Agricultural Bureaux, Slough, England.

Coakley S M (1988) Variation in climate and prediction of disease in plants. Annu. Rev. Phytopathol. 26:163-181.

Hau B, Kranz J, Dengel H J, Hamelink J (1980) On the development of loss assessment methods in the tropics. Pages 254-261 *in* Crop loss assessment. Miscellaneous Publication No. 7. Agricultural Experiment Station, University of Minnesota.

James W C (1969) A survey of foliar diseases of spring barley in England and Wales in 1967. Ann. Appl. Biol. 63:253-263.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Appl. Biol. 4:201-267.

King J E (1972) Surveys of foliar diseases of spring barley in England and Wales 1967-70. Plant Pathol. 21:23-35.

King J E (1977a) Surveys of diseases of winter wheat in England and Wales 1970-75. Plant Pathol. 26:18-20.

King J E (1977b) Surveys of diseases of spring barley in England and Wales 1972-75. Plant Pathol. 26:21-29.

King J E ( 1980) Cereal survey methodology in England and Wales. Pages 123-133 *in* Crop loss assessment. Miscellaneous Publication No. 7. Agricultural Experiment Station. University of Minnesota.

Lindow S E, Webb R R (1983) Use of digital video image analysis in plant disease assessment. Phytopathology 73:520-524.

Madden L V, Pennypacker S P, Antle C E. Kingsolver C H (1981) A loss model for crops. Phytopathology 71:685-689.

Main C E, Gurtz S K, eds. (1989) 1988 estimates of crop losses in North Carolina due to plant diseases and nematodes. Department of Plant Pathology Special Publication No. X. North Carolina State University, Raleigh, North Carolina.

Melville S C, Lanham C A (1972) A survey of leaf diseases of spring barley in South-west England. Plant Pathol. 21:59-66.

Olofsson B (1968) Determination of the critical injury threshold for potato blight *Phytophthora infestans* ). Medd. Waxtskyddsanst Stockholm 14:81-93.

Pedersen V R (1985) Design and operation of a multispectral radiometer and digital data acquisition system. Research Reporter 104. North Dakota State University, Agricultural Experiment Station, Fargo, North Dakota.

Richardson M J (1971) Yield losses in wheat and barley - 1970. Scot. Agric. 50:72-77.

Richardson M J (1980) The use of survey data to quantify and partition crop loss into its component causes. Pages 176-185 *in* Crop loss assessment. Miscellaneous Publication No. 7. Agricultural Experiment Station, University of Minnesota.

Richardson M J, Jacks M, Smith M (1 975) Assessment of loss caused by barley mildew using single tillers. Plant Pathol. 24:21-26.

Romig R W, Calpouzos L (1970) The relationship between stem rust and loss in yield of spring wheat. Phytopathology 60:1801-1805.

Schneider R W, Williams R J, Sinclair J B (1976) Cercospora leafspot of cowpea: models for estimating yield loss. Phytopathology 66:384-388.

Shane W W, Teng P S (1987) Generating the database for disease-loss modeling. Pages 82-89 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society, St. Paul.

Shane W W, Teng P S, Lamey A, Cattanach A (1985) Management of Cercospora leafspot of sugarbeets: decision aids. North Dakota Farm Res. 43:3-5.

Shaw M W, Royle D J (1987) A new method for disease-loss studies used to estimate effects of *Pyrenophora teres* and *Rhynchosporium secalis* on winter barley yields. Ann. Appl. Biol. 110:247-262.

Stynes B A (1980) Synoptic methodologies for crop loss assessment. Pages 166-175 *in* Crop loss assessment. Miscellaneous Publication No. 7. Agricultural Experiment Station, University of Minnesota.

Teng P S (1983) Estimating and interpreting disease intensity and loss in commercial fields. Phytopathology 73:1587-1590.

Teng P S (1984) Surveillance systems in disease management. FAO Plant Prot. Bull. 33:51-60.

Teng P S (198Sa) Construction of predictive models: II. Forecasting crop losses. Adv. Plant Pathol. 4:179-206.

Teng P S (1985b) Crop loss assessment methods: current situation and needs. Pages 149-158 *in* An advanced treatise on Meloidogyne. Vol. II: Methodolog. K. R. Barker, C. C. Carter, and J. N. Sasser, eds. North Carolina State University Graphics. Raleigh.

Teng P S (1986) Crop loss appraisal in the tropics. J. Plant Prot. Trop. 3:39-50.

Teng P S, ed. (1987) Crop loss assessment and pest management. American Phytopathological Society, St. Paul. 270 p.

Teng P S, Gaunt R E (1980) Modelling systems of disease and yield loss in cereals. Agric. Syst. 6:131-154.

Teng P S, Heong K L, eds. (1988) Pesticide management and integrated pest management in Southeast Asia. Consortium for International Crop Protection, College Park, Maryland.

Teng P S, Oshima R J (1983) Identification and assessment of losses. Pages 69-81 *in* Challenging problems in plant health. T. H. Kommedahl and P. H. Williams, eds. American Phytopathological Society, St. Paul.

Teng P S, Shane W W (1984) Crop losses due to plant pathogens. Crit. Rev. Plant Sci. 2(1):21-47.

Torres C Q, Teng P S (1988) Path coefficient analysis on the effects of blast on rice growth, yield components and yield loss. Paper presented at the Annual Convention of the Pest Control Council of the Philippines, May 3-7 1988, Cebu City.

Van der Graaff N A (1981) Increasing the reliability of crop loss information: the use of indirect data. Pages 65-69 *in* Crop loss assessment methods. Supplement 3. L. Chiarappa, ed. Food and Agriculture Orgnization/Commonwealth Agricultural Bureaux, Slough, England.

Van der Plank J E (1963) Plant diseases: epidemics and control. Academic Press, New York. 216 p.

Wallenmaier T E (1986) Development of the computerized state-federal pest reporting system. Plant Dis. 70:365-367.

Wiese M V (1980) Comprehensive and systematic assessment of crop yield determinants. Pages 262-269 *in* Crop loss assessment, Miscellaneous Publication No. 7. Agricultural Experiment Station, University of Minnesota.

Zadoks J C, Chang T T, Konzak C F (1974) A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

Zadoks J C, Schein R D (1979) Epidemiology and plant disease management. Oxford University Press, New York.

## Notes

*Author's address:* P. S. Teng, International Rice Research Institute, P.O. Box 933 Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933. Manila, Philippines.

# Current knowledge on crop losses in tropical rice

P. S. Teng, C. Q. Torres, F. L. Nuque, and S. B. Calvero

Few current estimates of actual field losses caused by pests in farmers' fields have been derived from direct field surveys. The generalized figures for crop losses in rice most often quoted are from Cramer (1967). His analysis showed losses of the following magnitude:

Losses due to all insects = 34.4%
Losses due to all diseases = 9.9%
Losses due to all weeds = 10.8%
Potential production harvested = 44.9%
Total potential production lost before harvest = 55.1%

On average, more was lost to pests than was harvested.

Although at first glance, Cramer's figures appear to be high, others have found no good evidence to the contrary (Ahrens et al 1982, Barr et al 1977, Edens and Haynes 1982), and have felt that the figures may even underestimate actual losses. Cramer's estimates remain, by default, the most authoritative, generalized estimates of loss, until an attempt is made to involve national crop protection programs in tropical Asia in collecting data more systematically.

Ahrens et al (1982), using data from pesticide evaluation trials over 12 yr, found that losses due to insects in East and Southeast Asia were 23.7%. Other generalized estimates of losses to insects are 35-44% for tropical rice (Pathak and Dhaliwal 1981). 35% in India (Way 1976), and 16-30% in the Philippines (Way 1976). Alam (1961) estimated that 6% of the total 1951 rice crop in Bangladesh was lost to insects. Fernando (1966) estimated average annual losses due to insects in Sri Lanka at 10-20%. Litsinger et al (1987) estimated that losses due to chronic pests (i.e. non-outbreak levels) were 18.3% of potential production. Moody (1982) estimated that weed losses in the Philippines ranged from 11 to 65%. No recent reports of estimated losses due to all diseases were found in a computerized literature search.

## Specific pest losses

### Stem borers

Rice stem borers, considered by many entomologists the most serious of insect pests (Barr et al 1975), consist of a group of some five species. Some loss estimates are as follows:

| | | |
|---|---|---|
| Bangladesh (Outbreak year) | - | 30-70% (Alam et a1 1972) |
| (Non-outbreak year) | - | 3-20% (Alam 1967) |
| India | - | 3-95% (Ghose et al 1960) |
| Indonesia | - | up to 95% (Soenardi 1967) |
| Malaysia (North Krian District) | - | 33% (Wyatt 1957) |

### Leaf and planthoppers

It is difficult to separate losses caused by leafhoppers alone from losses caused by the viruses they transmit. Some estimates of losses are

| | | |
|---|---|---|
| Bangladesh (leafhoppers) | - | 50-80% (Alam 1967) |
| Malaysia (brown planthopper) | - | M$ 10 million (Lim et al 1980) |
| India (BPH) | - | 1.1-32.5% (Jayaraj et al 1974) |

### Other insects

Apart from stem borers and hoppers, little consistent data exist on average losses from other insect pests. Rice bugs (*Leptocorisa* spp.) were reported to have caused a 10% loss in some 3 million ha in India in 1952 (Pruthi 1953). According to Reddy (1967), larvae of gall midge *Pachydiplosis oryzae*) that occurred at outbreak level: some years have caused 12-35% losses in India (1934) and 50-100% in Vietnam (1922), and severe losses in Sri Lanka (1951) and Burma (1934).

Rice hispa *Dicladispa armigera* has been reported to cause losses of 10-65% in Bangladesh; about l0,000 ha in Bihar, India, commonly suffer up to 50% loss (Bar et al 1975).

Of the remaining rice pests, leaffolders are reported to cause field losses of as much as 50% (Balasubramaniam et al 1973), and armyworms are reported to have devastated about 10,000 ha of rice in Malaysia in 1967 (Dunsmore 1970).

### Blast

Although in general, blast is considered an important disease, capable of causing severe losses (up to l00%), little information can be found on the extent and intensity of actual losses in farmers' fields. Padmanabhan (1965) reported that some states in India suffered a 1% overall loss in 1960-61, with a range of 5-10%. In temperate rice environments such as Japan and Korea, losses due to blast have been reported as 3% (Japan, 1953-60) and at epidemic levels (Korea, mid-1970s), despite extensive fungicide use. In mainland China, losses due to blast were estimated at 8.4% in 1980 and 14.0% in 1981 (Teng 1986). Yield loss was estimated at 50-60% in several thousand hectares of land planted to Peta in the provinces of Leyte and Southern Leyte, Philippines, in 1963 (Nuque 1963, Nuque et al 1983). In a blast outbreak in Laguna and Quezon in 1969-70, yield losses of cultivars BPI-76 and C4-63 were 70-85% (Nuque 1970).

### Tungro

In recent years, rice tungro virus (RTV) has become a problem in many tropical environments, because of the potential of the disease to cause total loss and because of the lack of effective, corrective measures once symptoms are observed by farmers. Surveys conducted after disease outbreaks in Malaysia showed only localized damage: when losses were averaged over production regions, average loss was less than 1% in 1981-84 (Heong and Ho 1987). Chang et al (1985) estimated RTV-induced losses in 17,628 ha affected in Malayaia in 1982 at M$21.6 million.

RTV caused total crop loss on about 21,000 ha in Indonesia in 1969-71, 40-606 loss in Bangladesh, and about 50% loss in parts of Thailand (Reddy 1973, Wathanakul and Weerapat 1969). In the Philippines in the 1940s, red disease *accep na pula* (probably RTV) caused annual losses of about 30%, equivalent to 1.4 million t of rough rice a year (Serrano 1957). In 1971, yield losses due to tungro in the Philippines were estimated at 456,000 t of rough rice (Ling et a1 1983).

## Bacterial blight

Bacterial blight is one of the major diseases of rice in many rice-growing areas of the world. Losses caused by the disease have been related to the increased use of nitrogen-responsive and high-yielding varieties in some countries. In recent years in Japan, 300,000-400,000 ha of riceland have been affected annually. Losses in severely infected fields range from 20 to 30%, and occasionally may reach 50%. In tropical Asia (India, Indonesia, Philippines), losses are higher than in Japan. However. reports on yield losses are scanty. Yield losses vary from 6 to 60% in some states of India (Srivastava 1967). Losses in different varieties grown in India vary from 6-7% in IR20 to 58% in TN1 and 74% in Bala (Rao and Kauffman 1977). In mainland China, losses due to bacterial blight were estimated at 6% in 1980 and 4.9% in 1981 (Teng 1986).

## Sheath blight

Sheath blight (ShB) has assumed economic importance in the last two decades, since modem, semidwarf nitrogen-responsive cultivars were introduced. Reports on actual yield losses in farmers' fields are few. In Japan, a loss of 24,000-38.000 t of rice annually was estimated by the National Institute of Agricultural Sciences in 1954. Yield reductions equivalent to 20% (Mizuta 1956) or 25% (Hori 1969) may be incurred if the disease develops and reaches the uppermost flag leaves. Ou and Bandong (1976; also IRRI 1976) reported 7.5-22.7% loss in high-N plots planted to a susceptible variety and 0.4-8.8% and 2.5- 13.2% loss for moderately resistant varieties. ShB prevalence in the field was estimated at about 10% of rice tillers in one district of Sri Lanka (Abeygunawardane 1966). Data from mainland China suggest that average losses due to ShB were 12.6% in 1980 and 9.1% in 1981 (Teng 1986).

## Brown spot

The Great Bengal Famine of 1942-43 in India was attributed to an epidemic of brown spot: yield reductions of as much as 80% probably were common (Padmanabhan 1973). More recent epidemics in India have resulted in 14-41% losses in high-yielding varieties (Vidyasekaran and Ramados 1973). Because the disease is associated with adverse soil conditions, it is not always possible to partition yield losses due to the disease from other factors that reduce yield.

### Other diseases

Much less data are available on field losses caused by other diseases, although, given favorable conditions, most pathogens have the potential to cause severe losses. Of the remaining important diseases in tropical rice, stem rot has been reported to cause losses of 5-10% annually in parts of India (Chauhan et al 1968). In the Philippines, losses have been estimated at 30-80% in Tarlac Province (Hernandez 1923). In Arkansas, USA, annual average yield loss was reported to be 16,000-35,000 t (Ou 1985).

Reports of yield losses due to nematodes are scanty. Losses due to white tip have been estimated at 30-35% in Japan (Yoshii and Yamamoto 1950) and 40-50% on artificially inoculated susceptible cultivars in USA (Atkins and Todd 1959). Reduction in grain yield in Taiwan ranged from 29 to 46% in 10 cultivars surveyed (Hung 1959).

Yield losses due to ufra or stem nematode in limited areas have been estimated at 50% in Uttar Pradesh, India (Sing 1953), 20-90% in Thailand (Hashioke 1963), and 30% in West Bengal, India (Pal 1970).

Almost no reports exist on losses caused by individual weed species.

## Rice pest-loss relationships

Current knowledge on various aspects of crop loss assessment has been the subject of some recent publications (Chiarappa 1971, 1981; James 1974; James and Teng 1979; Teng 1987; Teng and Krupa 1980). This section documents specific methods for estimating losses in farmers' fields from assessments of pest intensity in a field. Methods are only for tropical rice, those specifically developed for temperate rice are mentioned only for comparison. In general, much more work on developing methods to relate pest intensity to yield loss has been done on temperate rice.

### Rodents

A method used in the Philippines during 1970-72 (Swink et al 1972) calculated percent loss as

$$\text{Percent damage} = (a*b)/c$$

where $a$ = total number of damaged hills, $b$ = total number of damaged tillers, and $c$ = total number of tillers examined. The National Bureau of Plant Industry sampled one barrio per 10,000 ha of lowland rice per province and ten paddies for each barrio.

A more recent method developed by the National Crop Protection Center of the Philippines (Tuazon 1979) calculated loss from

Percent yield loss = 0.2023* (% cut tillers at 6 wk after transplanting [WT])
or = 0.4631* (%cut tillers at 10 WT)
or = 0.7239* (% cut tillers at 14 WT).

### Stem borers

Many attempts have been made to estimate yield loss due to stem borers from incidence of infested tillers. Some early work by Wyatt (1957) in Malaysia found that, for each 1% increase in stem borer infestation, yield was decreased 1.3%.

At Cuttack, India, corresponding relationships reported (Israel and Abraham 1967) were

1% increase in stem borers = 0.28% yield loss at the vegetative stage

1% increase in stem borers = 0.62% yield loss at heading

IRRI data (Israel and Abraham 1967) showed that

1% increase in deadhearts = 1.6% yield loss

1% increase in whiteheads = 2.2% yield loss

Catling et al's (1978) work in Bangladesh found the following relationship for *Scirpophaga:*

$$\text{Yield} = 100 - 11.6^{*} (\log \% \text{ deadhearts})$$

Gangwar et al (1986) used surveys to develop equations for estimating losses due to yellow stem borer in West Bengal, India. The authors distinguished between dwarf and tall varieties, as follows:

For dwarf varieties,

$$\text{Yield (t/ha)} = 4.947 - 0.289^{*} (\% \text{ deadhearts})$$

For tall varieties,

$$\text{Yield (t/ha)} = 3.354 - 0.122^{*} (\% \text{ deadhearts})$$

**Leaffolders**

$$\begin{aligned}\text{Percent unfilled grains} &= 13.3005 + 0.2276^{*} (\% \text{ leaf area eaten at tillering})\\ \text{or} &= 9.87.58 + 0.4522^{*} (\% \text{ damage to flag leaf}\\ &\qquad \text{at maximum tillering})\end{aligned}$$

(after Murugesan and Chelliah 1983).

## Blackbug

$$\begin{aligned}\text{Percent yield loss} &= 18.48 + 2.14^{*}\ 28 \text{ d after transplanting (DT)}\\ \text{or} &= 9.53 + 1.58^{*}\ 42 \text{ DT}\\ \text{or} &= 4.68 + 0.85^{*}\ 56 \text{ DT}\end{aligned}$$

(Mochida et al 1986).

## Whorl maggot

For protected rice, where % damage = 0-10,

$$\text{Yield (t/ha)} = 6.13 - 0.795^{*} (\% \text{ damaged leaves/20 hills})$$

For unprotected rice, where % damage is 11,

$$\text{Yield (t/ha)} = 6.4.5 - 0.13^{*} (\% \text{ damaged leaves/20 hills})$$

(IRRI Entomology Department, unpublished data).

## Gall midge

It was estimated in India (Reddy 1967) that

1% increase in gall midge level = 0.5% yield loss

## Blast

Padmanabhan (1965) gave several equations for estimating losses in India; the following two are the most practical:

For susceptible variety,

$$1\% \text{ neck blast} = 0.98\% \text{ loss}$$

For resistant variety,

$$1\% \text{ neck blast} = 0.40\% \text{ loss}$$

In an unrelated study in India, Mathur et al (1964) used a susceptible variety to evolve the following equation:

$$\text{Percent yield loss} = -0.7895 + 0.4474 * (\% \text{ incidence of tillers with node/neck infection})$$

Expressed in the manner of Padmanabhan (1965),

$$\% \text{ neck blast} = 0.45\% \text{ loss}$$

In an authoritative study in Japan, Goto (1963) elucidated yield loss from panicle blast, leaf blast, and leaf blast followed by panicle blast. However, the only equation he presented was the following:

$$\text{Percent yield loss} = 0.69 * (\% \text{ blasted panicles}) + 0.28.$$

Goto presented data that could be used to determine regression equations for loss due to leaf blast. The results of those analyses gave the following:

$$\text{Percent loss} = 3.24 + 6.31 * (\% \text{ leaf blast at 25 d before heading})$$

$$\text{Percent loss} = 12.56 + 2.32 * (\% \text{ leaf blast at 15 d before heading})$$

Both equations had highly significant $F$ and $r$ statistics.

Neck blast in Japan (Katsube and Koshimizu 1970) was estimated using the following equation:

$$\text{Percent loss} = 0.57 * (\% \text{ blasted nodes, 30 d after heading})$$

Recent studies at IRRI have confirmed that yield losses caused by the same blast intensities differ between leaf blast and panicle blast (IRRI 1987, Torres and Teng 1988). A rule-of-thumb for leaf blast before panicle exsertion is that 1% blast will cause 1% yield loss. For panicle blast, the rule is 1% blast incidence for 0.5% loss. Empirical data led to the determination of a single equation for estimating loss from percent leaf blast severity $L$ ) and percent panicle blast incidence ($P$):

$$\text{Loss} = 0.2101 + 1.0124L + 0.5102P$$

with 80% of the yield variability explained by the two variables (Torres and Teng 1988). Blast severity usually is more difficult to assess than incidence. Surin et al (1988) developed an equation for estimating severity from incidence, as follows:

$$\% \text{ average severity of top four leaves} = 0.272 + 0.193X - 0.012X^2$$

where $X$ is % incidence of blast on leaf 4. The equation could be used by field scouts in conjunction with a loss equation, using severity as the dependent variable.

## Rice tungro virus

RTV is known to cause differential losses in rice, depending on the duration and onset of infection (Reissig et al 1986). Although many studies have been conducted, most are useless for actual estimation of loss in the field. For example, data in the IRRI publication *An illustrated guide to integrated pest management in rice in tropical Asia* showed that delaying infection onset from about 10 d after sowing to about 75 d reduced losses from 70 to 5%. Yet the measurement of RTV intensity (either incidence or severity) required to cause corresponding loss is not known. In a similar study in India using a susceptible variety, yield losses were 83.3% with infection occurring at 30 DT, 74.1% at 45 DT, 59.3% at 60 DT, and 40.7% at 75 DT (John and Ghosh 1980).

A critical point model developed by Valencia and Mochida (1985) estimated yield reduction from a potential uninfected crop as follows:

$$\text{Yield (t/ha)} = 4.04 - 0.04^{*}\ (\%\ \text{infected hills at 40 DT})$$

In a recent study at IRRI, individual tungro-infested hills in close proximity to healthy plants were selected and labeled. Symptom severity and height of infected plants and healthy plants were compared. Both healthy and infected plants were harvested at soil level and data on tiller number, percentage of filled grains, 1,000-grain weight, grain yield per hill, and biomass compared. The quantitative relationship between RTV infection and yield components was evaluated using a modified single-tiller approach.

Results showed that yield losses per hill and per panicle varied, depending on symptom severity and reduction in height of RTV-infected IR64 plants (Nuque et al 1988). Losses were 1.1-99.1 %/hill and 1.0-96.1%/panicle. Losses in 1,000-grain weight ranged from 13.5 to 57.84. Filled grain percentages were higher in healthy than in infected plants. Yield losses per hill and per panicle correlated positively with height reduction and symptom severity. Height reduction and symptom severity correlated significantly with biomass. The regression model developed was

$$Y = B_0 + B_1X + B_2Z$$

where $X$ = 1,000-grain weight, and $Z$ = percent filled grain.

$$LH = 100.31 + 0.0007X - 0.5\,1262$$

where $LH$ = % loss grain weight/hill.

$$LP = 80.27 + 0.0039X - 0.9541Z$$

where $LP$ = % loss grain weight panicle.

## Bacterial blight

Singh (1970) gave the following equation for loss assessment:

$$\text{Percent yield loss} = D^{*}ID/100$$

where $D$ = average % incidence from three observations (at 1 mo after transplanting, at flowering, and at grain setting) and $ID$ = average damage index for disease intensity from three observations.

Reddy et al (1979), working on irrigated rice in India, derived the following relationship between 1,000-grain weight and percent blight severity at the soft dough stage (X).

$$\text{1,000-grain weight (g)} = 24.1 - 0.0303X$$

## Sheath blight

Several regression models for assessing loss due to ShB have been published. Early work at IRRI by Ou and Bandong (1976) resulted in several linear equations relating yield and ShB severity. Each equation represented a certain combination of fertilization and host susceptibility. Reddy et al (198l), using combinations of inoculation time and fungicides to produce different disease levels, arrived at the equation

$$Y = 5.024 - 0.19X$$

where $Y$ = yield in kg/ha and $X$ = percent severity.

A later study at IRRI (Ahn and Mew 1986) used data sets from five countries to arrive at a model relating loss ($Y$) and relative lesion height ($X$), where relative lesion height is the highest height reached by a lesion divided by plant height, as follows:

$$Y = 0.417X - 7.186$$

In extensive studies in Thailand, Arunyanart et al (1989) compared different disease indices in wet and dry seasons to assess loss due to ShB. With absolute lesion height in cm ($X$), percent yield loss ($Y$) was best estimated with the following equations:

$$\text{Wet season } Y = 0.969 + 0.337X$$
$$\text{Dry season } Y = 3.036 + 0.422X$$

with 79 and 63% of the yield variability explained, respectively. With relative lesion height ($Z$), percent yield loss ($Y$) was best estimated with the following equations:

$$\text{Wet season } Y = 0.04 + 0.412$$
$$\text{Dry season } Y = -6.34 + 0.92Z - 0.004X^2$$

with 57 and 83% of the yield variability explained, respectively. Arunyanart et al (1984) had previously used absolute lesion height in cm ($X$) at ripening stage to determine a loss ($L$) equation:

$$L = 3.78 + 0.35X$$

## Multiple pests and other pests

In West Bengal, India, Gangwar et al (1986) used data from farmers' fields to derive individual regression equations for estimating loss from single pests and combinations of pests, as follows:

$$\begin{aligned}
\text{Dwarf varieties' yield (t/ha)} &= 4.389 - 0.145^{*}\ (\%\text{ ground cover, narrow- leaved weeds})\\
&= 4.947 - 0.289^{*}\ (\%\text{ deadhearts, yellow stem borer})\\
&= 4.683 - 0.249^{*}\ (\%\text{ severity. bacterial leaf streak})\\
&= 4.802 - 0.195^{*}\ (\%\text{ bacterial leaf streak})\\
&\quad - 0.094^{*}\ (\%\text{ leaf blast})
\end{aligned}$$

Tall varieties' yield (t/ha) = 3.354 - 0.122* (% deadhearts, yellow stem borer)
= 3.078 - 0.182* (% ground cover, narrow- leaved weeds)
= 3.32 - 0.176* (% RTV)
- 0.138* (% ground cover, narrow-leaved weeds)
- 0.112* (% brown spot)
-0.069* (% leaf blast)

All pest intensities used were the maximum observed. The data are interesting because the authors were able to determine significant relationships for nearly all the pests they observed, using data from the same set of fields.

Abraham and Khosla (1967) related yield in India to three variables:

$$\text{Yield} = 3655 - 40.3X_1 - 32.2X_2 - 303.8X_3$$

where $X_1$ = percent whiteheads, $X_2$ = percent infested earheads, and $X_3$ = percent brown spot severity.

Yield loss due to sheath rot *Sarocludium oryzae* was estimated recently by Surin et al (1988) using the model

$$\%\ \text{loss} = 4.287X - 0.146 \ (r^2 = 0.623)$$

where $X$ is sheath rot severity assessed on the SES scale. The model was derived using data from transplanted rice RD23.

## Estimating losses using crop simulation

One problem underlies all the models for estimating losses—they are very locality oriented and cannot be used in conditions different from those in which they were derived. This is a weakness common to all empirical regression models (James and Teng 1979). To estimate the effect of pest infestations on different rice cultivars grown in different soil types and sites and under different management practices requires that physiological crop simulation models be used. The models must be capable of predicting pest-free yield and yield under different degrees of pest attack (Teng 1988). One such crop model is the IBSNAT CERES/RICE model (Alocilja 1988), developed using an approach that facilitates coupling of stress factors. Work is going on at IRRI to develop pest population models for brown planthopper, blast, and RTV. These models then may be coupled to the CERES RICE model to estimate yield loss.

In general, pests affect crop growth and development in the following ways (Boote et al 1983, Teng 1988):

- Stand reduction, through decreases in number of plants per unit area.
- Tissue consumption, through actual reduction in tissue biomass resulting from insect feeding or from necrotrophic fungi.
- Light stealing, in which tissue is rendered nonproductive and acts to reduce the proportion of photosynthetically useful radiation incident on the remaining tissue.

- Photosynthetic rate reduction, in which the activities of pests directly or indirectly reduce the rate of carbon dioxide assimilation, such as by toxin production.
- Leaf senescence acceleration.
- Tissue disruption, as with certain pathogens and insects that produce galls.
- Turgor reduction, as with some fungi that break the leaf epidermis with their spore-producing structures, therefore increasing evapotranspiration.
- Translocation disruption, as in collar blast, where phloem and xylem translocation may be restricted.
- Assimilate consumption, in which pathogens or insects. such as planthoppers, actually reduce the quantity of assimilates available for plant processes.
- Metabolic diversion, in which metabolites are diverted from their intended sinks.
- Resource competitors, such as weeds that compete for the same nutrients as crop plants.

Before modeling the effect of a specific pest on rice, it is necessary to identify which of the above processes are operating, and the relationship between the pest population and the process. Although many pests reduce leaf area via tissue consumption, this alone may account for only a fraction of the total effects. For example, by using the CERES RICE model, we have been able to quantify losses for different levels of defoliation at IRRI (Fig. 1).

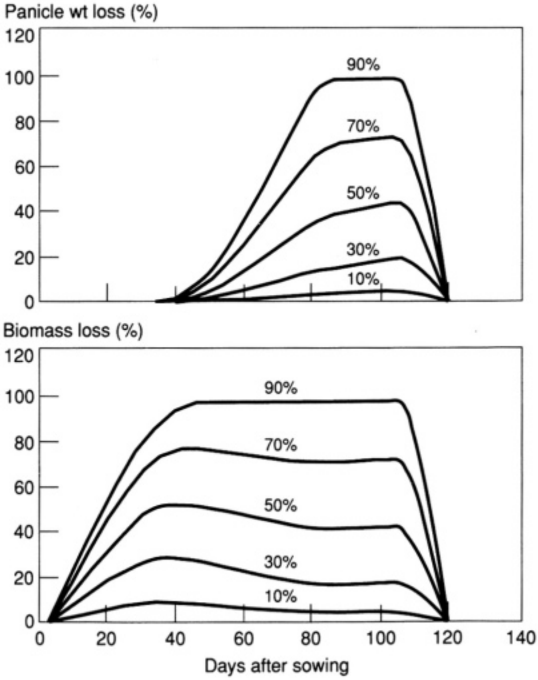
We used two approaches to represent leaf defoliation. In the first method, 1-99% severity levels introduced one at a time throughout all crop stages can estimate biomass loss of IR50 ranging from 0.04 to 11.02 t/ha and grain yield loss from 0 to 4.4 t/ha (simulations were done using 1987 IRRI weather data and IRRI pedon soil). At no disease pressure, predicted yields of biomass and grain were 11.05 and 4.4 t/ha, respectively; for observed yields, they were 10.1 and 4.5 t/ha.

In the second approach, we used a sigmoid curve for disease increase throughout crop growth to estimate crop loss from representative disease dynamics in the field. Simulation at different rates of disease increase in IR50 showed that, at a given time of onset of defoliation, a higher disease progress curve causes a decrease in yield, represented by a decrease in panicle weight per unit area.

The epidemiological considerations for estimating losses have been discussed by Teng and Johnson (1988). In general, data on the onset time of a disease, its rate of development, and its duration are needed before yield loss can be estimated. Data to allow for loss estimation using crop model are not available now. We hope that this workshop will stimulate more research relevant to pest-crop coupling.

## Conclusion

Crop loss data collected using acceptable methodology are helpful in guiding decisions at different levels of government, from the national policy level to the village level. Justification for and evaluation of plant protection programs often rely on the availability of loss data, yet little effort has been spent to ensure that data are



**1.** Simulated panicle weight loss and biomass loss of IR50, with varying defoliation.

adequately collected. Apart from its usefulness in decisionmaking, the study of pest effects on crop yield also should be a component of pest management programs. Many control actions are based on the pest intensity-yield loss relationship. Furthermore, developments in pest and crop modeling offer new opportunities for understanding pest-loss effects and for estimating locality-specific crop responses to pest infestations.

## References cited

Abeygunawardena D V W (1966) Recent investigations in the control of rice diseases. Pages 121-131 *in* Proceedings of a symposium on research and production of rice in Ceylon. D. V. W. Abeygunawardena, ed. Ceylon Association for the Advancement of Science, Colombo. 307 p.

Abraham T P, Khosla R K (1967) Assessment of losses due to incidence of pests and diseases on rice. J. Indian Soc. Agric. Stat. 19:69-82.

Ahn S W, Mew T W (1986) Relation between rice sheath blight and yield. Int. Rice Res. Newsl. 11(5):21-22.

Ahrens C, Cramer H H, Mogk M, Peschel H (1982) Economic impact of crop losses. Pages 65-73 *in* Proceedings of 10th International congress of plant protection. British Crop Protection Council, Croydon, England.

Alam M Z (1961) Insect pests of rice in East Pakistan and their control. East Pakistan Department of Agriculture, Dacca. 94 p.

Alam M Z (1967) Insect pests of rice in East Pakistan. Pages 643-655 *in* The major insect pests of the rice plant. International Rice Research Institute. P.O. Box 933, Manila, Philippines.

Alam M Z, Alam M S, Abbas M (1972) Status of different stem borers as pests of rice in Bangladesh. Int. Rice Comm. Newsl. 21(2):729.

Alocilja E (1987) Simulation multicriteria optimization technique as a decision support system for rice production. Ph D thesis, Michigan State University. USA. 238 p.

Arunyanart P, Sunn A, Dhitikiattipong R, Rojanahusdin W, Disthapom S, Heuel-Rolf B (1989) Crop loss assessment and chemical control of rice sheath blight disease. J. Plant Prot. Trop. (in press)

Arunyanart P, Sunn A, Rojanahusdin W, Dhitikiattipong R, Disthaporn R, Disthaporn S (1984) Rice yield loss to sheath blight. Int. Rice Res. Newsl. 9(6):10.

Atkins J G, Todd H E (1959) White tip disease of rice. II. Yield tests and varietal resistance. J. Trop. Plant Prot. 49:189-191.

Balasubramaniam G, Saravanabhavanandam M, Subramanian T R (1973) Control of the rice leaf roller *Cnaphalocrocis medinalis* Guenee. Madras Agric. J. 58:717-718.

Barr B A, Koehler C S, Smith R F (1975) Crop losses - rice: field losses to insects, diseases, weeds, and other pests. UC/AID Pest Management and Related Environmental Protection Project. University of California, Berkeley. 64 p.

Barr B A, Koehler C S, Smith R F (1975) Crop losses - rice: field losses to insects, diseases, weeds, and other pests. UC/AID Pest Management and Related Environmental Protection Project. 64 p.

Boote K J, Jones J W, Mishoe J W, Berger R D (1983) Coupling pests to crop growth stimulators to predict yield reductions. Phytopathology 73:1581-1587.

Catling H D, Alam S, Miah S (1978) Assessing losses in rice due to insects and diseases in Bangladesh. Exp. Agric. 14:277-287.

Chang P M, Hashim H, Omar O, Abdullah S, Mohd. Amin S (1985) Penyakit merah virus disease of paddy - the problem and strategy for disease control in Malaysia. Pages 159-182 *in* Integrated pest management in Malaysia. B. S. Lee, W. H. Loke, and K. L. Heong, eds. MAPPS/Malaysian Agricultural Research and Development Institute.

Chauhan L S, Verman S C, Rajpai G K (1968) Assessment of losses due to stem of rice caused by *Sclerotium oryzae* . Plant Dis. Rep. 52:963-965.

Cramer H H (1967) Plant protection and world crop production. Pflanzenschutz Nachr. Bayer 20:1-524.

Chiarappa L, ed. (1971) Crop loss assessment methods. Food and Agriculture Organization/ Commonwealth Agricultural Bureaux, Slough, England.

Chiarappa L, ed. (1981) Crop loss assessment methods. Supplement 3. Food and Agriculture Organization of the United Nations and Commonwealth Agricultural Bureaux, Slough, England. 123 p.

Dunsmore J R (1970) Investigations on the varieties, pests and diseases of upland rice (hill padi) in Sarawak, Malaysia. Int. Rice Comm. Newsl. 19(1):29-35.

Edens T C, Haynes D L (1982) Closed system agriculture: resource constraints, management options and design alternatives. Annu. Rev. Phytopathol. 20:363-395.

Fernando H E (1966) Recent developments in paddy pest control. Pages 103-120 *in* Proceedings of a symposium on research and production of rice in Ceylon. D. V. W. Abeygunawardena, ed. Ceylon Association for the Advancement of Science, Colombo. 307 p.

Gangwar S K, Gangwar S, Chakraborty M, Dasgupta K, Huda A K S (1986) Modelling yield loss in indica rice in farmers' yields due to multiple pests. Agric. Ecosyst. Environ. 17:165-171.

Ghose R L M, Ghatge M B, Subrahmanyan V (1960) Rice in India. Rev. ed. Indian Council of Agricultural Research, New Delhi. 474 p.

Goto K (1963) Estimating losses from rice blast in Japan. Pages 195-202 *in* The rice blast disease. Proceedings of a symposium at the International Rice Research Institute. July 1963. The Johns Hopkins Press, Baltimore, Maryland.

Hashioka Y (1963) The stem nematode *Ditylenchus angustus* in Thailand. FAO Plant Prot. Bull. 11:97-102.

Heong K L, Ho N K (1987) Farmers' perceptions of the rice tungro virus problem in the Muda irrigation scheme, Malaysia. Pages 165-174 *in* Management of pests and pesticides: farmers' perceptions and practices. J. Tait. D. Bottrell, and B. Napompeth, eds. Westview Press, Boulder, Colorado.

Hernandez A (1923) Report of plant disease section. Rep. Philipp. Bur. Agric. 23:159-172.

Hori M ( 1969) On forecasting the damage due to sheath blight of rice plants and the critical point for judging the necessity of chemical control of the disease. Rev. Plant Prot. Res. 2:70-73.

Hung Y P (1959) White tip disease of rice in Taiwan [in Chinese]. Plant Prot. Bull. Taiwan 1(4):1-4.

IRRI — International Rice Research Institute (1976) Annual report for 1975. P.O. Box 933, Manila, Philippines.

Israel P, Abraham T P (1967) Techniques for assessing crop losses caused by rice stem borers in tropical areas. Pages 265-275 *in* The major insect pests of the rice plant. Proceedings of a symposium at the International Rice Research Institute, September, 1964. The Johns Hopkins Press, Baltimore, Maryland.

James W C (1974) Assessment of plant diseases and losses. Annu. Rev. Phytopathol. 12:27-48.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Pages 201-267 *in* Applied biology. Vol. 4. T. H. Coaker, ed. Academic Press, New York.

Jayaraj S, Velayutham B, Rathinasamy C, Regupathy A (1974) Damage potential of the brown planthopper on rice. Madras Agric. J. 61:144-148.

John V T, Ghosh A (1980) Estimation of losses due to tungro virus. Pages 225-231 *in* Assessment of losses due to pests and diseases. H. C. Govindu, G. K. Veeresh, P. T. Walker, and J. F. Jenkyn, eds. University of Agricultural Sciences, Bangalore.

Lim G S, Ooi A C P, Koh A K (1980) Brown planthopper outbreaks and associated yield losses in Malaysia. Int. Rice Res. Newsl. 5:15-16.

Ling K C, Tiongco E R, Flores Z M (1983) Epidemiological studies of rice tungro. *In* R. T. Plumb and J. M. Thresh, eds. Plant virus disease epidemiology. Federation of British Plant Pathologists/Blackwell Scientific Publications, Oxford.

Litsinger J A, Canapi B L, Bandong J P, dela Cruz C G, Apostol R F, Pantua PC, Lumaban M D. Alviola III A L, Raymundo F, Libetario E M, Loevinsohn M E, Joshi R C (1987) Rice crop loss from insect pests in wetland and dryland environments of Asia with emphasis on the Philippines. Entomology Department, International Rice Research Institute, P.O. Box 933, Manila, Philippines. (mimeo.)

Katsube T, Koshimizu Y (1970) Influence of blast disease on harvests in rice plant. I. Effect of panicle infection on yield components and quality. Bull. Tohoku Natl. Agric. Exp. Stn. 39:155-96.

Mathur R S, Bajpai G K, Chauhan L S, Verma S C (1964) Assessment of losses caused by paddy blast. Plant Dis. Rep. 48(9):711-717.

Mizuta H (1956) On the relation between yield and inoculation times of sheath blight, *Corficium sasakii* in the earlier planted paddy rice. Assoc. Plant Prot. Kyushu 2:100-102.

Mochida O, de Sagun S, Parducho M, Gapasin D, Orolaza M (1986) General information on black bugs, insecticide evaluation, economic injury levels and principles of chemical control. Paper presented at the PCARRD/MAF/IRRI Workshop on Black Bug, 25-29 Oct 1986, Palawan.

Moody K (1982) The status of weed control in rice in Asia. FAO Plant Prot. Bull. 30:119-123.

Murugesan S, Chelliah S (1983) Rice yield loss caused by leaffolder damage at tillering stage. Int. Rice Res. Newsl. 8(4):13-14.

Nuque F L (1963) Panicle blast outbreak in Leyte provinces. Report to the IRRI Director General. 3 p.

Nuque F L (1970) Panicle blast outbreak in Laguna and Quezon provinces. Report to the IRRI Director General. 2 p.

Nuque F L, Bandong J M, Estrada B A, Lapis D B, Torres C Q ( 1983) Common diseases of rice. Pages 276-277 *in* Rice production manual Philippines. University of the Philippines, College, Laguna, Philippines.

Nuque F L, Magnaye A J P, Salamatin C S, Teng P S (1988) Rice yield loss caused by tungro using a modified single tiller method. Paper presented at the Annual Convention of the Pest Control Council of the Philippines, 3-7 May 1988, Cebu City.

Ou S H (1985) Rice diseases. 2d ed. Commonwealth Mycological Institute, Kew, Surrey, England. 380 p.

Ou S H, Bandong J M (1976) Yield losses due to sheath blight of rice. Int. Rice Res. Newsl. 1/76:14.

Pathak P K, Dhaliwal G S (1981) Trends and strategies for rice pest problems in tropical Asia. IRRI Res. Pap. Ser. 64. 15 p.

Padmanabhan S Y (1965) Estimating losses from rice blast in India. Pages 203-221 *in* The rice blast disease. Proceedings of a symposium at the International Rice Research Institute, July 1963. The Johns Hopkins Press, Baltimore, Maryland.

Padmanabhan S Y (1973) The great Bengal famine. Annu. Rev. Phytopathol. 11:11-26.

Pal A K (1970) Survey on nematodes of paddy and successful treatment with hexadrin. Proc. Indian Sci. Congr. Assoc. 57(3):496.

Pmthi H S (1953) An epidemic of rice bug in India. FA0 Plant Prot. Bull. 1:87-88.

Rao P S, Kauffman H E (1977) Potential yield losses in dwarf rice varieties due to bacterial blight in India. Phytopathol. Z. 90(3):281-284.

Reddy A P K, MacKenzie D R, Rouse D L, Rao A V (1979) Relationship of bacterial leaf blight severity to grain yield of rice. Phytopathology 69:967-969.

Reddy D B (1967) The rice gall midge *Pachydiplosis oryzae* (Wood-Mason). Pages 457-491 *in* The major insect pests of the rice plant. Proceedings of a symposium at the International Rice Research Institute, September, 1964. The Johns Hopkins Press, Baltimore, Maryland.

Reddy D B (1973) High yielding varieties and special plant protection problems with particular reference to tungro virus of rice. Int. Rice Comm. Newsl. 22(2):34-42.

Reddy A P K, Bhaktavatsalam G, John V T (1981) Sheath blight of rice: relationship between disease severity and yield. Pesticides 15:11-12.

Reissig W H, Heinrichs E A, Litsinger J A, Moody K, Fiedler L, Mew T W, Barrion AT (1986) Illustrated guide to integrated pest management in rice in tropical Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Serrano F B (1957) Rice “accep na pula” or stunt disease - a serious menace to the Philippine rice industry. Philipp. J. Sci. 86:203-230.

Sing L N (1953) Some important diseases of paddy. Agric. Anim. Husb. India 3(10-12):27-30.

Singh R N (1970) Studies on bacterial blight disease of paddy. Part II. Assessment of losses and yield loss equation. Labdev J. Sci. Technol. 8-B(1).

Soenardi I (1967) Insect pests of rice in Indonesia. Pages 675-683 *in* The major insect pests of the rice plant. Proceedings of a symposium at the International Rice Research Institute, September, 1964. The Johns Hopkins Press, Baltimore, Maryland.

Srivastava D N (1967) Epidemiology and control of bacterial blight of rice in India. Pages 11-18 *in* Proceedings of a symposium on rice diseases and their control by growing resistant varieties and other measures. Agriculture. Forestry, and Fisheries Research Council, Japan.

Surin A, Arunyanart P, Dhitikiattipong R, Rojanahusdin W, Disthaporn S, Soontrajarn K (1988) Rice yield loss to sheath rot. Int. Rice Res. Newsl. 13(6):34-35.

Surin A. Arunyanart P, Rojanahusdin W, Munkong S, Dhitikiattipong R, Disthaporn S (1988) A simple method of estimating rice blast (B1) severity. Int. Rice Res. Newsl. 13(6):33-34.

Swink F N. Sumangil J P, Tolentino D C (1973) A simple quantitative method for estimating rat damage to growing rice. *In* Proceedings of short course on integrated pest control for irrigated rice in South and Southeast Asia. Oct. 16-Nov. 18, 1978. Manila, Philippines. FAO/USAID/BPI. (mimeo.)

Teng P S (1986) Crop loss appraisal in the tropics. J. Plant Prot. Trop. 3(1):39-50.

Teng P S, ed. (1987) Crop loss assessment and pest management. APS Press, The American Phytopathological Society, St. Paul, Minnesota. 270 p.

Teng P S (1988) Pests and pest-loss models. Agrotechnol. Transfer 8:1-10.

Teng P S, Johnson K B (1988) Analysis of epidemiological components in yield loss assessment. Pages 179-190 *in* Experimental techniques in plant disease epidemiology. J. Kranz and J. Rotem, eds. Springer-Verlag. Berlin.

Teng P S, Krupa S V (1980) Crop loss assessment. Proceedings of E. C. Stakman commemorative symposium on crop losses. Miscellaneous Publication No. 7. Minnesota Agriculture Experiment Station, Minneapolis. Minnesota. 327 p.

Torres C O, Teng P S (1988) Path coefficient analysis on the effects of blast on rice growth. yield components and yield loss. Paper presented at the Annual Meeting of the Pest Control Council of the Philippines, 3-7 May 1988. Cebu City.

Tuazon E D (1979) The yield loss of rice at different stages of growth and intensities of damage. MS thesis, University of the Philippines at Los Baños, College, Laguna. 24 p.

Valencia S L, Mochida O (1985) Rice whorl maggot (RWM) effect on yield loss. Int. Rice Res. Newsl. 10(3):30.

Vidhyasekaran P, Ramados N (1973) Quantitative and qualitative losses in paddy due to helminthosporiose epidemic. Indian Phytopathol. 26:479-484.

Wathanakul L, Weerapat P (1969) Virus diseases of rice in Thailand. Pages 79-85 *in* The virus diseases of the rice plant. Proceedings of a symposium at the International Rice Research Institute, April, 1967. The Johns Hopkins Press, Baltimore, Maryland.

Way M J (1976) Entomology and world food situation. Bull. Entomol. Soc. Am. 22:125-129.

Wyatt I J (1957) Field investigations of padi stem-borers, 1955-1956. Federation of Malaya Department of Agriculture. Bull. No. 102. 42 p.

Yoshii H, Yamamoto S (1950) A rice nematode disease "Senchu Singare Biyo." I. Symptoms and pathogenic nematode. II. Hibernation of *Aphelanchoides oryzae.* III. Infection course of the present disease. IV. Prevention of the present disease. J. Fac. Agric. Kyushu Univ. 9:209-222; 223-233; 289-292; 293-310.

## Notes

*Authors' address:* P. S. Teng, C. Q. Torres, F. L. Nuque. and S. B. Calvero, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Quantifying insect populations and crop damage

P. T. Walker

For decisions to be made about pest control. whether in rice or in other crops in a cropping system, the population of insects, mites, or other organisms—harmful or beneficial—must be measured, as well as plant diseases, weeds, and other causes of low yield.

Population density is the actual number of insects per unit area. This should be recorded, if possible. The survey should have a constant base, not depend on who records it, and be repeatable from place to place and year to year. Pest density may be impossible to measure completely, because it is too difficult, too costly, or too time-consuming. Populations are often estimated from samples. If a pest population cannot be measured or estimated, assessment may be done indirectly by measuring or estimating the effect of the pests on the crop. as injury or damage.

Pest and damage assessment is needed

- For studying the biology and ecology of pests and natural enemies, to know how and when to control them.
- For measuring the effects of different pest management measures, such as pesticides, economic action thresholds, biological and cultural measures, crop resistance, etc.
- For surveying pests, studying migration, and forecasting outbreaks.
- For making decisions based on the economics of pest attack—the benefits of reducing pest attack compared to the costs and the relationship between yield and pest attack. Those establishing economic thresholds need a pest level from which to work.

## Pest and damage assessment for decisionmaking

Pest management can be seen as a decisionmaking system. The decision may be whether or not to develop and use biocontrols, to select and distribute pest-resistant varieties, to use a cultural control method, or to apply a pesticide. And if so, which one, how much, and when. Such decisions may be made daily by the farmer or his technical adviser, by the researcher considering research methods, or by the administrator allocating resources at the national level.

First, pest density ( $i$ ) or crop damage ( $x$ ) is surveyed (pest assessment). Second, the relationship between yield ( $y$ ) and pest density ( $i$ ) or damage ( $x$ ), the production function, is found by experiment.

$$y = f(i)$$
$$\text{or } y = f(x)$$

This relationship and the methods of finding it are part of crop loss assessment. From economic data such as the value of the crop and the cost of pest management, the pest density at which it is economic for the farmer to control pests is found. This is the economic threshold (ET), defined in other chapters.

The pest level ( $i$ ) or ( $x$ ) found is compared with the ET. If i is greater than ET, action to reduce pest attack is taken.

Expressing this as a system or model focuses attention on the information needed to make decisions, the relationship between pests and yield, and how to find the decisionmaking level. The many factors that influence each stage can be examined. Quantitative values can be put into the system to find the expected outcome.

## Assessment methods

There are almost as many ways to assess pests as there are types of pest. A good guide to all aspects is Southwood (1978). For general accounts, see Bardner and Fletcher (1974); chapters in Chiarappa (1971), Bram (1978), Youdeowei and Service (1983), and Matthews (1984); and a review by Strickland (1961). Survey manuals have been produced by USDA (1969) and the Philippines, Thailand, India, and other countries. Methods are given in publications on particular pests (Nishida and Torii 1970 on rice stem borers and Van Emden 1972 on aphids), in books on pest management (Reissig et a1 1986), or in papers in the International Rice Research Newsletter, Environmental Entomology, and other journals.

Standard pest evaluation methods have been published by IRRI for germplasm selection in rice and other crops (Standard evaluation system for rice) and by other international agricultural institutes for other crops. Agrochemical companies sometimes produce guides to pest assessment in connection with pesticide trials (Puntener 1981).

## Choosing assessment methods

When choosing or developing methods, consider the following aspects (Walker 1980): they should be quick, simple, and inexpensive, and should measure the actual pest population or damage as accurately as possible.

Methods should be standardized, to make possible comparison of different assessments, to remove bias due to the observer, and to allow study and testing of the value of the method. Standard methods should be published in a survey manual, with details of how, where, and when to sample; the size and number of samples; and the stage of pest and crop, with keys and growth stage charts (Reissig et al 1986). Single-sheet identification charts are useful (East African *Spodoptera* armyworm survey and UK Ministry of Agriculture leaflets). When assessing intensity or severity of damage, standard area keys, such as those used for disease lesions, are valuable to avoid observer error. Diagrams showing a range of known areas of damaged leaf, fruit, stem, root, or plant should be available to compare with damage found.

Crop growth stage charts should be based on morphological and physiological characters, not on a time scale (crop time scales vary with variety and conditions). A decimal numbering system should be used for ease in putting data in a computer. Many are given in Chiarappa (1971) and Zadoks et al (1974); more precise charts are discussed by Tottman et al (1985). Stages based on the growing point of cereals are useful when considering effects on yield.

An estimate of accuracy, or nearness to the real value, and precision, nearness to the mean, of the method should be given in terms of standard error, confidence limits, or coefficient of variation. A statistician should be consulted before deciding on a sampling system.

## Direct assessment methods

### On the ground

Insects and other animals should, if possible, be counted on a standard base, usually area of ground (e.g. number of larvae per $m^2$). If counted on a nonstandard unit, such as length of crop row, weight of crop, hill, plant, shoot, tiller, stem, internode, leaf, head, grain, or panicle, the unit should be converted to a $m^2$ base.

*Direct counts.* Aphids are counted per unit of leaf or tiller, bugs per panicle, leafhoppers per stem, beetle larvae per volume of soil, etc. Absolute pest density is found by multiplying by the number of units per $m^2$.

*Cutting open.* Grains are cut open to count fly or beetle larvae, legume pods to count pod borers, stems for stem borers, roots for root borers, etc.

*Beating, brushing, and knockdown.* Plants or panicles may be shaken into a box or on a sheet, hoppers or bugs collected with an electric pump (Cariño et al 1979) or by mouth suction inside a walled quadrat. A nonpersistent knockdown agent such as $CO_2$ (Aquino and Heinrichs 1986) or insecticide such as dichlorvos or a pyrethroid may be used on a plant or panicle in a bag, box, or on a sheet to collect fallen insects. Pests such as aphids or mites can be brushed off leaves, sometimes with a mechanical brush, and sometimes collected in a preservative liquid.

*Washing off.* Aphids, mites, or eggs removed with a solvent can be washed off and measured by volume.

*Crushing.* Colored aphids or mites can be crushed on glossy or absorbent paper, or grains containing live insects crushed on ninhydrin paper, and the spots produced counted.

*Pests in soil and debris.* Samples of a standard area to a known depth and specified volume are taken with a core borer or by digging. A preliminary survey will ensure that samples are representative of pest distribution. In dry extraction (K. E. Fletcher in Chiarappa 1971), such as the Tullgren funnel, a light bulb or other source of heat drives out insects which are collected in an alcohol tube. In wet extraction (J. F. Newman in Chiarappa 197l), as in the Salt and Hollick method, samples may be soaked, shaken with detergent, insects floated off in salt solutions such as magnesium sulfate, and separated by centrifuging. Some soil insects can be driven out of the soil with an insecticide or an irritant such as formaldehyde.

## In the air

Counts in the environment are more difficult to standardize. It may be possible to relate catches by suction trap, sweep net, light trap, or pheromone trap to actual pest population densities on the ground by correcting for differences in the trap or differences in surroundings (brightness, position, temperature, wind speed, etc.), but such counts are usually no more than estimates of actual pest populations. As with all samples, they are liable to sampling error. These methods, however, are so valuable the limitations are often accepted.

Some methods for locusts are given by Symmons (1981). Methods for birds include visual counting, counting catches in nets, or counting hills with avicides or explosives. Rodents also are trapped with baits. In many of the following methods, protection of the insect catch from birds, ants, etc., may be necessary.

*Sticky traps.* Aphids, mites, hoppers, flies, hymenoptera, caterpillars, and beetles may be caught by this method. A flat, cylindrical, or round board or plastic sheet is coated with sticky material, such as tree-banding grease (Ryan and Molyneux 1981) or car grease, and placed on the ground or in an attractant trap within the standing crop. The catch is washed off in solvent, identified, and counted. Height and position of the trap in the crop are important, and regular attention is necessary to protect it from rain or dust. Southwood (1978) compares catches by different hinds of trap.

*Color traps.* Leaf pests are often attracted to BS 0.001 or Munsell 5 OY 9/14 Yellow, other pests like white, some fruit pests like red. The best size, shape, and color of trap to use is determined through trial. Color is sometimes combined with water traps, as Kisimoto (1968) did for *Laodelphax* in rice, or with sticky or pheromone traps.

*Water traps.* Aphids, hoppers, and flies are commonly caught. Shallow plastic dishes, 5-8 cm deep, containing water, detergent, and an oil film are placed in or near the crop. Trap height and wind direction are important. A colored dish may add attraction. Overflow holes are useful to prevent flooding.

*Chemical attraction.* Attraction to a trap is a piece of the food plant, a chemical from the plant, or other substance. Fruit flies, sorghum shootflies, banana weevils, coconut beetles, and moths and hymenoptera can be trapped this way. A trap crop may also be used, particularly if destructive sampling is planned.

*Pheromone traps.* Trapping by attracting males to female pheromone or, if the pheromone is not available, to the female (or in some cases, females to male), has a great advantage in that it is specific and traps are simple, relatively inexpensive, easy to maintain, and less liable to theft or vandalism. These traps can indicate when a pest attack is near and, sometimes, how large an infestation to expect (Campion and Nesbitt 1981). The development and supply of pheromone are best left to experts.

Trap design is important (Lewis and Macauley 1976, Steck and Bailey 1978). Flat, cylindrical, and triangular shapes; and cartons, funnels, and plastic bags with talc, sticky surfaces, and water baths have been used, depending on the size and behavior of the insect and the weather. The position of the trap in the crop and the condition and rate of release of pheromone are important. The difficulty is to relate the number caught. particularly if the insects caught are only males, to the actual pest life cycle, level of pest attack, the best time to apply a control, and crop yield loss.

*Sweep net.* Sweeping can give repeatable results if the diameter of the net opening and the number, extent, and frequency of sweeps are constant. The method was analyzed by Ruesink and Haynes (1973).

*Suction traps.* Trapping or collecting insects by air suction is useful where attraction to light or chemicals is of no use and where motor, mains, or battery electric power is available. Continuous sampling at different levels above the crop can give valuable indications of when, which. and how many pests will attack. In the Johnson-Taylor trap, which has a 23-cm opening, the wire mesh cone may or may not be enclosed. A device to segregate the catch into timed samples can be added. Diameter of the opening and speed of suction depend on the density and size of insects to be caught and the wind speed over the trap. Correction for some of these variables is possible (Van Emden 1972, Taylor 1962). Portable suction traps are described by Arnold et al (1954), Cariño et a1 (1979), and others (Clinch 1971, Thornhill 1978). The Dietrick (1961) type is a large motor-driven trap, carried on the back.

*Light traps.* If an oil, gas pressure, or electric light source is available, a light trap is valuable for monitoring relative and absolute pest numbers and the seasonal appearance of many species of moths, hoppers, and beetles (Rabb and Kennedy 1979, Bouden 1982). The strength, wavelength, and direction of the light, the weather, and the presence of other light, including moonlight (Verheijen 1960), are important. Some traps use ultraviolet or black light, have a timing mechanism, or are daylight activated, and are equipped with a protective roof, electrified vanes, or a suction pump. Insecticide (e.g. dichlorvos) and something to prevent damage to the insects should be placed in the trap container. A serious disadvantage is that the large, nonspecific catches often demand some sort of sample divider (Shepard 1984).

*Pitfall traps.* In dry areas, smooth-sided plastic pots level with the soil surface will collect mobile ground insects, predators, etc. They need frequent attention and protection from flooding, birds, and ants.

*Shelter traps and emergence traps.* Some animals may be trapped and counted by collecting them under some form of shelter (for example, termites under sheets of paper [McMahen and Watson 1977]). Insects emerging from the soil can be caught using an inverted funnel with a collecting tube at the top.

*Mark, release, and recapture.* If marking does not alter behavior, insects or other animals can be marked, released, and recaptured. Populations can be estimated using the Lincoln Index:

$$\text{Population} = \frac{\text{number marked and released} \times \text{total number caught}}{\text{number marked caught}}$$

The method used depends on whether pests are removed or replaced, and on survival and migration (Blower et al 1981). Marking can be with combinations of paint spots, external coloring or UV fluorescent dust, internal dye, or radioactive, bacterial, or genetic markers. Eddlestone et al (1983) give a bibliography.

### Factors affecting assessments

Three main factors influence estimates of insects or other animal populations:

- The number present, which is affected by the crop, the crop stage, the insect generation, its feeding behavior, its reproductive stage, and weather.
- Pest activity, which is affected by temperature and other factors. There may be a threshold below which there is no response to a trap.
- Conditions at the time of trapping or sampling (weather, position, attractant, etc.).

Running means, averaged over several samples, are useful for smoothing out minor changes in population to identify any long-term trends.

## Indirect assessment methods

It is often easier, quicker, and cheaper to count or estimate the indirect effects of pests. The difference between incidence (damage or number of damaged plants) and intensity or severity (degree or extent of damage) should be noted. Incidence is a discrete measure, intensity is continuous and finite. Percentages, with a constant base of 100, are often more valuable, but absolute values may be important for scale—1 of 2 and 500 of 1,000 both are 50%.

### On the plant

*Whole plants.* The number or percentage of missing or damaged plants is often recorded. Soil pests, cutworms, stem borers, etc., may cause loss of plant stand. Errors in damage assessment may occur if the number of missing plants is not taken into account.

*Stems.* The number or percentage of wilted sterns or dead central shoots (deadhearts) indicates the intensity of attack by stem borers, shootflies, or boring beetles; the number of silvershoots (galls) indicates intensity of attack by gall midge. Number of exit holes or the presence or length of tunnels have also been used. The usefulness of number of nodes bored depends on the pest species and the variety and stage of crop. Termite, ant, cutworm, sawfly, and rodent attack can be assessed from fallen or cut stems, cassava mite and mealybug attack by number of stunted, leafless shoots.

*Leaves.* Holes, spots, mines, rolls, or epidermis removal indicate attack by stem borers, leaf caterpillars, semiloopers, caseworms, leaf miners, leaf beetles and their larvae, termites, or orthoptera. Damage can be counted or its area measured by counting the dots of a dot matrix grid seen through the holes, by weighing paper of the same area, by photographic methods and photometry, or, more expensively, by laboratory or portable electronic scanning and area integration devices, such as the Lincor. With these, the degree of contrast to be measured can be selected. The area of undamaged leaf can be obtained from a "length x breadth x a constant" formula.

*Seeds, grain, and fruit.* Damaged seed, seed heads, and cobs; exit holes; and unfilled grain panicles, or whiteheads in rice are counted. In larger fruit, the area of damage can be measured. Damage to coffee, cacao, cotton, fruit, coconut, etc. is often assessed this way.

*Roots.* Root length and volume or dry weight of damaged and undamaged fibrous roots are used to assess pest attack. Whole roots, samples, or even sections of the root mass, if a correction factor has been calculated, can be used. Damage to tuberous roots is measured by counting lesions or areas of damage on the surface or from a cut section.

### Amount of by-product

The presence or amount of insect product, such as borer excreta or aphid or planthopper honeydew, may be used to quantify pest attack.

### Remote sensing

When photographs or image recordings from a tower, balloon, plane, or satellite are available, they can give a useful indication of the area and intensity of dead or wilting plants or leaves and differences in crop yield caused by pest attack. The presence of growing vegetation is useful in surveying locust, grasshopper, or bird outbreaks. Filters and color and infrared recording are used to show different vegetation conditions (Chiang and Wallen in Chiarappa 1971, Olfert et al 1980. Wallen et al 1976). Radar is another form of remote sensing that can be used to show the amount, area, or density of flying pests such as moths, locusts, and birds (Riley 1979). The difficulty, apart from clouds, is to be able to relate pest and crop events on the ground to the pictures obtained.

## Relationship between direct and indirect methods

Direct ($n$) and indirect ($x$) methods of pest assessment should be related to population density ($i$) per standard base, usually area, as

$$i = f(n)$$

$$\text{or } i = f(x)$$

These relationships are examined for their relationship to crop loss (Walker 1981). The form of the relationship varies with change in the method of assessment (for example, from percent tillers topercent hills infested). It may vary with the values measured, and often is different at low or high infestation densities. If percentages are used, or a pest attack increases until every unit is attacked (for example, with stem borers in rice hills), a curved relationship between pest density and percentage of hills attacked will be found. Once the relationships are known, indirect methods can be used to measure pest populations, and populations can be related to damage and crop yield.

Formulae for finding percent tiller infestation by stem borers from samples in infested hills are available (Gomez and Gomez 1964). One is

$$\text{Percent infested tillers} = \frac{\text{no. of infested tillers in } H_i}{\text{total tillers in } H_i} \times \frac{\text{no. of } H_i \times 100}{\text{total hills}}$$

where $H_i$ = number of infested hills.

## Sampling and data collection

### Time to sample and method to use

The best time to sample pests or crop damage usually is when pests will have the maximum effect on the economic crop yield (*y*). This may be at a critical event in pest development (*a*), such as first egg appearance or adult emergence. or at a critical growth stage of the crop, such as at germination or early tillering. The best choice is what correlates best withy. Maximum prediction of yield will be obtained using the method

$$y = f(a)$$

The time or sampling method that gives the highest correlation coefficient (*r*) or coefficient of determination ( $r^2$ ) in a regression is the one to use (Comez and Gomez 1984). Nonlinear regressions and no-response thresholds may complicate the situation.

### Scores or rating scales

For quicker and easier assessment, or because of the difficulty of counting great numbers or complicated areas of damage, both pests and their damage are often grouped into grades, or scales ( *Standard evaluation system for rice,* IRRI 1980) or given scores or ratings. Scales may be arithmetic (grades 1, 2, and 3 being 0- 10, 11-20, 21 -30, etc.) or geometric (logarithmic: 0 (really 1)- 10. 11 - 100, 101-1,000, etc.). The width of the scale or the base of the logs is chosen to cover the range of infestation or damage expected. Grades and scores can be added, averaged, and analyzed, but they are discontinuous and finite and may not be normally distributed, needing transformation before analysis.

Too many small divisions may be difficult to separate, while only a few, large ones mean loss of information. Actual counts or percentages lose no information. To reduce observer error, standard area or scale diagrams are valuable.

### Pest or damage frequency distribution

The frequency distribution of pests or damage (the number of samples of different sizes) should be known before a sampling plan is designed or data analyzed. A preliminary survey will show whether pests or damage are distributed in a regular pattern, at random, or in clumps. The number of zero counts and the average number of pests per sample are important. If the frequency distribution is nonnormal, parametric statistics, and hence standard errors, confidence limits, analyses of variance, and regressions will not be valid. Transformation of *i* or *n* to Log ( $i + 1$) etc. or to the square root, reciprocal, or other transformation of *i* will be necessary. Altematively, nonparametric or ranking methods can be used. Percentages of 20-80 are often transformed to arcsine ( *x* %). The subject is dealt with by Gomez and Gomez (1984).

Taylor's Power Law (Taylor 1961) can be used to find the appropriate transformation. Another method is to plot the range of sample values against their means. If a straight line results, [log ( $i$ ) + $k$ ] is used, with *k* being the intercept on the means axis. If the line curves down, the square root transformation is used.

Frequency distributions may change with time, with pest stage, with the part of the crop plant sampled, or with the units of assessment used. Do not forget to detransform before presenting results of assessments.

### Number and size of samples

Advice on size and number of samples needed is often requested. But that is impossible to give without considering the frequency distribution of the pest or its damage, its distribution in the area, and the precision needed. Factors such as ease of sampling, accessibility, and time and money available for sampling should be considered. There are formulae for calculating sample size from the variance, cost, etc. The purpose of the sample is important. Is it descriptive and qualitative, or quantitative but only preliminary? Is it to give relative results or an exact economic assessment on a valuable crop?

In general, the more sample units at a given number of pests per sample or the more pests per sample at a given number of sample units, the greater the precision of the sample and the lower the coefficient of variation. Plot size may have variable effects (Smith 1958). The subject of sampling is covered by Church (in Chiarappa 1971), Yates (1977), Cochran (1977), Gomez and Gomez (1984), Ives and Moon (1987), and others.

### Sequential sampling

If the basic statistics of the pest or damage population are known, sequential sampling is useful in deciding whether or not to control. Sample size depends on the population found. Upper and lower limits are specified and sampling continued until the number of pests found goes above or below those limits. The method is described by Onsager (1976). Nishida and Torii (1970) give examples for rice stem borer and Shepard (1973) for cabbage looper. Successive sampling is discussed by Abraham et al (1969).

## Conclusion

Sampling method is a compromise between the need for accurate estimates of an actual pest or damage attack and the time, money, or technical expertise available. As more simple, inexpensive, easy, and accurate methods become available, the practical farmer will be better able to make decisions to improve his farming practices for his particular set of conditions.

## References cited

Abraham T P, Khosla R K, Kathuria O P (1969) Some investigations on the use of successive sampling in pest and disease surveys. J. Indian. Soc. Agric. Stat. 21:43-57.

Aquino G B, Heinrichs E A (1986) A carbon dioxide (CO2NE) sampler for arthropods in flooded rice. Int. Rice Res. Newsl. 11:13-14.

Arnold A J, Needham P H, Stevenson J H (1954) A self-powered portable insect suction sampler and its use. Ann. Appl. Biol. 75:229-233.

Bardner R, Fletcher K E (1974) Insect infestations and their effects on the growth and yield of field crops: a review. Bull. Entomol. Res. 64:141-160.

Blower J G, Cook L M, Bishop J A (1981) Estimating the size of animal populations. Alien and Unwin, London. 128 p.

Bowden J (1982) An analysis offactors affecting catches of insects inlight-traps. Bull. Entomol. Res. 72:535-556.

Bram R A (1978) Surveillance and collection of arthropods of veterinary importance. Agricultural Research Services Handbook 518. United States Department of Agriculture, Washington, D.C. 125 p.

Campion D G, Nesbitt B E (1981) Lepidopteran sex pheromones and pest management in developing countries. Trop. Pest Manage. 27:53-61.

Cariño F O, Kenmore P E, Dyck V A (1979) The Farmcop suction sampler for hoppers and predators in flooded ricefields. Int. Rice Res. Newsl. 4:21-22.

Chiarappa L, ed. (1971) Crop loss assessment methods: FAO manual on the evaluation and prevention of losses by pests. diseases and weeds. Food and Agriculture Organization and Commonwealth Agricultural Bureaux International, Wallingford. Oxford.

Clinch P G (1971) A battery-operated vacuum device for collecting insects unharmed. N. Z. Entomol. 5:28-30.

Cochran W G (1977) Sampling techniques. 3d ed. Wiley. Neu York. 428 p.

Dietrick E J (1961) An improved back-pack motor fan for suction sampling of insect populations. J. Econ. Entomol. 54:394-395.

Eddlestone F K, Setter J, Schofield P (1984) Insect marking methods for dispersal and other ecological studies. Biblio. 4. TDRI (now Overseas Development Natural Resources Institute), Overseas Development Administration, London. 63 p.

Gomez K A, Gomez A A (1984) Statistical procedures for agricultural research. 2d ed. Wiley, London and New York. 680 p.

Greaves D A, Hooper A J, Walpole B J (1983) Identification of barley yellow dwarf virus and cereal aphid infestation in winter wheat by aerial photography. Plant Pathol. 32:159-172.

IRRI—International Rice Research Institute (1980) Standard evaluation system for rice. International Rice Testing Program, P.O. Box 933, Manila, Philippines.

Ives P M, Moon R D (1987) Sampling theory and protocol for insects. Pages 49-75 in Crop loss assessment and pest management. P. S. Teng, ed. A.P.S. Press, St. Paul, Minnesota. 270 p.

Kisimoto R (1968) Yellow pan water trap for sampling the small brown planthopper *Laodelphax striatellus,* a vector of the rice stripe virus. Appl. Entomol. Zool. 3:37-48.

Lewis T, Macauley E D M (1976) Towards rational design and elevation of pheromone traps. Pestic. Sci. 7:634-635.

Matthews G A (1984) Pest management. Longman, New York and London. 231 p.

McMahen E A, Watson J A L (1977) The effect of separation by papering on caste ratios in *Nasutitermes exitiosus*. J. Aust. Entomol. Soc. 16:455-457.

Nishida T, Torii T (1970) A handbook of field methods for research on rice stem borers and their natural enemies. International Biology Programme Handbook 14. Blackwell, Oxford. 132 p.

Olfert O O, Gage S H, Mukerji M K (1980) Aerial photography for detection and assessment of grasshopper damage to small grain crops in Saskatchewan. Can. Entomol. 112:559-566.

Onsager J A (1976) The rationale of sequential sampling, with emphasis on its use in pest management. USDA/ARS/S Carolina A.E.S. Tech. Bull. 1526. Washington, D.C. 19 p.

Puntener W, ed. (1981) Manual for field trials in plant protection. Documenta Ciba-Geigy, Basel. 205 p.

Rabb R L, Kennedy G G (1979) Movement of highly mobile insects. Proceedings of conference. Raleigh, North Carolina. 456 p.

Reissig W H, Heinrichs E A, Litsinger J A, Moody K, Fiedler L. Mew T W, Barrion AT (1986) Illustrated guide to integrated pest management in rice in tropical Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Riley J R (1979) Quantitative analysis of radar returns from insects. Pages 131-158 *in* Radar, insect populationecology and pest management. C. R. Vaughan, W. Wolf, and W. Classen, eds. Conference Publication 2070. NASA. Wallops Island, Virginia.

Ruesink W G, Haynes D L (1973) Sweepnet sampling for the cereal leaf beetle, *Oulema melanopus*. Environ. Entomol. 2:161-172.

Ryan L, Molyneux D H (1981) Non-setting adhesives for insect traps. J. Insect Sci. Appl. 1:349-355.

Shepard M (1973) A sequential sampling plan for treatment decisions on the cabbage looper. Environ. Entomol. 2:901-903.

Shepard M (1984) A splitter device for subsampling small insects. J. Plant Prot. Trop. 1:117-120.

Smith F L (1958) Effects of plot size. plot shape and number of replications on efficiency of bean yield trials. Hilgardia 28:43-63.

Southwood T R E (1978) Ecological methods, with particular reference to the study of insect populations. 2d ed. Chapman and Hall. London. 524 p.

Steck W, Bailey B K (1978) Pheromone traps for moths: evaluation of cone trap design parameters. Environ. Entomol. 7:449-455.

Strickland A H (1961) Sampling crop pests and their hosts. Annu. Rev. Entomol. 6:201-220.

Symmons P M (1981) Routine estimation of populations of the Australian plague locust. *Chortoicetes terminifera*. Technical Report 2. Australian Plague Locust Commission, Bartos, Canberra. 10 p.

Taylor L R (1961) Aggregation, variance and the mean. Nature 189:732-735.

Taylor L R (1962) The absolute efficiency of insect suction traps. Ann. Appl. Biol. 50:105-421.

Thornhill E W (1978) A motorized insect sampler. PANS 24:205-207.

Tottman D R, Appleyard M, Sylvestre-Bradley R (1985) Cereal growth stages: stem extension and apical development. Aspects Appl. Biol. 10:401-413.

USDA—United States Department of Agriculture (1969) Survey methods for some economic insects. ARS-81-31. Agricultural Research Services, Hyattsville, USA. 137 p.

Van Emden H F (1972) Aphid technology. Academic Press, London. 344 p.

Verheijen F J (1960) Mechanisms of the trapping effect of artificial light sources upon animals. Arch. Neérland. Zool. 13:l-107.

Wallen V R, Jackson H R, MacDiarmid S W (1976) Remote sensing of corn aphid infestation 1974. Can. Entomol. 108:751-754.

Walker P T (1980) Standardization of pest assessment and the FAO methods as applied to pests of cereals, olive and citrus. EPPO Bull. 1093-96.

Walker P T (1981) The relation between infestation by lepidopterous stem borers and yield in maize: methods and results. EPPO Bull. 11:101-106.

Yates F R S (1977) Sampling methods for censuses and surveys. Griffin, London. 428 p.

Youdeowei A, Service M W (1983) Pest and vector management in the tropics. with particular reference to insects, ticks, mites and snails. Longman, London and New York. 399 p.

Zadoks J C, Chang T T, Konzak C F (1974) A decimal code for the growth stages of cereals. Weed Res. 14:415-521.

## Notes

*Author's address:* P. T. Walker, 10 Cambridge Road, Salisbury, Wiltshire SP1 3BW, England.
*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Practical methods for quantifying diseases and pathogen populations

R. E. Gaunt

Any pest measurement system, whether it is part of a study of an epidemic, of crop loss, of plant resistance, or of crop response to chemical treatment, must be chosen to suit specific objectives. The many methods that have been developed (see recent reviews by Berger 1980, Gaunt 1987, James and Teng 1979, Teng 1983) provide an apparently bewildering choice. That choice can be markedly simplified by analyzing the reasons measurement is needed and by assessing the resources available.

The degree of accuracy required (in relation to actual value) and the precision and repeatability (variation in measurements taken by one or multiple observers) must be considered in choosing a measurement method. Too often, measurements are taken and data generated without adequate consideration of these factors. When an inappropriate measurement method is used, especially in conjunction with an inappropriate sampling system, there is at best an inefficient use of resources. In extreme cases, the data may be unreliable and completely unsuitable for analysis. The result is that the objectives of the study are not met.

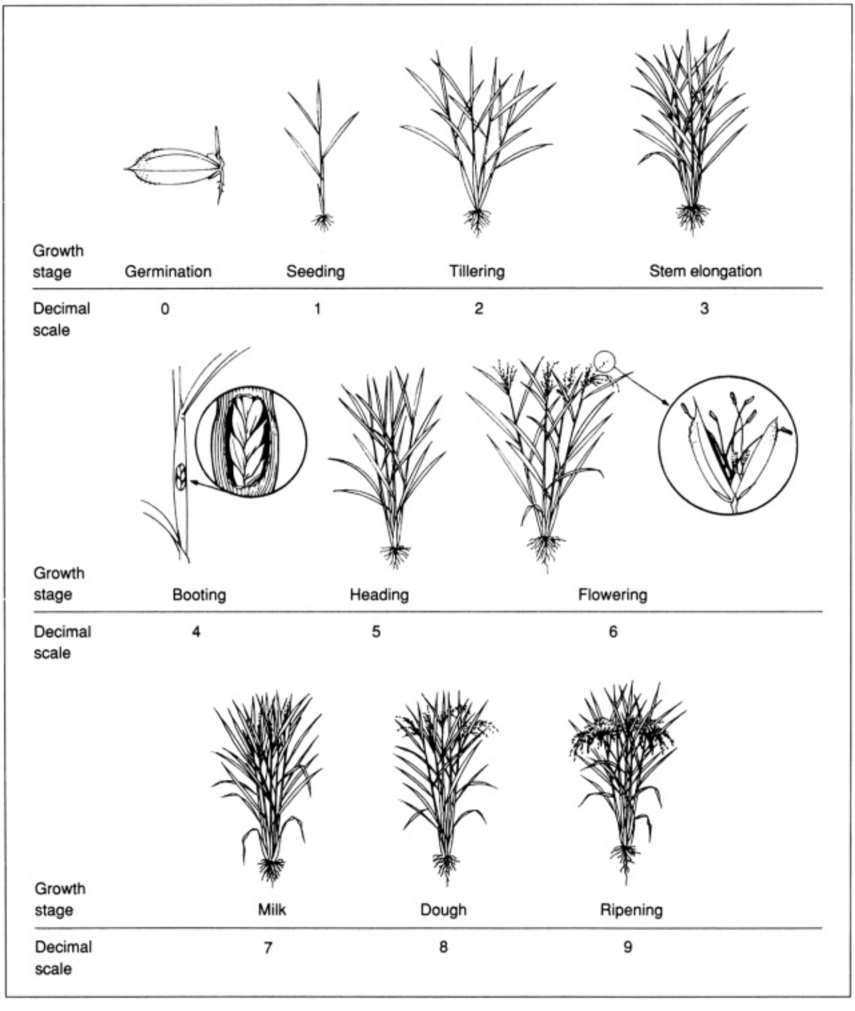
The steps in measuring disease are

1. Analyze the objectives of the study and available sampling systems.
2. Consider methodsfor defining the time of measurement and whether to measure the pathogen population or the disease.
3. Define the scale of measurement appropriate to the objectives.
4. Integrate the chosen method of measurement with the sampling plan selected.

## Time of measurement

Time can be defined as hours, days, months, or years, depending on the type of study and the organism involved. An appropriate time scale can be related to the calendar (e.g. Julian days) or to such events as seasons of the year (e.g. arrival of rain), crop establishment, infection (or inoculation), and treatment (e.g. chemical sprays). Special cases may include the use of degree or rainfall days, especially in studies of epidemics.

Time can also be expressed indirectly, by describing the stage of the plant on which measurements are made. Such descriptions allow comparisons to be based on the physiology of the plant, usually expressed as growth stages. Growth scales have been developed for cereals (Zadoks et al 1974) and many other crops. An example of a scale of rice growth stages is given in Figure 1. The decimal scale describes the major development stages (0-9 scale). The amount of growth within each stage is shown by an additional range (0-9). For example, growth stage (GS) 23 indicates that the rice plant has a main stem and three tillers. A common practice is to use the primary scale (GS 0-9) for general observations and treatment recommendations, a single two-figure stage to define the most advanced stage of development and growth, and a multiple stage when detailed information is required. Thus, a plant at GS 17, 23, 32 (7 leaves



**1.** Growth stages of rice (adapted from Reissig et al 1986), on a decimal scale (Zadoks et al 1974).

unfolded, 4 stems, 2 nodes detectable) might also be described as being at GS 32 or GS 3. depending on the objectives. An appropriate time scale in conjunction with a growth stage scale may be useful in tropical systems with cultivars that differ in duration.

Whatever the method chosen, it is important that the time measurement used be a commonly accepted form, so that direct comparisons with other work are possible. Standardization is an objective in all areas of pathogen and disease measurement (Chiarappa 1971, 1981).

## Pathogen measurement

Many techniques based on direct and indirect estimations of pathogen incidence or frequency have been devised for quantifying plant pathogen populations. In some, measurement is straightforward, even though time-consuming and tedious. More consideration should be given to the method of sampling. For example, spore numbers can be counted directly, using microscope preparations or mechanical and electronic aids such as the Coulter Counter and balances. Other fungal propagules (e.g. sclerotia), nematodes, bacterial cells, and virus particles also can be counted directly, although virus particles usually would be quantified by other methods (Bajet et al 1986, Hsu et al 1986).

Direct counting is suitable for pathogens that produce readily accessible propagules that can be collected in spore traps and other special devices. Most have been designed for dry, airborne spores. Systems also are available for wet, splash-dispersed spores and other propagules (Fitt and Bainbridge 1983). Identifying the material collected can sometimes be a problem and additional steps, such as using selective media (including host plants) in the collection process, may be required. Bacteria and viruses are especially difficult to identify and count. Progress is being made in developing molecular techniques for identification (Irwin 1987, Gitaitis et al 1985).

Some pathogens are not readily accessible to collection. Pathogens resident in soil are often difficult to isolate. Methods such as wet sieving and flotation of a suitable sample of the soil volume are used. Estimates of a population may be derived from soil plated onto selective media, from bait plants grown in soil samples (or vice versa), or by dilution to extinction, such as is done with MPN methods (Pfender et al 1981). All require considerable labor and estimates are subject to large error.

Some seedborne pathogens are accessible on the outside of the seed coat. Many others are measured indirectly, such as the proportion of diseased seeds in a population, and special methods have been devised for that purpose. Seed may be observed directly for external pathogens or washed, with the wash water plated onto media (Neergaard 1977). Some methods respond to the viability of propagules, which may limit their usefulness with young seed lots (as are used in measuring *Pyricularia oryzae,* the causal agent of rice blast). For bacteria and viruses, it is often necessary to homogenize a seed sample and test the homogenate by plating it onto media or by using immunological methods or DNA probes. Similar problems and solutions are found with pathogens associated with plant debris or carried in animal vectors.

Often, it is so difficult to measure the pathogen population, directly or indirectly, that quantification is confined to measurement of the disease.

## Disease measurement

Disease can be measured as incidence of diseased material or as degree of disease development and expression (referred to as disease severity). Incidence can be measured on a large scale, such as the proportion of fields in a production area that have at least some disease (referred to as disease prevalence). Within fields, numbers of infected plants in a sample can be counted. This, expressed as proportion of infected plants, is one of the most commonly reported measures of disease incidence.

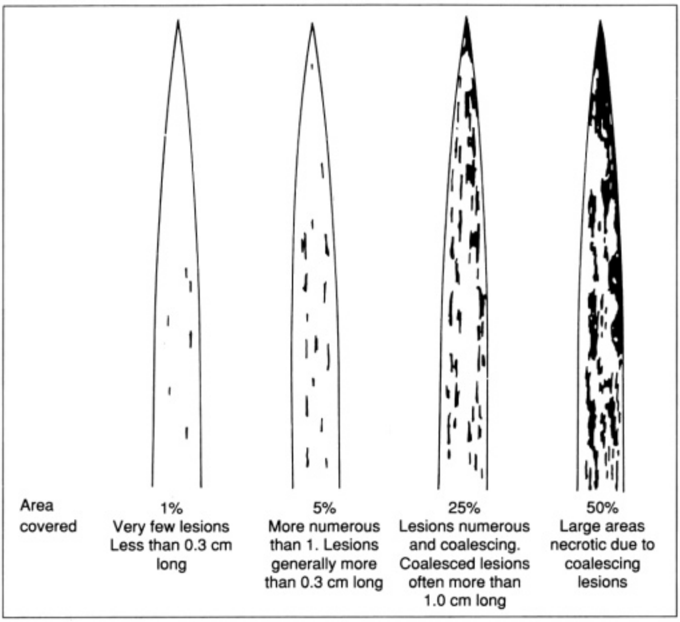
For more detailed studies, it is often necessary to measure disease incidence on individual plant zones (e.g. stems or canopy layers), plant parts (e.g. specific leaves), orparts of plantparts (e.g. cells for nematodes, bacteria, and viruses). Special methods developed to measure disease incidence in seeds often are used as an indirect measurement of pathogen incidence. For example, *Pyricularia oryzae* can be seedborne but normally cannot be seen by direct examination of seeds or by washing seeds and counting spores. The International Seed Testing Association recommends that seeds be placed on moist filter paper in trays and incubated for 7 d at 20 °C with 12 h NUV light in each 24 h. Alternatively, seeds may be transferred to - 20 °C on the second day only of the 7-d incubation period, to kill the seeds. Each seed is then examined by microscope to identify typical colonies of conidiophores and conidia.

Disease incidence also may be used as an indirect measurement of disease severity (Seem 1984). At low disease levels, incidence and severity are often closely correlated. At incidences greater than 30-40%, that relationship is not reliable. The relationship should be defined for each disease or cultivar combination and for markedly different environments. Incidence usually is measured on the whole plant or on a group of leaves known to correlate significantly with severity.

The amount of plant material occupied by disease symptoms or signs is measured when more detailed assessments of disease severity are required. Most assessments are based on measurement of diseased areas, often including disease-induced chlorotic areas of the plant.

The proportional area of plant surface occupied by disease is the most common measurement of severity. This approach can be used for roots, stems, leaves, flower parts, and fruit. For three-dimensional objects, volume estimation may be used, but volume is difficult to estimate and is often in proportion to surface area.

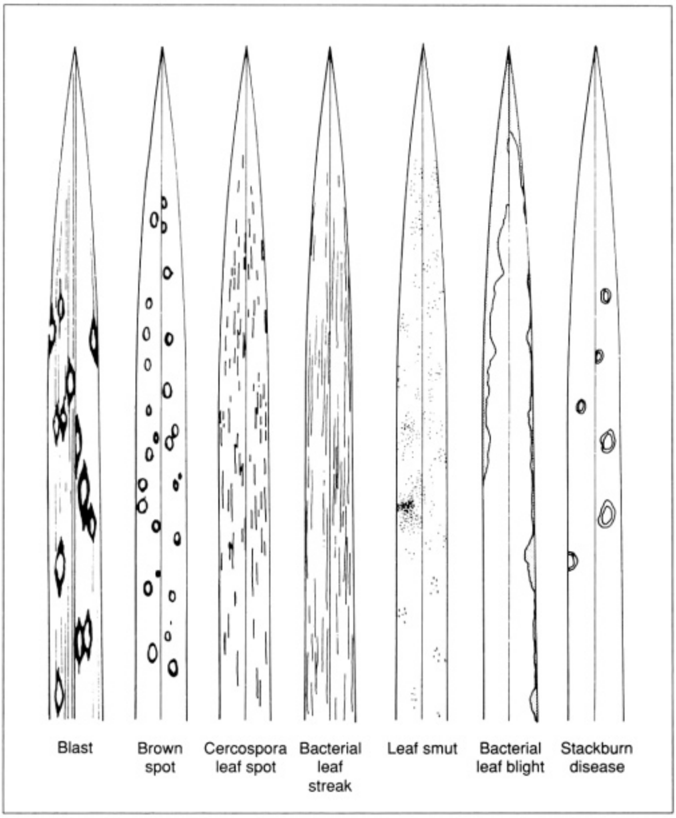
Area may be estimated visually, with a visual guide such as a standard area diagram (Fig. 2). Diagrams have been produced for most rice pathogens and for other major tropical crops, largely in response to training programs initiated by the Food and Agriculture Organization, international research centers, and similar bodies. A standard area diagram should include a realistic representation of both the relevant plant part and the diseased area (Fig. 3), with several levels of disease seventy indicated. Visual estimates of severity commonly are recorded as percentage diseased tissue. Sometimes it is useful to condense a percentage scale into classes or groups.



**2.** Standard area diagram of assessment key for narrow brown spot disease (after Chin and Ho 1973).

Several problems associated with the use of standard area diagrams may lead to inadequate accuracy and precision. Shenvood et al (1983), working with a foliar disease of *Dactylis glomerata,* showed that large errors may occur in visual measurements, usually by overestimation. Errors were greatest at low disease severities and when similar amounts of disease occurred in many, but smaller, areas of a plant part. Training technicians to accurately and consistently estimate disease severity visually is an important part of a research program. It can be facilitated by having trainees practice with known standards using fresh or preserved material. Training materials can include photographic records or computer graphics, such as the program for cereal diseases called DISTRAIN (Tomerlin and Howell 1988). As computer technology improves, especially with the development of less costly methods of storing and retrieving digitized images, it probably will be used more widely for this purpose.

For some purposes, especially those related to the measurement of production losses, it is more relevant to measure remaining green area, either as a proportion or in absolute units (Lim and Gaunt 1985). Percentage green area is measured in much the same way as diseased area, using standard area diagrams for reference. Actual areas can be measured by comparing a leaf to leaf shapes printed on standard weight paper or by using meters that respond to light interception. Image analysis by computer is ideal for discriminating diseased and healthy tissue and measuring area. The technique has been used for roots, where discrimination is relatively straightforward, but its use for green areas has been limited. Lindow and Webb (1983) reported using an Apple



**3.** Diagrammatic representation of a range of rice foliar diseases (Ou 1985).

computer system to discriminate and measure diseased areas of several plant pathogens (the areas show up as grey tones on the computer screen). Successful discrimination required using light filters to enhance differences; the procedure is not readily adaptable to routine analyses. S. E. Lindow (pers. comm.) and I have found that color images are often much better for discriminating diseased and healthy areas for a wide range of disease types, but the technology is not yet adequately developed for routine analyses. Also the instrumentation is expensive and not readily accessible.

Imaging methods are applicable using any scale. They are being developed most rapidly for remote sensing of diseases and other factors (see Nutter, this volume).

Both proportionate and absolute measurements of disease severity and green area can be limited to selected plant parts or can include the total green area of the plant. For studies related to understanding disease-induced yield losses, it is desirable to measure total green area, including leaves, stems, and relevant floral parts. This is possible with relatively simple plants, such as rice, that have few leaves and stems. Nonetheless, considerable resources are required. Such measurements should be taken only to meet specific research goals. In plants such as cassava, peanuts, and tree crops, total green area measurement is not possible. Calibration of canopy green areas taken by remote sensing with green area measured directly on sample plants is likely to become an important method.

Most measurements are of specific parts of the canopy, usually of single or several leaves. Choice of the appropriate leaf or leaves should be based on the objectives of the investigation. In a cereal such as rice, the two or three uppermost leaves often are sensitive to small changes in the rate of epidemic development, especially leaves associated with chemical treatment or resistance. These leaves are often chosen for sequential analyses. Leaves lower in the canopy often have the earliest and greatest amounts of infection and are useful for measurements related to disease and crop loss surveys and to disease management.

Knowledge of disease epidemiology and of yield physiology are important bases for choosing the plant parts most suitable for meeting the objectives of the study. Empirical models can help define the choice by specifying the time (growth stage) and plant part on which disease development is mostly closely correlated with yield loss.

## Data analysis and interpretation

Pathogen and disease measurements usually generate a large amount of raw data. Choosing the appropriate analysis method is critical to maximizing the information to be gained. Raw data recorded by pencil and paper or electronically (Rouse and Teng 1984) must be condensed into a useful form. Using computer spreadsheet software to summarize replication measurements into means before statistical analysis can save time and reduce error. Careful design of the spreadsheets on which raw data are recorded can considerably increase the efficiency of data manipulation. That design should be an integral part of experimental design, done before data collection.

## References cited

Bajet N B, Aguiero V M, Daquioag R D, Jonson G B, Cabunagan R C, Mesina E M, Hibino H (1986) Occurrence and spread of rice tungro spherical virus in the Philippines. Plant Dis. 70:971-973.

Berger R D (1980) Measuring disease intensity. Pages 28-31 *in* Crop loss assessment. Miscellaneous Publications 7. Agricultural Experiment Station, University of Minnesota, St. Paul, Minnesota.

Chiarappa L, ed. (1971) Crop loss assessment methods. FAO manual on the evaluation and prevention of losses by pests, diseases and weeds. Commonwealth Agricultural Bureaux. Slough, England. 255 p.

Chiarappa L, ed. (1981) Crop loss assessment methods - supplement 3. Food and Agriculture Organization/Commonwealth Agricultural Bureaux, Slough, England. 123 p.

Chin K M, Ho B L (1973) Assessment keys for some rice diseases. MARDI Report No. 4. MARDI. Serdang, Malaysia. 9 p.

Fitt B DL, Bainbridge A (1983) Recovery of *Pseudocercosporella herpotrichoides* spores from rainsplash samples. Phytopathol. Z. 106:177-182.

Gaunt R E (1987) Measurement of disease and pathogens. Pages 6-18 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press. St. Paul. Minnesota, USA.

Gitaitis R D, Jones J B, Jaworski C A, Phatak S C (1985) Incidence and development of *Pseudomonas syringae* pv. *syringae* on tomato transplants in Georgia. Plant Dis. 69:32-35.

Hsu H T, Cabauatan P Q, Hibino H (1986) Mouse anticlonal antibody to rice grassy stunt virus and its use for disease detection. Phytopathology 76:1132.

Irwin J A (1987) Recent advances in the detection of seed borne pathogens. Seed Sci. Technol. 15:755-763.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Pages 201-267 *in* Applied biology. Vol. IV. T. H. Coaker, ed. Academic Press, New York.

Lim L G, Gaunt R E (1985) The effect of powdery mildew (*Erysiphe graminis* DC. f. sp. *hordei*) and leaf rust (*Puccinia hordei* Otth.) on spring barley in New Zealand. I. Epidemic development, green leaf area and yield. Plant Pathol. 34:44-53.

Lindow S E, Webb R R (1983) Quantification of foliar plant disease symptoms by microcomputer-digitized video image analysis. Phytopathology 73:520-524.

Neergaard P (1977) Seed pathology. Vol. I. Macmillan Press, London, UK. 839 p.

Nutter F W Jr. (1990) Remote sensing and image analysis for crop loss assessment. Pages 93-105 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Ou S H (1985) Rice diseases. Commonwealth Mycological Institute, London, UK. 380 p.

Pfender W F, Rouse D I, Hagedorn D J (1981) A “most probable number” method for estimating inoculum density of *Aphanomyces euteiches* in naturally infested soil. Phytopathology 71:1169-1172.

Reissig W H, Heinrichs E A, Litsinger J A, Moody K, Fiedler L, Mew T W, Barrion AT (1986) Illustrated guide to integrated pest management in rice in tropical Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines. 411 p.

Rouse D I, Teng P S (1984) Understanding computers: applications in plant pathology. Plant Dis. 68:539-543.

Seem R C (1984) Disease incidence and severity relationships. Annu. Rev. Phytopathol. 22:133-150.

Sherwood R T, Berg C C, Hoover M R, Zeiders K E (1983) Illusions in visual assessment of stagonospora leaf spot of orchardgrass. Phytopathology 73:173-177.

Teng P S (1983) Estimating and interpreting disease intensity and loss in commercial fields. Phytopathology 73:1587-1590.

Tomerlin J R, Howell T A (1988) DISTRAIN: a computer program for training people to estimate disease severity on cereal leaves. Plant Dis. 72:455-450.

Zadoks J C, Chang T T, Konzak C F (1974) A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

## Notes

*Author’s address:* R. E. Gaunt, Plant Protection Research Unit. Microbiology Department, Lincoln University College of Agriculture, Christchurch, New Zealand.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Weeds: generating populations, field sampling, and data analysis

K. Moody

Determining the effects of crop-weed competition requires information on the following factors (Smith 1988):

- What weed densities in what crop density will reduce yields?
- In the development of crops and weeds. when does competition occur?
- What is the effect of soil fertility and moisture on crop and weed competition?
- How do weed species differ in their competitiveness with the crop?

The objective of weed control is to maximize the desirable biological crop production for the least cost (Mortimer and Firbank 1983). In effective weed management programs for rice, control should be applied only after weeds reach levels that cause economic losses to the crop. Basic information on the economic thresholds of individual need species or groups of species can be used to develop a series of models

- To determine control options for specific weed situations.
- To determine when to initiate control inputs.
- To determine costs of various control inputs.
- To predict economic returns of different control programs.

Economics is a prime consideration in implementing weed control measures. Control measures should not be implemented unless increased yield or improved quality more than offset the cost of control. This can be determined only by measuring the effect of individual weed species on crop yield (Buchanan 1977).

## Establishing experimental weed densities

If possible, natural populations of weeds should be used in studies involving crop loss at different weed levels. Weeds should be thinned to the desired level 1-2 wk after their emergence, by hand or with selective or nonselective nonresidual herbicides. Desired weeds should be covered during herbicide application to prevent herbicide contact. A minimum of five population levels, including a zero weed level (weed-free check). should be established.

A major task in conducting weed competition experiments is control of unwanted weed species. Routine weed control measures often interfere with the weed species being studied. Hand labor can be costly and some weeds are difficult to remove from crops, making use of herbicides advantageous. Considerable care must be exercised in choosing herbicides to control undesirable weeds in crop-weed experiments. Select those that are relatively noninjurious to the crop and to the weed species being studied (Buchanan 1977).

The weed population levels to be established depend on the objectives of the experiment. If the objective is to establish the relationship between crop yield and low weed levels, such as in determining an economic threshold, then weed population levels should be kept below that level at which intraspecific competition occurs (e.g. 0, 2, 4, 6, 8 weeds per unit area). If the objective is to determine the effect of a wide range of weed populations on crop yield, then the minimum number of levels needed would be two or three low levels (nonintraspecifically competitive), one level where intraspecific competition just begins, and one level at the maximum possible weed population.

Where natural populations of a desired weed do not exist, that weed may be seeded or transplanted at the desired population levels. The objective is to simulate as closely as possible natural conditions for weed seed germination and emergence. Weed seeds should be collected from a local source and have good germination percentage.

Crop and weed seeds should be planted the same day. While planting can be done by hand, Buchanan notes that using a garden-type seeder (such as a Planet-Jr.) is usually better. Plant the seeds either continuously in rows or in hills. Planting in hills takes more time but saves labor during weed thinning.

The number of weed seeds to be planted will depend on the desired population and potential seed germination. Enough seed should be planted to ensure that a weed seedling will become established where desired, but care should be taken not to overplant. Excessive stands make thinning difficult: the desired seedlings could be uprooted during the thinning operation.

Weeds should be thinned over a period of several weeks. The first thinning should be about 1 wk after emergence. The final thinning should be after weeds are well established and past the danger of seedling diseases. Each thinning should be done early enough that a minimum amount of interplant competition has occurred and that adjacent weeds or crop plants will not be uprooted. Thinning after a light rain or following irrigation makes removal easier and helps avoid uprooting adjacent plants.

To prevent a failure in getting a stand of weeds, it is often advantageous to plant small weed seeds at two depths. Depending on moisture availability, slight differences in planting depth can affect germination (Buchanan 1977). Another way to ensure good weed emergence is to imbibe the seeds before planting. If the soil is dry, a small amount of water should be added directly after planting to prevent excessive drying of the imbibed seeds.

Weed seedlings at the two- to three-leaf stage can be transplanted into the crop at the desired density 1-2 wk after the crop has been planted, depending on growth rate of the weeds. Transplanted weeds undergo transplanting shock and are not as competitive, at least in early growth stages, as those that emerge from seeds.

## Assessing weed control treatments

Once a weed control trial has been established and the treatments applied, it is important to regularly assess the effects of the treatment on the crop and the weeds. The objective of field sampling for weeds is to get a reasonable idea of the status of a weed population in a field at a given point in time. Because it is impossible to get a perfect sample, we strive to obtain the most representative sample possible, taking into account time and manpower constraints, economic considerations, and other factors.

Several methods can be used to assess the response of crop and weeds to a treatment. The method chosen will depend on the objectives of the experiment and on the time and personnel available to collect the data. Counting and/or harvesting and separating weeds into species or into broad classes based on type of weeds is time-consuming and laborious compared with visual ratings. When large numbers of plots or plant species are involved and rapid accumulation of data is required, visual ratings should be used.

## When to sample

### Sampling for use in control decisions

Control practices for weeds fall into two categories: prophylactic and remedial. A prophylactic practice is used to prevent a weed population from being expressed, even though the weed propagules may remain viable in the field. A remedial practice is implemented after the weed population has become established.

Because prophylactic control is imposed before weeds emerge, field sampling for use in decisionmaking must be done in the previous crop. Relatively good information regarding species composition within a population of weeds can be gained from such sampling, but prediction of population numbers is poor.

Field sampling to be used as a basis for remedial control decisions should be done 2-3 d before the anticipated control action. Information on species composition, relative weed size, and number of weeds per unit land area is taken, along with observations on any other factors that would affect the efficacy of the control action.

### Sampling for crop loss assessment

Field sampling for crop loss assessment due to weeds preferably should be carried out when weeds can no longer affect crop yield, or at crop harvest. Late-germinating weeds may grow very rapidly and produce large amounts of dry matter, yet have little effect on yield.

For rice, Kim and Moody (1980a,b) found that *Scirpus maritimus* L. should be sampled 40 d after transplanting, *Echinochloa glahrescens* Munro ex Hook. f. at rice heading, and *Monochoria vaginalis* (Burm. f.) Presl and *Echinochloa crus-galli* (L.) P. Beauv. ssp. *hispidula* (Retz.) Honda at rice maturity. If a mixed weed vegetation was to be sampled once, they recommended that it be done at rice heading to obtain maximum floristic information. Correlations between crop yield and weed weight were almost always highest when weed data were collected at the flowering stage of rice (IRRI 1977).

## Sampling area

Weed samples can be cut or weed counts made from any sampling area convenient for the particular vegetation being investigated. A small quadrat can be used if the weed species has small, numerous plants, so that counting of individual weeds is easier. A large quadrat is appropriate if the species is large or thinly scattered. The smaller the sampling area, the less precision. For small research plots. at least two weed samples should be taken from each plot: the area for each sample should be at least 0.25 $m^2$. When the crop is row seeded, place the quadrat so that it lies across the row, to sample weeds within and between rows.

When more and larger samples are required for acceptable precision, the area used for a sample should be at least 5 $m^2$, usually taken from the center of each plot. (Outside rows act as a border between two treatments.)

In fields where weed populations are uniformly distributed, sampling should be in a predetermined uniform pattern, with equal spacing between sample sites. The number of sample sites needed depends on field size and time constraints: a minimum of 10 sample sites/field for fields 1 ha or less in size and 5 samples/ha for larger fields.

In fields with high weed populations (where weeds interfere with each other), relatively small samples (1 $m^2$ or less) are adequate. Where weeds are far enough apart that their individual effects do not overlap, sample size should be no smaller than the average distance between any two weeds in the field. This guarantees that the sample size will not be so small as to eliminate the lowest weed population present in the field.

In fields where weed populations are not uniformly distributed, examine the field border to border to determine if it can be subdivided into areas with similar populations. If subdividing is feasible, then sample each subfield as if it were a uniform field. If a nonuniform field cannot be conveniently subdivided, then the entire field should be sampled, but in a nonsystematic manner, taking care to include all levels of weediness in the sample.

## Sampling method

### Visual estimation

Visual estimates of the number of individual weeds in a stand can provide useful data. Such ratings are used to accumulate data rapidly, particularly where large numbers of plots or plant species are involved and resources are limited. Such systems depend on unbiased observers utilizing a readily understandable rating system that is simple to use while generating data suitable for statistical analysis (Frans and Talbert 1977).

Such estimates are more reliable when they are made on pure weed stands or when the weed species in question is visually prominent. When weeds are sparse or covered by other vegetation or when their growth has been changed by herbicide treatment, reliable visual estimates are difficult to make. If estimation of the numbers of different weeds in a mixed stand must be made, a more objective method than visual estimates will be required (Klingman 1971).

Reliability is increased if independent estimates by three or more workers are averaged. Bias can be reduced by sampling plots randomly, by plot number, with no regard to treatments imposed. Data should be recorded in numerical rather than in descriptive terms, so that they can be analyzed statistically (Klingman 1971). The standard basis for comparison is an untreated, weed-free check plot for herbicide injury ratings or an untreated weedy check for weed control ratings (Frans and Talbert 1977). Those estimating weed populations should continually refer back to the check plots while making their visual ratings.

When starting to score plots, the rater should first look quickly at all plots and establish the appearances of extreme conditions—the palest and the darkest, the least weedy and the most weedy, etc. Scores can be allotted to these extremes. Then study the plots in order, one block or row or column at a time. Raters should score plots without knowledge of plot treatments. If possible, a rater should look at all plots from the same direction (Pearce et al 1988).

While a number of rating methods exist, the most common is to estimate the percentage reduction in stand compared with the unweeded check. The system used is a 0-100 rating scale (direct percentage figures). A value of 0 represents no weed control; 100 represents total destruction of weeds. One variation uses a 0-10 scale.

In principle, scores may be analyzed statistically. In practice, using such estimates can cause problems because of discontinuity. Ideally, the scores should allow for at least 20 possible values, and preferably 30. But it would be unwise to attempt so many grades, even when they have a quantitative basis: most people can usefully distinguish only about 2-10 different grades (Pearce et al 1988). The data may need to be transformed before analysis (see Gomez and Gomez 1984. p. 307).

Visual rankings tend to underestimate the plants having low cover value. Results may have low accuracy and be subject to bias.

## Weed counts (density)

This method is accurate, allows direct comparison of different areas and different species, and is an absolute measure of the abundance of a plant. However, the process is laborious and time-consuming, particularly if large numbers of plots are involved.

Counts of individual weed species give a more precisere presentation of both weed infestation and degree of control. They are most useful when weed infestations are scattered. The total number of weeds occurring in a plot may be counted, but usually counts are made in uniform areas randomly selected in each experimental plot. The number and size of the sample areas will vary with weed stand and plot size, but enough samples must be taken to provide an accurate estimate (Frans and Talbert 1977).

Because plant counts are time-consuming, it is important to minimize the area of a sample (or sample unit). But the data obtained from counting the number of individual weeds within small samples have high variability. Reasonable accuracy is possible if the number of individuals of a species in a sample exceeds 30 (Cottam et al 1953). For a given level of precision, low-density weed populations require a larger sampling area than do high-density ones (Klingman 1971).

Reductions in numbers of weeds in treated plots compared with the unweeded check are commonly used in assessing the performance of a weed control treatment. For precise results, the weeds should be counted by species. Many researchers divide the weeds into three broad classes — broadleaved weeds, grasses, and sedges.

Weed counts are usually done early during crop growth, when weed competition is greatest and weeds are small and easy to count. A count of individuals is feasible only when plants are spaced far enough apart and have a discrete growth habit. For creeping perennials, counts should be made of individual stems or shoots rather than of individual plants.

While the number of weeds within any one growth form is closely correlated with plant cover, it is not necessarily a good criterion for judging the relative harmfulness to crops of widely differing growth forms. Because of their large size and growth habit, a small number of weeds of certain species may be far more injurious than many times that number of weeds of species with smaller stature (Klingman 1971).

### Weed weight

Weed weight gives a more accurate evaluation of the effect of a weed control treatment on weed growth than do weed numbers: weight combines plant density and plant size. Weight also more accurately reflects the effect of weeds on crop yield. Aboveground portions of weeds are harvested from randomly selected quadrats within a plot and weighed, preferably after drying. Dry weight data are more useful than fresh weight data (Klingman 1971).

For dry weight assessments, samples should be dried immediately or kept at low temperature to minimize loss through respiration. All of the weeds harvested or a subsample can be used. Drying can be carried out overnight. It should be done in air-circulating ovens at 85-95 °C for 16 h or at up to 105 °C for 12 h (Klingman 1971). Harvested weeds can be separated by species or into the three broad classes of species before drying, but that is extremely time-consuming.

The disadvantage of destructively harvesting weeds before harvesting rice is that parts of the plots are destroyed, precluding the use of those areas for subsequent data collection (Klingman 1971). Sampling must be done outside the area that will be used to assess rice crop harvest. It is preferable to leave an area in the center of the plot for rice harvest and to use the surrounding area for sampling weeds. This method is also laborious and time-consuming, and is best adapted to experiments with a small number of treatments.

## Weed flora

Regardless of the method of weed assessment used, every effort should be made to identify all the weeds present in all plots and to list them by scientific name in order of importance. If this is too time-consuming, at least those weeds present in the no-treatment plot should be recorded.

## Regression analysis

Regression analysis is widely used to estimate decrease in crop yield with a given increase in weed pressure. Regression analysis can show the effect of weed density or weed weight. In most economic threshold studies, yields are more highly correlated with weed weight than with weed number (Buchanan 1977).

Coble (1986) reported research conducted at North Carolina State University to develop a multispecies economic threshold for weeds in soybean [*Glycine max* (L.) Merr.]. The approach was to establish an index for comparing the competitive ability of the different weed species infesting the crop. Five weed species were chosen to evaluate research methodology and to begin the indexing: *Xanthium strumarium* L., *Polygonum pensylvanicum* L., *Chenopodium album* L., *Cassia obtusifolia* L., and *Sida spinosa* L. These weeds are common in a major part of the soybean-growing area and previous studies had shown differential effects of the five species on soybean yield.

In earlier, additive experiments (De Wit 1960). 100 soybean plants were spaced 15 cm apart in a 1.5- × 1.5-m plots. Individual weed species were added at population levels of 0, 2, 5, 10, and 15 weeds/plot. Both crop and weeds were established from seed. Plots were harvested 10 wk after seeding and biomass of both soybeans and weeds measured. Linear regression equations were computed for the effects of weed population on soybean biomass (Table 1).

The competitive index (CI) is derived by dividing the regression coefficient by the Y intercept for each equation (Dew 1972), then arbitrarily setting the CI for the most competitive species at 10.0. The competitive indices for the other species are determined using

$$CI_2 = \frac{[b_2/a_2]}{b_1/a_1} \times 10$$

where $CI_2$ is the competitive index value for species 2; $b_2$ and $a_2$ are the regression coefficient and Y intercept, respectively, for species 2; and $b_1$ and $a_1$ are the regression coefficient and Y intercept for the most competitive species in the study. The multiplier (10) converts the index to a 0-10 scale.

CI only measures relative competitive effects of the different weed species, not absolute effects. Yield effects are determined by comparing the CI with yield losses from large-plot competition studies (Table 2).

**Table 1. Linear regression equations describing weed effect on soybean biomass and computation of resulting competitive indices (Coble 1986).**

| Weed species | Equation | b/a | Competitive index |
|---|---|---|---|
| *Xanthium strumarium* | Y = 583 - 26.1X | .045 | 10.0 |
| *Polygonum pensylvanicum* | Y = 535 - 11.2X | .021 | 4.7 |
| *Chenopodium album* | Y = 577 - 12.0X | .021 | 4.7 |
| *Sida spinosa* | Y = 586 - 7.1X | .012 | 2.7 |
| *Cassia obtusifolia* | Y = 573 - 5.3X | .009 | 2.0 |

**Table 2. Relationship of competitive index values to known values for losses due to weeds, resulting in the competitive load concept (Coble 1986).**

| Weed species | Competitive index | Weeds/ row[a] | Competitive load |
|---|---|---|---|
| *Xanthium strumarium* | 10.0 | 2 | 20.0 |
| *Polygonum pensylvanicum* | 4.7 | 4 | 18.8 |
| *Cassia obtusifolia* | 2.0 | 10 | 20.0 |

[a]Number of weeds needed to cause 10% yield reduction.

**Table 3. Example using field survey information to determine soybean losses due to a weed complex (Coble 1986).**

| Weed species | Av no. of weeds/10-m row | Competitive index | Competitive load |
|---|---|---|---|
| *Xanthium strumarium* | 0.8 | 10.0 | 8.0 |
| *Polygonum pensylvanicum* | 3.2 | 4.7 | 15.0 |
| *Sida spinosa* | 5.4 | 2.0 | 10.8 |
| Total competitive load | | | 33.8 |
| Projected soybean yield loss (%) | | | 16.9 |

If the CI results in the same relative ranking of weed competitive ability as values reported in the literature for the same species, then multiplying the CI by the number of weeds per unit area, given some set level of yield loss, should result in the same product for each species. Previously established values are available for three of the weeds used in Coble's study: *X. strumarium* (Barrentine and Oliver 1977), *P. pensylvanicum* (Coble and Ritter 1978), and *C. obtusifolia* (Thurlow and Buchanan 1972). Multiplying the CI values from this study by the values reported earlier for the number of weeds per 10-m row that would cause a 10% soybean yield loss resulted in a figure close to 20 for each weed (Table 2). This result confirmed that the small-plot experiments Coble used resulted in the same relative ranking of weed competitive ability as was found in previous studies. In addition, the product of the CI multiplied by the expected 10% yield loss due to weeds (hereafter referred to as the competitive load [CL]) was always about 20. Therefore, each unit of CL should be equivalent to approximately 0.5% yield loss.

The CL concept can be used to determine the economic threshold for a multispecies weed complex. Field survey information (scouting reports) are used to determine the number of weeds of each species per unit area (in this case, a 10-m row). The number of a species per 10-m row is multiplied by the CI value for that species to determine the individual species CL. The CL values for each species present are summed to give a total competitive load (TCL) for the crop. Multiplying the TCL by 0.5 results in an estimate of the percent yield loss due to the weed complex (Table 3).

The projected percent yield loss from the weed complex can be used to calculate actual yield loss by multiplying by estimated weed-free crop yield. Actual yield loss

**Table 4. Relationship between yield reduction and weed weight for different types of weed communities (Kim and Moody 1980b).**

| Weed community type | Yield reduction (%) at various weed weights (g/m$^2$) | | | | | Weed weight required for 50% yield reduction (g/m$^2$) |
|---|---|---|---|---|---|---|
| | 100 | 200 | 300 | 400 | 500 | |
| *Echmochloa crus-galli ssp. hispidula-Scirpus maritimus* | 42 | 80 | 100 | | | 123 |
| *Monochoria vaginalis-Fimbristylis miliacea-Echinochloa glabrescens-S. maritimus* | 21 | 42 | 63 | 84 | 95 | 239 |
| *M. vaginalis-Scirpus supinus* | 15 | 31 | 46 | 62 | 77 | 333 |
| *M. vaginalis* | 15 | 31 | 46 | 61 | 75 | 365 |
| *E. glabrescens* | 10 | 20 | 30 | 40 | 51 | 497 |

is then multiplied by the crop price per unit and compared with cost of the control tactic used to determine profitability of treatment.

This type of economic model is useful for short-term (single crop season) decisions. It does not consider such factors as weed seed bank increases in the soil that result from subthreshold populations of weeds. Also, the model is based on linear regression equations. The assumption is that the weed population is low enough that no competition occurs among the weeds present. In practice, weed populations high enough for competition to occur among the weeds are far above economic thresholds.

Kim and Moody (1980a,b) reported a high negative linear relationship between rice grain yield and weed weight at heading. The yield reduction due to weed competition varied, depending on nitrogen level (Kim and Moody 1980a) and weed species (Kim and Moody 1980b). Yield reduction at 0 and 160 kg N/ha was about the same: it was lower at 80 kg N/ha. The weed weight required for 50% yield reduction was approximately 330 g/m$^2$ for 0 and 160 kg N/ha and 520 g/m$^2$ for 80 kg N/ha (Kim and Moody 1980a).

When no nitrogen is applied, nitrogen will be the factor that most limits growth. Available nitrogen will be exhausted rapidly by the weed and rice plants. Fewer weeds will be needed to severely inhibit rice growth than at a higher nitrogen level. At 80 kg N/ha, rice and weed competition will be less severe and more weed biomass will be required to decrease rice yield the same amount as when no nitrogen was applied.

The primary competition at 160 kg N/ha will be for light (at lower N levels, it is for nutrients). Because of different competition patterns, less weed weight is required to reduce rice yield at 160 kg N/ha than at 80 kg N/ha.

Kim and Moody (1980b) calculated the expected yield reduction due to competition by different weed complexes (Table 4). The highest yield decrease occurred with the *E. crus-galli* ssp. *hispidula-S. maritimus* community. Yield reduction caused by competition of 100 g dry weight of weeds/m$^2$ of this community type at rice heading was 42%. The yield decrease with the same amount of weeds was 10% for the

**Table 5. Economic thresholds for implementing control practices to prevent yield and quality losses of rice grain due to weeds (adapted from Smith 1988).**

| Weed species | Threshold (no. of plants/m$^2$) | Regression |
|---|---|---|
| *Sesbania exaltata* | 1-2 | Linear |
| *Oryza sativa* (red rice) | 1-3 | Curvilinear (concave) |
| *Aeschynomene virginica* | 3-6 | Linear |
| *Echinochloa crus-galli* | 5-10 | Curvilinear (concave) |
| *Leptochloa fascicularis* | 15-30 | Linear |
| *Brachiaria platyphylla* | 20-40 | Linear |

**Table 6. Relationship between grain yield and duration of weed competition (adapted from Smith 1988).**

| Weed species | Density (no./m$^2$) | Days to 10% yield reduction | Regression |
|---|---|---|---|
| *Sesbania exaltata* | 5 | 74 | Linear |
| *Oryza sativa (red rice)* | 20 | 46 | Curvilinear (convex) |
| *Aeschynomene virginica* | 5 | 80 | Linear |
| *Echinochloa crus-galli* | 100 | 17 | Linear |
| *Brachiaria platyphylla* | 180 | 21 | Curvilinear (concave) |

*E. glabrescens* community, 15% for the *M. vaginalis* and *M. vaginalis-Scirpus supinus* L. communities, and 21% for the *M. vaginalis-Fimbristylis miliacea* (L.) Vahl- *E. glabrescens-S. maritimus* community. The weed weight required for 50% yield reduction was least (123 g/m$^2$) for the *E. crus-galli* ssp. *hispidula-S. maritimus* weed community and greatest (497 g/m$^2$) for the *E. glabrescens* community.

The yield decrease due to competition was similar to that reported by Arai (1967). In that study, the relationship between weed weight at maturity and rice grain yield was linear. The rate of decrease in yield was greater for *M. vaginalis* than for *E. crus-galli* ssp. *hispidula.* Arai said this may have been due to the high nitrogen content of *M. vaginalis.*

Lubigan and Moody (unpublished) observed greater competition between rice and *Ischaemum rugosum* Salisb. in the wet season than in the dry season. Five *I. rugosum* plants/m$^2$, the lowest density used, significantly reduced rice yield in the wet season. In the dry season, 20 *I. rugosum* plants/m$^2$ were needed to cause significant yield reductions. In the wet season, an average 3.5 *I. rugosum* plants/m$^2$ were needed to reduce yield 10%; in the dry season, 16 plants were needed for 10% yield reduction.

Grain yield and weed density were correlated in both seasons. The relationship was curvilinear during the wet season ($Y = 3.46^{e-0.0217x}$, $r = 0.97^{**}$) and linear during the dry season ($Y = 3.88 - 0.02X$; $r = 0.90^{*}$).

Zimdahl (1980) noted that reduction in yield due to weed competition is usually sigmoidal rather than linear because very low weed densities do not usually result in yield reductions.

Smith (1988) used regression analysis to determine threshold levels of weed densities and durations of competition by major weeds of rice in the southern United States. In density experiments, *Seshania exaltata* (Raf.) Cory and red rice *Oryzae sativa* L. were the most competitive, *Brachiaria platyphylla* (Griseb.) Nash the least competitive (Table 5). *E. crus-galli* and *B. platyphylla* competing with rice during early season reduced grain yields; red rice, *S. exaltata,* and *Aeschynomene virginica* (L.) B.S.P. reduced grain yields during mid- to late-season (Table 6).

## References cited

Arai M (1967) Competition between rice plants and weeds. Pages 37-41 *in* Proceedings of the 1st Asian-Pacific Weed Control Interchange. Honolulu, Hawaii, USA.

Barrentine W L, Oliver L R (1977) Competition threshold levels and control of cocklebur in soybeans. Mississippi Agricultural Forestry Experiment Station and Arkansas Agricultural Experiment Station Technical Bulletin 83. University of Arkansas. Fayetteville, Arkansas, USA.

Buchanan GA (1977) Weed biology and competition. Pages 25-41 *in* Research methods in weed science. 2d ed. B. Truelove, ed. Southern Weed Science Society. Auburn, Alabama, USA.

Coble H D (1986) Development and implementation of economic thresholds for soybean. Pages 295-307 *in* Integrated pest management on major agricultural systems. Consortium for integrated pest management. R. E. Frisbie and P. L. Adkisson. eds. Texas A&M University, College Station, Texas, USA.

Coble H D, Ritter R L (1978) Pennsylvania smartweed ( *Polygonum pensylvanicum* ) interference in soybeans *Glycine max.* Weed Sci. 26:556-559.

Cottam G, Curtis J T, Hale B W (1953) Some sampling characteristics of a population of randomly dispersed individuals. Ecology 34:741.

Dew D A (1972) An index of competition for estimating crop loss due to weeds. Can. J. Plant Sci. 52:1921-927.

De Wit C T (1960) On competition. Versl. Landbouwk. Onderz. 66:1-82.

Frans R E, Talbert R E (1977) Design of field experiments and the measurement and analysis of plant responses. Pages 15-23 *in* Research methods in weed science. 2d ed. B. Truelove, ed. Southern Weed Science Society, Auburn, Alabama, USA.

Gomez K A, Gomez A A (1984) Statistical procedures for agricultural research. 2d ed. Wiley, New York, USA. 680 p.

IRRI — International Rice Research Institute (1977) Annual report for 1976. P.O. Box 933, Manila, Philippines.

Kim S C, Moody K (1980a) Effect of plant spacing on the competitive ability of rice growing in association with various weed communities at different nitrogen levels. J. Korean Soc. Crop Sci. 25(4):17-27.

Kim S C, Moody K (1980b) Types of weed community in transplanted lowland rice and relationship between yield and weed weight in weed communities. J. Korean Soc. Crop Sci. 25(3):1-8.

Klingman D L (1971) Measuring weed density in crops. Pages 3.1.5/1-3.1.5/5 *in* Crop loss assessment methods. L. Chiarappa, ed. Food and Agriculture Organization, Rome, Italy.

Mortimer A M, Firbank L G (1983) Towards a rationale for the production of weed infestations and the assessment of control strategies. Pages 146-153 *in* Proceedings of the 10th International Congress on Plant Protection. British Crop Protection Council, Brighton, England.

Pearce S C, Clarke G M, Dyke G V, Kempson R E (1988) A manual of crop experimentation. Griffin, London, England. 358 p.

Smith R J Jr. (1988) Weed thresholds in southern U.S. rice, *Oryza sativa.* Weed Technol. 2:232-241.

Thurlow D L, Buchanan G A (1972) Competition of sicklepod with soybeans. Weed Sci. 20:379-384.

Zimdahl R L (1980) Weed crop competition - a review. International Plant Protection Center, Oregon State University, Corvallis, Oregon, USA. 196 p.

## Notes

*Author's address:* K. Moody, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Monitoring the physical environment for yield loss studies

S. M. Coakley

The physical environment of a plant plays an important role in determining its growth and productivity. The physical environment includes all parts of the plant's environment that are not biological—soil characteristics (type, structure, pH), chemical environment (soil and atmosphere), etc. The discussion here is limited to measuring the ambient meteorological conditions (climate) that affect plant health (Coakley 1983).

To a large degree, climate delimits what species of plants will grow in a particular area. Weather—moisture, solar radiation, temperature—during the growing season determines a large portion of the year-to-year variation in crop yields (Coakley 1988, Jeger 1987).

Meteorological conditions directly affect the crop being grown, the pests (insects, pathogens, weeds, vertebrates) of that crop, and the interactions between the crop and its pests. To maximize crop yields, full advantage must be taken of all positive aspects of the meteorological environment, while any negative effects are minimized. To do this, we must assess how meteorological conditions affect the crop and its pests.

This overview examines how the physical environment can be monitored and the problems associated with making and using such measurements. Specific interactions between climate and rice are comprehensively discussed in *Agrometeorology* of the *rice crop* (WMO-IRRI 1980) and Climate and rice (IRRI 1976).

## How to monitor and why

Meteorological variables may be measured with instruments used routinely (e.g. rain gauges, minimum and maximum thermometers, etc.) or with instruments devised especially for specific research projects. Routine measurements, usually made daily, have one of two purposes: 1) to clarify diurnal and seasonal variation in weather at a particular location, or 2) to relate crop growth and yield or pest populations to weather. Studying the physical processes of energy transfer between plants and their environment or developing process-based models of pest-host interactions may require continuous and detailed monitoring of microclimatic conditions. Most studies, however, require less frequent measurements.

Measurements can be made at different environmental levels. The microclimate is measured within or very near the plant canopy, in the area where the plant affects the environment. The macroclimate is measured outside the plant canopy, usually at some distance, either at agricultural weather stations in the vicinity of the fields or at standard weather stations often located at airports or in city centers.

For a particular pest at a given time, the microclimate may be more favorable than the macroclimate. However, the microclimate is always a product of the macroclimate. It is possible to develop equations to predict microclimate from the macroclimate (Bourke 1970, Brown 1985, Burrage 1978, Pedro and Gillespie 1982, Wallin 1967). In an unfavorable macroclimate, there is a limit to how much microclimate can facilitate pest activity.

## What to monitor

What variables should be monitored? Ideally, a complete set of meteorological variables would include daily data on maximum and minimum air temperature, water and soil temperature, relative humidity and dew deposition (duration, amount, intensity), solar radiation and sunshine duration, evaporation, precipitation (amount, duration, intensity), and wind (direction, speed). Uchijima (1980) also suggests 5 d totals and means.

When collection of such detailed data is not feasible, the minimum variables to be collected would be daily temperature (maximum and minimum) and total precipitation. For tropical regions, some measure of solar radiation (e.g. sunshine duration) and evaporation is necessary (Angus 1980).

It is not necessary to collect your own meteorological data if data of sufficient detail are available from a reliable source, such as a national weather network. Such routinely collected data will be adequate for a variety of studies of crop-pest interactions. And they offer an opportunity to examine historical data that are not available for a specific site.

If you are designing your own data collection, it is important to answer the following questions:

- Why is the measurement needed? To answer this question, it is necessary to concentrate on the biology of the organism being studied. The important factor is to collect only the information specifically needed.
- What sensor will give the most useful information? The researcher should understand the principle of the measurement to be made and be familiar with the available instruments and how they operate. Useful guidelines can be obtained by consulting other researchers with experience in the field and by talking to equipment representatives.
- How accurate must the measurements be? The level of accuracy will determine the cost, frequency of maintenance, and environmental limits of the sensors needed. It is possible to take physical measurements that are far more precise than the biological measurements that are possible. The decision on the accuracy required for the environmental data should be based on the precision of the

**Table 1. Recommended criteria for reporting meteorological data (Coakley 1985).**

- Investigation
    - Full description, including equipment used
- Site
    - Location, including latitude, longitude, and elevation
    - Description
    - Gradient and exposure
    - Type and height of vegetation
- Measurements
    - Description
    - Heights at which made
    - Unit of measure in which numerical value was recorded
    - Significant digits in recorded data
- Data report
    - Complete description of units of measure in all results. Including tables and diagrams
    - Formulas used in data reduction expressed as symbolic equations wherever possible. so that units of measure do not matter.

biological measurements being made in the particular situation. The data should be at similar levels of precision.

- How frequently must measurements be made? Comparable time scales should be used for biological and meteorological data, and only the minimum data necessary collected. Collecting excess data leads to more frequent equipment failures and makes analyzing the data collected difficult. If disease data are taken on a daily or less frequent basis, meteorological data should be collected daily, but it should not be necessary to collect it more frequently than that. If sampling is done with a micrologger, values from frequent samplings can be averaged before they are recorded.
- How will the data be collected, stored, and analyzed? When planning a new experiment to monitor the environment, help should be obtained from statisticians, computer programmers, and equipment manufacturers. It is important to report the units of measurement and the significant digits in the recorded data. Studies should be planned for timely analysis and reporting. A complete record of how the data were collected should be kept (Table 1).

## Sources of error

Four important sources of error can limit the usefulness of weather data: the instrument, the observer, the exposure of the instrument, and sampling error.

The instrument must be calibrated and standardized regularly (at least once every 6 mo) and its operation checked to eliminate gaps in the data.

The observer must understand why and how the measurement is being taken. The observer also must be motivated to do the job properly. Observer errors can be corrected only at the time of the measurement; if not discovered then, the errors will usually go undetected. Unreliable observers have been known to enter imaginary data if they fail to make the recordings on time.

Exposure of instruments should be correct (e.g. thermometers should be in a shelter and out of direct sunlight). Incorrect placement or alteration of the exposure of instruments can lead to data errors that may be less obvious than instrument or observer errors.

Sampling error, particularly important in microclimatic studies, may occur if sampling frequency is not adequately matched to temporal or spatial variation in meteorological variables. A single measurement may not reflect the average environment, and multiple measurements may be needed. If only one measurement is possible, its reliability must be recorded.

In general, all instruments used for meteorological measurements should be reliable, accurate, simple, convenient to operate and maintain, and sturdy (Coakley 1985). Reliability is probably the single most important factor. Deployment of sensors and problems associated with their use have been described elsewhere (Coakley 1985, Sutton et a1 1984).

It is important not to take too seriously the claims manufacturers make for their equipment. Beware of a "..heatproof, coldproof, floodproof ... foolproof digital data logger," for it is surely not userproof. Do not believe statements that one can "turn on, start taking data, use without reading a lengthy instruction manual."

The researcher must understand the basic operation of the equipment used and must monitor the data collection frequently to prevent large gaps in the database. Sensor failure is the most common cause of data loss. Plotting the data collected is a useful way to detect missing and/or erroneous data. Such errors usually are obscured in numerical summaries.

A variety of factors can hamper collection of accurate data. Perhaps the human factor is the greatest limitation. Only a few of the limitations to data collection are listed here (for a more detailed list, see Coakley 1985). Vandals or animals may damage equipment. In some regions, equipment theft is common. Inappropriate exposure or positioning of equipment may lead to mishaps or erroneous results. Operator failures can include not switching on the equipment, setting the wrong date, or using the wrong multiplier in the micrologger. Dust accumulation and more than 75% humidity in equipment shelters can reduce the accuracy and reliability of electrical components. Battery voltage must be maintained above a constant threshold and a backup battery supply should be available.

The collection of accurate data should be the goal of all of us who collect or use meteorological data. Remember the words of Smith (1971): "All too often, published meteorological data are accepted at their face value, with a blind faith that is rarely justified by the facts ... the main unforgivable effect of incompetence is the trouble it causes for other people."

## References cited

Angus J F (1980) Minimum data requirements in rice experiments. Pages 95-100 *in* Proceedings of a symposium on the agrometeorology of the rice crop. World Meteorological Organization-International Rice Research Institute. P.O. Box 933, Manila, Philippines.

Bourke P M A (1970) Use ofweather information in the prediction of plant disease epiphytotics. Annu. Rev. Phytopathol. 8:345-370.

Brown R D (1985) Estimation of remote microclimatic from weather station data with applications to landscape architecture. Ph D thesis, University of Guelph, Ontario, Canada. 133 p.

Burrage S W (1978) Monitoring the environment in relation to epidemiology. Pages 93-101 *in* Plant disease epidemiology. P. R. Scott and A. Bainbridge, eds. Blackwell Scientific Publication, Oxford.

Coakley S M (1983) Ambient meteorological factors light, temperature, and moisture. Pages 154-167 *in* Challenging problems in plant health. T. Kommedahl and P. H. Williams. eds. American Phytopathological Society. St. Paul, Minnesota.

Coakley S M (1985) Describing and quantifying the environment. Plant Dis. 69:461-466.

Coakiey S M (1988) Variation in climate and prediction of disease in plants. Annu. Rev. Phytopathol. 26:163-181.

IRRI — International Rice Research Institute (1976) Climate and rice. P.O. Box 933, Manila, Philippines.

Jeger M J (1987) Meteorology and plant disease. Pages 255-276 *in* International conference on agrometeorology. F. Prodi, F. Rossi, and G. Cristoferi, eds. Fondazione Cesena Agricultural Publications, Cesena, Italy.

Pedro M J Jr., Gillespie T J (1982) Estimating dew duration. II. Utilizing standard weather station data. Agric. Meteorol. 25:297-310.

Smith L P (1972) Processes in micrometeorology. Pages 300-305 *in* Agriculture Meteorology No. 310. World Meteorological Organization, Geneva.

Sutton J C, Gillespie T J, Hildebrand P D (1984) Monitoring weather factors in relation to plant diseae. Plant Dis. 68:78-84.

Uchijima Z (1980) Measurements of meteorological variables in rice-weather experiments. Pages 71-86 *in* Proceedings of a symposium on the agrometeorology of the rice crop. World Meteorological Organization-International Rice Research Institute, P.O. Box 933, Manila. Philippines.

Wallin J R (1967) Ground level climate in relation to forecasting plant diseases. Pages 149-163 *in* Ground level climatology. R. H. Shaw, ed. American Association for the Advancement of Science. Washington, D.C.

World Meteorological Organization and the International Rice Research Institute (IRRI) Proceedings of a symposium on the agrometeorology of the rice crop. P.O. Box 933, Manila, Philippines.

## Notes

*Author's address:* S. M. Coakley, Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon 97331, USA.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Remote sensing and image analysis for crop loss assessment

F.W. Nutter, Jr.

Plant populations become stressed when a biotic or abiotic factor adversely affects growth and development (Jackson 1986). To maximize the benefits from management strategies and tactics, it is necessary to recognize when plants are stressed, what is causing the stress, and how much plants are stressed. Once plant stress is detected, identified, and quantified, stress thresholds for plant populations can be developed to signal when control measures are needed to maximize net return.

Plants respond to stress in several ways; many of the responses are visible. But visible response to stress in plants is difficult to quantify accurately, precisely, and rapidly. Stress may be expressed by the closing of stomates, resulting in higher leaf surface temperatures; changes in plant morphology, such as leaf curling, wilting, or stunting; chlorosis and/or necrosis of plant parts; and/or abscission of plant parts. These responses to stress also affect the amount and quality of radiation reflected and emitted from plant canopies.

Remote sensing techniques that measure and record changes in electromagnetic radiation can be used as objective and quantifiable means of assessing plant stress. Several excellent reviews (Brenchley 1968, Jackson 1986) and books (ASPRS 1987, Hord 1986) about remote sensing have been published.

## Remote sensing

Remote sensing is defined as the acquisition and interpretation of measurements made on an object without having the measuring device in physical contact with the object. The most powerful remote sensing system is the human eye and brain. People can acquire, enhance, analyze and store images at enormous rates of speed (Baxes 1984). However, each person's visual image processing system is unique (Lindow and Webb 1983, Sherwood et al 1983). Individuals involved in crop loss assessment are no different from most people in the general population: they may be nearsighted, farsighted, or both; some may be unable to discern colors. Although eyeglasses can be used to correct most vision problems, they cannot correct the fact that people vary greatly in their perception of scale.

Several researchers in plant pathology and entomology have developed systems designed to calibrate or standardize visual assessments of damage or injury from agricultural pests (James 1971, Tomerlin and Howell 1988). Even so, variation among raters remains an important source of error in crop loss assessment studies (Horsfall and Cowling 1978, Shokes et al 1987).

Remote sensing technology offers a more objective means of obtaining crop loss assessment information, with greatly reduced variation among raters (Adcock et al 1989). Other important advantages of remote sensing technology include its ability to cover large areas (for disease detection and early warning) and its utility in assembling regional, national, and global information concerning crop losses.

Remote sensing is used in agriculture to detect, measure, record, and analyze energy in selected portions of the electromagnetic spectrum (Parks 1973). Remote sensing of crop canopies involves measuring the electromagnetic radiation reflected or emitted from a matrix of plant parts growing above a background of soil and organic matter (Jackson 1986).

The amount and quality of light reflected from a crop canopy are strongly dependent on both the crop species and the condition of the crop (Perry and Lautenschager 1984). Gausman et al (1974) demonstrated that the internal structure of plant leaves affects the spectral quality of sunlight reflected from plant canopies. Other factors that influence reflectance from plant canopies include intensity of solar irradiance (Learner and Noriega 1981), healthy green leaf area (Nutter 1989), leaf morphology (Kumar and Silva 1973), leaf orientation and sun geometry (Colwell 1974, Suits and Safir 1972), geometry of the plant canopy (Suits 1972), crop maturity (Kanemasu et al 1974), canopy biomass, water content, and chlorophyll content (Ahlrichs and Bauer 1982, Sinclair et al 1971), and soil and plant litter (Tucker and Maxwell 1976, Wooley 1971). Comprehensive reviews have been published by Knipling (1970), Parks et a1 (1973), Sinclair et a1 (1971), Colwell (1974), and Jackson (1986).

Often plant pests are responsible for many of the factors that affect reflectance. This provides a sound theoretical basis for using remote sensing to measure plant stress. The use of narrow band filters to obtain information about specific wavelengths of the electromagnetic spectrum can be used to overcome nonpest-related factors that influence reflectance. Solar irradiance measurements can be obtained at the same rime that reflectance measurements are taken, to account for variation in reflectance values caused by this factor (Pederson and Fiechtner 1980).

## The electromagnetic spectrum

The reflectance of light from plant leaves is relatively low in the visible blue and red portion of the electromagnetic spectrum (0.4-0.7 μ). Maximum reflectance in the visible area occurs between 0.54 and 0.56 μ (Bauer 1975). The low reflectance of visible radiation is attributed to high absorption by leaf pigments, primarily the chlorophylls. In this portion of the spectrum, healthy green leaf tissue usually reflects less radiation than stressed plant tissue (Jackson 1986, Nutter and Cunfer 1987). An increase in reflectance often indicates the presence of a stress that reduces photosynthetically active green leaf area (Nutter 1987, 1989).

The quality and amount of sunlight reflected from a crop canopy have been used to quantify the effects of plant pests on crop health. In the near part of the infrared spectrum, diseased foliage reflects less energy than healthy foliage. This is because necrotic lesions result in loss of both chlorophyll and water (Ausmus and Hilty 1972, Bauer et al 1971, Gudmenstad and Pederson 1976, Nutter et al 1985) and because of a change in the internal structure of stressed leaves (Knipling 1970, Kumar and Silva 1973).

Low reflectance from plant canopies in the 1.3-2.5 μ range (mid-infrared) is due to strong water absorption (Gausman and Allen 1973). Both visible reflectance and mid-infrared reflectance increase as leaf water content decreases (Gausman et al 1974, Sinclair et al 1971).

The thermal portion of the electromagnetic spectrum (3-20 μ) is emitted naturally by all objects and is related to their surface temperatures. Although atmospheric water vapor strongly absorbs radiation in much of this region of the spectrum, measurements made a short distance from the object (8-14 μ) are less affected. This provides a thermal-infrared radiometry window within which to estimate the surface temperatures of objects (Jackson 1986).

Microwave (millimeter to centimeter wavelengths) radiation emitted from leaf surfaces is not obstructed by water vapor in the atmosphere—an important advantage for monitoring crops from satellites (Hord 1986). Ulaby et al (1984) used microwave measurements to estimate leaf area index. Brakke et al (1981) related microwave radar response to canopy moisture, leaf area index, and dry weight in maize, sorghum, and wheat.

## Instrumentation and methods

### Photographic techniques

Photography has been used extensively as a tool to obtain crop loss information. Colwell (1956) demonstrated the potential of using panchromatic, color, and infrared film to detect stem rusts *Puccinia* spp. in cereals and virus diseases of citrus. Color infrared photography has been used in surveys to detect late blight caused by *Phytophthora infestans* in potato (Manzer and Cooper 1967, Jackson and Wallen 1976), to detect bacterial blight caused by *Xanthomonas phaseoli* in field beans (Wallen and Jackson 1975), and to detect diseased trees (Meyer and French 1967). On color infrared film, healthy plant foliage characteristically appears as bright red or magenta; unhealthy foliage appears darker.

Photographic images also can be digitized and analyzed statistically. Wallen and Galway (1979) used a drum scanner to process aerial photographs. They were able to measure the extent and severity of bacterial blight *Xanthomonas phaseoli* in bean fields. This information was combined with ground data to develop a yield loss formula that could determine overall crop loss on a regional basis from year to year.

Greaves et al (1983) used black-and-white infrared film to take aerial photographs of fields of winter wheat. They found that healthy foliage reflected more near-infrared radiation than did diseased areas. Healthy foliage appeared as light tones on photographs; stressed and senescent foliage appeared darker. Total crop areas affected by barley yellow dwarf virus (BYDV) or aphid feeding were calculated by computer image analysis (digitization). Yield losses were estimated to be 10% due BYDV and 2% due to aphid feeding. This further demonstrated the usefulness of aerial photography to monitor seasonal changes in BYDV distribution and to identify areas of risk (pest zones) when winter cereals are sown early.

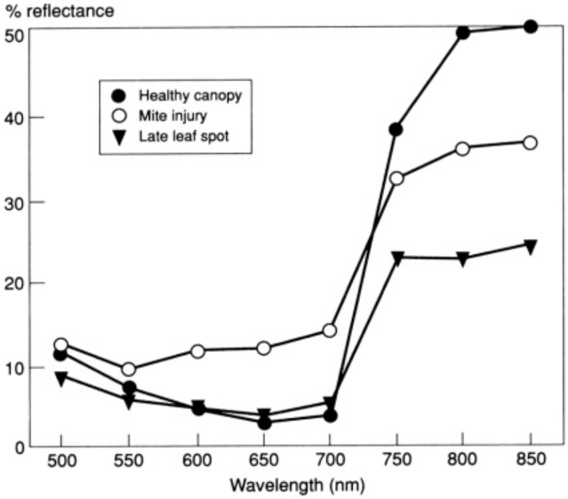
Nutter and Pederson (1984) found a good relationship between optical density readings from 2- × 2-inch color infrared aerial photos (slides) of barley plots affected with different levels of spot blotch caused by *Cochlioholus sutivus* and visual assessments on the ground of spot blotch severity. The optical density readings from the slides had higher correlations with barley yield than did visual disease severity assessments.

## Nonphotographic techniques

Nonphotographic sensors (multispectral) collect data in the visible, infrared, and thermal portions of the electromagnetic spectrum (0.3-14.0 μ). Discrimination capabilities usually are improved by selectively measuring and analyzing the energy from several discrete wavelength bands (Bauer 1975, Nutter et al 1985). Multispectral sensors may be hand-held (Nilsson 1987, Pederson and Fiechtner 1980) or mounted on aircraft or satellites (Kanemasu et al 1974). Bauer et al (1971) reported that several levels of severity of southern corn leaf blight caused by *Helminthosporium maydis* could be detected using multispectral scanning methods. A nationwide Corn Blight Watch program was undertaken to detect and monitor its spread in the U.S.

Multispectral scanners have proven useful in identifying as well as quantifying the effects of plant stress. Nutter (unpublished) found that peanuts with mite injury had a different spectral signature than peanuts infected with late leaf spot (Fig. 1). Pennypacker et al (1982) reported that characteristic reflectance signatures were obtained from wheat canopies infected with BYDV and that a characteristic spectral signature also distinguished plants infected with stripe rust caused by *Puccinia striiformis* from healthy plants. Sharp et al (1985) used band ratios of multispectral data to develop a vegetation index (James 1971) to monitor the development of stem rust caused by *P. grammis* and stripe rust caused by *P. striiformis* in wheat. They found that differences in the vegetation index of inoculated and control plots became progressively greater as rust epidemics developed.

Marshall and Shaner (1982) found that leaf rust progress in both space and time could be accurately determined using multispectral sensing. They could detect rust severities as low as 0.1-0.2% using an Exotech Model 100A multispectral radiometer. Teng and Close (1977) obtained different spectral reflectance measurements for healthy barley leaves and leaves infected with leaf rust. Gausman et al (1975) used an Exotech Model 20 spectroradiometer, placed 1.5 m above cotton canopies, to detect stress caused by nematodes. Reflectance measurements from fields with low nematode populations and fields stressed by high populations of *Rotylenchulus reniformis* showed significant differences in spectral reflectance in the visible (0.5-0.75 μ) and near-infrared (0.75-1.35 μ) ranges (Gausman et al 1975).

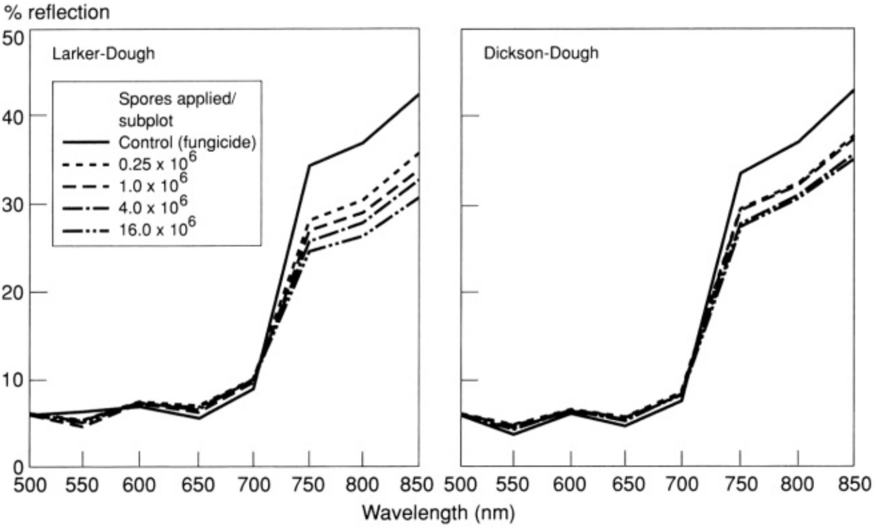


**1.** Spectral reflectance signatures from field plots of Fiorunner peanuts damaged by the two-spotted mite *Tetranychus urticae,* peanuts infected with late leafspot *Cercosporidium personatum,* and healthy peanuts. Note higher reflectance in the 600-700 nm wavelength range for mite-damaged canopies compared with healthy and diseased canopies; diseased (partially defoliated) canopies reflected less radiation in the 750-850 nm range.

Barley spot blotch caused by *Cochliobolus sativus* reduces green leaf area due to lesion development and areduction in the chlorophyll content of leaves. Nutter (1983) showed that a hand-held, multispectral radiometer could detect differences in disease severity levels resulting from different numbers of *C. sativus* spores applied to field plots of Larker (susceptible) and Dickson barley varieties (Fig. 2). *Cercosporidium personatum* causes infected peanut leaves to defoliate, greatly reducing healthy green leaf area. Nutter et al (1985) found that different levels of defoliation caused by *C. personatum* could be quantified using the percent reflectance at 0.8 µ measured by a hand-held, multispectral radiometer.

Casey (1978) developed a system that used two Exotech radiometers to measure incoming radiation from the sky and reflectance from soybean canopies simultaneously, thus accounting for changes in reflectance due to changing cloud cover. Instruments mounted on the bucket of a travel tower positioned 7 m above the soybean canopy were used to measure reflectance from healthy soybean canopies and canopies diseased with soybean rust caused by *Phakospora pachyrhizi.* Correlations between reflectance and rust severity and between reflectance and yield were highly significant.

Aase and Siddoway (1980) demonstrated the usefulness of spectral reflectance measurements to quantify the reduction by winterkill of winter wheat stand densities. Pederson (1986) used a radiometer to quantify stand densities in spring barley plots in a study to evaluate fungicide seed treatments to control root rot caused by *Cochliobolus sativus.*



**2.** Special reflectance signatures from field plots of Larker (susceptible) and Dickson (resistant) barleys at the dough stage following inoculation with different numbers of *C. sativus* spores at the early boot stage.

Remote sensing instruments often generate considerable amounts of data in a short time, making data management and analysis cumbersome if not overwhelming. Nilsson (1987) was one of the first researchers to link a data acquisition system to remote sensing instrumentation. He used an Exotech-100AX radiometer interfaced with an Omnidata Polycorder. In a study of wheat plots infected with various fungal pathogens, he found a significant correlation between spectral reflectance data and leaf blotch caused by *Septoria nodorum* and leaf rust caused by *Puccinia recondita tritic.* Although his system greatly improved data collection and management, it was unwieldy.

Pederson (1986) designed a more portable hand-held radiometer and A/D converter interfaced with a Radioshack Model 100 (or 102) computer. The lightweight (6 kg) system measures incoming as well as reflected radiation in 8 wavelength bands (CROPSCAN, Inc., Fargo, ND).

Ease of operation of multispectral radiometers continues to improve. They may soon replace visual rating scales and keys as more efficient and objective means to evaluate experimental fungicides and/or levels of disease resistance.

Infrared thermometry has been widely used for remote detection of biological stresses in plants. Pinter et al (1979) used a hand-held infrared thermometer to record the surface temperatures of green leaves of sugar beets. Plants infected with *Pythium aphanidermatum,* a soil-borne fungus that attacks the roots, had midday radiant leaf temperatures 3-5 °C warmer than adjacent healthy plants. They obtained similar results when they compared the surface temperatures of cotton plants infected with *Phymatotrichum omnivorum* (root rot) with temperatures obtained from healthy cotton plants. Tu and Tan (1985) found that bean plants infected with root rot pathogens had higher leaf surface temperatures than healthy plants. Apparently, reduced water uptake due to diseased roots results in a reduced water supply to the leaves. Evapotranspirational cooling is reduced, resulting in significantly higher leaf temperatures in diseased plants. Tu and Tan proposed using infrared thermometry for nondestructive screening of bean root rot resistance and susceptibility.

Interest is high in developing remote sensing techniques to monitor global forest resources and the rate of decline in forest vigor due to acid rain. Williams et al (1984) compared measurements of forest canopy reflectance attributes using an 8-band radiometer (Barnes Model 12-1000) and a Spectron Engineering SE-591 Spectroradiometer mounted on a helicopter platform. Spectral data from a height of 300 m above the forest canopy were recorded using an Omnidata Model 516 Polycorder. Spectral measurements from all instruments discriminated hardwood from pine forests and agreed well. More recently, Bruck and Khorram (1987) used data obtained from a NASA LANDSAT IV satellite equipped with a Thematic Mapper to detect and quantify mortality and decline symptoms in spruce-fir forests. Regression and principal components analyses showed that TM 5 band data (1.55-1.75 μ were highly correlated with percent mortality; slightly declining trees also could be detected.

## Yield loss modeling

Models are often used to quantify the relationship between disease intensity and yield loss (Teng et al 1979). Many of today's yield loss models are based on the assumption that pest intensity (stress) is related to yield loss. The several classes of models proposed include critical point, multiple point, and area under the disease progress curve (James 1974, James and Teng 1979). Development of yield loss models based on remotely sensed data is an exciting prospect. Nutter and Cunfer (1987) have used percent reflectance measurements (800 nm) in place of visual assessments of disease intensity to more accurately quantify yield losses due to scald caused by *Rhyncosporium secalis* in barley. Even more exciting is the potential to develop yield loss models using remotely sensed data that will provide regional or global information on disease losses. In 1978, serious epidemics of yellow rust and leaf rust occurred in the major wheat-growing plains of Pakistan. Critical point assessments at the early dough stage using LANDSAT-2 satellite imagery showed that severely rusted wheatland areas reflected more light in the 0.7-0.8 μ wavelength region than did healthy wheatland areas (Nagarajan et al 1984).

## Image analysis

Image analysis has become an important tool in obtaining information at all levels of biological scale, from the molecular to global estimates of food production. Image processing is perhaps a better, more appropriate term to describe what is actually a two-step process. First, an image is altered or enhanced. Second, the enhanced image is analyzed. Image analysis usually produces numeric or graphic, nonpictorial data (Baxes 1984).

Image processing visually enhances or statistically evaluates some aspect of an image which, in its original form, is not very meaningful or useful. Image enhancements can be subjective or objective and may involve contrast and/or spatial enhancement. Contrast enhancements alter the brightness within an image: black, white, and different shades of gray may be intensified, suppressed, or grouped to bring out new details. Adjusting the brightness and contrast controls of a television set or the brightness and Nomarski filter controls of a compound microscope are examples of image enhancement.

Spatial enhancements modify the detail within an image. Three basic types of operations may be performed to improve image quality. One is optical and two are electronic (analog and digital).

Optical processing uses optics theory to enhance an image. Different combinations of lenses, filters, and films are used to alter and capture the desired image. Jackson et al (1978) used high contrast black-and-white negatives of aerial photographs of pea fields infested with different levels of root rot caused by *Fusarium solani.* They projected the negatives through combinations of colored exposing filters onto color print material. The procedure emphasized tonal differences between healthy and stressed areas of the fields.

Analog processing uses electronic operations to improve image quality. The brightness and contrast controls on a television set adjust the amplitude and reference of the video signal, resulting in an altered image (Baxes 1984). Analog electronic images often are converted to digital form before processing. The Ranger satellite program used analog images of the lunar surface converted to digital form to transmit the images back to earth. Several nations now have earth-orbiting satellites returning earth-surface imagery on a day-to-day basis (ASPRS 1987).

Digital processing, an outgrowth of the advent of the digital computer, has been used extensively in plant pathology and entomology. An image is represented by discrete points (pixels) in an array. Each point has a numeric location and a numeric brightness. The spatial resolution of an image depends on the number of rows and columns that make up the array. The row coordinate is referred to as the line number and the column number is the position of a pixel within a specified line. An image of 256 rows by 256 columns provides a spatial resolution of 65,536 pixels. Digital processing allows the greatest flexibility and power in image processing, because a computer can carry out complex operations rapidly and efficiently.

A digital image-processing system consists of a number of hardware devices that collectively handle all the steps for processing an image. The system uses a television or video camera, an analog-to-digital converter, a computer and computer interface for storing and processing images, a display monitor for viewing the original and enhanced images, and a printer for hard copies of the images generated.

The first step is to digitize an image. The input device is normally a video camera to capture and freeze the selected image. The analog form of this image is converted into a digital form and stored in the memory of the host computer. Once an image is in digital memory, the digitized image can be altered by coding and regrouping brightness (gray) levels. The new images can be restored to analog form and viewed pictorially on the monitor. The enhanced or altered image is now ready for analysis. A common method of viewing the digitized image is to produce a histogram of the number of pixels (y-axis) possessing a specified level of brightness (x-axis). Recoding, viewing, and analyzing images can be repeated as needed.

This process was the basis of a system developed by Lindow and Webb (1983) to quantify foliar disease symptoms in individual plant leaves. They used a black-and-white video camera with appropriate lenses and filters (optical processing). an analog-to-digital board to convert the signal, and an Apple II computer to electronically improve the digital image. They coded and sorted the gray levels of pixels corresponding to healthy leaf, necrotic leaf, and background areas to create a new image for analysis. Pixels of different brightness could be grouped into three categories of magnitude. Pixels from images with a black velvet background had 0-6 brightness magnitudes, healthy green leaf tissue had magnitudes from >6 to <51, and necrotic leaf tissue was associated with brightness magnitude >51. The computer was used to count the number of pixels in each category, to determine relative necrotic and healthy leaf areas. Disease proportion can be calculated as

$$\text{Disease proportion} = \frac{\text{no. of pixels corresponding to necrotic tissues}}{\text{no. of pixels corresponding to necrotic + healthy tissues}}$$

Blanchette (1982) developed a similar video image processing system to measure the amount of discolored and decayed wood in trees.

Hargrove and Crossley (1988) developed a video digitizer system to measure feeding damage by chewing insect herbivores. To rapidly measure leaf area lost, an IBM PC or compatible microcomputer equipped with a digitizer card was interfaced with a standard video camera. The video digitizer simultaneously measured area removed from and area remaining in the leaf. The video signal digitally encoded into a 256 × 256 pixel frame provided a false-color picture of reconstructed damaged leaves on the computer monitor. Brightness was adjusted to enhance the contrast between leaf and background.

## Digital image processing from aircraft

Nixon et al (1987) designed a multispectral false-color video imaging system to monitor fields of cotton infested with the soil-borne fungus *Phymatotrichum omnivorum,* which causes root rot. Video was taken from an airplane flying at 90 m altitude, with color composite and black-and-white narrow band imagery viewed on monitors and recorded on 1/2-inch-fomat video cassettes. The video images were digitized in the laboratory and read into a computer by means of a digitizing board. Digitized images were enhanced and analyzed as described earlier. Infrared and black-and-white images showed diseased areas corresponding to areas of the cotton fields where plants were necrotic or wilting as a result of root rot.

In the middle and late 1970s, the United States Department of Agriculture, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration cooperated in the Large Area Crop Inventory Experiment

(LACIE). Satellite-mounted multispectral scanners (MSS) were used to estimate crop areas (Ahlrichs and Bauer 1982, Hord 1986). The AgRISTARS program, an outgrowth of LACIE, used aerospace remote sensing technology to estimate crop areas and to provide early warning of changes affecting global commodity production (Hord 1986).

## Conclusion

The science of remote sensing has been greatly enhanced by the advent of the computer. Now images can be captured by photographic or nonphotographic methods and enhanced through optical, analog, and digital processing techniques. Information can be obtained from ground-based instruments or from instruments mounted on helicopters, aircraft, and satellites. Remote sensing offers an objective means to obtain information rapidly and efficiently. Remotely sensed data can be used as independent variables to construct critical point, multiple point, and area-under-the-curve model, for crop loss assessment.

## References cited

Aase J K, Siddoway F H (1980) Determining winter wheat stand densities using spectral reflectance measurements. Agron. J. 72:149-152.

Adcock T E, Nutter F W Jr., Banks PA (1989) Measuring herbicide injury to soybeans using a hand-held, multispectral radiometer. Weed Sci. (Accepted for publication)

Ahlrichs J S, Bauer M E (1982) Relation of agronomic and multispectral reflectance characteristics of spring wheat canopies. Technical Report SR-12-04384. Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette. Indiana. 26 p.

ASPRS—American Society for Photogrammetry and Remote Sensing (1987) Color aerial photography and videography in the plant sciences and related fields. Eleventh biennial workshop of the American Society for Photogrammetry and Remote Sensing. Falls Church, Virginia. 343 p.

Ausmus R S, Hilty J W (1972) Reflectance studies of healthy, maize dwarf mosaic virus-infected, and *Helminthosporium maydis*-infected corn leaves. Remote Sensing Environ. 2:77-81.

Bauer M E (1975) The role of remote sensing in determining the distribution and yield of crops. Adv. Agron. 27:271-304.

Bauer M E, Swain P H, Mroczynski R D, Anuta P E, MacDonald R B (1971) Detection of southern corn leaf blight by remote sensing techniques. *In* Proceedings of the seventh international symposium on remote sensing of environment. Vol. I. The University of Michigan, Ann Arbor, Michigan.

Baxes G A (1984) Digital image processing: a practical primer. Cascade Press, Denver, Colorado. 182 p.

Blanchette R A (1982) New technique to measure tree defect using an image analyzer. Plant Dis. 66:394-397.

Brakke T W, Kanemasu E T, Steiner J L, Ulaby FT, Wilson E (1981) Microwave radar response to canopy moisture, leaf-area-index, and dry weight of wheat. corn, and sorghum. Remote Sensing Environ. 11:207-220.

Brenchley G H (1968) Aerial photography for the study of plant diseases. Annu. Rev. Phytopathol. 6:1-22.

Bruck R I, Khorram S (1987) Use of an orbital thematic mapper for detection of forest decline in the Southern Appalachian Mountains. Phytopathology 77:1699.

Casey P (1978) Ground-based measurements of the reflectance factors of a diseased canopy. *In* Epidemiology and crop loss assessment. Proceedings of the APPS workshop. Lincoln College, August 1977:5-1 to 5-2. American Phytopathological Society, St. Paul, Minnesota.

Colwell R N (1956) Determining the prevalence of certain cereal diseases by means of aerial photography. Hilgardia 26:223-286.

Colwell J E (1974) Vegetation canopy reflectance. Remote Sensing Environ. 3:175-183.

Gausman H W, Allen W A (1973) Optical parameters of leaves of 30 plant species. Plant Physiol. 52:57-62.

Gausman H W, Allen W A, Escobar D E (1974) Refractive index of plant cell walls. Appl. Opt. 13:109-111.

Gausman H W, Heald C M Jr., Escobar D E (1975) Effect of *Rotylenchulus reniformis* on reflectance of cotton leaves. J. Nematol. 7:368-374.

Greaves D A, Hooper A J, Walpole B M (1983) Identification of barley yellow dwarf virus and cereal aphid infestations in winter wheat by aerial photography. Plant Pathol. 32:159-172.

Gudmestad N C, Pederson V D (1976) Evaluation of barley foliar disease by multispectral sensors. Proc. N. D. Acad. Sci. 30:18.

Hargrove W W, Crossley D A Jr. (1988) Video digitizer for the rapid measurement of leaf area lost to herbivorous insects. Annu. Entomol. Soc. Am. 81:593-598.

Hord R M (1986) Remote sensing methods and applications. John Wiley and Sons, New York. 362 p.

Horsfall J G, Cowling E B (1978) Pathometry: the measurement of plant disease. Pages 119-136 *in* Plant disease, an advanced treatise. Vol. II. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York. 436 p.

Jackson H R, Wallen V R (1976) The epiphytology of late blight of potato monitored by sequential color infrared aerial photography. J. Appl. Photogr. Eng. 2:207-212.

Jackson H R, Wallen V R, Downer J F (1978) Analysis and electronic area measurement of complex aerial photographic images. J. Appl. Photogr. Eng. 4:101-106.

Jackson R D (1986) Remote sensing of biotic and abiotic plant stress. Annu. Rev. Phytopathol. 24:265-287.

James W C (1971) An illustrated series of assessment keys for plant diseases. their preparation and usage. Can. Plant Dis. Surv. 51:39-65.

James W C (1974) Assessment of plant diseases and losses. Annu. Rev. Phytopathol. 12:27-46.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Appl. Biol. 4:201-267.

Kanemasu E T, Schimmelpfinnig H, Choy E, Eversmeyer M G, Lenhert D (1974) ERTS-1 data collection systems used to predict wheat disease severities. Remote Sensing Environ. 3:93-97.

Knipling E B (1970) Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sensing Environ. 1: 155-159.

Kumar R, Silva L (1973) Light ray tracing through a leaf cross section. AppL Opt. 12:2950-2954.

Learner R W, Noriega J R (1981) Reflectance brightness measured over agricultural areas. Agric. Meteorol. 23:l-8.

Lindow S E, Webb R R (1983) Quantification of foliar plant disease symptoms by microcomputer-digitized video image analysis. Phytopathology 73:520-524.

Manzer F E, Cooper GR (1967) Aerial photographic methods of potato disease detection. Maine Agric. Exp. Stn. Bull. 646. 14 p.

Marshall D, Shaner G (1982) Multispectral sensing of leaf rust of wheat. Phytopathology 72:1006.

Meyer M P, French D W (1967) Detection of diseased trees. Photogramm. Eng. 33:1035-1040.

Nagarajan S, Seibold G, Kraz J, Saari E E, Joshi L M (1984) Monitoring wheat rust epidemics with the Landsat-2 satellite. Phytopathology 74:585-587.

Nilsson H E (1987) Experiments on hand-held radiometry and IR-thermography of winter wheat in fieldplot experiments. Vaxtskyddsrapp. Jordbruk 44. Swed. Univ. Agric. Sci. Uppsala. 49 p.

Nixon P R, Escobar D E, Bowen R L (1987) A multispectral false color video imaging system for remote sensing applications. Pages 295-305 *in* Proceedings of the eleventh biennial workshop on color aerial photography and videography in the plant sciences and related fields. American Society for Photogrammetry and Remote Sensing. Falls Church, Virginia. 343 p.

Nutter F W Jr. (1983) Modeling yield loss of barley due to spot blotch. Ph D thesis, North Dakota State University, Fargo, North Dakota. 123 p.

Nutter F W Jr. (1987) Detection of plant disease gradients using a hand-held, multispectral radiometer. Phytopathology 77:643.

Nutter F W Jr. (1989) Detection and measurement of plant disease gradients in peanut using a multispectral radiometer. Phytopathology 79:958-963.

Nutter F W Jr., Cunfer B M (1987) Modeling barley yield loss from scald and *Septoria nodorum* blotch using visual versus remote sensing assessment methods. Barley Newsl. 31:34.

Nutter F W Jr., Littrell R H, Pederson V D (1985) Use of a low-cost. multispectral radiometer to estimate yield loss in peanuts caused by late leafspot ( *Crecosporidium personatum* ). Phytopathology 75:502.

Nutter F W Jr., Pederson V D (1984) A simplified method to estimate yield losses from infrared color photographs. Phytopathology 74:1271.

Parks W L, Sewell J I, Hilty J W, Rennie J C (1973) The use of remote multispectral sensing in agriculture. Agric. Exp. Stn. Bull. 505. University of Tennessee, Knoxville, Tennessee. 55 p.

Pederson V D (1986) Spectroradiometric readings of barley canopies grown from fungicide treated seed. Phytopathology 76:757.

Pederson V D, Fiechtner G (1980) A low-cost, compact data acquisition system for recording visible and infrared reflection from barley canopies. Pages 71-75 *in* Crop loss assessment. Miscellaneous Publication 7. P. S. Teng and S. V. Krupa. eds. Agricultural Experiment Station, St. Paul, Minnesota.

Pennypacker S P, Scharen A L, Sharp E L, Sands D C (1983) Spectral classification of wheat infected with barley yellow dwarf and stripe rust. Phytopathology 82:1006.

Perry C R, Lautenschager L F (1984) Functional equivalence and spectral vegetation indices. Remote Sensing Environ. 14:169-172.

Pinter P J Jr., Stanghellini M E, Reginato R J, Idso S B, Lenkins A D, Jackson R D (1979) Remote detection of biological stress in plants with infrared thermometry. Science 205:585-587.

Sharp EL, Perry C R, Scharen A L, Boatwright G O, Sands D C. Lautenschager L F, Yahyaoui C M, Ravel F W (1985) Monitoring cereal rust development with a spectral radiometer. Phytopathology 75:936-939.

Sherwood R T, Berg C C, Hoover M R, Zeiders K E (1983) Illusions in visual assessment of Stagonospora leaf spot of orchardgrass. Phytopathology 73:173-177.

Shokes F M, Berger R D, Smith D H, Rasp J M (1987) Reliability of disease assessment procedures: a case study with late leafspot of peanut. Oléagineux 42:245-251.

Sinclair T R, Hoffer R M, Schreiber MN (1971) Reflectance and internal structure of leaves from several crops during a growing season. Agron. J. 63:864-868.

Sinclair T R, Hoffer R M, Schreiber M M (1971) Reflectance and internal structure of leaves from several crops during a growing season. Agron. J. 63:864-868.

Suits G H (1972) The cause of azimuthal variations in directional reflectance of vegetative canopies. Remote Sensing Environ. 2:175-182.

Suits G H, Safir G R (1972) Verification of a reflectance model for mature corn with applications to corn blight detection. Remote Sensing Environ. 2:183-192.

Teng P S, Close R C (1977) Spectral reflectance of healthy and leaf rust infected barley leaves, Aust. Plant Pathol. Soc. Newsl. 6:7-9.

Teng P S, Close R C, Blackie M J (1979) Comparison of models for estimating yield loss caused by leaf rust (*Puccinia hordei*) on Zephyr barley in New Zealand. Phytopathology 69:1239-1244.

Tomerlin J R, Howell T A (1988) DISTRAIN: a computer program for training people to estimate disease seventy on cereal leaves. Plant Dis. 72:455-459.

Tu J C, Tan C S (1985) Infrared thermometry for determination of root rot seventy in beans. Phytopathology 75:840-844.

Tucker C J, Maxwell E L (1976) Sensor design for monitoring vegetation canopies. Photogramm. Eng. Remote Sensing 42:1399-1410.

Ulaby F T, Allen C T, Eger G III, Kanamasu E (1984) Relating the microwave backscattering to leaf area index. Remote Sensing Environ. 14:113-133.

Wallen V R, Galway D (1979) Effective management ofbacterial blight of field beans in Ontario - a ten year program. Plant Pathol. 1:42-46.

Wallen V R, Jackson H R (1971) Aerial photography as a survey technique for the assessment of bacterial blight of field beans. Can. Plant Dis. Surv. 51:163-169.

Wallen V R, Jackson H R (1975) Model for yield loss determination of bacterial blight of field beans utilizing aerial infrared photography combined with field plot studies. Phytopathology 65:942-948.

Williams D L, Walthall C L, Goward S N (1984) Collection of in situ forest canopy spectra using a helicopter: a discussion of methodology and preliminary results. Pages 94-106 *in* Machine processing of remotely sensed data symposium. Laboratory for Applications of Remote Sensing, West Lafayette, Indiana.

Wooley J T (1971) Reflectance and transmittance of light by leaves. Plant Physiol. 47:656-662.

## Notes

*Author's address:* F. W. Nutter, Jr., University of Georgia, Athens, Georgia, USA (Current address: Iowa State University, Ames, Iowa 50011).

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Sampling insects and diseases in rice

B. M. Shepard and E. R. Ferrer

The bases for making accurate decisions on whether or not to apply an insect control tactic or for determining the status of plant diseases should depend on the density of an insect pest and its major natural enemies or on the occurrence and intensity of a disease. The only way to determine these factors is field monitoring.

Unfortunately, many farmers apply insecticides to rice without considering an action threshold. Also, the effects of natural enemies of rice pests rarely are considered in determining thresholds. Programs for sampling diseases and making control decisions are used even less, or even known.

The discussion here is limited to sampling techniques and methods for the insects and diseases in rice which are relevant to decisionmaking in integrated pest management (IPM) programs. We make no attempt to review the literature on insect and disease sampling.

Most of the basic information about sampling insects is covered in Southwood (1978). Knowledge of basic statistical procedures is necessary to calibrate procedures useful in IPM decisionmaking.

## Statistical aspects of sampling

### Important statistical parameters

Some useful statistics applicable to field sampling include

- Arithmetic mean.

$$\bar{X} = \frac{\Sigma X_i}{n}$$

- Variance.

$$S^2 = \frac{\Sigma X_i^2 - \frac{(\Sigma X_i)^2}{n}}{n - 1}$$

- Standard error of the mean ($S_{\bar{x}}$), a measure of the distance of $\bar{X}$ from the true mean ($\mu$) of the population being sampled.

$$S_{\bar{x}} = \frac{S}{\sqrt{n}}$$

- Coefficient of variation (CV), used to compare the amount of variation in relation to the mean.

$$CV = \frac{S}{\bar{X}} \times 100$$

- Relative variation (RV), commonly used in entomology (Ruesink 1980).

$$RV = \frac{S_{\bar{x}}}{\bar{X}} \times 100$$

CV and RV are particularly useful for comparing techniques that use different sample units.

- Relative net precision (RNP), a measure of sampling efficiency (Ruesink 1980).

$$RNP = \frac{100}{(RV)(C_s)}$$

where $C_s$ = time consumed/sampling unit in labor-hours.

- Regression, used to calibrate relative sampling methods against absolut methods.

$$Y = x + ßx + a$$

where Y = no. caught by the absolute sampling method.
ß = regression coefficient, and
a = intercept.

- Efficiency (E), the relationship between the sample estimate and the absolute mean density.

$$E = \frac{\text{mean obtained with some technique}}{\text{absolute mean density}} \times 100$$

Because the absolute mean density cannot be ascertained, this statistic is less useful in rice than in other systems.

- Accuracy (synonymous with efficiency), the difference between a sample result and a real population value (Ruesink 1980).
- Reliability (synonymous with precision). Because the real population value is rarely known, reliability or precision of a sample result is of more interest. RNP is one measure.

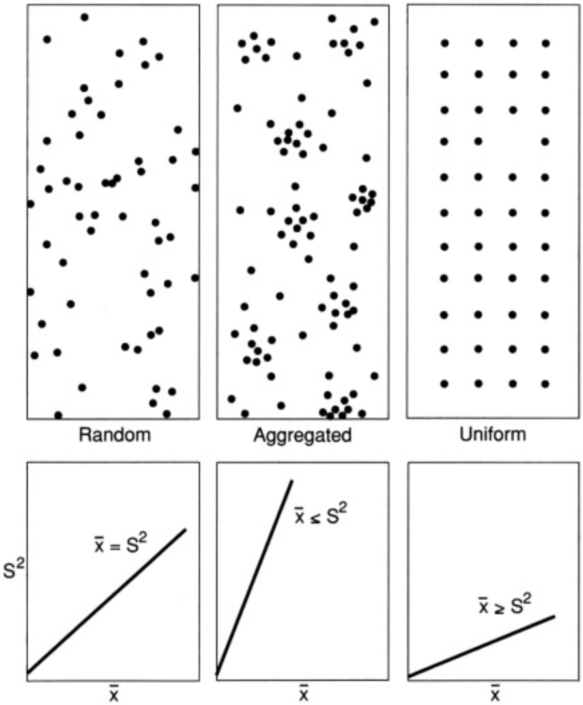
## Spatial distribution and measures of aggregation

Knowledge of the distribution pattern of an insect or disease in a field is important in developing a sampling protocol. Usually, distribution patterns have a high influence on field estimations of insect pests, diseases, and crop losses. Insect and disease distributions are most often described as negative binomial, positive binomial, or Poisson.

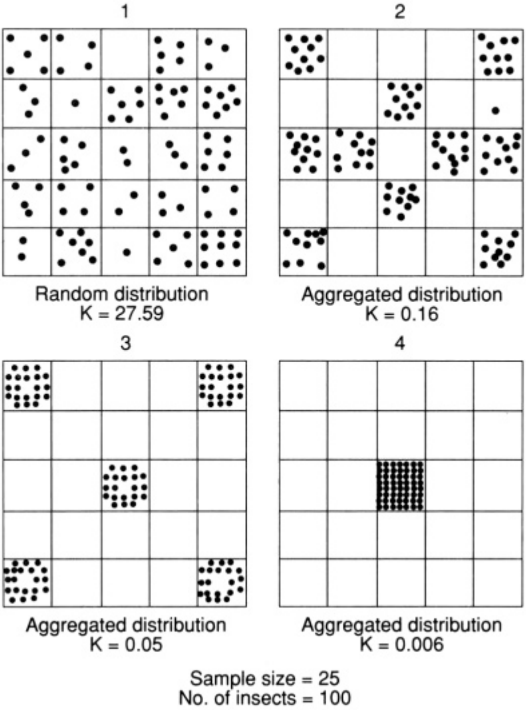
The sample unit must be selected and preliminary sampling carried out to determine if an insect or disease distribution pattern is Poisson (random), negative binomial (clumped or aggregated), binomial, or other distributions (Ruesink 1980, Southwood 1978). In general, changes in distribution pattern are reflected in changes in the mean-variance relationship (Fig. 1). With a random distribution, the variance and the mean are approximately equal. With an aggregated distribution, the variance is larger than the mean. With a uniform distribution, the variance is less than the mean.

For a negative binomial distribution, the degree of aggregation is determined by the parameter k. A lower value fork indicates more aggregation in the population. As k approaches 8 or more, the distribution becomes Poisson. Figure 2 shows how distribution patterns change with varying k.

The distribution may shift with change in insect population density or disease intensity. Teng et a1 (1988, unpubl.) observed that the pattern of rice tungro virus (RTV) infection changed as disease intensity progressed in a field. At first, disease distribution was random. As the disease progressed, aggregation appeared. Later in the season, when more plants became infected, the spread of disease approached a



**1.** Effect of distribution pattern on mean-variance relationship.



**2.** A schematic diagram showing the relationship between the clumping parameter k and the distribution pattern (after Waters 1955).

regular distribution. Similar patterns have been found for insects, particularly such species as brown planthopper (BPH) *Nilaparvata lugens* (Stål).

Other methods that can be used to determine the degree of aggregation in a population include Taylor's power law (Southwood 1978; Taylor 1961, 1984), Lloyd's mean crowding (Lloyd 1967), m*-m statistics (Iwao 1977a), and index of dispersion (Southwood 1978).

Several studies have elucidated dispersion and spatial distribution of disease progression. They include studies of southern blight caused by *Sclerotium rolfsii* on apple rootstock (Tomasino and Conway 1987), maize dwarf mosaic (Madden et a1 1987), alfalfa leaf spot caused by *Leptophaerilina briosiana* (Thai and Campbell 1986), and lettuce drop caused by *Sclerotinia minor* (Jarvis and Hawthorne 1972). Information on rice diseases is limited.

For rice insect pests, studies of distribution patterns have been conducted for BPH *Nilaparvata lugens* (Stål) and whitebacked planthopper (WBPH) *Sogatella furcifera* Horvath (Kuno 1977, Shepard et a1 1986), Malayan black bug *Scotinophara coarctata* (F.) (Ferrer and Shepard 1987), striped stem borer *Chilo suppressalis* (Kanno 1962, Nishida and Torii 1970, Zhong 1986), and leaffolders (Ferrer and Shepard, unpubl.).

## Sample size

A sample should provide an acceptable estimate of population density or disease intensity. Obviously, the larger the sample, the more reliable the estimate. However, unless resources are unlimited, a compromise must be reached between sample size and reliability. The relationship between precision (expressed in terms of standard error [%S.E.]) and cost is shown in Figure 3. Much has been written about sample size and allocation of sample resources (Cochran 1977, Karandinos 1976, Ruesink 1980). Karandinos (1976) summarized approaches for determining the optimum sample size, depending on the definition of "reliability."

If reliability can be defined in terms of the coefficient of variability (CV) (e.g. $C = (S/\sqrt{n})/X$), then for a given C, the optimum sample size (n) for a population with a Poisson distribution is

$$n = \frac{1}{\bar{X}C^2}$$

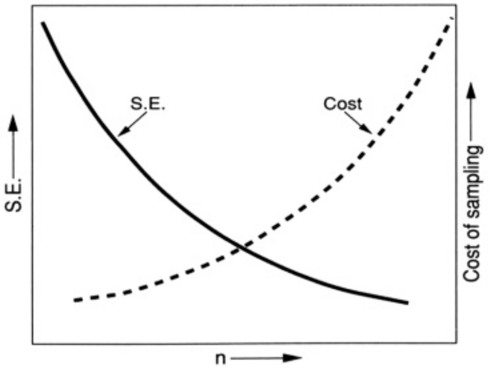
For a population with a negative binomial distribution, it is

$$n = \frac{1}{\bar{X}} + \frac{1}{k}$$

If the preliminary sample estimate of the mean ($\bar{X}$) was 25, and the distribution a negative binomial with a k value of 2, then for a CV of 0.1, the optimum sample size would be 54. It is unlikely that this many could be taken routinely in an insect or disease management program. The degree of precision required should be considered along with the time and resources available.

## Sample unit

Sampling unit is the smallest element of habitat from which measurements are taken (Southwood 1978). In developing a sampling plan, it is important that the sampling unit be determined first. The unit will depend on the kind of information desired and the intensity of the study. Research on diseases usually calls for number of spores per



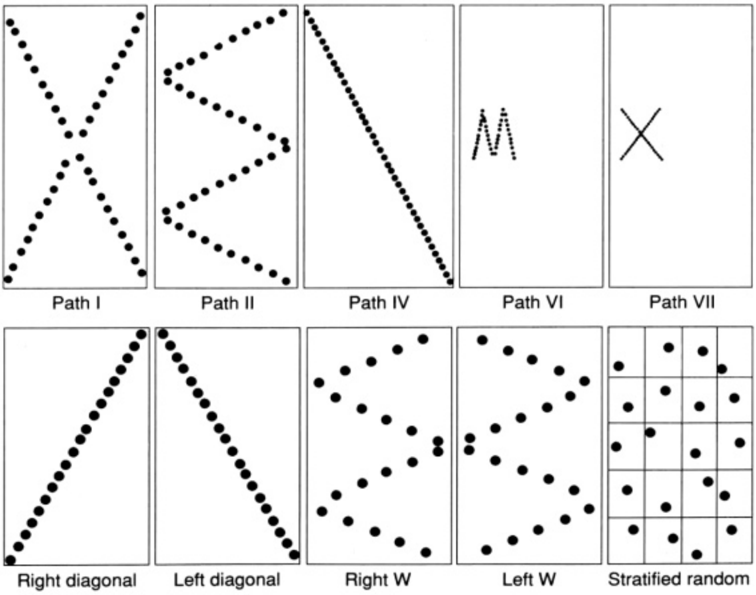
**3.** Relationship between number of samples taken, standard error, and cost of sampling.

lesion, number of lesions per leaf, and number of infected leaves per plant. For insects, the rice hill is the normal sampling unit, although in some cases, the unit is a 1-m$^2$ area. In general, it is better to take samples from many small units than from a few large units (Southwood 1978).

In pest management studies, sampling very small units is impractical. Number of infected hills, percent infection per unit area, or percent infection per plant are more appropriate for rice diseases. Estimates of the incidence of certain diseases tend to be more precise when larger squares are used as sampling units. When small squares are used, errors can be compensated for by increasing sample size (Gilligan 1980). The shape of the sampling unit also may affect precision. Gilligan (1982) reported that square quadrats provided a higher degree of precision than long, rectangular sampling units.

## Sampling pattern

The appropriate sampling pattern depends on the spatial distribution of the insect or disease. Lin et al (1979) compared five sampling patterns—X, W, and diagonal designs in entire fields and X and W designs in partial fields—fomeasuring random and aggregated disease distribution (Fig. 4a). Sample size was more important than sampling pattern when disease distribution was random. Sampling pattern was more important when disease distribution was aggregated. In aggregated distribution, the degree of precision was, in order: entire field X = W > diagonal > partial field X =W.



**4.** Sampling patterns. Points represent sampling sites. (a) Compared by Lin et al 1979, (b) compared by Delp et al 1986a.

In a similar study, Delp et a1 (1986a) compared five sampling patterns — right diagonal, left diagonal, right W, left W, and stratified random sample [SRS] (Fig. 4b). For diseases, SRS was more precise than the W and diagonal patterns.

A zigzag pattern was appropriate for sequentially sampling BPH and predators (Shepard et a1 1988). No difference in estimates of mean population density was found when green leafhoppers were sweep-sampled using an X pattern through the middle of the field or along the borders (Estano and Shepard 1988).

### Sampling interval

If the purpose of sampling is to monitor disease progression and to estimate insect population densities, weekly intervals usually are satisfactory (Gaunt 1985, Shepard et a1 1988). Closer intervals are not practical for IPM implementation. Estimates of insect density also may vary with time of day. Significantly fewer green leafhopper (GLH) *Nephotettix* spp. were estimated by sweep net sampling during 1400-1430 h than during 0730-0800 h or 1800-1830 h (Estano and Shepard 1988). It is likely that estimates of population densities of other rice arthropods also differ with the time of day samples are taken.

For detailed epidemiological studies, disease progression and factors affecting its development must be monitored intensively. In some cases, daily or even hourly measurements are necessary. The sampling interval also depends on the infection rate of the disease and on crop age.

## Sampling methods and devices

### Basic aspects

Field sampling methods can be divided into three major types: absolute, relative, and population indices (Beardsley et a1 1979, Ruesink 1980).

*Absolute methods.* Absolute methods estimate density per unit area in a habitat. Presumably, all or virtually all the target species in the sample unit are collected. These methods are used in research to calibrate relative methods; they are too costly and time-consuming to be used in IPM.

For insects, absolute samples may be taken to

- Determine the density of insect pests and their natural enemies, for in-depth studies of population dynamics.
- Establish economic thresholds.
- Estimate effectiveness of control measures.
- Evaluate resistant varieties.
- Calibrate relative techniques.

Absolute sampling devices for rice arthropods include D-vac (Dietrick 1961, Perfect et al 1983). FARMCOP (Cariño et a1 1979), $CO_2$NE sampler (Aquino and Heinrichs 1986, Shepard et a1 1985), and bagging (Ferrer and Shepard 1987).

For diseases, basic studies are important in determining the relationship between a pathogen or disease and its host plant and between the environment and human interference. These studies include

- Quantification of disease epidemics in time and space.
- Crop or yield loss assessment.
- Evaluation of plant resistance to diseases.
- Evaluation of efficacy of control agents, i.e. fungicides, biological control agents, etc.
- Development and verification of predictive models and decision aids.

*Relative methods.* Relative methods give density estimates based on sampling a unit of habitat, with only a proportion of individuals collected. Because these methods are selective and require less time and effort, they are the choice for IPM.

Population indices. These are damaged plants or plant parts (e.g. whiteheads, deadhearts, percent foliage area covered by a disease, etc.). For insects, it is normally not wise to recommend treatment when a certain level of damage is reached unless live insects are present. For diseases, population indices are widely used because it is more practical to assess disease incidence than presence of the causal agent.

### Methods for sampling diseases

Two important parameters for assessing disease intensity in the field are incidence and severity. Incidence is the proportion of plants or plant parts infected with a disease. Severity is the amount or proportion of tissue damaged by the disease. Most methods for sampling diseases are based on severity, especially when information on quantitative relationship between the degree of infection and amount of yield loss is needed. Ratings are based on visual differences between proportions of infected and healthy plants or plant parts. As with insects, before a sampling method is adopted, its accuracy (efficiency) and reliability (repeatability or precision) must be determined. Accuracy is highly influenced by the level of subjectivity in the method of calibration and reliability by the level of standardization and training (Gaunt 1985, Large 1966). In addition, choice of sampling method is based on the causal agent, spatial distribution pattern, and location of the disease and pathogens in the plant (Gaunt 1985).

*Standard area diagrams.* Diagrams are used to estimate the area of a plant part affected by the disease. These are commonly used for foliar diseases but can also be adopted for other plant parts (normally expressed as percent cover). Based on the symptoms, different severity levels are set, taking into account lesion size, shape, and distribution. A plant part is scored by a category number representing a severity level; the mean score of the sample is obtained by adding up the scores and dividing by the number of plant parts examined.

A scale developed to determine severity levels of sheath blight in rice was based on lesion height (Ahn et al 1986). The higher the lesion, the higher the severity level; severity level corresponded to a certain yield reduction. Standard scales developed for assessing different rice diseases (IRRI 1980) have been used mainly for varietal screening.

*Field keys.* Keys are used for rapid visual assessment of a leaf disease on. whole plants, plots, or specific sampling areas of a standing crop (Large 1966). The method is more practical to measure plant diseases in the field. Death of tissues attributable to the disease also is measured. A field key has to be simple and easy to use to minimize subjectivity. It should be tested by different assessors for reliability. A pictorial key was developed for RTV to assess different severity levels of RTV in the field (Ferrer et al. unpubl.).

*Computer-based assessment keys.* Computer-based assessment is becoming more popular. An example is Field Runner developed by Delp et al (1986b). This software package facilitates assessment of disease incidence, severity, and spatial distribution. It calculates mean and variance of incidence, k, the parameter of the negative binomial distribution and Lloyd's mean crowding and mean patchiness.

*Remote sensing and image analysis.* Remote sensing uses radiodensitometers and electronic scanners to determine disease severity (James and Teng 1979). Spectral reflectance distinguishes between healthy and diseased plants. Disease severity is based on the near infrared wavelength region (700-950 nm) (Gaunt 1985, Teng 1983). A low-cost, multispectral radiometer has been used to estimate disease severity in relation to yield loss due to late leaf spot on peanuts (Nutter et al 1985) and barley spot blotch (Nutter and Pederson 1983). Infrared photography also can be used, especially for large-area surveillance; aerial photographs are taken of the diseased area.

*Other methods.* Other methods include spore trapping or lesion counts and, in the case of insect-borne diseases, insect trapping and field sampling of the vector.

## Techniques for sampling rice arthropods

Several sampling approaches have been used to monitor populations of rice arthropods. Some of these are visual inspection of the rice hill (or some convenient unit area), sweep nets, suction samplers, aerial nets, and sticky boards. Light traps and pheromone traps that measure only the relative activity of insects usually are not very useful for IPM decisionmaking in rice. Absolute sampling devices such as suction traps and $CO_2$NE samplers are limited to population studies and for calibrating devices that can be used for IPM decisionmaking.

In developing a sampling program for IPM purposes, a knowledge of the life history and behavior of the species is as important as its distribution. It helps the researcher decide on the appropriate sample unit, sampling interval, and technique.

*Comparison of sampling techniques.* The most appropriate first step in comparing sampling techniques is to plot the results (means) of each technique on a graph. This allows a quick overview of how each technique estimates population trends over time. A scatter plot diagram may also be used to determine relationship between sampling techniques. However, the amount of variation in relation to the mean (usually measured by the CV) is equally if not more important. Other methods that can be used to compare efficiency of sampling techniques are correlation coefficient, regression analysis, and comparison of means (i.e. *t*-test).

Perfect et al (1983) determined the efficiency of two absolute samplers, the D-vac and FARMCOP, for sampling cicadellids and delphacids and their predators. They found the D-vac in conjunction with an enclosure placed over the rice hill before sampling most suitable. Its efficiency was not affected by crop age for most taxa, except for Aranae *Microvelia douglasi atrolineata* (Bergoth) and brachypterous female BPH and WBPH.

These devices would be inappropriate for an IPM program, but could be used to calibrate more practical methods. The FARMCOP and a $CO_2$NE sampler had similar CVs for most arthropods considered, although the $CO_2$NE device yielded higher mean numbers of spiders (Aquino and Heinrichs 1986, Shepard et al 1985). Also, the $CO_2$NE sampler costs less, requires fewer materials to construct, and is easier to use. However, it can only be used to sample a crop in standing water because insects anesthetized by the $CO_2$ must be scooped from the water's surface.

We compared visual counting and bagging for Malayan black bug *Scotinophora coarctata* (F.) in Palawan (Ferrer and Shepard 1987). There was good correlation between the two techniques (*r* = 0.95), with no significant difference between estimations of the population means.

We also compared a water pan sampler designed for sampling planthoppers (BPH and WBPH) and predators in flooded rice with the CO2NE sampler (Ferrer and Shepard 1988). A pan containing a small amount of water and a few drops of liquid detergent is placed at the base of the hill and the hill struck by the hand to dislodge arthropods into the pan (Fig. 5). Reliability of the water pan sampler was comparable to that of the CO2NE sampler in direct seeded and transplanted rice (Ferrer and Shepard 1988). The sample unit in transplanted rice was a hill; in direct seeded rice. a 25- × 25-cm area. In general, both techniques detected the same population trends and their CVs were similar. The water pan is a practical technique to use in IPM programs because it is simple and easy to use.

**5.** Water pan sampling technique.

Nagata and Masuda (1978) determined the efficiency of sticky boards for estimating BPH populations in Japan. Sticky boards were also used for field sampling in Malaysia as part of surveillance for BPH (Ooi 1982). Although sticky boards may be useful, they are not practical for most IPM programs in rice because the material is difficult to handle and expensive.

## Sequential sampling

Sequential sampling (developed by Wald [1945]) is a rapid and easy method of classifying populations into broad categories (i.e. light, medium, and heavy infestations) where pest management decisions must be quickly made. Although many surveillance programs require a fixed number of samples, sequential sampling allows the sampler to classify a population into broad categories using a minimum number of samples, especially when population densities are low or high. Sample units are chosen and examined in sequence until the count falls into one or more categories (e.g. low or high) distinguished by specified limits (Waters 1955).

Among the advantages of sequential sampling are

- It is time saving.
- It is easy to use.
- It is flexible.
- Sample size is variable.
- It is economical.

To develop a sequential sampling plan, the following information is needed:

- Spatial distribution of the pest.
- The action threshold.
- Level of risk.

Although sequential sampling has been used mainly for insects, some workers have used it to determine treatment decisions for diseases. It has been used for management of wheat stripe rust in New Zealand (Cole 1985, Gaunt and Cole 1987), leaf blight caused by *Botrytis squamosa* in onion (Boivin and Sauriol 1984), and cabbage black rot (Strandberg 1973). No sequential sampling protocols have been developed for rice diseases.

### Sequential sampling for planthoppers and predators

A sequential sampling model for planthoppers was developed using a Fortran program developed by Gates and Ethridge (1972); field counts were fitted to their distribution pattern (Shepard et al 1986). Planthoppers were distributed most often as a negative binomial. Formulas for calculation of decision lines based on negative binomial distribution are as follows:

$$d_1 = bn + h_1$$
$$d_2 = bn + h_2$$

$$\text{where} \quad b = k\,\frac{\log \dfrac{q_2}{q_1}}{\log \dfrac{p_2 q_1}{p_1 q_2}} \qquad k = \frac{x^2}{s^2 - \bar{x}}$$

$$h_1 = \frac{\log \dfrac{\beta}{1 - \alpha}}{\log \dfrac{p_2 q_1}{p_1 q_2}} \qquad p_1 = \frac{m_1}{k}\ , \quad q_1 = 1 + p_1$$

$$p_2 = \frac{m_2}{k}\ , \quad q_2 = 1 + p_2$$

$$h_2 = \frac{\log \dfrac{1 - \alpha}{\beta}}{\log \dfrac{p_2 q_1}{p_1 q_2}}$$

where

$d_1$ and $d_2$ = decision lines or class limits,

$\left.\begin{array}{l} m_1 = 17 \\ m_2 = 23 \end{array}\right\}$ (damage thresholds)

k = 5.3,

b = the slope of the line,

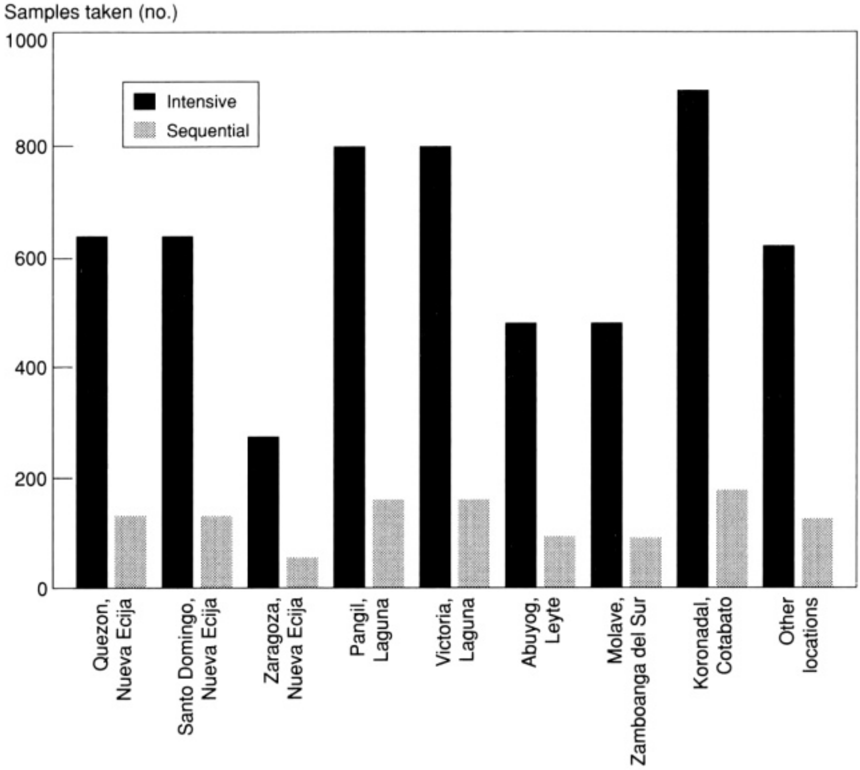
$h_1$ and $h_2$ = the intercepts, and

n = the sample number.

A sequential table for the major rice planthoppers is shown in Table 1. The plan was tested in farmers' fields in different locations in the Philippines and compared with more intensive sampling (Shepard et al 1986). The techniques agreed 100%, with an 80% savings in time with the sequential sampling plan (Fig. 6).

**Table 1. Sequential sampling plan for rice planthoppers.**

| Sample number | Number of hoppers | Cumulative number of hoppers | | Lower limit | | Upper limit | |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | do not treat | < 57 | continue sampling | 100 > | treat |
| 5 | | | | < 77 | | 120 > | |
| 6 | | | | < 97 | | 140 > | |
| 7 | | | | < 116 | | 160 > | |
| 8 | | | | < 136 | | 179 > | |
| 9 | | | | < 156 | | 199 > | |
| 10 | | | | < 176 | | 219 > | |
| 11 | | | | < 195 | | 239 > | |
| 12 | | | | < 215 | | 258 > | |
| 13 | | | | < 235 | | 278 > | |



**6.** Comparison of total number of samples per location using intensive sampling (SEWS) and sequential sampling (Shepard et al 1986).

Because predators play a major role in regulating hopper populations, the scheme incorporates predators (Table 2). The modified sequential plan, SEQPRED, allows adjustments to be made to the decision lines in response to the number of predators found (Shepard et al 1988).

The SEQPRED plan consists of the following steps:

1. The sampler follows a zigzag pattern across the field (approximately 1/8 to 1/4 ha) and samples preferentially where infestations appear highest.
2. The number of hoppers (Table 2, column 1) and of predators (column 2) found in a sampled hill are recorded. The adjusted number of hoppers (column 3) is determined by subtracting 5 hoppers for each major predator found. (This adjustment was based on the literature and on our studies which showed that a general predator can consume more than 5 hoppers/d.) Predators include spiders and beetle adults and larvae (Coccinellidae and Carabidae). The cumulative adjusted number of hoppers (column 4) provides a running total of the adjusted number of hoppers.

**Table 2. Sequential sampling plan for rice planthoppers and predators (SEQPRED).**

Date ________ Location __________________ Days after transplanting: _____________
Field no. _____ Variety _________________

| Sample no. | Hoppers (no.) | Predators (no.) | Adjusted no. of hoppers | Cumulatlve/adjusted no. of hoppers | | Lower limit | | Upper limit | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2 | | | | | | | | | |
| 3 | | | | | | | | | |
| 4 | | | | | | < 32 | | 76 > | |
| 5 | | | | | do not treat | < 45 | continue sampling | 89 > | treat |
| 6 | | | | | | < 59 | | 102 > | |
| 7 | | | | | | < 72 | | 116 > | |
| 8 | | | | | | < 85 | | 129 > | |
| 9 | | | | | | < 99 | | 143 > | |
| 10 | | | | | | <112 | | 156 > | |
| 11 | | | | | | <126 | | 169 > | |
| 12 | | | | | | <139 | | 183 > | |
| 13 | | | | | | <152 | | 196 > | |

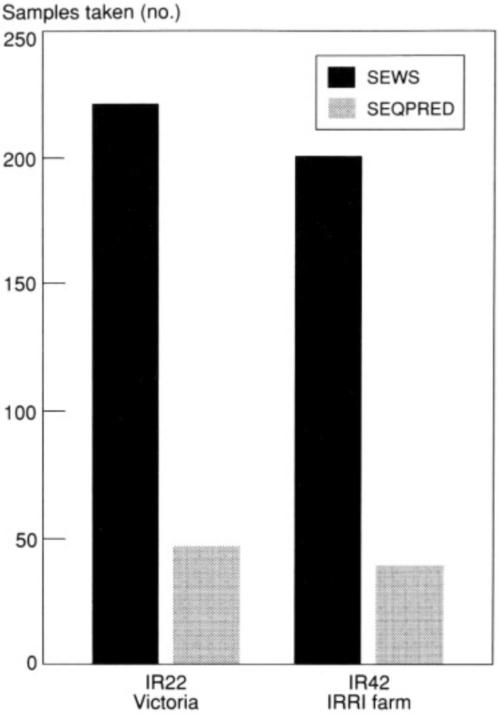
**Table 3a. Decisions made using SEQPRED and SEWS on treated and untreated plots in Victoria, Laguna, Philippines (Shepard et al 1988).**

| Days after transplanting | Decision[a] | | | |
|---|---|---|---|---|
| | Treated | | Untreated | |
| | Sequential | SEWS | Sequential | SEWS |
| 28 | DT | DT | DT | DT |
| 35 | DT | DT | DT | DT |
| 42 | DT | DT | DT | DT |
| 49 | DT | DT | DT | DT |
| 56 | T | T | T | T |
| 63 | T | T | T | T |
| 70 | DT | DT | T | T |
| 74 | DT | DT | T | T |
| 77 | DT | DT | T | T |
| 84 | T | T | T | T |
| 91 | DT | DT | T | T |

[a] DT = do not treat, T = treat.

**Table 3b. SEQPRED-SEWS yield comparison in Victoria, Laguna, Philippines (Shepard et al 1988).**

| Plot | Yield (t/ha) |
|---|---|
| SEQPRED-Treated | 4.91 a |
| SEWS-Treated | 4.37 ab |
| SEQPRED-Untreated | 3.61 b |
| SEWS-Untreated | 3.44 b |

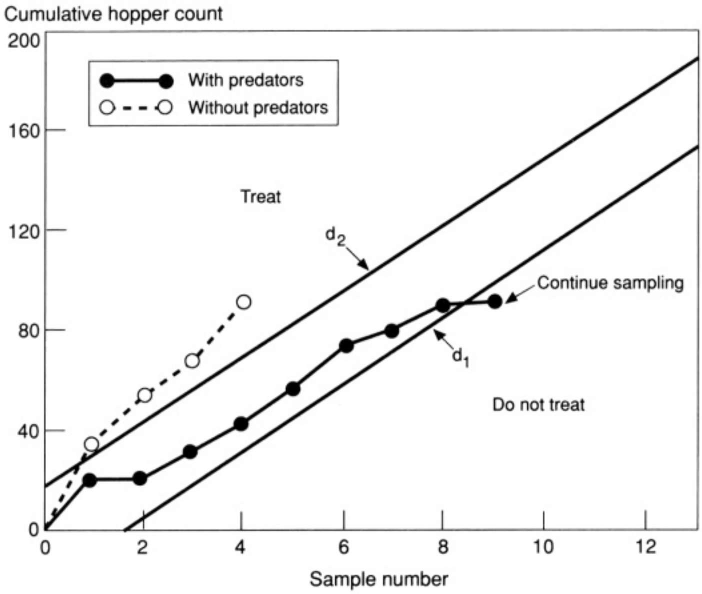


***7.*** Number of samples required using SEWS and SEQPRED to make a decision about the necessity of insecticide treatment (Shepard et al 1988).

3. The sequential table is consulted after the 4th sample. If a "continue sampling" decision is reached, the table is checked after each additional sample. If after the 13th sample the decision is still to continue sampling, then the decision to treat is taken.

SEQPRED was compared with SEWS (Surveillance and Early Warning System) developed under the Philippine-German Crop Protection Program (MAF-BPI 1984). With SEWS, the decision to treat is based on sampling 20 randomly selected hills weekly from each plot. The economic threshold is 20 hoppers/hill.

In an experiment that sampled planthoppers in ricefields of Victoria, Laguna, Philippines, decisions made on the basis of SEWS and SEQPRED agreed 100% (Table 3a). A 70.80% savings in time (based on total number of samples taken) was realized with SEQPRED compared with SEWS (Fig. 7). In many instances, incorporation of predators prevented unnecessary pesticide application (Fig. 8). There were no significant differences in yields between plots sampled by SEQPRED and SEWS and treated. Classification of hopper populations sampled by both methods from untreated plots did not differ (Table 3b).



**8.** Sequential sampling model showing insecticide treatment decisions with and without predators (Shepard et al 1988).

## Sequential sampling for black bug *Scotinophara coarctata* (F.)

A sequential sampling plan for black bug *S. coarctata* (Table 4) was developed based on negative binomial distribution (Ferrer and Shepard 1987). To compute the decision lines, the following parameters were used:

$m_1$ = 2 bugs/hill
$m_2$ = 4 bugshill
$\alpha = 0.20$
$\beta = 0.20$
$k = 0.50$

The scheme was tested in three locations in Palawan, Philippines, and compared with intensive sampling (20 hills taken at random and visually inspected). Sampling was carried out over a range of population densities. A 44-56% savings in number of samples was realized with the sequential scheme compared with intensive sampling (Fig. 9) and fewer samples were needed to reach a decision on whether or not to spray, especially when populations were low or high. Sequential sampling agreed with more intensive sampling about 90% of the time.

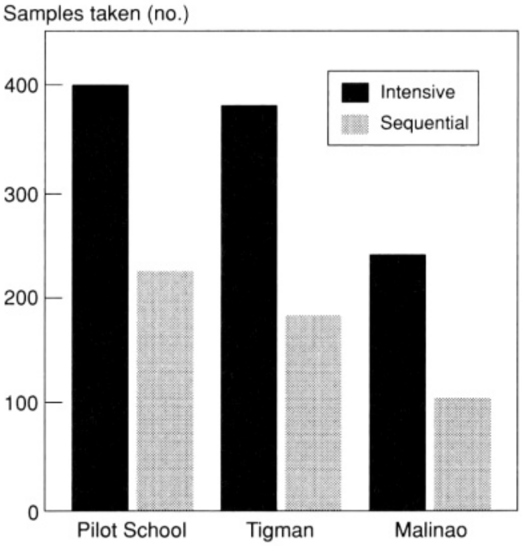
## Presence/absence sampling for planthoppers and major predators

The tedium associated with counting insects and other pest organisms in the field is often a major deterrent to development and implementation of IPM. The challenge for researchers is to develop simple, easy to use, yet scientifically sound sampling methods.

**Table 4. Sequential sampling plan for the rice black bug *S. coarctata.***

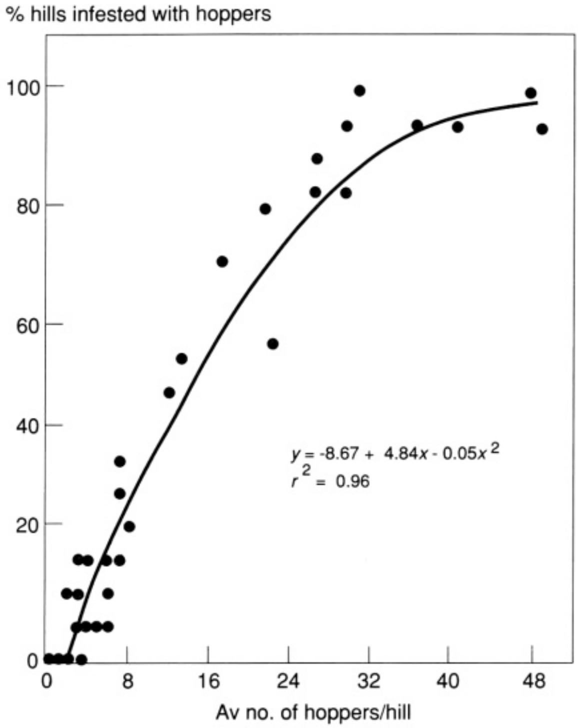
Location ____________________ Days after transplanting __________________
Date ____________________ Field no. _________ Variety __________________

| Sample number | Number found | Running total | | Lower limit | | Upper limit | |
|---|---|---|---|---|---|---|---|
| 1 | _________ | _________ | | | | | |
| 2 | _________ | _________ | | | | | |
| 3 | _________ | _________ | | | | | |
| 4 | _________ | _________ | do not treat | < 0 | continue sampling | 24 > | treat |
| 5 | _________ | _________ | | < 1 | | 27 > | |
| 6 | _________ | _________ | | < 4 | | 30 > | |
| 7 | _________ | _________ | | < 6 | | 33 > | |
| 8 | _________ | _________ | | < 9 | | 35 > | |
| 9 | _________ | _________ | | <12 | | 38 > | |
| 10 | _________ | _________ | | <15 | | 41 > | |
| 11 | _________ | _________ | | <18 | | 44 > | |
| 12 | _________ | _________ | | <20 | | 47 > | |



**9.** Number of samples required for sequential sampling and intensive sampling of *Scotinophara coarctata* (Ferrer and Shepard 1987).

When adequate data have been collected to determine the relationship between number of plants (hills) infested and insect density (Fig. 10), a presence/absence or binomial sequential sampling model can be developed. With planthoppers, however, as population density approaches the action threshold, almost all plants are infested, although the population is clumped. To implement presence/absence sampling for



**10.** Relationship between the number of plants (hills) infested and planthopper density.

planthoppers and major predators, a sequential model was developed (Shepard et al 1989) using the following criteria:

- 10 or more hoppers present = presence
- Fewer than 10 hoppers present = absence
- Class limits

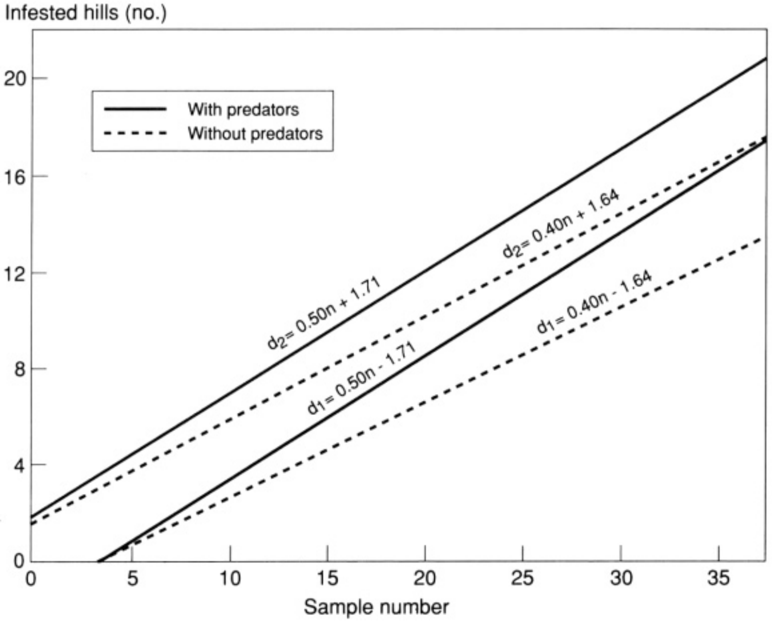
$$\left.\begin{array}{l} m_1 = 0.30 \\ m_2 = 0.50 \end{array}\right\} \text{(without predators)}$$

$$\left.\begin{array}{l} m_1 = 0.40 \\ m_2 = 0.60 \end{array}\right\} \text{(with predators)}$$

- Level of risk

$$a = b = 0.20$$

The graphic representation of the model with and without predator is shown in Figure 11. A table was more appropriate for field use (Table 5). The decision on whether to use "predators present" or "predators absent" side of the table is based on predators found in the first five samples. If five major predators are found in the first five samples, then the "predators present" side is used.



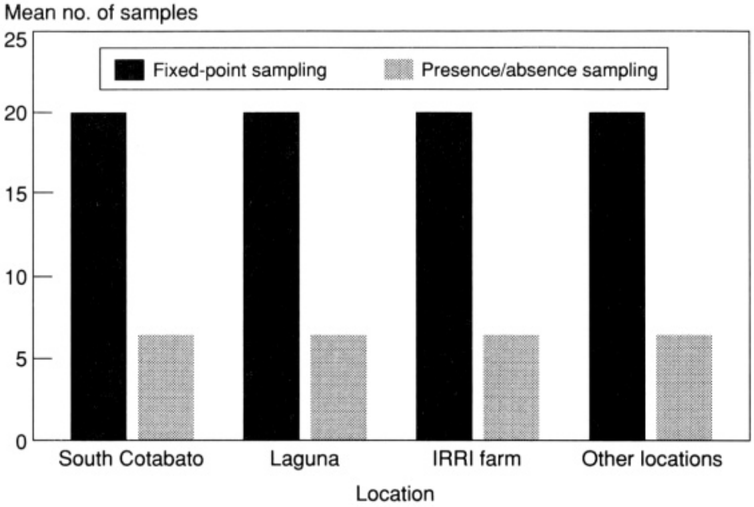
**11.** Graphic representation of the presence/absence sequential sampling for rice planthoppers.

**Table 5. Sequential sampling plan for planthoppers and predators in rice using binomial distribution.**

Days after transplanting ______

Date: ______ Location ______ Field no. ______ Variety ______

| Sample no. | Predator no. | | Predators present | | | | Hills infested | | Predators present | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Lower limit | | Upper limit | | | | Lower limit | | Upper limit | |
| 1 | ______ | | — | | | | ______ | | — | | — | |
| 2 | ______ | | — | | | | ______ | | — | | — | |
| 3 | ______ | | — | | | | ______ | | — | | — | |
| 4 | ______ | | — | continue sampling | | | ______ | | — | continue sampling | — | |
| 5 | ______ | do not treat | 0 | | 4 > | | ______ | do not treat | — | | — | |
| 6 | Total____ | | <1 | | 5 > | treat | ______ | | <0 | | 4 > | treat |
| 7 | | | <2 | | 5 > | | ______ | | <1 | | 4 > | |
| 8 | | | <2 | | 6 > | | ______ | | <2 | | 5 > | |
| 9 | | | <3 | | 6 > | | ______ | | <2 | | 5 > | |
| 10 | | | <3 | | 7 > | | ______ | | <2 | | 5 > | |
| 11 | | | <4 | | 7 > | | ______ | | <3 | | 6 > | |
| 12 | | | <4 | | 8 > | | ______ | | <3 | | 6 > | |



**12.** Number of samples taken using fixed-point sampling and presence/absence sequential sampling (Shepard et al 1989).

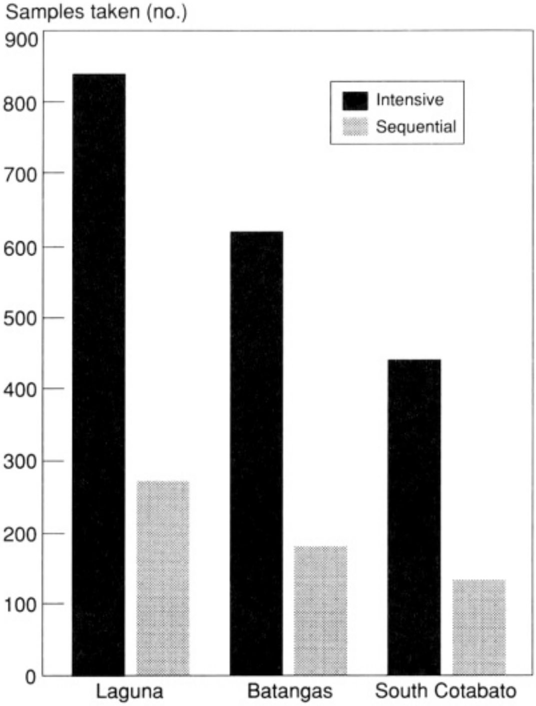
**Table 6. Sequential sampling plan for rice leaffolder larvae.**

Farmer's name:
Date ____________ Field no. ____________ Days after
Location ____________ Variety ____________ transplanting

| Sample no. | No. larvae | Running total | | Lower limit | | Upper limit | |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | do not treat | < 1 | continue sampling | 10 > | treat |
| 5 | | | | < 3 | | 12 > | |
| 6 | | | | < 4 | | 13 > | |
| 7 | | | | < 5 | | 14 > | |
| 8 | | | | < 7 | | 16 > | |
| 9 | | | | < 8 | | 17 > | |
| 10 | | | | <10 | | 19 > | |
| 11 | | | | <11 | | 20 > | |
| 12 | | | | <12 | | 21 > | |

Defoliators: CSW = Caseworm LF = Leaffolder GHC = Green hairy caterpillar
CW = Cutworm AW = Armyworm GC = Green-horned caterpillar
RS = Rice skipper GSL = Green semi-looper

A comparison of the presence/absence model with a more intensive fixed-number sampling program is shown in Figure 12. A 70% savings in number of samples was realized with the presence/absence model, with 96-100% agreement in decisions made.



**13.** Number of samples taken using intensive and sequential sampling for rice leaffolder.

### Sequential sampling for leaffolders

A sequential sampling plan for leaffolders has been developed and tested in the Philippines (Table 6) (Ferrer and Shepard 1988, unpubl.). Based on the negative binomial distribution with a clumping coefficient (K) of 1.1, the pertinent values used are

$$\left.\begin{array}{l} m_1 = 1 \text{ larva/hill} \\ m_2 = 2 \text{ larvae/hill} \end{array}\right\} \text{(damage thresholds)}$$

$$a = ß = 0.20 \text{ (the risk level)}$$

Results from testing the plan in Laguna, Batangas, and South Cotabato revealed highly significant savings in number of samples required (Fig. 13). In addition, approximately 79% savings in time was realized compared with a fixed sample size ($n = 20$) with $> 90\%$ agreement with intensive sampling in decisions made.

The flexibility, reliability, and ease of use of sequential sampling make it an ideal choice for IPM programs in rice.

As new data are gathered over a range of population densities and field situations, further refinements of the sequential sampling models will be made and tested for precision against more intensive techniques.

## References cited

Ahn A W, de la Peña R C, Candole B L, Mew T W (1986) A new scale for rice sheath blight (ShB) disease assessment. Int. Rice Res. Newsl. 11(6):17.

Aquino G B, Heinrichs E A (1986) A carbon dioxide-cone (CO2NE) sampler for arthropods in flooded rice. Int. Rice Res. Newsl. 2(1):13-14.

Beardsley J W, AliNiazee M T, Watson T F (1979) Sampling and monitoring. Pages 11-27 *in* Biological control and insect pest management. Division of Agricultural Sciences, University of California, Berkeley.

Boivin G, Sauriol P (1984) Dispersion statistics and sequential sampling plan for leaf blight caused by *Botlytis squamosa* in onions. Am. Phytopathol. Soc. 74:1385-1387.

Cariño F O, Kenmore P E, Dyck V A (1979) The FARMCOP suction sampler for hoppers and predators in flooded ricefields. Int. Rice Res. Newsl. 4(5):21-22.

Cochran W G (1977) Sampling techniques. 3d ed. John Wiley and Sons, New York. 428 p.

Cole M J s(1985) The development of a sequential sampling plan for management of stripe rust (*Puccinia striiformis* West) in winter wheat (*Triticum aestivum* L.). Ph D thesis, Lincoln University College, Christchurch, New Zealand. 120 p.

Delp B R, Stowell L J, Marois J J (1986a) Evaluation of field sampling techniques for accuracy of disease incidence estimation. Phytopathology 76:1399-1305.

Delp B R, Stowell L J, Marois J J (1986b) Field runner: a disease incidence, severity and spatial pattern assessment system. Plant Dis. 70:954-957.

Dietrick E J (1961) An improved backpack motor fan for suction sampling of insect populations. J. Econ. Entomol. 54:394-395.

Estano D B, Shepard B M (1988) Influence of time of day and sweeping pattern on catches of green leafhoppers (GLH). Int. Rice Res. Newsl. 13:21-22.

Ferrer E R, Fabellar N G, Teng P S (1988) A tentative pictorial key for assessment of RTV in the field. (unpubl.)

Ferrer E R, Shepard B M (1987) Sampling the Malayan black bug *Scotinophara coarctata* (F.) (Hemiptera: Pentatamidae) in rice. Environ. Entomol. 16:259-263.

Ferrer E R, Shepard B M (1988) Sampling methods for estimating population densities of planthoppers predators in direct-seeded and transplanted rice. Agric. Entomol. 5:119-204.

Ferrer E R, Shepard B M (1988) Sequential sampling rice leaffolder. (unpubl.)

Gates C E, Ethridge G F (1972) A generalized set of discrete frequency distributions with Fortran program. J. Exp. Stat. Math. Geol. 4:1-7.

Gaunt R E (1985) Measurement of disease and pathogens. Pages 6-18 *in* Crop loss assessment. P. S. Teng, ed. APS Press, St. Paul, Minnesota.

Gaunt R E, Cole M J (1987) A disease management response to the introduction of wheat stripe rust to New Zealand. Plant Dis. 71:102-107.

Gilligan C A (1980) Size and shape of sampling units for estimating incidence of stem canker on oil seed rape stubble in field plots after swathing. J. Agric. Sci. Camb. 94:493-496.

Gilligan C A (1982) Size and shape of sampling units for estimating incidence of sharp eyespot *Rhizoctonia cerialis* in plots of wheat. J. Agric. Sci. Camb. 99:461-464.

IRRI — International Rice Research Institute (1980) Standard evaluation system for rice. International Rice Testing Program. P.O. Box 933. Manila, Philippines. p. 13-20.

Iwao S (1977a) The m*-m statistics as a comprehensive method for analyzing spatial patterns of biological populations and its application to sampling problems. Pages 21-46 *in* Studies on methods of estimating population density, biomass and productivity in terrestrial animals. M. Morisita, ed. University of Tokyo Press, Tokyo.

Iwao S (1977b) Relation of frequency index to population density and distribution pattern. Physiol. Ecol. Jpn. 17:457-463.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Appl. Biol. 4:201-266.

Jarvis W R, Hawthorne B T (1972) *Sclerotinia minor* on lettuce: progress of an epidemic. Ann. Appl. Biol. 70:207-217.

Kanno M (1962) On the distribution patterns of the rice stem borer in a paddy field. Jpn. J. Appl. Entomol. Zool. 6:85-89.

Karandinos M G (1976) Optimum sample size and comments on some published formulas. Bull. Entomol. Soc. Am. 22:417-421.

Kuno E (1977) Distribution pattern of the rice brown planthopper and field sampling techniques. Pages 135-146 *in* The rice brown planthopper. Food and Fertilizer Technology Center for Asia and Pacific Region, Taipei.

Large E C (1986) Measuring plant disease. Annu. Rev. Phytopathol. 4:9-28.

Lin C S, Poushinsky G, Mauer M (1979) An examination of five sampling methods using random and clustered disease distribution using simulation. Can. J. Plant Sci. 59:121-130.

Lloyd M (1967) Mean crowding. J. Anim. Ecol. 36:l-30.

MAF-BPI — Ministryof Agriculture and Food and Bureau of Plant and Industry (1984) Philippine-German crop protection programme: implementing guidelines for the surveillance and early warning system in Masagana. Rev. ed. 1983/84. Manila, Philippines. 45 p.

Madden L V, Louis R, Knoke J K (1987) Temporal and spatial analysis of maize dwarf mosaic epidemics. Phytopathology 77:148-156.

Nagata T, Masuda T (1978) Efficiency of sticky boards for population estimation of the brown planthopper, *Nilaparvata lugens* Stal (Hemiptera: Delphacidae) on rice hills. Appl. Entomol. Zool. 13:55-62.

Nishida T, Torii T (1970) A handbook of field methods for research on rice stem borers and their natural enemies. IBP Handbook No. 14. International Biological Programme. London. Blackwell Scientific Publications, Oxford and Edinburgh. p. 85-94.

Nutter F W Jr., Pederson V D (1983) Yield loss determination in the barley spot blotch system using visual and remotely sensed disease assessment schemes. Phytopathology 73:803.

Nutter F W Jr., Littrell R H, Pederson V D (1985) Use of a low cost multispectral radiometer to estimate yield loss in peanuts caused by late leaf spot (*Cercosporidium personatum*). Phytopathology 75:502.

Ooi PAC (1982) A surveillance system for rice planthoppers in Malaysia. Proc. Int. Conf. Plant Prot. Trop. 551-566.

Perfect T J, Cook A G, Ferrer E R (1983) Population sampling of planthoppers, leafhoppers (Hemiptera:Delphacidae and Cicadellidae) and their predators in flooded rice. Bull. Entomol. Res. 73:345-355.

Ruesink W G (1980) Sampling methods for soybean entomology. M. Kogan and D. C. Herzog, eds. Springer-Verlag, New York. p. 62-104.

Shepard B M, Aquino G, Ferrer E R, Heinrichs E A (1985) Comparison of vacuum and carbon dioxide sampling devices for arthropods in flooded rice. J. Agric. Entomol. 2:364-369.

Shepard B M, Ferrer E R, Kenmore P E (1988) Sequential sampling of planthoppers and predators in rice. J. Plant Prot. Trop. 5:39-43.

Shepard B M, Ferrer E R, Soriano J S, Kenmore P E (1989) Presence-absence sampling planthopper and major predators in rice. J. Plant Prot. Trop. (in press)

Shepard M, Ferrer E R, Kenmore P E, Sumangil J P (1986) Sequential sampling: planthoppers in rice. Crop Prot. 5:319-322.

Shepard M, Grothusen J (1984) A simple calculator program for flexible sequential sampling of Insects. Bull. Entomol. Soc. Am. 30:35-36.

Southwood T R E (1978) Ecological methods. 2d ed. Methuen. London. 524 p.

Strandberg J (1973) Spatial distribution of cabbage black rot and the estimation of diseased plant populations. Phytopathology 63:998-1003.

Taylor J (1961) Aggregation, variance and the mean. Nature 189:732-735.

Taylor J (1984) Assessing and interpreting the spatial distribution of insect population. Annu. Rev. Entomol. 29:321-357.

Teng P S (1983) Assessing and interpreting disease intensity and loss in commercial fields. Phytopathology 73:1587-1590.

Teng P S, Ferrer E R, Fabellar N G (1988) Epidemiology of the rice tungro virus (RTV). (unpubl.)

Thal W M, Campbell C L (1986) Spatial pattern analysis of disease seventy data for alfalfa leaf spot caused primarily by *Leptosphaerulina briosiana. Phytopathology* 76:190-194.

Tomasino S F, Conway K E (1987) Spatial pattern, inoculum density-disease incidence relationship and population dynamics of *Sclerotium rolfsii* on apple rootstock. Am. Phytopathol. Soc. 71:719-724.

Wald A (1945) Sequential tests of statistical hypothesis. Ann. Math. Stat. 16:117-186.

Waters W E (1955) Sequential sampling in forest insect survey. For. Sci. 1:68-79.

Zhong S J (1986) Studies on the spatial pattern of striped stemborer *Chilo suppressalis* Walker and damage rice stem in paddy fields. Pages 57-61 *in* 2nd international conference on plant protection in the tropics. Colorcom Grafix System, SDN BHD. Kuala Lumpur, Malaysia.

## Notes

*Authors' addresses:* B. M. Shepard and E. R. Ferrer, International Rice Research Institute, P.O. Box 933, Manila, Philippines (Present address: B. M. Shepard, College of Agricultural Sciences, Coastal Research and Education Center, 2865 Savannah Highway. Charleston, South Carolina 29407; E. R. Ferrer, Clemson University, South Carolina 29631, USA).

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Empirical models for predicting yield loss caused by stem borers

P. T. Walker

The lepidopterous stem borers of cereals and sugarcane are a distinct type of insect pest that has been intensively studied (Jepson 1954). They occupy a similar environment and their population and damage are often assessed in similar ways. Their effects on crop growth and yield may also be similar. Their habit and effect on crop yield often resemble those of other borers such as the dipterous larvae, *Diopsis, Atherigona* sorghum shootfly, *Hydrellia* rice whorl maggot, *Delia* barley fly, etc. Some beetle and hymenopterous sawfly larvae also live in the stems of some crops.

Common plant hosts are cereals, particularly rice (including deepwater rice), maize, and wheat. Millets, tef, etc., also are attacked. Beetle and moth larvae attack tree and shrub crops such as tea, coffee, fruit, etc.

They are usually less mobile and live longer than many crop pests. Because of their protected habitat, their population and damage often are easier to assess. Several models of the relationship between infestation and crop yield have been developed (Walker 1983).

## Population and damage assessment

To develop a relationship between infestation and yield from which to predict yields or losses, some measure of the amount of infestation of damage must be made (Singh and Khosla 1983).

### Direct assessment

The number of egg batches, larvae, and pupae per unit of stem, internode, tiller, etc. or per hill or clump of plants is usually counted or expressed as percent incidence. Area of ground is a better base unit than per plot or length of row, unless these can be converted to population of pests per square meter. Number of tillers, stems, etc. per square meter should be known. Ratings or grades of population are sometimes used, but may give less information. Separate counts of live or active insects and dead insects or emerged pupa cases are needed to give a measure of total attack. Amount of parasitization may be important in studies on yield.

Adults may be caught in light, pheromone, color, or other types of traps. The number caught often gives a good indication of the actual population of insects present, but it is difficult to relate these numbers to crop damage and yield because of many intervening variables. Pheromone trap catches are being used to predict the need for measures to control cereal stem borer populations that have an established relationship to yield.

### Indirect or damage assessment

The plants, tillers, earheads, grains, etc. attacked are often counted, as numbers of discolored leaf sheaths (Koyama 1975), deadhearts (dead core stems), whiteheads, etc. These counts are easier and cheaper than counting insects. Other measures that can be related to pest population are number or length of tunnels or bores or number of exit holes in the stem.

The usefulness of damage counts in modeling infestation-yield can be found by looking at the significance of a regression of yield on the measure. If the regression is poor, the measure is of little use. Also the relationship between the indicator (say, borer tunnel length) and yield may not be linear. In addition. it may he difficult to compare measures taken in different growing conditions.

The effect of missing plants or tillers destroyed by pests (Calora et al 1968) should be considered when relating infestation to yield. Comparison with the original plant stand or with uninfested check plots will be necessary. Formulae are available that take into account the number of infested and uninfested tillers and hills (FAO 1979, Gomez 1972).

### Relationship between assessment methods

Because pest assessment methods depend on different actions of insects on the crop (for example, destruction of leaf area, the growing point, or part of the stem), the relationship between the measure and the pest population, and hence the relationship to crop yield, will vary widely. As reviewed by Walker (1981), they include the relationships between percent rice hills and percent tillers attacked by rice stem borers, ratings of maize leaf attack, and plant attack by *Chilo partellus* (which Kalode and Pant [1966] found to be linear), the curved relationship between the number of *Ostrinia nubilalis* corn borer and the percent of plants bearing eggs (Chiang and Hodson 1959) and the percent sugarcane stems and nodes bored by *Diatraea saccharalis* sugarcane borer (Ruinard 1971).

If one of the measures is finite, such as percent stems bored, and the other infinite, such as number of larvae per square meter, the relationship would be expected to be curved, unless only a limited range of values is examined.

## Methods of yield loss assessment

### Natural infestations

The relationship between infestation and yield is often found by surveying natural infestation and measuring yields over a range of infestation or damage levels. In India, Kishen et al (1970) used natural infestations of maize by *Chilo partellus,* in Brazil, Graça (1976) estimated losses in sugar caused by the borer *Diatraea saccharalis.* Ho et al (1983) measured losses in rice in Kenya due to *Maliarpha separatella.*

### Pesticides

Insecticides often are used to establish a range of infestation levels on experimental plots (for example, trials on losses of maize caused by the stem borer *Busseola fusca* in Tanznia and Kenya [Walker 1960]). Surveys of losses in deepwater rice caused by *Scirpophaga* in Bangladesh (Catling et al 1978) used plots where half had been treated with insecticide and half untreated. Mathes et al (1965) also used insecticides to measure losses in sugarcane caused by *Diatraea* stem borer in Southern USA.

### Artificial infestation

Stem borer eggs can be removed from leaves or from under leaf sheaths to vary infestation levels. Levels can be established by infestation with eggs or egg batches (as in studies of maize losses due to *Busseola fusca* in Ethiopia [Tchekmenev 1981] and *Ostrinia nubilasis* in the USA [Lynch 1980]). In Madagascar, rice was artificially infested with *Maliarpha* eggs by Brenière (1982) and with larvae by Appert (1970). Catling et al (1987) used five different methods in Bangladesh and Thailand to relate infestation of deepwater rice by *Scirpophaga incertulas* to yield.

### Simulated damage

Imitating insect damage artificially has some advantages, but it is difficult to imitate accurately the amount, time, and position of borer attack. A rice crop can be compensated for the loss of plants or tillers (Gomez 1972). Than et a1 ( 1976) simulated deadhearts and whiteheads caused by stem borer in rice, and Chiang (1964) attempted to make artificial tunnels in maize stems to imitate *Ostrinia* attack. Loss of leaf area is seldom an important cause of yield loss to stem borers.

### Susceptible and resistant varieties

Yields of a number of maize varieties were compared by Patch et al (1942) in regressions of yield on infestation by the stem borer *Ostrinia* in the USA. Van Halteren (1979) examined yields of varieties of rice attacked by *Scirpophaga* in Indonesia. Models for the effect of the internode stem borer on yield of different varieties of sugarcane in India were studied by Avasthy and Krishnamurthy (1968) to obtain relationships between amount of attack and yield.

## Yield prediction models

The type of model developed, its simplicity or complexity, how many factors it includes, and how accurate or useful it will be in predicting yields depend on the data; the funds, manpower, and technical expertise available: and the purpose for which the model is developed. The model may be to simply find what crop yield to expect from a narrow range of infestation rates on a small farm. It may be to estimate crop production over a wide area, using data from a survey of infestation rates. It may be designed to estimate the proportions of yield loss due to a number of interacting causes, such as various pests or diseases, and to assess their significance and interaction. A model may be improved by the inclusion of terms for climate, crop variety, type of farming, and such economic data as farm inputs, crop price, etc.

## Linear models

If great accuracy is not needed, a simple negative linear regression may be adequate to relate yield ($y$) to infestation rate ($i$) over a limited range. No account is taken of a level of infestation under which no loss occurs. In trials in Ethiopia, Tchekmenev (1981) found yield of maize per plant was related to number of 1st-instar *Busseola fusca* stem borer larvae per plant by

$$y = 43.6 - 6.62\,i \quad (r = 0.96)$$

This is equivalent to 15% loss per larva per plant. and compares with rates of loss found elsewhere. It can be varied with growing conditions and used to estimate regional losses by surveying infestation over the region.

The amount of loss depends on the maximum yield in the absence of attack, the point on the $y$ axis at $i = 0$. There will be different regression lines. and hence different rates of loss, for different types of farming. Walker (1960) found the following linear regressions for maize stem borer *Busseola* infestations in Tanzania, with $i$ being the percentage of plants attacked, transformed to angles:

$$y = 45.1 - 0.55\,i \text{ (high-yielding crop)}$$

$$y = 14.5 - 0.22\,i \text{ (low-yielding crop)}$$

In Kenya, Ho et al (1983) fitted regressions of rice grain weight and such components of yield as percent empty grains ($y$), plant height, tiller number, and 1,000-grain weight, on percent tiller infestation by borer *Maliarpha separatella* and stem tunnel length ($i$)

$$y = 1.03 + 0.434 \text{ i (variety Sindano)}$$

$$y = 7.91 + 0.402 \text{ i (variety IR579-48-6)}$$

Age of the crop when infested may produce different regressions, as Sarup et al (1977) and Panwar and Sarup (1979) found for the number of eggs of *Chilopartellus* per maize plant in India.

$$y = 0.21 - 0.009\,i \text{ (plants attacked at 16 d old)}$$

$$y = 0.19 - 0.005\,i \text{ (plants attacked at 17 d old)}$$

$$y = 0.50 - 0.01\,i \text{ (plants attacked at 25 d old)}$$

These regressions indicate that plant susceptibility to attack varies with age; 17-d-old plants were the most tolerant, allowing a higher economic threshold for pests at that crop age.

In more recent work on *Chilopartellus* infestations and yields on maize in India, Sharma and Sharma (1987) published linear regression coefficients for the four different crop growth stages they used in developing economic injury levels.

In Japan, Koyama (1975) studied economic injury levels for rice borer *Chilo suppressalis*. He related percentage of deadhearts due to borer ($D$) that cause yield loss, to percentage of stems with discolored leaf sheaths ($L$), using the linear expression

$$D = 0.229 + 0.409\,L$$

## Sigmoid relationships

Good reasons for using anonlinear form to express relationships have been given. The sigmoid curve can be satisfactorily explained biologically. Rate of loss, or slope of the curve ($y/i$), varies with infestation rate. Usua (1968) found a sigmoid relationship between yield and infestation by *Busseola* in maize in Nigeria. Using tunnel length as a measure of borer attack, Chatterji (1968) found the upper, concave downward part of the curve for maize attacked by Chilopartellus in India, and Atwal et al (1970) found the lower, concave upward part of the curve.

Sigmoid relationships are difficult to express mathematically, although it is possible. A straight line generalization is sometimes used if great accuracy is not needed.

## Logarithmic or power functions

The relationship between yield and infestation is sometimes better fitted by a logarithmic transformation of $i$, depending on the form of the frequency distribution of the data. Catling et al (1978) found that percent deadhearts ($i$) caused by rice stem borer *Scirpophaga incertulas* was related to rice yields ($y$) in Bangladesh by

$$y = 100 - 11.6 \log i$$

## Multifactorial regression

Where more than one cause of yield reduction can be identified and measured, a multifactorial regression of yield ($y$) on the various factors ($i_1$, $i_2 ... i_n$) can be developed, and their significance and interaction quantified. Those factors not contributing significantly to the regression can be omitted and their variance added to the residual. On rice in India, Abraham and Khosla (1967) found that percent whiteheads ($i_1$) caused by borer, percent infested earheads ($i_4$), and *Helminthospore* disease incidence ($i_2$) were significant.

$$y = 3655 - 40.3\ i_1 - 32.2\ i_4 - 303.8\ i_s$$

From this model, an avoidable loss of 204 kg/ha +/ - 32 (SE) was calculated. After deducting costs, a net return of 76 + /- 22 rupees/ha was obtained.

Other factors that affect yields, such as the position of attack in the stem, the generation of the borer, or the different kinds of damage, can be incorporated into the model. For *Diatraea* sugarcane borer in the USA, McGuire et al (1965) related crop yield to percent joints bored ($i_1$) and to position of attack in the canes ($i_2$) by

$$y = 2.7 - 0.01\ i_1 + 0.06\ i_2$$

In Zimbabwe, Rose (1976), quoting Wall, found that attack by stem borer *Busseola fusca* on maize caused 43% yieldreduction after stalk attack only, 13% after leaf attack, and 49% after both leaf and stalk attack. Attack on cobs by second-generation borers caused only 10% yield reduction. In the USA, Chiang et al (in Chiarappa 1971) divided loss in maize due to *Ostrinia nubilalis* corn borer into loss in ear weight ($A$) and waste at harvest due to stalk breakage ($B$). Taking ($n_1$, $n_2$, $n_3$) as the number of 2d-generation larvae in the first three nodes of the stem, ($N$) as percent stem breakage, ($z$) as percent machine harvestable, and ($t$) as effect of weathering:

$$A = an_1 + bn_2 + cn_3 \qquad B = N(z + t)$$

**Polynomial models**

Most relationships can be fitted by a polynomial expression by partitioning the variance into linear, quadratic, cubic, or even higher power components (although this is seldom necessary). Ishikura (1967) related rice yield ($y$) in Japan to percent stems infested by borers per hill ($i$) by the expression

$$y = 100 - \mathrm{ai} - \mathrm{bi}^2$$

Takagi et al (1958) related rice grain yield ($y$) to percent of rice stems injured by *C. suppressalis* ($i$) by

$$y = 100 - 0.097\, i - 0.0059\, i^2$$

In the USA, Lynch (1980) found linear, quadratic, and cubic components in the relationship between maize yield and number of egg masses per plant of the European corn borer *Ostrinia.* The model varied with variety, time of infestation, place, and year. Rate of loss varied as infestation increased.

The spatial distribution of an attack is important in deciding the form of the regression equation. Lynch (1980) infested maize plants with *Ostrinia* eggs in a Poisson distribution to make his study as representative of natural field conditions as possible.

## Conclusion

Once a model has been developed, it may be used to forecast yields from infestation rates, and hence the effects of different pest management options. Pimentel and Shoemaker (1974) used a linear model that included maize stem borer control to predict the effects of not using pesticides on crop yields, prices, and land cropping area. Models can be expanded to include the effects of temperature on pest development (as Anderson et al [1982] did for *Ostrinia* borer in the USA) or the effect of the amount or time of rainfall (as in the multifactorial regression of sorghum infestation by *Chilo partellus* on weather factors by Mahadevan and Chelliah [1986] in India). Number of borers in the previous generation has been used in models developed for *Ostrinia* in Canada. If economic factors are included (for example, in the models developed for soybean and peanut production), a complete production model for a crop becomes possible.

We have said that the final form of a model is often a compromise between complexity, which may give greater accuracy, and simplicity, which will allow wider applicability. There is also a compromise between what is desirable and what is possible in terms of cost, labor, and expertise.

## References cited

Abraham T P, Khosla R K (1967) Assessment of losses due to incidence of pests and diseases on rice. J. Indian Agric. Stat. 19:69-82.

Anderson T E, Kennedy G G, Stinner R E (1982) Temperature dependent models of European corn borer developed in North Carolina. J. Econ. Entomol. 11:1145-1150.

Appert J (1970) *Maliarpha separatella:* observations nouvellee et rappel des problems entomologiques du riz á Madagascar. Agron. Trop. 25:329-367.

Atwal A S, Chahal B S, Ramzan M (1970) Insecticidal control of the maize borer, *Chilo zonellus*. Indian J. Agric. Sci. 40:110-116.

Avasthy P N, Krishnamurthy T N (1968) Distribution and sampling of sugarcane internode borer. Proc. 13th Int. Soc. Sugar Cane Technol. Taiwan: 1285.

Breniere J (1982) Estimation des pertes dues aux ravageurs du riz en Afrique de I'Ouest. Entomophaga 27:71-80.

Calora F B, Ferino M P, Glass E H, Abalos R S (1968) Systemic granular insecticides against rice stem borers, with consideration of the pattern and characteristics of the infestation. Philipp. Entomol. 1:54-56.

Catling H D, Alam S, Miah S A (1978) Assessing losses in rice to insects and diseases in Bangladesh. Exp. Agric. 14:277-287.

Catling H D, Islam Z, Pattrasudhi R (1987) Assessing yield losses in deepwater rice due to yellow stem borer, *Scirpophaga incertulas* in Bangladesh and Thailand. Crop Prot. 6:20-27.

Chatrerji S M (1968) Research on insect pests of maize, with special reference to stalk borers. Annu. Rep. Indian Agric. Res. Inst. 1967-1968.

Chiang H C (1964) The effects of feeding site on the interaction of the European corn borer, *Ostrinia nubilalis* and its host, the field corn. Entomol. Exp. Appl. 7:144-148.

Chiang H C, Hodson A C (1959) Distribution of 1st generation egg masses of European corn borer in corn fields. J. Econ. Entomol. 52:295-299.

Chiarappa L, ed. (1971) Crop loss assessment methods: FAO manual. Food and Agriculture Organization and Commonwealth Agricultural Bureaux-International. Wallingford. Oxford, UK.

FAO — Food and Agriculture Organization (1979) Guidelines for integrated control of rice insect pests. Plant Prod. Prot. Pap. 13. Rome. 115 p.

Gomez K A (1972) Techniques for field experiments with rice. International Rice Research Institute. P.O. Box 933, Manila, Philippines. 46 p.

Grap L R (1976) Estimativa econômica dos prejulzos causados pelo complexo broca-prodri-doñes na cana-de-açucar no Brasil. Brasil Açucareiro 88:12-34.

Ho Dang Thanh, Njokah J J, Kibuka J G (1983) Studies on rice stem borers in Kenya with emphasis on *Maliarpha separatella* Rag. Ins. Sci. Appl. 4:65-73.

lshikura H ( 1967) Assessment of rice loss caused by the rice stem borer. Pages 251-264 *in* Major insect pests of the rice plant. The Johns Hopkins Press, Baltimore, Maryland, USA.

Jepson W B (1954) A critical review of the world literature on the lepidopterous stalk borers of tropical graminaceous crops. Centro de Investigaciones Economicas/Commonwealth Agricultural Bureaux-International, Wallingford, Oxford. 127 p.

Kalode M P, Pant N C (1966) Studies on the susceptibilities of different varieties of sorghum, maize and bajra to *Chilo zonellus* under field and cage conditions. Indian J. Entomol. 28:448-464.

Kishen K, Sardana M G, Khosla R K, Dhube R C (1970) Field losses caused by pests and diseases in the maize crop. Agric. Situation India 25:591-593.

Koyama J (1975) Studies on the diminution of insecticide application to the rice stem borer, *Chilo suppressalis.* 2. The economic injury level and its predictive estimation. Jpn. J. Appl. Entomol. Zool. 19:63-69.

Lynch R E (1980) European corn borer: yield losses in relation to hybrid and stage of corn development. J. Econ. Entomol. 73:359-164.

Mahadevan N R, Chelliah S (1986) Influence of season and weather factors on the occurrence of the sorghum stem borer, *Chilo partellus* in Tamil Nadu. Trop. Pest Manage. 32:212-214.

Mathes R, Baum R J, Charpentier L J (1965) A method of relating yields of sugar and sugarcane borer damage. Proc. 12th Int. Soc. Sugarcane Technol. 1388-1396.

McGuire J U, Mathes R, Charpentier L J (1965) Sugarcane yields affected by borer infestation and position of injury in the stalk. Proc. 12th Int. Soc. Sugar Cane Technol. 1368-1396.

Panwar V P S, Sarup P (1979) Relationship between successive dates of sowing maize and damage caused by *Chilo partellus* affecting grain yield. J. Entomol. Res. 3:9-24.

Patch L H, Still G W, Schlosberg M, Bottger G T (1942) Factors determining the reduction in yield of field corn by the European corn borer. J. Agric. Res. 65:473-482.

Pimentel D, Shoemaker C (1974) Economic and land use model for reducing insecticides on cotton and corn. Environ. Entomol. 3:3-20.

Rose D J W (1 976) The relation between maize pests and crop loss. Rhodesia Agric. J. 73: 139.

Ruinard J (1971) Nature and assessment of losses caused by sugarcane borers. Entomophaga 16:175-183.

Sarup P, Sharma V K, Panwar V P S, Siddiqi K H, Marwaha K K, Agarwal K N (1977) Economic threshold of *Chilo partellus* infesting maize crop. J. Entomol. Res. 1:92-99.

Sharma A N, Sharma V K (1987) Studies on the economic injury level in maize to stem borer, *Chilo partellus* in India. Trop. Pest Manage. 33:44-51.

Singh D, Khosla R K (1983) Assessment and collection of data on pre-harvest food grain losses due to pests and diseases. Economic and Social Development Paper 28. Food and Agriculture Organization. Rome. 127 p.

Takagi S, Sugino T, Nishino M (1958) Reexaminations on injury in the second generation of rice stem borer. Bull. Shizuoka Agric. Exp. Stn. 3:23-35.

Tchekmenev S Y (1981) The effect of the maize stalk borer, *Busseola fusca* on maize growth, percentage of broken panicles, and yield of maize. Beitr. Trop. Landwirt. Vet. 19:91-95.

Than Htun, Arida G, Dyck V A (1976) Population dynamics of the yellow rice borer, *Tryporyza incertulas* and its damage to the rice plant. International Rice Research Institute, P.O. Box 933, Manila, Philippines. (mimeo.)

Usua E J (1968) Effect of varying populations of *Busseola fusca* larvae on growth and yield of maize. J. Econ. Entomol. 61:375-376.

Van Halteren P (1979) The insect pest complex in South Sulawesi. Indonesia. Meded. 305, Lab. Entomol. Landbouwhogesch. Wageningen 79:33-47.

Walker P T (1960) The relation between infestation by the maize stalk borer, *Busseola fusca* and yield of maize in East Africa. Ann. Appl. Biol. 48:780-786.

Walker P T (1981) The relation between infestation by lepidopterous stem borers and yield in maize: methods and results. Eur. Plant Prot. Org. Bull. 11:101-106.

Walker P T (1983) Crop losses: the need to quantify the effects of pests. diseases and weeds on agricultural production: a review. Agric. Ecosyst. Environ. 9:119-158.

## Notes

*Author's address:* P. T. Walker, 10 Cambridge Road, Salisbury. Wiltshire SP1 3BW, United Kingdom.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Generating plant disease epidemics in yield loss experiments

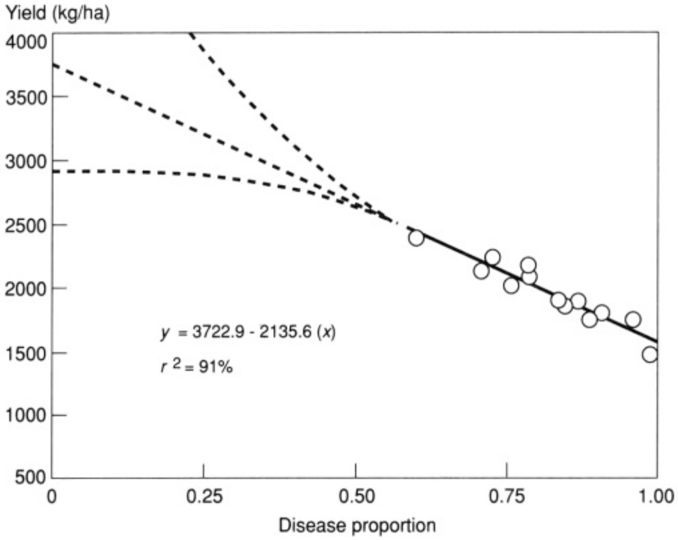
F. W. Nutter, Jr.

The efficient application of any disease management program hinges on having accurate and precise information on disease intensity and on the relationship between disease intensity ($x$) and yield loss ($y$). But a farmer's decision to use a disease management strategy is often influenced by his perception of this relationship. If he is risk averse, he may perceive that $x$ causes a greater loss in $y$ than will actually occur. The time and resources he uses to apply disease control technologies are spent to provide insurance against crop loss rather than to manage pests to optimize net returns. If the farmer is profit maximizing, he must choose carefully whether to use his limited resources only to buy certified seed and fertilizer or to also include expenditure for pest control.

Rational decisionmaking demands a detailed cost-benefit analysis of crop protection tactics (Waibel 1986). Because farmers tend to overestimate crop losses caused by diseases, it is essential to accurately quantify the relationship between disease intensity and yield loss. The establishment of approximate damage coefficients relating disease intensity to yield loss, coupled with reliable disease assessments at the farm level, will enable the farmer to make more realistic disease control decisions (James 1974).

Teng (1985) noted that linear regression models appear valid for a large portion of the disease-loss relationship, but the linear range needs to be determined experimentally. To elucidate the relationship between disease intensity and yield loss, not only must disease be measured accurately but a wide range of disease (stress) intensities are needed to appropriately utilize the power of ordinary least-squares regression.

More often than researchers care to admit, regression models are based on a rather limited range of pest intensity levels. This may be cause for concern when these models are used to help make pest management decisions. For example, Figure 1 shows the relationship between the proportion of infected plant tissue and yield (kg/ha) for a barley cultivar susceptible to spot blotch caused by *Cochliobolus sativus.* Disease levels ($x$) range between 0.60 and 0.96. According to regression theory, the model can be used to estimate yield ($y$) based on values of $x$. However, this model is only valid for values of $x$ in the range of 0.60 to 0.96 (solid line). Predicting yield response at a disease level of 0.3 would be extrapolating beyond the range of data for which the model was developed (dashed lines).

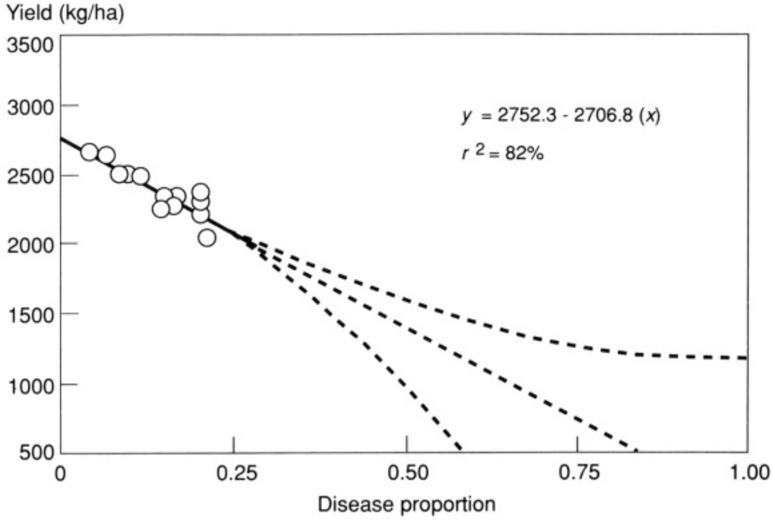


**1.** Relationship between disease proportion *x* and yield *y* (kg/ha) on spot blotch-susceptible barley variety Larker. Spot blotch was assessed at dough stage. Solid line (—) indicates range in which values of *x* can be used to predict yield response (*y*). Dashed lines (- - -) represent theoretical relationships between *x* and *y* not observed in the experiment).

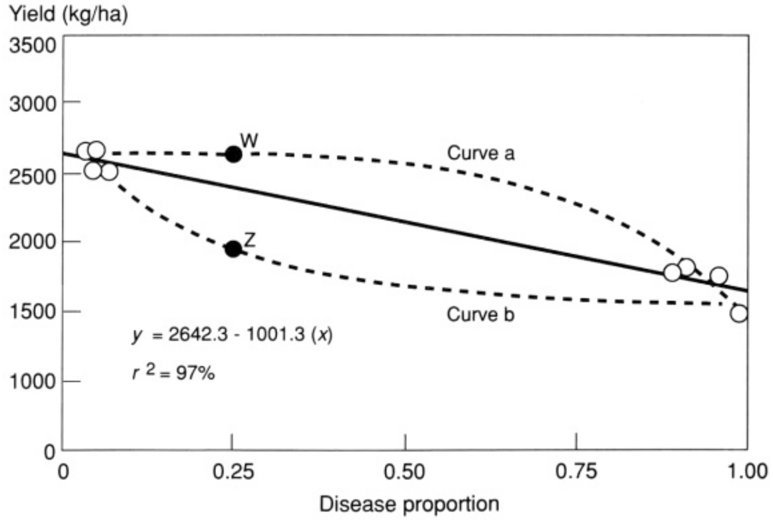
Extrapolation is a dangerous practice because pest intensity and yield reduction sometimes may be related in a nonlinear fashion (Madden et al 1981). Figure 2 shows the relationship between disease level and yield for a barley cultivar resistant to spot blotch. Here the value of the stimulus $x$ ranges from 0.04 to 0.21. Again, for disease values greater than 0.21, yield response cannot be predicted because the relationship cannot be assumed to remain linear for values above 0.21.

To characterize disease intensity-yield loss relationships, the researcher must aim not only for a wide range of pest levels, but also for an adequate number of levels. Computing yield loss by simply comparing yields from treated plots and from nontreated control plots, no matter how well replicated, often is inadequate for approximating damage coefficients. Teng (1985) has proposed that more treatments be used, to the point of little or no replication, in order to explore as many points on the disease stimulus-yield response curve as possible.

Figure 3 shows the relationship between disease assessed at the dough stage and yield when barley spot blotch is reduced to low population levels using protectant fungicides, compared with plots inoculated with *C. sativus* spores at the early boot stage of barley development. Although there is a wide range in the levels used to produce the regression line, $x$ values between 0.04 and 0.88 are lacking. Actual stimulus ($x$)-response ($y$) values in this range may not necessarily fall on the predicted (solid) regression line. Response curves a or b also are possible, but there are not enough stress levels at appropriate intervals over the entire range to characterize the



**2.** Relationship between disease proportion $x$ and yield $y$ (kg/ha) on spot biotch-resistant barley variety Dickson when spot blotch was assessed at the dough stage. Solid line (—) indicates range in which values of $x$ can be used to predict yield response $y$. Dashed lines (- - -) represent theoretical relationships between $x$ and $y$ (not observed in the experiment).



**3.** Regression of disease proportion $x$ and yield $y$ (kg/ha) from plots of Larker barley treated with fungicide versus plots inoculated with spores of *Cocchiobolus sativus.* Solid line (—) and dashed lines (---) represent possible response curves for values of $x$ and $y$ when fungicide-treated versus nonsprayed treatments are used to generate estimates of $y$ on $x$.

true disease-loss relationship. A disease level of 0.25 (point W) on curve a may not require control because the damage threshold has not been exceeded. whereas a disease level of 0.25 on curve b (point Z) is well past the damage threshold, with yield already reduced by more than 700 kg/ha.

Disease-loss relationships are essentially stress-response models. Levitt (1972) defined stress as any potentially injurious biotic or abiotic environmental factor. Plant disease stress can be measured by determining disease intensity and response can be quantified by measuring yield and/or one of its components. It is not easy to obtain a range of disease intensities, but the probability of obtaining the required range of disease levels is greatly improved when epidemiological principles are used.

## Generating disease epidemics

Model selection is extremely important. The biology of the pathogen must be considered and a pathogen growth model that best describes a given disease should be chosen. The dynamics of pathogen growth may vary considerably, but two general models proposed by Van der Plank (1963) are useful in identifying the most efficient strategies to use in generating different disease intensities.

In the first model, the amount of disease at the end of the growing season is related to the amount of inoculum present at the start of the season. This model has been termed the *monomolecular* model, because of the analogy to monomolecular chemical reactions of the first order, or the *simple interest* model, because disease increases in a fashion similar to money invested at a simple interest rate of return. The model can be written as

$$dy/dt = IR(1 - y) \text{ (model 1)}$$

The absolute rate of increase in disease ($y$) with time ($t$) is proportional to the amount of inoculum present at the beginning of the season ($I$), the efficacy of the inoculum ($R$), and the proportion of diseased tissue or plants ($y$) subtracted from the maximum level of disease (1.0). It is possible to influence $dy/dt$, and thus the amount of disease present at the end of the season, by manipulating $I$ and/or $R$. Different sanitation practices could be used to affect $I$; chemicals or biocontrol agents could be used to affect $I$ and/or $R$.

In the second model, absolute rate of increase ($dy/dt$) is related to the current level of disease ($y$), the apparent rate of increase during the season ($r$), and the proportion of healthy tissue or plant units not yet infected ($1 - y$). Because two or more pathogen disease cycles occur within the same season, Van der Plank referred to this situation as analogous to money that earns compound interest. The model is written as

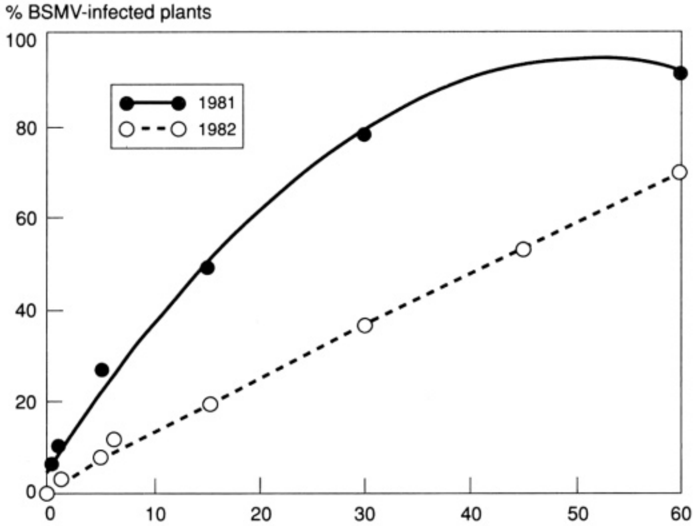
$$dy/dt = ry(1 - y) \text{ (model 2)}$$

Because the objective is to generate a wide range of disease intensity levels at one or more points during the growing season ($t$), we can use this model most effectively if we have estimates of $r$ and $y$.

For example, if the pathogen has a high apparent infection rate ($r$), as with late leaf spot of peanut *Cercosporidium personatum,* then, according to Table 1, we can best

**Table 1. Theoretical effect of changes in initial level of disease (*y*) or rate of infection (*r*) on absolute rate of infection (*dy/dt*).**

| when *r* is: | Effect of change in *y* on *dy/dt* | Effect of change in *r* on *dy/dt* |
|---|---|---|
| High | small | large |
| Low | large | small |



**4.** Relationship between percent barley stripe mosaic virus-infected (BSMV) seed planted and percentage of plants Infected with BSMV at harvest. Fargo, North Dakota. 1981 and 1982.

generate a range of disease intensities by using a control tactic that affects *r* rather than *y*. Nutter (1986b) used different active ingredient concentrations of the fungicide chlorothalonil to differentially reduce *r*, thereby obtaining a range of disease incidence and defoliation values. He used the ranges to model pod losses due to late leaf spot in peanut. Fry (1977) pointed out that in some pathosystems, more pesticide may be needed to reduce high pathogen population levels than to reduce low pathogen populations (i.e. the relationship between pesticide concentration and the reduction of pathogen populations is not necessarily linear).

For pathogens with a low apparent infection rate, it is more efficient to use tactics that affect *y* to generate a range of discrete levels of pathogen stress. Nutteret al (1984) used this principle to study the amount of yield reduction in barley caused by barley stripe mosaic virus (BSMV). An initial seed lot determined to have 64% seed infected by BSMV was blended with healthy seed to establish seed lots with known levels of BSMV-infected seed (0, 0.1, 1, 5, 15, 45, and 60%). The seeds were planted in replicated plots in 1981 and 1982. Since r was constant across seed infection levels and independent of $y$, different proportions of the barley crop were diseased at harvest (Fig. 4). The relationship between level of seed infection and yield was determined using least-squares regression.

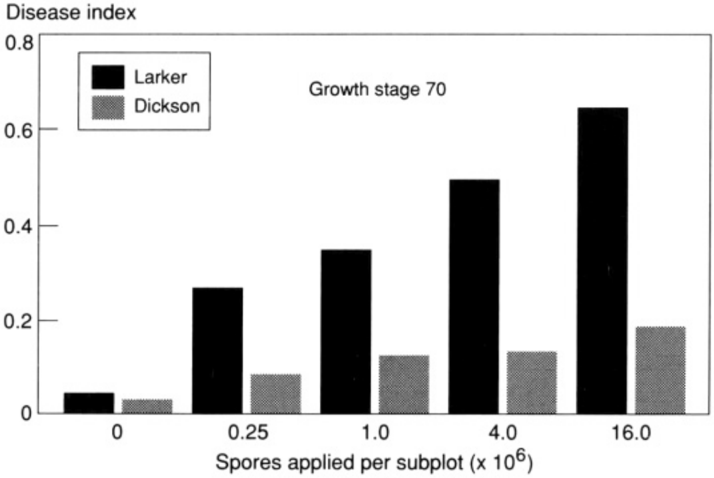
## Using control tactics to affect *I, R, r, y,* and *t*

After a model is chosen and the parameters that must be manipulated to generate a range of discrete levels of disease intensity identified, consideration is given to the specific disease control tactic(s) that will be used to differentially affect $I$ and/or $R$, for simple interest diseases, and $r$, $y$, and/or $t$, for compound interest diseases.

### Varying the effectiveness of initial inoculum

If the pathogen is completely lacking and $r$ is low, different pathogen population levels can be introduced to obtain a range of disease intensities. Nutter et a1 (1985) used this technique to establish a range of disease levels of spot blotch *Cochliobolus sativus* in barley. Figure 5 shows five levels of pathogen stress obtained by inoculating field plots of barley with different numbers of *C. sativus* spores. A fourfold increase from one inoculum level to the next resulted in a linear increase in disease on the susceptible cultivar Larker. Disease also increased linearly on the resistant cultivar Dickson, but the increase for each level was much smaller. That indicated that more spores are needed on Dickson plots than on Larker to obtain similar disease levels.

Niblack et al (1986) used this approach to quantify losses in soybean caused by *Meloidogyne incognita.* They established a range of initial nematode population densities in fumigated field microplots. Slinkard and Elliott ( 1954) quantified the relationship between incidence of wheat bunt and yield loss by mixing a susceptible



**5.** Effect of number of *Cochliobolus sativus* spores applied to plots of Larker (susceptible) and Dickson (resistant) barleys on amount of spot blotch present at the milk stage (GS 70). Plots inoculated at early boot stage.

wheat variety witharesistant backcross derivative in 10% increments, then inoculating the mixtures with a bunt race compatible with the susceptible component. Other researchers have introduced known quantities of foliar or soil-borne pathogens (sclerotia, oospores) into field soils to quantify inoculum density-yield loss relationships (Ali et al 1987, Carson 1985, Eyal and Ziv 1974).

Different levels of *I* can be achieved by taking advantage of differences in inoculum density within infected fields, thereby eliminating the need to artificially introduce pathogen propagules. Pataky et a1 (1983) assayed fields infested with microsclerotia of *Cylindrocladium crotalariae* and stratified the fields into 20 or 21 blocks. He was able to use the different blocks to determine the relationship between inoculum density and pod yield of two peanut cultivars. The procedure of stratifying fields is similar to the concept of *pest zoning* on a regional scale proposed by P. S. Teng (pers. comm.).

Methods to introduce a pathogen have one major drawback; the pattern in which inoculum is introduced may not be typical of natural occurrence. Spraying spores onto plots may result in a pathogen population distributed in a regular pattern, as opposed to a random or aggregated pattern. A random pattern may allow for some yield compensation by neighboring healthy plants, while aggregations of infected plants or pathogen populations may not allow for compensation (James et a1 1973). When all plants within an experimental plot are diseased to nearly the same degree, yield compensation may not be possible, and the resulting yield loss equation may overestimate actual losses.

When different levels of seed infection or infestation are used to create a range of epidemics, the spatial distribution of the pathogen usually is not a problem. Infected or infested seed will be randomly distributed in the field, as is normal with these pathogens (Schaad et a1 1980).

## Sanitation to reduce initial inoculum levels

Several methods based on sanitation have been used to reduce initial levels of inoculum. These methods best generate a range of different disease intensity levels when *r* is low. Crop rotations can result in different initial pathogen population levels (Kinloch 1983). This is particularly true of several soil-borne disease and nematode pathosystems (Castillo et a1 1978, Mai and Abawi 1980, Slope and Etheridge 1971). Biocontrol agents may be used to reduce the effectiveness of initial inoculum (*R*) by outcompeting the pathogen population for space and/or food (Smith et al 1986). Initial levels of inoculum *(I)* also may bereduced by direct parasitization by biocontrol agents (Cook and Baker 1983).

Burning or removing crop residue, deep plowing, conservation tillage, and minimum tillage may be used to suppress the amount of inoculum available to start an epidemic. Conversely, pathogen-infested crop residues may be collected, stored, and placed back in the field in different quantities to establish different levels of inoculum (Gilbertson et a1 1988). Fertilizers and pesticides also may be used to increase or decrease the effectiveness of inoculum (*R*) (Reddy et a1 1979a).

## Spreader rows

The spreader row method involves planting susceptible crops in rows parallel or perpendicular to experimental units to provide a uniform source of inoculum throughout the experimental area. Experimental units may then be treated with different chemicals or different active ingredient concentrations of pesticides to establish different disease intensity levels (Nutter 1986a, Teng et al 1979). The spreader row approach usually is used where the pathogen infection rate $r$ is high and interplot interference is a hazard. Spreader rows may have an advantage in that the inoculum produced results in what I call *uniform interplot interference.* All plots receive a large influx of spores, whether or not additional spores are produced within some plots and few or none are produced in others (Nutter and MacHardy 1981). Zadoks and Schein (1979) refer to this as tough testing. When effective methods to reduce $r$ are available, spreader rows can be coupled with them to produce a range of disease intensity levels (Schneider et al 1976).

## Manipulation of the environment

Environment manipulation usually affects $r$. Rotem et al (1970) used different irrigation schedules in Israel to affect $r$, thereby obtaining different epidemics of potato late blight. Mathur et al (1964) used ammonium sulfate fertilizer and irrigation early in the rice growing season to establish different levels of rice blast. Reddy et al (1979a) used different nitrogen levels to obtain different epidemics of bacterial leaf blight in rice. Cole et al (1982) designed and built rain shelters mounted on tracks to obtain a range of moisture stress levels that favored or hindered the development of aflatoxin in peanuts.

## Fungicides

Fungicides have long been used by researchers to affect $I$, $R$, $Y$, and/or $r$, thereby creating several discrete levels of disease intensity. The majority of these studies used fungicides primarily to affect $r$. Often the pathogen is introduced and the environment manipulated to insure that $y$ is not limiting (Kohls et al 1987, Pataky 1987). Fungicides are then superimposed to differentially reduce $r$. Nutter and Cunfer (unpubl.) inoculated barley plots with *Leptosphaeria nodorum* at the early boot stage, then applied propiconazole (Tilt) at different growth stages to obtain a range of pathogen stress levels. Fungicides applied at specific stages of crop development have been used to study the effects of pathogen populations on specific yield components (Groth et al 1983, Nutter et al 1985). Such studies have helped to identify the critical periods of crop development when disease assessments have the most clear relationship to yield loss (James et al 1968).

## Host resistance

Host resistance can be used to reduce both the effectiveness of inoculum $R$ and the rate of pathogen development $r$ within the host population. Sah and MacKenzie (1987) point out that using different cultivars can cause a great deal of confusion about cause (stress) and effect (yield), since agronomic characteristics among cultivars can be quite diverse. For instance, when pathogen stress results in seed or flower abortion, a wheat cultivar with shorter heads and fewer but larger seeds may not compensate as much as a smaller-seeded wheat cultivar with more seeds per head. The smaller-seeded wheat may compensate for a reduction in seed number by producing larger seeds. The larger-seeded wheat may not have the genetic capability to compensate by producing even larger seeds. In addition, genotype x environment interactions will complicate the situation. Cultivars that differ in resistance to or tolerance for other stresses (drought, insect infestation, etc.) may greatly affect yield potential, distorting the true disease intensity-yield loss relationship.

Only when cultivars respond to increasing pathogen stress levels in the same manner can this method be considered an effective means to produce a wide range of disease intensities (i.e. the slope of the regression equation relating changes in pathogen stress levels to changes in yield is the same). Even then, genotype x environment interactions may still be a problem. Schaller (1963) used a set of near-isogenic lines to quantify yield losses due to scald and mildew. This approach resulted in an all or nothing situation, and the objective of obtaining a range of disease intensity levels was not achieved. A multiline approach, varying the number and proportions of component lines, may provide a useful tool for yield loss research.

## Time of inoculation

The stage of crop development at which a pathogen population is introduced may affect one or more yield components. For example, inoculating barley with *Cochliobolus sativus* at the late boot stage did not affect the number of spikes per unit area, but increasing the inoculum level reduced kernel number per spike and kernel weight. Inoculating at the milk stage reduced kernel weight but not kernel number (Nutter et al 1985). Mikel et al (1981) and Gregory and Ayers (1982) showed that yield loss due to maize dwarf mosaic virus in sweet corn is related to time of inoculation. Reddy et al (1975b) inoculated rice with *Xanthomonas campestris* at four different growth stages to generate different disease progress curves of bacterial leaf blight. They used ordinary least-squares regression to estimate the relationship between bacterial leaf blight severity and rice yield.

Timing inoculation to coincide with specific stages of crop development essentially affects the time different levels of $I$ or $y$ are introduced and how long the pathogen and host populations interact before harvest. Different environmental conditions at the time inoculum is introduced may, however, affect development of the pathogen population. Romig and Calpouzos (1970) created long- and short-duration epidemics of stem rust by manipulating date of inoculation. Young and Ross (1978) inoculated soybean cultivars with *Septoria glycines* at different growth stages to estimate yield loss. Some researchers have used successive inoculations to simulate disease increase over time (Gregory et al 1978). Thus, duration in time ($t$) to harvest that an epidemic is allowed to proceed can be manipulated, without affecting $r$, to obtain different disease intensities.

## Conclusion

Disease management at the farm level demands understanding the disease intensity-yield loss relationship. The methodology used to establish different plant disease epidemics often will dictate the results. It is relatively easy to generate epidemics with progress curves which are not representative of the on-farm situation. As a result, crop losses may be over- or underestimated. Sah and MacKenzie (1987) noted several additional limitations concerning some of the methods discussed.

Still, using epidemiological principles can greatly improve the probability of generating the range of disease intensities needed to improve understanding of disease intensity-yield loss relationships. A better understanding of those relationships will enable researchers to develop more realistic damage coefficients that will aid farmers in making efficient pest management decisions.

## References cited

Ali M E K, Warren H L, Latin R X (1987) Relationship between anthracnose leaf blight and losses in grain yield of sorghum. Plant Dis. 71:803-806.

Carson M L (1985) Epidemiology and yield losses associated with *Alternaria* blight of sunflower. Phytopathology 75:1151-1156.

Castillo M B, Alejar M S, Litsinger J A (1978) Effect of crop rotation on nematode populations in dryland rice-based cropping systems of Batangas, Philippines. Int. Rice Res. Newsl. 3:18-19.

Cole R J, Hill R A, Blankenship F D, Sanders T H, Garren K H (1982) Influence of irrigation and drought stress on invasion by *Aspergillus flavus* of corn kernels and peanut pods. Dev. Ind. Microbiol. 23:229-236.

Cook R J, Baker K F (1983) The nature and practice of biological control of plant pathogens. American Phytopathological Society, St. Paul, Minnesota. 539 p.

Eyal Z, Ziv O (1974) The relationship between epidemics of *Septoria* leaf blotch and yield losses in spring wheat. Phytopathology 64:1385-1389.

Fry W E (1977) Management with chemicals. Pages 213-238 *in* Plant disease: an advanced treatise. Vol. 1. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York. 465 p.

Gilbertson R L, Rand R E, Carlson E, Hagedorn D J (1988) The use of dry-leaf inoculum for establishment of common bacterial blight of beans. Plant Dis. 72:385-389.

Gregory L V, Ayers J E (1 982) Effect of inoculum with maize dwarf mosaic virus at several growth stages on yield of sweet corn. Plant Dis. 66:801-804.

Gregory L V, Ayers J E, Nelson R R (1978) Predicting yield losses in corn from southern corn leaf blight. Phytopathology 68:517-521.

Groth J V, Zeyen R J, Davis D W, Christ B J (1983) Yield and quality losses caused by common rust (*Puccinia sorghi* Schw.) in sweet corn (*Zea mays*) hybrids. Crop Prot. 2:105-111.

James W C (1974) Assessment of plant diseases and losses. Annu. Rev. Phytopathol. 12:27-48.

James W C, Jenkins J E E, Jemmett J L (1968) The relationship between leaf blotch, caused by *Rhynchosporium secalis* and losses in grain yield of spring barley. Ann. Appl. Biol. 62:273-288.

James W C, Lawrence C H, Shih C S (1973) Yield losses due to missing plants in potato crops. Am. Potato J. 50:345-352.

Kinloch R A (1983) Influence of maize rotations on the yield of soybean grown in *Meloidogyne incognita* infested soil. J. Nematol. 15:398-405.

Kohls C L, Percich J A, Huot C M (1987) Wild rice yield losses associated with growth-stage-specific fungal brown spot epidemics. Plant Dis. 71:419-422.

Levitt J (1972) Responses of plants to environmental stresses. Academic Press, New York. 697 p.

Madden L V, Pennypacker S P, Antle C E, Kingsolver C H (1981) A loss model for crops. Phytopathology 71:685-689.

Mai W F, Abawi C S (1980) Influence of crop rotation on spread and density of *Heterodera schachtii* on a commercial vegetable farm in New York. Plant Dis. 64:302-305.

Mathur R S, Rajpai G K, Chaubon L S, Verma S C (1964) Assessment of losses caused by paddy blast. Plant Dis. Rep. 48:711-713.

Mikel M A, D'Arcy C J, Rhodes AH, Ford R E (1981) Yield loss in sweet corn correlated with time of inoculation with maize dwarf mosaic virus. Plant Dis. 65:902-904.

Niblack T L, Hussey R S, Boerma H R (1986) Effects of environments, *Meloidogyne incognita* inoculum levels, and *Glycine max* genotype on root-knot nematode-soybean interactions in field microplots. J. Nematol. 10:43-47.

Nutter F W Jr. (1986a) Inducing plant disease epidemics: theory and practice. Phytopathology 76:1088.

Nutter F W Jr. (1986b) Use of sublethal doses of fungicide to obtain a range of late leafspot epidemics for pod loss studies. Proc. Am. Peanut Res. Ed. Soc. 18:52.

Nutter F W Jr., MacHardy W E (1981) Timing of additional sprays for control of potato early blight (*Alternaria solani*) when following a late blight forecasting spray schedule in New Hampshire. U.S.A. Prot. Ecol. 3:47-54.

Nutter F W Jr., Pederson V C, Foster A E (1985) Effect of inoculations with *Cochliobolus sativus* at specific growth stages on grain yield and quality of malting barley. Crop Sci. 25:933-938.

Nutter F W Jr., Pederson V D, Timian R G (1983) Relationship between seed infection by barley stripe mosaic virus and yield loss. Phytopathology 74:363-366.

Pataky J K (1987) Quantitative relationships between corn yield and rust, *Puccinia sorghi*. Phytopathology 77:1066-1071.

Pataky J K, Beute M K, Wynne J C, Carlson G A (1983) A critical-point yield loss model for *Cylindrocladium* black rot of peanut. Phytopathology 73:1559-1563.

Reddy A P K, Katyal J C, Rouse D I, MacKenzie D R (1979a) Relationship between nitrogen fertilization, bacterial leaf blight severity and yield of rice. Phytopathology 69:970-973.

Reddy A P K, MacKenzie DR, Rouse D I, Rao A V (1979b) Relationship of bacterial leaf blight severity to grain yield of rice. Phytopathology 69:967-969.

Romig R W, Calpouzos L (1970) The relationship between stem rust and loss of spring wheat. Phytopathology 60:1801-1805.

Rotem J, Palti J, Lomas J (1970) Effects of sprinkler irrigation of various times of the day on the development of potato late blight. Phytopathology 60:839-843.

Sah D N, MacKenzie D R (1987) Methods of generating different levels of disease epidemics in loss experiments. Pages 90-96 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, St. Paul, Minnesota.

Schaad N W, Sitterly W R, Humaydan H (1980) Relationship of incidence of seedborne *Xanthomonas campestris* to black rot of crucifers. Plant Dis. 64:91-92.

Schaller C W (1963) The effect of mildew and scald infection on yield and quality of barley. Agron. J. 43:183-188.

Schneider R W, Williams R J, Sinclair T B (1976) *Cercospora* leaf spot of cowpea models for estimating yield loss. Phytopathology 66:384-388.

Slinkard A E, Elliott F C (1954) The effect of bunt incidence on the yield of wheat in Eastern Washington. Agron. J. 46:439-441.

Slope D B, Etheridge J (1971) Grain yield and incidence of take-all (*Ophiobolus graminis* Sacc.) in wheat grown in different crop sequences. Ann. Appl. Biol. 67:13-22.

Smith G S, Hussey R S, Roncadori R W (1986) Penetration and postinfection development of *Meloidogyne incognita* on cotton as affected by *Glomus intaradices* and phosphorus. J. Nematol. 18:429-435.

Teng P S (1985) Construction of predictive models. II. Forecasting crop losses. Pages 178-206 *in* Advances in plant pathology: mathematical modeling of crop disease. D. S. Ingram and P. H. Williams, eds. Academic Press, London.

Teng P S, Close R C, Blackie M J (1979) Comparison of models for estimating yield loss caused by leaf rust (*Puccinia hordei*) on Zephyr barley in New Zealand. Phytopathology 69:1239-1244.

Van der Plank J E (1963) Plant diseases: epidemics and control. Academic Press, New York. 249 p.

Waibel H (1986) The economics of integrated pest management in irrigated rice. Springer-Verlag Press, New York. 196 p.

Young L D, Ross JP (1978) Brown spot development and yield response of soybean inoculated with *Septoria glycines* at various growth stages. Phytopathology 88:8-11.

Zadoks J C, Schein R D (1979) Epidemiology and plant disease management. Oxford University Press, New York. 427 p.

## Notes

*Author's address:* F. W. Nutter, Jr., Department of Plant Pathology, University of Georgia, Athens, Georgia 30602, USA (Current address: Department of Plant Pathology, Iowa State University, Ames, Iowa 50011).

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Determining pest-loss relationships and quantifying loss

P. T. Walker

Pest management decisions depend heavily on the relationship between pest attack and yield. Here we look at how to assess that relationship and some methods for surveying losses in the field.

## Measuring yield

Although yield, as the quantity of economic product harvested, is sometimes expressed in per unit of crop (such as per tiller, plant, hill, cane, or tree), a more constant base (such as area) is usually preferred. If trials give yield in terms of tillers, hills, or row length, the number of tillers, hills, or rows per hectare is needed to calculate yield per hectare. Grams per plot are as meaningless to the farmer as they are to the comparative research worker. Of course, grain weight and number of panicles, tillers, etc. are important components of yield; they are needed to explain how yield is made up, how pests affect it, and how it might be improved.

Production is total yield — yield per hectare multiplied by area of production. Quality also is important, and should be measured and reported in trials and surveys. Produce grade often can be established from marketing requirements: grade sizes; tests for color, taste, constituents; and special properties such as baking quality, hardness. oil content, fiber length, etc.

Sometimes it is necessary to measure the production area by special sampling methods, such as are used in censuses (Simaika 1982). Equipment for sowing, harvesting, and threshing small trials has been developed and can be used in taking crop censuses (AAB 1985, Dyke 1974, Little and Hills 1978, Pearce 1983, Simaika 1982). Methods for rice are given in Israel and Abraham (1967), Gomez and Gomez (1983), Khosla (1977), and Litsinger et a1 (1987); those for potato and cereals (Sylvester-Bradley et a1 1985) are in AAB (1985). Some crops require special methods for measuring yield, and experts on the agronomy of the crop must be consulted. Herbage can be measured by capacitance, timber by girth calipers, sugar by optical methods. Yield can sometimes be estimated by remote sensing from airplane or satellite. Even visual estimates by an experienced person can be accurate.

The condition of yield is important. Details of moisture content; whether cleaned, shelled, or dehusked; and age or degree of maturity should be given. Variation in some of these factors can be greater than the variation due to pest attack, making conclusions about the effects of pests difficult.

## Relationship between infestation and yield

Yields at a wide range of infestations are needed, to describe the full relationship and to know how yield is affected at low and high infestation rates. There are several methods for obtaining these figures (Bardner and Fletcher 1974; Chiarappa 1971; Judenko 1973; Pradhan 1964; Singh and Khosla 1983; Walker 1983a,b).

Usually yields from single, paired, or several plants attacked and not attacked by pests are measured. The amount of attack, pest density, or amount of damage should be taken over a wide range, from 0 to 100% if possible. Plants or plots should be selected at random or in an accepted plot design, such as randomized complete or incomplete blocks, split plots, or latin square. Single plants can be marked with plastic tags. The proportion of plants attacked in the population and in the area must be known, to calculate yield loss per hectare. Single plants can be protected and observed more minutely, but a disadvantage in yield studies is that no account is taken of compensation by unattacked plants. If plants are not in plots and attack is variable (e.g. in bananas or palms), single plants may have to be used. The pattern of attack may also be unnatural. Results from paired plants should be compared with results from larger plots or from more natural areas of attack.

Losses in grain or other harvested produce may be measured by comparing the weight of attacked and unattacked grains, fruit, berries, etc. Loss per attacked grain, per 1000 grain weight, or per known volume or weight of produce, multiplied by the percentage of grains attacked or the total volume or weight of produce, will give total loss. Methods are described by Harris and Lindblatt (1980).

One empirical method is to measure how much of a plant is eaten or even how much frass or excreta is produced by one pest, multiplied by the number of pests. This method has been used for locusts, leaf-eating caterpillars, and beetles. This method depends on also counting the number of pests. Although it will give an indication of loss, it should be checked against other methods in the field.

Methods to measure infestation can be classified into natural infestation, chemical use, artificial infestation, simulated damage, using resistant varieties, and comparing yields.

### Natural infestation

Naturally occurring infestations often are used to give a range of infestation or damage in single plants, plots, or fields. In some cases, infestation can be measured at harvest (e.g. stem borers on cereals or sugarcane or Hessian fly on cereals). Infestations may be related to yield the following year, as is the case in some tree crops (e.g. cacao attacked by bugs). Other tree crops bear biennially, so a measurement taken in only one year may be inaccurate. Lim (1980) measured losses due to *Nilaparvata* on naturally infested rice crops. Rogers (1979) examined losses due to bud moth on natural infestations of paired sunflower plants (he reduced variation by stratifying by flower-head diameter).

The advantages of using natural infestations are 1) crop yield responses to attack are exactly as they are in the field, 2) there are no side effects from chemicals, 3) there is no interference, and 4) pest distribution is natural. A disadvantage is that there is less experimental control, and hence more variation due to differences in climate, soil, and other pests or diseases and often a less useful range of infestation rates. Partitioning and stratification of trials could help remove some of this variation.

### Chemical use

Chemicals have been widely used in loss assessment trials to establish a range of infestation rates of insects, rodents, birds and other pests, weeds, and plant diseases. Chemicals also may be used with artificial infestation, caged experiments, and other methods.

Usually half the crop area is treated with pesticide, the other half is not. But much more information should be obtained. Preliminary trials are needed to establish the response of the pest to the pesticide used, and to establish 0 and 100% infestation rates for maximum and minimum yield. Then, different chemicals, times of application, numbers of applications, concentration rates, or methods of application may be used to give a range of infestation rates. Chiarappa (1971) gives examples.

Many loss assessments come from trials designed to test pesticides. Although the results are valuable, the difficulties of using pesticides should be taken into account in selecting methods. Trials with chemicals also can give biased results when they are deliberately conducted in high-infestation areas.

Losses due to a complex of pests or diseases can be assessed using specific pesticides, method of application, or method of reaching the pests. *Bacillus thuringiensis* or viruses may affect only lepidopterous larvae, acaricides only mites. Systemic insecticides will affect sucking insects: granules and seed dressing, soil insects: spray on stems only insects that migrate up the stem; and insecticidal bait only pests that eat it (such as fruit flies or cutworms). Wilson et a1 (1979) used *B. thuringiensis* and five different insecticides applied at different times to assess losses in alfalfa due to three different insects.

The advantage of using chemicals, apart from speed and simplicity, is that populations of individual pests can be controlled. The disadvantages are 1) pesticides themselves may affect crop yield, reducing it (if phytotoxic) or stimulating it (as with carbofuran); 2) unknown pests may be affecting yield, and pesticides may affect them as well as the main pest; 3) pesticides may kill or repel parasitoids, affecting the pest population; and 4) pesticides also contribute to interplot interference and drift or runoff may affect untreated pests and plants on nearby plots.

### Artificial infestation

Pest infestation may be artificially increased or decreased to establish known pest densities or amounts of damage. Eggs, larvae, or adults may be placed in or on the crop, sometimes with a specially designed dispenser. Larvae may be placed in cereal funnels with a brush. Cages or other barriers may be used to keep pest numbers constant.

If cages are used, the mesh size is important, particularly if birds are to be kept in or out (Bruggers and Ruelle 1982). Metal barriers will retain cutworm populations and exclude rodents. Metal containers also have been used for soil beetle larvae.

Natural infestation should be removed by hand, by trapping or with a nonpersistent pesticide, and further infestation prevented. These techniques have been used with egg batches of cereal moth borers and eggs of vegetable lepidoptera (Judenko 1973, Prasad 1961), with the caterpillars themselves, and with adult sucking bugs (Todd et al 1973). Hall and Teetes (1982) infested sorghum panicles with four kinds of bugs.

Infestation rates should cover as wide a range as possible in relation to the way infestation affects yield loss. If an arithmetic or proportional relationship is expected, pest numbers might be 0, 2, 4, 6, 8, 10; if a logarithmic relationship is expected, 0, 2, 4, 8, 16, 32. The number of pests that establish themselves and survive should be monitored.

The pattern of pest distribution is important in the pest-yield relationship and artificial infestation should be as similar to natural pest attack as possible. Fery et al (1979) distributed *Heliothis* eggs uniformly on tomato; Lynch et al (1980) infested maize with *Ostrinia* eggs in a Poisson distribution.

Pest attack can be increased by putting infested plant material in test plots (e.g. rice infested with stem borer or leaffolder), by sowing trap rows of a pest-susceptible variety, or by using attractant material such as fish meal for sorghum shoot fly. Such methods may not be popular with farmers.

The advantages of artificial infestation are that the infestation can be controlled and other factors removed. The disadvantages are

- Pest material for infestation must be collected at the appropriate stage in the field, or bred (often with difficulty) in an insectary.
- Infestation by hand can be tiresome and laborious.
- Timing infestation in relation to crop growth stage or climate may be critical.
- Cages may affect plant yield as well as the pest population inside them.

Results from cage experiments may need to be corrected, perhaps by putting infested and uninfested plants in similar cages, by using both closed and open cages (Sparks et al 1966 on maize), or by removing cages as soon as possible (Webster and Smith 1983 for *Oulema* beetle on wheat).

Cages may affect yield by changing light or air flow, but they have little effect on temperature or humidity (Way and Banks 1968). Catling et al (1978) used floating cages to assess losses in deepwater rice artificially infested with yellow stem borer *Scirpophaga.*

Infestations have also been increased by placing light or pheromones in the test plots, or decreased by trapping.

Several techniques were used in a study of loss in rice due to whorl maggot *Hydrellia* by Viajante and Heinrichs (1986). They artificially infested seedlings in cages with flies, artificially removed areas of leaf, and controlled further attack with insecticide.

## Simulated damage

Effects of pest attack can be imitated or simulated by artificial damage. Whole plants can be removed at random, in a regular pattern, or in groups. Flowers or seed heads can be removed, leaves cut or removed (Poston and Pedigo 1976), stems damaged, or roots cut. Such experiments are often done for agronomic or physiological purposes, and there are examples for most crops. The amount of damage done (leaf area, root length, dry weight) should be measured.

The advantage of this method is that the amount of damage can be exactly controlled. A disadvantage is that the time of damage in relation to climate and crop growth stage is often critical. For example, the position of the growing point or the flag leaf of cereals when damaged by armyworm, or the position of borer damage in the stem of sugarcane. The effect on yield depends on how stressed the plant is by such climatic factors as water or light deficiency, by nutrient status, or by other pests or diseases. The plant's ability to recover also depends on genetic factors. Studies on yield components are very important (e.g. those for sorghum [Williams et al 1977] and wheat [Wratten and Redhead 19761).

It may be easy to find the relationship between damage and yield, but more difficult to get the basic relationship between pest density and damage. Different stages of a pest may be present, attacking for varying lengths of time. Other factors, such as temperature, rainfall, biological control, and crop variety, may vary. However, the basic relationship between pest damage and yield should be established.

### Resistant varieties

Yield loss due to pests can sometimes be measured by comparing crop varieties that are susceptible and those that are resistant to pest attack. Differences between the varieties in yield with no pests can be used to correct for the differences due to pests. Schoonhoven and Peña (1976) used this method to study losses in cassava due to thrips, Harvey and Hackerott (1974) studied losses in sorghum due to aphids. Difficulties may arise if one variety is tolerant of or can recover from pests, so that pest attack does not reduce its yield.

### Comparison of annual yields

If no information is available on the relationship between infestation and yield from experiments, figures of infestation from surveys and of yields from crop production figures or censuses may be used to compare yields in years of high and low infestation, or before and after attack. Nichols (1970) suggested a normal-year method for estimating losses. Allowance must be made for yield differences in some years due to climate, the presence of other pests or diseases, the use of pesticides, or the status of biological controls. Such information can be used to supplement other loss estimates, as was done by Walker (1987) for cassava mite and mealybug.

## Interplot interference

Measurement of the relationship between infestation and yield is often done in plots infested with different numbers of pests or treated with different levels of pesticides. If the plots are close together and the pests very active and mobile, or if pesticides drift in the wind, pest populations may not be independent and yields not as closely related to pest populations as expected. Similar situations arise with plant diseases.

A plot with few pests may act as a sink into which pests migrate from plots with many pests, resulting in higher populations in the low plots and lower populations in the high plots. If pests in a treated plot damage the crop before dying and more pests then migrate into it, that plot may have more damage than an untreated plot. If pesticides repel pests, they may migrate into an untreated plot, which will sustain more damage than expected.

To avoid the effects of interplot interference, plots can be made larger, with only the center sampled for pests and yield. Or test plots can be screened with hessian cloth or burlap; a high border crop such as pigeonpea can he established; or plots can be placed farther apart. The best way to establish this distance is to measure the amount of interference between side-by-side treated and untreated plots and side-by-side treated plots some distance apart, as is recommended for plant diseases. The farther apart the plots, however, the greater the variation due to differences in soil or climate. The problem is discussed in AAB (1985) and for pests in cotton by Joyce and Roberts (1959) and Reed (1972).

## Calculating loss

The method and extent of a survey depend on its purpose. Surveys may be conducted to simply identify the causes of loss and compare their importance, to find out what kind of losses occur in different areas, or to estimate losses to make control decisions or forecast agricultural production (Walker 1983a,b). The choice of survey method depends on the accuracy required, the time and money available, and the variability and distribution of the losses.

### Direct surveys of loss

If losses and their causes are highly variable (perhaps due to different causes, types of farming, or climate), actual crop-cutting to measure the yields of attacked and unattacked plots or different levels of infestation will provide a range of losses that can be attributed to the different stresses. Losses can then be averaged. If the distribution of losses is not normal, a geometric mean or mean of log losses may be more accurate than a simple arithmetic mean. Yields from areas with different infestation or with other stresses should be weighted according to the area, multiplied by the area on which they are grown, and the total divided by the total area. This prevents undue importance being given to small areas with high infestation. Crop yield surveys can often be designed similarly to those done for agricultural censuses. In all cases, statistical advice should be sought on the sampling plan and the size and number of samples.

Such surveys have been published on rice in India (Abraham and Khosla 1967; Seth et a1 1969, 1970), on maize (Kishen et al 1970, Singh et al 1971), and on wheat (Kishen et a1 1972). Catling et a1 (1978) surveyed losses in rice in Bangladesh, Wood et al (1980) studied losses in yams and maize in Nigeria, and Litsinger et al (1987) examined losses in rice in the Philippines.

### Indirect surveys of infestation-yield

If infestation and type of farming are fairly uniform and a reliable model or relationship between infestation and yield has been obtained, infestation can be surveyed and expected yield derived from the model. Losses can then be established from yields with and without pest attack. This may be quicker and cheaper than a crop-cutting survey.

Other forms of the infestation-yield model are the yield loss *conversion factor* (CF) used by Basu (1978) for peas in Canada and the *coefficient of harmfulness* proposed by Judenko (1973). The CF for each grade of pest attack is found experimentally (for example, heavy 0.7; moderate 0.5; light 0.2). The average CF found by surveying for infestation and weighting for area or number of samples of each grade found is used to calculate actual yield as a proportion of maximum yield.

Strickland (1957) used infestation surveys to estimate loss in vegetables due to aphids; losses in maize caused by European corn borer have been surveyed in the U.S. using a factor of 3% yield loss/borer per plant (USDA 1977). Graça (1976) surveyed sugar loss due to *Diatraea* in Brazil by this method.

### The probability of loss

Risk can be included in loss surveys if the number of attacks over several years is known. Bullen (1969) used a crop vulnerability index to predict the chance of losses of crops to desert locust attack in different countries, and estimated total losses. The information can be provided on maps using lines of iso-risk and iso-loss (Rijsdijk and Zadoks 1979).

### Estimating loss from economic indicators

Losses can sometimes be estimated from the economic effects they cause: a rise in market price of the product, seed, or planting material when pests cause a fall in production, or increased imports of the product from elsewhere. There may be increased trade in an alternative product, and a rise in its price (e.g. the price of maize if cassava production is reduced by pests). Care should be taken that other pests or diseases, drought, or economic factors such as inflation are not confusing the situation (Walker 1987).

## Conclusion

Yield loss assessment is far from being an exact science. Yield losses due to pests can be highly variable, with wide margins of error. Sometimes the question is asked, is loss assessment worth the time and expense? However, some information is better than none at all. Information can always be improved. Ultimately, yield loss assessment remains the only basis for making reasonable decisions on pest management.

## References cited

AAB — Association of Applied Biologists (1985) Field trial methods and data handling. Aspects of applied biology 10. Wellesbourne, Wanvick, UK. 528 p.

Abraham T P, Khosla R K (1967) Assessment of losses due to incidence of pests and diseases in rice. J. Indian Soc. Stat. 19:69-82.

Bardner R, Fletcher K E (1974) Insect infestations and their effects on the growth and yield of field crops. Bull. Entomol. Res. 64:141-160.

Basu P K (1978) A yield loss conversion factor for peas moderately affected by *Fusarium* root rot. Can. Plant Dis. Surv. 58:5-8.

Bruggers R L, Ruelle P (1982) Efficacy of nets and fibres for protecting crops from grain-eating birds. Crop Prot. 1:55-65.

Bullen F T (1969) The distribution of the damage potential of the desert locust, *Schisrocerca gregaria.* Antilocust Memoir 10. Centre for Overseas Pest Research (now Overseas Development Natural Resources Institute), Overseas Development Administration, London. 72 p.

Catling H D, Alam S, Miah S A (1978) Assessing losses in rice to insects and diseases in Bangladesh. Exp. Agric. 14:277-287.

Chiarappa L, ed. (1971) Crop loss assessment methods: FAO manual on the evaluation and prevention of losses by pests, diseases and weeds. FAO and CABI, Wallingford, UK. 123 p.

Dyke G V (1974) Comparative experiments with field crops. Butterworth, London. 209 p.

Fery R L, Cuthbert F P, Perkins W D (1979) Artificial infestation of tomato with eggs of the tomato fruitworm. J. Econ. Entomol. 72:392-394.

Gomez K A, Gomez A A (1983) Statistical procedures for agricultural research. 2d ed. Wiley, London and New York. 688 p.

Graça L R (1976) Estimativa econômica dos prejulzos causados pelo complexo broca-prodridões ne cana-de-açucar no Brasil. Brasil Açcareiro 88:12-43.

Hall D G, Teetes G L (1982) Yield loss-density relationships of four panicle-feeding bugs in sorghum. Environ. Entomol. 11:738-741.

Harris K L, Lindblatt C J (1980) Postharvest grain loss assessment methods. American Association of Cereal Chemists, St. Paul, Minnesota. 193 p.

Harvey T L, Hackerott H L (1974) Effects of green bugs on resistant and susceptible sorghum seedlings in the field. J. Econ. Entomol. 67:377-380.

Israel P, Abraham T P (1967) Techniques for assessing crop losses caused by rice stem borers in tropical areas. Pages 265-275 *in* The major insect pests of the rice plant. The Johns Hopkins Press, Baltimore, Maryland.

Joyce R J V, Roberts P (1959) The determination of size of plot suitable for cotton spraying experiments in the Sudan Gezira. Ann. Appl. Biol. 47:287-305.

Judenko E (1973) Analytical method for assessing field losses caused by pests on cereals with and without pesticides. Bull. 2. Centre for Overseas Pest Research (now Overseas Development Natural Resources Institute), Overseas Development Administration, London. 31 p.

Khosla R K (1977) Techniques for assessment of losses due to pests and diseases of rice. Indian J. Agric. Sci. 47:171-174.

Kishen K, Sardana M G, Khosla R K, Dube R C (1970) Field losses caused by pests and diseases in the maize crop. Agric. Situation India 25:591-593.

Kishen K, Sardana M G, Khosla R K, Dube R C (1972) Estimates of the incidence of pests and diseases and consequent yield losses in wheat. Indian J. Agric. Sci. 42:908-912.

Lim G S (1980) Brown planthopper outbreaks and associated yield losses in Malaysia. Int. Rice Res. Newsl. 5:15-16.

Litsinger J A, Canapi B L, Bandong J P, Dela Cruz C G, Apostol R F, Pantua P C, Lumaban M D, Alviola A L III, Raymundo F, Libetario E M, Loevinsohn M E, Joshi R C (1987) Rice crop loss from insect pests in wetland and dryland environments of Asia with emphasis on the Philippines. Insect Sci. Appl. 8:677-692.

Little T M. Hills F J (1978) Agricultural experimentation; design and analysis. Wiley, New York. 350 p.

Lynch R E, Robinson J F, Beny E C (1980) European corn borer: yield losses and damage resulting from simulated natural infestation. J. Econ. Entomol. 73:141-144.

Nichols C W (1970) Compiling and reporting crop loss data by the normal year method. FAO Plant Prot. Bull. 18:25-28.

Pearce S C (1983) The agricultural field experiment: a statistical examination of theory and practice. Wiley, London and New York. 335 p.

Poston F L, Pedigo L P (1976) Simulation of painted lady and green cloverworm damage to soybeans. J. Econ. Entomol. 69(4):423-426.

Pradhan S (1964) Assessment of losses caused by insect pests of crops and estimation of insect populations. Pages 17-58 *in* Entomology in India. Special Number. Entomology Society of India, New Delhi. 529 p.

Prasad S K (1961) Quantitative estimation of damage to cabbage by cabbageworm. Indian J. Entomol. 23:54-61.

Reed W (1972) Uses and abuses of unsprayed controls in spraying trials. Cotton Growing Rev. 49:67-72.

Rijsdijk F H, Zadoks J D (1979) A data-bank on crop losses. EPPO Bull. 9:297-303.

Ropers C R (1979) Sunflower bud moth, *Suleima:* behavior and impact of larva on sunflower seed production in the Southern Plains. Environ. Entomol. 8:113- 116.

Schoonhoven A V, Peña J E (1976) Estimation of yield losses in cassava following attack by thrips. J. Econ. Entomol. 69:514-516.

Seth G R. Sardana M G, Khosla R K, Kalyanaraman V M (1969) Preharvest losses due to pests and diseases in rice. Indian J. Agric. Sci. 39:1113-1124.

Seth G R, Sardana M G, Khosla R K (1970) Assessment in loss of yield of paddy in West Godavari district. Oryza 7:1-12.

Simaika J B (1982) Estimation of crop areas and yields in agricultural statistics. FAO Economic and Social Development Paper 22. Food and Agriculture Organization, Rome. 186 p.

Singh D, Khosla R K (1983) Assessment and collection of data on preharvest food grain losses due to pests and diseases. FAO Economic and Social Development Paper 28. Food and Agriculture Organization, Rome. 127 p.

Singh D, Tyagi B N, Khosla R K, Avasthy K P (1971) Estimate of the incidence of pests and diseases and consequent losses in yield of maize. Indian J. Agric. Sci. 41:1094-1097.

Sparks A N, Chiang H C, Burkhardt C C, Fairchild M L, Weekman G T (1966) Evaluation of the influence of predation on corn borer populations. J. Econ. Entomol. 589:104-107.

Strickland A H (1957) Cabbage aphid assessment and damage in England and Wales 1946-1955. Plant Pathol. 6:1-9.

Sylvester-Bradley R, Grylls J P, Roebuck J F (1985) Methods for measuring cereal crops. Pages 213-239 *in* Field trial methods and data handling. Aspects of applied biology 10. Association of Applied Biologists, Wellesboume. Warwick, UK.

Todd J W, Jellum M D, Leuck D B (1973) Effects of southern green stink bug *Nezara* on fatty acid composition of soybean oil. Environ. Entomol. 2:685-689.

USDA — United States Department of Agriculture (1977) Estimation of damage by European corn borer to grain corn in U.S. in 1976. Crop Plant Pest Rep. 2:375-376.

Viajante V D, Heinrichs E A (1986) Rice growth and yield as affected by the whorl maggot *Hydrellia philippina.* Crop Rot. 5:176-181.

Walker P T (1983a) The assessment of crop losses in cereals. Insect Sci. Appl. 4:97-104.

Walker P T (1983b) Crop losses: the need to quantify the effects of pests, diseases and weeds on agricultural production: a review. Agric. Ecosyst. Environ. 9:119-158.

Walker PT (1987) Losses in yield due to pests in tropical crops and their value in policy decision-making. Insect Sci. Appl. 8:665-671.

Way M J, Barks C J (1968) Population studies on the active stages of the black bean aphid on its winter host. Ann. Appl. Biol. 62:177-197.

Webster J A, Smith D H (1983) Cereal leafbeetle, *Oulema* population densities and winter wheat yield. Crop Prot. 2:431-436.

Williams W T, Boundy C A P, Millington A J (1977) Effect of survey date on growth and yield of three sorghum cultivars. Aust. Agric. Res. 28:381-387.

Wilson M C, Stewart J K, Vail H D (1979) Full season impact of the alfalfa weevil, meadow spittlebug and potato leafhopper in an alfalfa field. J. Econ. Entomol. 72:830-834.

Wood TG, Smith R W, Johnson R A, Komolafe P O (1980) Termite damage and crop loss studies in Nigeria: pre-harvest losses of yams due to termites and other soil pests. Trop. Pest Manage. 26:355-370.

Wratten S D, Redhead PC (1976) Effects of cereal aphids on the growth of wheat. Ann. Appl. Biol. 84:437-455.

## Notes

*Author's address:* P. T. Walker, 10 Cambridge Road, Salisbury, Wiltshire SP1 3BW, United Kingdom.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Using yield physiology to model pest losses

R. E. Gaunt

The effect of plant diseases on yield has been studied at several trophic levels by both plant pathologists and plant physiologists. Approaches have ranged from descriptive to fully quantitative, using a wide range of available techniques. The methods used have been derived from such diverse disciplines as agronomy and molecular biology, as well as from disciplines more familiar to pathologists and physiologists. Reliance on the knowledge and techniques of a particular discipline depends on the aspect of yield studied and the degree of explanation and understanding required.

Theoretical yield represents the level currently considered the maximum. It assumes that all limiting factors are removed, that all beneficial inputs (e.g. plant growth regulators) are provided, and that the plant is functioning at maximum efficiency at all times. Efficiencies are derived from theoretical calculations based on detailed knowledge of plant processes.

Attainable yield is measured under optimal conditions, usually in small experimental plots. It is only limited by such natural factors as irradiation, daylength, and temperature. Factors such as nutrient level, water availability, and pest pressure are manipulated to achieve maximum production.

Yields in commercial production systems, almost always lower than attainable yield, can be defined at several levels. Economic yield is the level that provides the maximum economic return to investment. Actual yield is that obtained in a particular field or region at a given time. Primitive yield is that obtained without the benefit of any available technologies for yield enhancement and protection.

Each definition of yield is useful in different circumstances and can be used to define responses to pests and pest control in different ways. Often field pathologists are most interested in the yield of a community of plants or a crop in situations representative of production systems. Depending on the focus, the reference point may be attainable yield, economic yield, or actual yield (Zadoks and Schein 1979).

Crop loss or yield loss is defined by the Food and Agriculture Organization as the difference between attainable yield and actual yield in individual fields (Chiarappa 1971, 1981). It is a measure of the extra yield that could have been achieved if full crop management had been practiced. Attainable yield is used as the reference because it is uniquely defined and can be quantified readily. However, it should be noted that it is rarely economic to produce the attainable yield.

The objective of crop protection is to ensure that actual yield is as close as possible to economic yield. Although for some purposes, a definition based on economic yield is more realistic, it is impractical as the sole reference. Economic yield fluctuates markedly in response to global market conditions, production subsidies, and other factors not directly related to crop production.

Recent criticism of the terms crop and yield loss identified some misunderstanding of these terms (Cook 1985) and interest has turned to the potential gains that accrue from the control of diseases and other pests. This approach is useful in some cases, but it suffers from lack of a general reference yield (although actual yield without pest control is often used in this context). Expected yield might be a useful alternative reference. Theoretical loss, defined as the difference between theoretical and attainable yield, is often the basis for studies on crop improvement conducted by physiologists and breeders.

## Yield physiology and yield constraints

The physiology of processes related to yield and the identification and explanation of constraints to yield are studied in plant communities (crops), individual plants, plant parts, and at cellular and subcellular levels (Ayres 1981). The level of study is dictated primarily by the objectives and degree of explanation sought, but is influenced by the philosophical approach of the investigator. Studies based on systems analysis tend toward crop level, holistic approaches, with some plant and subplant studies identified as important to an understanding of the system.

Studies from all trophic levels have contributed to current understanding of the major abiotic constraints to yield. That provides the basis for crop and yield loss studies related to pests. An understanding of the major yield constraints in a crop free of pests is fundamental to an interpretation of pest-induced loss. Production constraints in healthy crops have been reviewed elsewhere (Gaunt and Robertson 1988). However, a brief summary of the major factors is appropriate because existing constraints are the basis of response to additional biotic (pest) constraints.

The major abiotic factors that constrain yield are nutrient availability, water, temperature, and incident light. Each contributes to yield to different degrees, depending on location, crop, and production system. It may be possible to identify the most important constraining factor at each crop growth stage, but across the growing season, several factors are likely to contribute to yield. Factors causing spatial variation in yields of healthy crops vary on different scales of resolution. Table 1 summarizes and ranks the factors that in general constrain yield the most.

The factors probably will rank at different levels of importance in different contexts. For example, rice production is likely to have different constraints in upland than in lowland areas, in rainfed than in irrigated systems. or with indica instead of japonica varieties. Understanding the interactions between the constraints and the consequences of their modification by management is important in any study of a crop, especially of yield loss.

**Table 1. Factors that cause spatial variations in yield, in the absence of disease and pest constraints (Gaunt and Robertson 1989).**

| Scale | Factors[a] |
|---|---|
| Adjacent plants | Sowing density, genetic diversity |
| Within fields | |
| <10m | Soil fertility, depth, texture |
| >10 m | Soil type, shelter, edge effects |
| Between fields | Management, soil type, topography |
| Between regions | Precipitation, temperature, evapotranspiration, soil type |
| Between countries | Temperature, precipitation, evapotranspiration, incident radiation |

[a] Listed in decreasing order of importance within each scale.

Plant pathogens and diseases, insect pests, and other biotic factors that constrain yield can be described and counted. Or they may be classified by their effect on host plant physiology (this could be especially useful in crop loss studies).

McNew (1960) classified diseases into six categories: destruction of food reserves, prevention of seedling metabolism, interference with food procurement, interference with upward translocation, destruction of food manufacture, and division of food stuffs. Boote et al (1983) classified diseases on the basis of their effects on carbon flow processes in crops: stand reducers, photosynthetic rate reducers, leaf senescence accelerators, light stealers, assimilate sappers, tissue users, and turgor reducers. Rouse (1988) suggested that leaf appearance reducers, growth rate reducers, and respiration accelerators be added. Charles-Edwards (1982) suggested that attention be focused on the major physiological determinants of yield at the whole-plant level: the amount of light intercepted by the crop, light-use efficiency, dry matter partitioning, rate of loss of dry matter, and duration of production of plant parts.

These and other classifications overlap considerably, but each reflects an intrinsically different objective. Categorization based on the dynamics of production physiology is likely to be most useful in explaining yield loss. This aspect is discussed here in relation to analytical and explanatory models.

## Implications for crop loss studies

The definitions of yield, loss, and constraints provide a basis for considering the relevance of yield physiology to crop loss studies. Physiological knowledge can assist in establishing or modifying techniques for disease measurement and empirical modeling of losses, to provide a sound conceptual basis for modeling losses at analytical or explanatory levels and to improve experimental procedures.

### Disease measurement

Traditional methods of pathogen and disease measurement are discussed by Teng (this volume). Most well-established and commonly used methods do not incorporate specific physiological aspects, although increasing use of green area measurements (Waggoner and Berger 1987) and remote sensing of canopy reflectance (Nutter, this volume) recognize the value of such approaches. However, current technology limits the addition of physiological attributes to such studies. Yield physiologists have considerable difficulty finding physiologically meaningful measurements.

Photosynthetic area and the arrangement of this area in the crop are recognized as being fundamental to yield physiology. If the area can be determined, either by measurement or through models, weather and other environmental variables such as nutrient status can be used to modify experimentally determined maximum photosynthetic and respiration rates. Changes in green area across time can be used to estimate biomass productivity. Unfortunately, measuring and modeling of green area are tedious, time-consuming, and difficult tasks. Regular destructive sampling usually is required to measure green area. Stratification into canopy layers, although difficult in most crops, is important in developing a more complete understanding of production.

Pathogen development in crops is dependent on such physical variables as temperature, humidity, water availability, and wind. At different positions in the crop canopy, these variables will be at different levels and will modify disease development differentially. Age of plant and plant parts also may modify disease development.

Conversely, the presence of pathogens modifies plant growth and development. Although the effect is seen most clearly in biomass production and yield, significant effects on canopy development may be important in production potential and as a feedback to disease development. For example, foliar diseases in early stages of cereal development may reduce the size of leaves produced subsequently (Lim and Gaunt 1981) and may affect the root system (Balasubramaniam and Gaunt 1985). These and other effects should be included in disease assessments based on physiological variables. Direct measurement of healthy green areas during the cropping season (Rotem et a1 1983), remote sensing of green areas (Whelan and Gaunt 1988), and calculation of infection rates modified by plant growth (Kushalappa and Ludwig 1982) are examples of such approaches.

## Empirical models

Decisions on when to assess a disease and the part of the plant to be assessed can be based on empirical models derived from best-fit regression or similar analyses. Many different assessments can be used in an exploratory experiment. This approach is useful where little knowledge is available on the development of a disease, the yield physiology of the crop, or the environment being studied.

Knowledge of epidemic development and yield physiology can reduce the number of assessments needed. For example, in cereals such as rice, disease development and the effects of disease on the main stem and tillers are closely correlated: only main-stem measurements are required. Similarly, foliar diseases often follow a well-established distribution on leaves in different positions on the stem. Partitioning studies have shown that these leaves contribute to known plant processes. Thus, for a disease known to affect only grain filling, in rice, it would be reasonable to concentrate assessments on the three topmost leaves (especially on the first leaf below the flag leaf) at early grain filling.

When a single assessment is used, assessment time and plant part can be based on the best statistical relationship or on a relationship that has reasonable physiological validity. Any model that gives a good correlation with yield loss is adequate for survey purposes, provided it is used only within production environments like that from which the model was derived. If the model is to be used in a more variable environment or for making management decisions, yield physiology should be a more dominant consideration. The decision on whether and how to use a model should be based on its characteristics and the objectives of the investigation.

Analysis of yield components has been the basis for selecting an empirical model in several crops, especially in cereals. Rice yields can be analyzed as number of fertile panicles (or fertile tillers) per unit area, as number of grains per panicle, or as mean grain weight. In cereals where there is the potential for more than one fertile floret per spikelet (e.g. wheat), an additional component is number of grains per spikelet. Each component is determined across a well-defined period of crop growth, making it possible to identify the period during which disease constrains yield (Gaunt 1980). An empirical model for management can be developed from such information. It should be recognized, however, that disease during the period of component determination is not necessarily responsible for the yield constraint, although it may be likely. Disease after component determination cannot affect the component; disease at earlier growth stages can, indirectly.

## Functional and analytical models

Models that contain largely empirical relationships between environmental variables and yield but which are structured on the basis of prior physiological analyses can be referred to as functional or analytical. While a purely empirical crop growth model will be based on one or more statistical relationships between the environment and yield. a functional and analytical model is based on the plant processes considered to be most important. The environment is often the modifying factor for the plant process. In a potato model developed by Johnson et al (1986), separate differential equations quantify the modification of leaf, stem, root, and tuber growth rates by the major abiotic yield constraint. moisture stress.

In loss models, the physiological factors used by Charles-Edwards (1982) may be a means of relating disease measurements to yield. Waggoner and Berger (1987) suggested that radiation interception by green parts of the crop canopy is a major determinant of plant growth. The integration of healthy tissue area across time (absorption of incident radiation) in peanut, potato, and maize crops was cited as evidence. Several others have reported the enhanced relationship to yield of disease measured as green area rather than as lesion area (e.g. in potato. Rotem et al 1983, Johnson et al 1986, Havekort and Bicamumpaka 1986 and in cereals, Lim and Gaunt 1985a,b). Similarly, numerous physiologists have shown good relationships between absorbed radiation and crop yield in a variety of environments (e.g. Gallagher and Biscoe 1978). Johnson (1987) drew attention to the additional effect ofthe efficiency of use of absorbed radiation; that may be affected by pests directly, independent of the effects of pests on the amount of radiation absorbed. This may account for the variation in yield in the relationships developed by Waggoner and Berger (1987).

It is interesting that many of the models based only on absorbed radiation are for crops grown under optimal conditions and for diseases that affect only the yield accumulation phase of growth. In crops grown in suboptimal conditions and for diseases of long duration in determinate crops such as wheat and rice, efficiency may be an important factor and worthy of inclusion in such models. Similarly, models of yield are more likely to require information on efficiency than are models of biomass production.

The objectives of most functional and analytical models of yield loss are to estimate the effect of disease on yield, to estimate yield, and to identify the physiological constraints in general. The models are likely to be used regionally rather than for individual fields, to predict the likely outcome of the introduction of a crop or disease to a new area or the outcome of changes in crop management. Errors in the models associated with physiological simplifications may be acceptable for some crop-disease systems. More precise estimates and increased understanding of the relationships cannot be achieved using this type of model. It is necessary to examine the potential of explanatory models.

## Explanatory models

Explanatory models of crop growth and yield loss are a step closer to full representation of biological relationships. The models invariably contain a degree of empiricism, often as parameters for physiological processes which are not fully understood. A major objective of explanatory models is to identify areas that require further investigation, to lead to a reduction in the empirical content. A long-term objective is to produce models that can estimate yield under a wider range of conditions—different locations, seasons, management practices, and pest constraints. Such models could be used to predict the need for pest management.

One aspect in the development of models based on detailed physiology is their use in testing simple assumptions found in other models. Thus, a model may incorporate the effects of environment and pests on partitioning, loss of dry matter, and duration of production (Charles-Edwards 1982), factors that are ignored in functional and analytical models based on absorbed radiation. Detailed analysis of the development of yield components has been shown to be useful in crop loss studies, especially for identifying the timing of production constraints. Detailed sequential analyses are not necessarily required, since most of the information needed can be acquired from a few careful measurements (Thomson and Gaunt 1986). In particular, measurements of maximum spikelet production and dieback at about GS 40 (Reissig et al 1986, Zadoks et al 1974), fertile floret number at anthesis, final grain number per panicle, and grain weight at harvest are sufficient to identify the primary periods of constraints to production caused by disease. Reduction in any of these components is an indication of a lack of balance in the crop, between its ability to produce assimilates for growth and its utilization of assimilates.

Growth strategies are often described on the basis of carbon source and sink functions of plant parts (Venkateswarlu and Visperas 1987). While the concept is useful in describing the current status of a particular unit, it is also confusing when dealing with the whole crop over the growing season. Roots and a few other organs totally lacking in chlorophyll may be considered sites of carbon utilization and storage (sinks). All photosynthetic organs are also sinks, because of the respiration associated with maintenance of cell function, structural development, and growth. These organs function as sources because of their photosynthetic activity. The relative activity of respiration and photosynthesis determine whether there is net utilization or production. For most plant parts, this relationship changes with time. Thus, most leaves initially (before emergence) are a site of utilization. They will pass through phases of net utilization with some production and net production with some utilization. Finally, there will be a phase of balance or net utilization (during senescence).

Disease commonly affects both utilization (often increased) and production (often decreased). The specific effects are determined by the type of disease (necrotroph or biotroph), the type of pathogen, and the type of plant. The dual function of many tissues is relevant to interpretation of disease effects, an aspect often lost when tissues are considered for their net function only. For example, disease on a newly emerged leaf classified as a net utilization site (sink) may affect only production of the leaf. The net effect on the leaf is that it utilizes more carbon, but the net effect on the plant is reduced production, not increased utilization.

Confusion also occurs when plant parts are classified as either sinks or sources. For example, many fruits can produce some of their carbon by photosynthesis. The rice panicle makes a significant contribution to grain filling. The concept is useful, however, in describing partitioning of assimilates and the effect of disease on partitioning, as is illustratedin the partitioning rules table used in RICEMOD (McMennamy and O'Toole 1983). It should be noted that a component that is sink-limited at a late stage reflects a source limitation at earlier growth stages.

## Experimental tools

Yield physiology can be used as both a source of useful techniques for crop loss research and a source (especially in explanatory modeling) of hypotheses to be tested. Considerable progress has been made in methods for quantifying disease on the basis of damage to plant function caused by the disease (Rouse 1988, Zadoks 1985). Treatments such as defoliation, desiccation, and shading, which have been used occasionally in research related to disease-induced losses (e.g. Zilberstein et al 1985), have been used more often in yield physiology studies. Although such treatments do not mimic disease treatments, they can be used to test hypotheses related to disease-induced losses. They are especially relevant in investigations of the direct effect of disease on plant processes related to yield, particularly as part of the determination of thresholds. Similarly, studies on the reallocation of stored carbohydrates to grain filling (Bidinger et al 1977) are relevant to the measurement of the balance between production and utilization of carbon materials. Physiological methods also could be used in determining the energy costs of different types of disease, about which there is currently little information (Kosuga 1978).

## Conclusion

Increasingly, research on crop loss is becoming a multidisciplinary activity that includes most branches of science, economics, and management. The interaction of physiologists and pathologists (e.g. Prew et al 1985) is proving to be very productive in accelerating further understanding of functional relationships. Physiological approaches and techniques, coupled with improved capability to manipulate and analyze data, are stimulating new types of investigations. In rice and other tropical crops, especially those already being intensively investigated by physiologists, there is tremendous scope for integrated research to extend current knowledge.

## References cited

Ayres P G (1981) Effects of disease on the physiology of the growing plant. Society for Experimental Biology Seminar Series No. 11. Cambridge University Press, Cambridge. 228 p.

Balasubramaniam R, Gaunt RE (1985) The effect of wheat foliar diseases on root growth, water use, and yield. Proc. Agron. Soc. N. Z. 15:35-39.

Bidinger F, Musgrave R B, Fischer R A (1977) Contribution of stored pre-anthesis assimilate to grain yield in wheat and barley. Nature 270:431-433.

Boote K J, Jones J W, Mishoe J W, Berger R D (1983) Coupling pests to crop growth simulators to predict yield reductions. Phytopathology 73:1581-1587.

Charles-Edwards D A (1982) Physiological determinants of crop growth. Academic Press, Sydney. 161 p.

Chiarappa L, ed. (1971) Crop loss assessment methods. FAO manual on the evaluation and prevention of losses by pests, diseases, and weeds. Commonwealth Agricultural Bureaux, Slough, England. 255 p.

Chiarappa L, ed. (1981) Crop loss assessment methods - supplement 3. Food and Agriculture Organization/Commonwealth Agricultural Bureaux, Slough, England. 123 p.

Cook R J (1985) Use of the term "crop loss." Plant Dis. 69:95.

Gallagher J N, Biscoe P V (1978) Radiation absorption, growth, and yield of cereals. J. Agric. Sci. Camb. 91:47-60.

Gaunt R E (1980) Physiological basis of yield loss. Pages 98-111 *in* Crop loss assessment. P. S. Teng and S. V. Krupa, eds. Proceedings of Stakman Commemorative Symposium. Miscellaneous Publications No. 7. University of Minnesota Agricultural Experiment Station, St. Paul, Minnesota.

Gaunt RE, Robertson M J (1989) Yield variability and the impact on local and regional estimates of yield reductions caused by disease. Pages 204-227 *in* The spatial component of plant disease epidemics. M. J. Jeger, ed. Prentice Hall, UK.

Havekort A J, Bicamumpaka M (1986) Correlation between intercepted radiation and yield of potato crops infested by *Phytophthora infestans* in central Africa. Neth. J. Plant Pathol. 92:239-247.

Johnson K B (1987) Defoliation, disease, and growth: a reply. Phytopathology 77:1495-1497.

Johnson K B, Johnson S B, Teng P S (1986) Development of a simple potato growth model for use in crop-pest management. Agric. Syst. 19:189-209.

Kosuga T (1978) The capture and use of energy by diseased plants. Pages 86-116 *in* Plant disease: an advanced treatise. Vol. III. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York.

Kushalappa A C, Ludwig A (1982) Calculation of apparent infection rate in plant diseases: development of a method to correct for host growth. Phytopathology 72:1373-1377.

Lim L G, Gaunt R E (1981) Leaf area as a factor in disease assessment. J. Agric. Sci. Camb. 97:481-483.

Lim L G, Gaunt R E (1985a) The effect of powdery mildew (*Erysiphe graminis* DC.f.sp. *hordei*) and leaf rust (*Puccinia hordei* Otth.) on spring barley in New Zealand. I. Epidemic development, green leaf area and yield. Plant Pathol. 34:44-53.

Lim L G, Gaunt R E (1985b) The effect of powdery mildew (*Erysiphe graminis* DC. f. sp. *hordei*) and leaf rust (*Puccinia hordei* Otth.) on sping barley in New Zealand. II. Apical development and yield potential. Plant Pathol. 34:54-60.

McMennamy J A, O'Toole J C (1983) RICEMOD: a physiologically based rice growth and yield model. IRRI Res. Pap. Ser. 87. 33 p.

McNeu G L (1960) The nature, origin and evolution of parasitism. Pages 19-69 *in* Piant pathology: an advanced treatise. Vol. II. J. G. Horsfall and A. E. Dimond. eds. University of Wisconsin Press, Madison.

Nutter F W Jr. (1990) Remote sensing and image analysis for crop loss assessment. Pages 93-105 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Preu R D, Church B M, Dewar A M, Lacey J, Magan N, Penny A, Plumb R T, Thome G N, Todd A D, Williams T D (1985) Some factors limiting the growth and yield of winter wheat and their variation in two seasons. J. Agric. Sci. Camb. 104:135-162.

Reissig W H, Heinrichs E A, Litsinger J A, Moody K, Fiedler L, Mew T W, Barrion A T (1986) Illustrated guide to integrated pest management in rice in tropical Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines. 411 p.

Rotem J, Kranz J, Bashi E (1983) Measurement of healthy and diseased haulm area for assessing late blight epidemics in potatoes. Plant Pathol. 32:109-115.

Rouse D I (1988) Use of crop growth-models to predict the effects of disease. Annu. Rev. Phytopathol. 26:183-201.

Teng P S (1990) Crop loss assessment: a review of representative approaches and current technology. Pages 19-37 *in* Crop loss assessment in rice. P.O. Box 933. Manila. Philippines.

Thomson W J, Gaunt RE (1986) The effect of speckled leaf blotch on apical development and yield in winter wheat in New Zealand. Ann. Bot. 58:39-48.

Venhateswarlu B, Visperas R M (1987) Source-sink relationships in crop plants. IRRI Res. Pap. Ser. 125. 19 p.

Waggoner P E, Berger R D (1987) Defoliation, disease, and growth. Phytopathology 77:393-398.

Whelan H G, Gaunt RE (1988) Disease measurement in barley crops. Proc. N. Z. Weed Pest Contr. Conf. 411:26-29.

Zadoks J C (1985) On the conceptual basis of crop loss assessment: the threshold theory. Annu. Rev. Phytopathol. 23:455-473.

Zadoks J C, Chang T T, Konzak C F (1974) A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

Zadoks J C, Schein R D (1979) Epidemiology and plant disease management. Oxford University Press. Oxford, England. 427 p.

Zilberstein M, Blum A, Eyal Z (1985) Chemical desiccation of wheat plants as a simulator of post-anthesis speckled leaf blotch stress. Phytopathology 75:226-230.

## Notes

*Author's address:* R. E. Gaunt, Plant Protection Research Unit, Microbiology Department, Lincoln University College of Agriculture, Christchurch, New Zealand.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Insect pest-loss relationships: characteristics and importance

P. T. Walker

For decisions to be made in insect pest management, the amount of pest attack or damage ($i$) must be measured. The relationship of ($i$) to crop yield ($y$) is then

$$y=f(i)$$

The benefits and costs of pest management can be evaluated and economic thresholds developed as guides to the pest or damage level at which farmers should start pest control. The type of relationship between infestation and yield is important, along with some economic aspects of crop loss assessment.

The basic principles of crop loss assessment apply to crop diseases and weeds, and to other types of loss caused by pests, such as the meat or milk yield in livestock and health and loss of earnings in humans.

## Background

Crop loss assessment and its economics have been reviewed by Bardner and Fletcher (1974), Chiarappa (1971), FAO (1967), Mumford and Norton (1987), Ordish (1952), Reichelderfer et al (1984), and Walker (1983a,b). Ahrens et al (1983), Reed (1983), and Waibel (1986) refer to crop loss in rice and to developing countries. Judenko (1983) defined many of the terms. World crop losses were summarized by Cramer (1967), with additions and a description of a database by Walker (1975, 1987). Work in the USA has been reported by Pimentel et al (1980) and Pimentel (1981).

## Reasons for quantifying yield loss

*Economic decisions on pests.* To compare the economic benefits (usually as increased yield or quality of crop) with costs of pest management, to determine action thresholds, to compare different methods of management, and to identify the relative importance of different pests.

*Allocation of resources.* To decide which causes of reduced optimum crop yield should receive scarce resources (money, manpower, time, etc.). Examples are allocation of research effort, improved extension services, or initiating a development project.

*Agricultural planning.* If the effects of pests on crop yield have been established, planning of cash input and food crop production may be possible, particularly if the model can include climate.

*Research on yield.* If the mechanisms of crop yield are known, research can be directed toward increasing yields by reducing the effect of pests on yield and yield quality, increasing crop resistance to pests, reducing pest attack by forecasting pest outbreaks, and limiting pest attack and control measures to critical crop growth periods.

## Definition of loss due to pests

Crop loss is a negative term. A more optimistic expression might be *yield reduction. Yield gap* or *preventive loss* are other terms for the same thing.

Yield loss ($w$) caused by pests should be expressed as the percentage of reduction in potential yield in the absence of pests $m$. If yield in the presence of pests is $y$, then

$$\text{yield loss}\,(w) = \frac{(m - y) \times 100}{m}$$

It is often difficult to establish the maximum potential yield in the absence of pests on which to base the calculation of yield reductions, and hence benefits. The type of farming, whether peasant or research, and the amount of inputs are important. The decision depends on the purpose: to answer a research problem, to assess the economic benefits of a development project, or to evaluate the relative importance of various pests, weeds, or diseases.

### A profile of yield reduction

If there are a number of different causes of yield reduction ($y_1, y_2$, etc. ), they can be compared graphically in a profile (Pinstrup-Andersen et al 1976) or pie chart, with sections proportional to the yield loss caused by each pest, disease, or other cause such as seed rate or availability of water or fertilizer. The method assumes that causes of yield reduction are independent and do not interact, which often is not the case.

### Pre- and postharvest yield reduction

Entomology is often divided into problems before and problems after harvest, when different methods of assessment and control are needed. Some methods are similar, however, and many postharvest problems start in the field, before harvest or storage (legume pod borers, grain weevils, cob borers, potato tuber moths, carob moths, etc.). A survey of postharvest losses has been published by FAO (1977) and there are reviews by Adams (1964, 1976, 1977), Pimentel (1980), and Pimentel et al (1981).

### Type and units of yield

Yield is usually the economic product harvested, either the primary product or a natural or processed constituent of it. Quality or marketing grade also may be important. Wheatley (1974) divided pest attacks into those with high or low incidence and high or low severity of damage. Cases of low incidence of low seventy in a high-value crop are sometimes called cosmetic damage—when a small pest attack causes great loss in crop value.

Yield and loss also can be expressed in terms of energy equivalent, assessed on inputs of fertilizer, pesticide, and fuel used in producing the yield. Monetary value at the farm gate, in the market, or on board (if exported) is commonly used. But prices often vary rapidly with supply and demand. Tax, subsidy and support prices, exchange rate, and even shadow prices may be used. For subsistence crops, the price of an alternative crop or an opportunity price may have to be calculated. Using yield quantity avoids these difficulties.

Area may be important if efficient production on a limited growing area is needed. If preventing loss due to pests, diseases, or weeds allows the same yield from less land, that releases a loss-equivalent area, or *Ordish* area (Ordish 1952). The released land can be used for growing cash crops or livestock, or for other uses.

## Mechanism of yield reduction due to pests

The effect of pests and other causes of yield reduction in a crop is best seen as a system or flow chart. In an individual plant, inputs of radiation, water, and nutrients enter the leaves and roots, and are translocated to a sink. From the sink they are partitioned and carried by translocation to the reproductive parts (grain, fruit, or storage organs such as cassava roots or sugarcane stems) — the yield.

The system is plastic and dynamic. Yields of individual parts or modules such as tillers or spikelets interact and compensate to give the plant or *genet* yield (Harper 1977). Plant yields interact and compensate to give the crop yield. Reduction in one part of the system can be compensated for by an increase in another. If values are put on the inputs and the rates of change, we have a crop production system that can be modeled: the effects of different inputs (such as a pest attack) can be simulated and yield predicted. Such production system models are being developed for many crops.

Pests may affect crop yields in the following ways:

- *Establishment,* if germination and early growth of plants are affected by beetle larvae, cutworms, armyworms, crickets, termites, etc.
- *Photosynthetic area,* if lost due to damage by leaf-eating, mining, or leaffolding pests, aphids, and bugs, or by shading of leaves with honeydew or sooty mold.
- *Uptake of water or nutrients,* if reduced by root pests, beetle larvae, borers, termites, etc.
- *Translocation,* if interrupted from leaves and roots to stores and to yielding parts by stem borers, cutworms, scales, mealybugs, rodents, etc.
- *Storage organs,* if stems, roots, and tubers are damaged by borers, tuber moth larvae, beetle larvae, rodents, etc.
- *Reproductive parts,* if seeds and grain are damaged by midges, beetles, bugs, caterpillars, locusts, rodents, and birds, or fruit by moths, fruit flies, bugs, hoppers, scales, etc. Loss of quality is important.
- *Secondary loss,* if secondary pests or diseases enter primary damage lesions or diseases are introduced by insect vectors.
- *Spoilage and down grading,* if a product becomes unacceptable in the market because of holes, spots, insect parts, rodent excreta, etc., even if there is no loss of weight or quality.

- *Harvesting and processing,* if pest attack makes crops difficult to harvest or process, such as fire-ants in cashew, moth webbing, sticky cotton lint, mealybug mold on citrus, etc.

## Pest-loss relationship: infestation and yield

How yield varies with changes in pest infestation or damage is important in predicting the yields, and hence the benefits, that will be obtained with pest control measures. The relationship is useful in evaluating economic action thresholds, pest densities, or damage levels that cause different amounts of yield loss.

One estimate of infestation ($i$) and yield ($y$) is of only limited value; two data points will show a trend; three or more points are needed to fully relate infestation and yield over the range of values normally found. This is expressed as a regression, usually negative, of yield ($y$) on infestation or damage ($i$):

$$y = m - b\,(i)$$

where $m$ is the potential yield in the absence of pests, $i = 0$, and $b$ is the rate of yield reduction or loss. A regression of loss $w$ on infestation $i$ is sometimes used:

$$w = a + b\,(i)$$

The regression is then usually positive, but there may be difficulties if there is an increase in yield at low infestations.

The regression may be simple, ignoring many other factors, or complex, incorporating individual relationships for several plant parts or the effects of several different pests or other causes of loss (Fig. 1). The relationship may change with time of attack, stage of pest, method of assessment, growth stage of the crop, or general growing conditions (Bardner and Fletcher 1974; Southwood and Norton 1973; Walker 1983a,b).

### A straight-line relationship (Fig. 1A)

When one individual or group of pests damages one plant or one plant part (e.g. a midge infesting one floret), a proportional decrease in yield may occur with an increase in infestation. No compensation by the plant or by parts of it occurs, and there is no threshold level below which yield is not reduced.

### A sigmoid or S-shaped relationship (Fig. 1B)

If the relation between $y$ and $i$ is examined over a full range of values of $i$, there is often a threshold value below which no reduction in yield occurs, mostly due to compensation by unattacked parts or by clean plants for attacked ones. The result is a sigmoid curve, with a central, straight-line section, and a final flattening at high values of $i$ when some yield is often produced, Rate of loss $b$ changes with the value of $i$. Sometimes only the convex half of the curve is found, when attack is early, on vegetative parts, leaves, etc., and compensation can occur. Sometimes only the concave curve is found, when attack is on reproductive parts, such as grain, and compensation is impossible. This relationship has been found for *Maliarpha* stem borer and rice yield. Justesen and Tammes (1960) and Tammes (1961) examined the reasons for such yield responses.

It is difficult to fit a formula to a sigmoid curve, unless summed and a probit transformation of the normal probability distribution of yields is used to linearize the relationship, as with dosage-mortality curves.

## A logarithmic relationship (Fig. 1C)

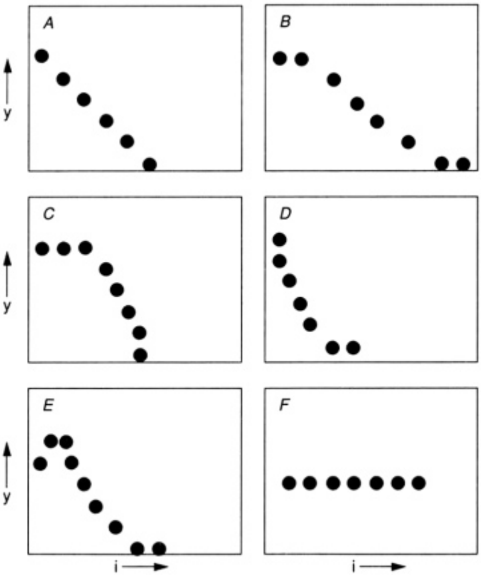
Yield may be related to the logarithm or a power of the number of pests, where their effects are multiplicative rather than additive. Examples are mobile or rapidly multiplying pests, such as whiteflies or aphids. There may be compensation for attack. Transformation of pest density, for example (*i*) to log (*i* + 1), may be needed.

## Rapid yield loss at low rates of infestation (Fig. 1D)

Small numbers of pests sometimes can cause a disproportionate reduction in yield, for example, if the pest is a disease vector, as in the effect on rice yield of brown planthopper, the vector of grassy stunt disease (Dyck 1974). Cosmetic damage, such as scale on citrus, is another example. Gradients of disease attack are discussed by Thresh (1976).

## An increase in yield (Fig. 1E)

Low infestations can cause an increase in yield; yield falls with a further increase in infestation. Pest attack may stimulate growth and yield. Destruction of the growing



**1.** Relationships between yield ( *y* ) and infestation (i). A shows a straight-line relationship; *B,* sigmoid S-shaped; *C,* logarithmic; *D,* rapid yield loss at low rates of infestation; *E,* Increase in yield; *F,* no relationship.

point of tillering plants such as rice, or of plants with continuous production of fruiting points such as cotton, will cause a yield increase if growing conditions are favorable. If there is too much foliage and not enough light, reduction of leaf area by leaf-eating pests may increase light falling on the plants and increase yield. Pest attack also may increase drying at maturity, increasing the sugar content of sugarcane. Or pests may selectively attack higher yielding plants, giving a positive relationship between infestation and yield. The subject is reviewed by Harris (1974).

**No relation between infestation and yield (Fig. 1F)**
Sometimes, unaccountably, no relationship is found. This may result from trying to average highly variable data, from not having a full range of infestations (such as no zero attack) or from some other effect. Variation should be reduced by altering plot or sampling design, by stratifying sources of variation into types of farming, soil, or other cause of variation, or by improving the techniques of measuring infestation, control, or yield.

## Quantification of pest-loss relationship

The response of yield ($y$) to pest infestation ($i$) is often taken to be linear:

$$y = m - b\,(i)$$

If the full range of infestation rates from 0 to 100% are taken into account, relationship is sigmoid or S-shaped. Models using the logarithm or power of infestation are often derived, more for practical than for scientific reasons.

Most relationships can be fitted to a polynomial equation

$$y = m - a_{1} - b_{1}^{2} - c_{1}^{3}$$

in which the variance is partitioned into linear, quadratic, and cubic components to obtain a good prediction of $y$ from $i$ (Lynch 1980). If there are other causes of yield reduction, such as other pests or diseases, and the relationship between yield and the amount of pest or disease attack has been found from experimentation or surveys, a multifactorial regression (Gomez and Gomez 1984) can be used to separate the effect of each factor and assess its importance in yield reduction. Khosla (1977) used the method to examine rice yield losses due to several causes in India.

If $i_1$ and $i_2$ are the amounts of two causes of yield loss, then

$$y = m_{i1i2} - b_{i1i2}\,(i_1 - \bar{i}_1) - b_{i2i1}\,(i_2 - \bar{i}_2)$$

where $b_{i1i2}$ is the partial regression coefficient of $y$ on $i$ at constant $i_2$, etc.

A model for predicting yield from the amount of pest infestation can be improved by including factors that affect pest population. Biocontrols such as parasitoids or disease, temperature as degree days, and rainfall can be used. For example, loss of forage due to grasshoppers has been forecast from grasshopper development (Hewitt and Onsager 1982). That prediction depended on temperature summation (Gage and Mukerji 1971). Such models must take into account the distribution and probability of attack and a possible nonlinear response of the pest to a controlling factor (Feldman and Curry 1982).

### Duration of pest attack

Crop yield reduction depends on the duration of pest attack as well as pest density. This can be quantified by relating yields to *bug days,* the number of pests multiplied by the number of days they are present. This method has been used for brown planthopper.

### Mixed crops

In multiple cropping, two or more crops are often grown together—at once, overlapping, or serially during the season. One way to relate yield (*y*) to pest attack is to express the different crops (a and b) in terms of the pure stand of one crop (a) on the same area—a land equivalent ratio (LER) (Zandstra et al 1981):

$$\text{LER} = \frac{\text{yield of a + b}}{\text{yield of a}}$$

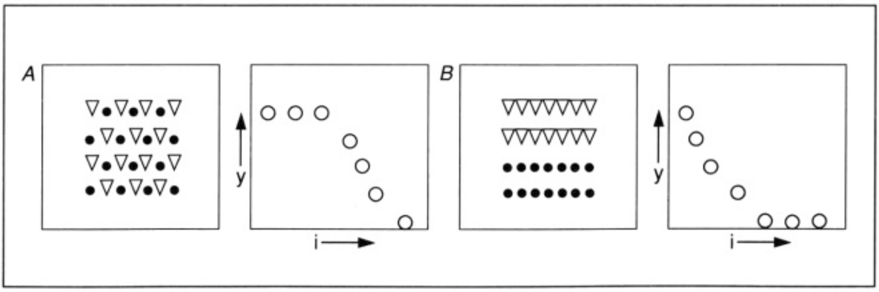
If different crops are grown for different periods of time, an area time equivalent ratio is useful (Hiebsch 1978). That brings in the proportion and time each crop occupies an area in the total crop pattern. The effect of pests on yield is measured by the same techniques as in single crops, with and without pests, etc.

### Missing plants and plant interaction and compensation

The distribution of a pest attack in a field affects the relationship between yield and attack (Fig. 2). In a spaced-out attack with missing plants (*A*), unattacked plants next to a missing or attacked plant usually yield more than if all are unattacked, due to the removal of competition for light, water, or nutrients. The compensation depends on the degree of competition resulting from plant spacing, weeds, and growing conditions. Often, some pest attack can be tolerated without loss of yield.

If attacked or missing plants occur in large groups (*B*), however, compensation cannot occur. Yield falls rapidly with a rise in infestation.

Compensation can be measured by examining the yield of an unattacked plant surrounded by different arrangements of attacked plants—for example, groups of five (pentads) of potato plants (Killick 1979) or in *cylinders of influence* around tobacco plants attacked by cutworm (Shaw 1980). The effect of missing plants is seen in the



**2.** The effect of the spacing of a pest attack on the relationship between yield (y) and infestation (i). *A* shows spaced-out attack; *B,* clumped attack.

hyperbolic relationship between plant weight and population, the 3/2 thinning rule (Solbrig 1980), and the simple model of Hardwick and Andrews (1983). The difference between actual and expected yield of attacked potatoes has been used to show how well different plants can compensate for attack (Adams and Lapwood 1983).

Different causes of loss interact so much and yield response is so variable, one is really dealing with a *response surface.* Multivariate methods are the only accurate way to look at all the factors involved. Ecology and weed science are providing some answers (Begon and Mortimer 1986).

### Distribution of loss

The statistical distribution of crop loss over a wide area in both space and time is obviously related to pest distribution. Distributions are often nonrandom, either because climate or crops often occur in aggregated groups or because they occur at regular intervals. If the distribution were known, it would be easier to predict crop losses and the need for pesticides. Tanner (1962) found similar loss distribution curves when the summed frequency of losses as percentages of total loss were plotted against multiples of the average loss. Curves can be linearized by taking logs. In this way, the actual and expected curves can be compared to explain why differences in loss distribution exist (e.g. because of different sowing times [Walker 1965]).

## Crop yield reduction and economic thresholds

Information on crop loss due to pests is used to set an economic threshold to be used in making decisions about crop protection. The subject is reviewed by Headley (1972a,b), Stern (1973), and Norton (1984); in rice by Andow and Kiritani (1983); and in general by Reichelderfer et al (1984) and Pedigo et al (1986).

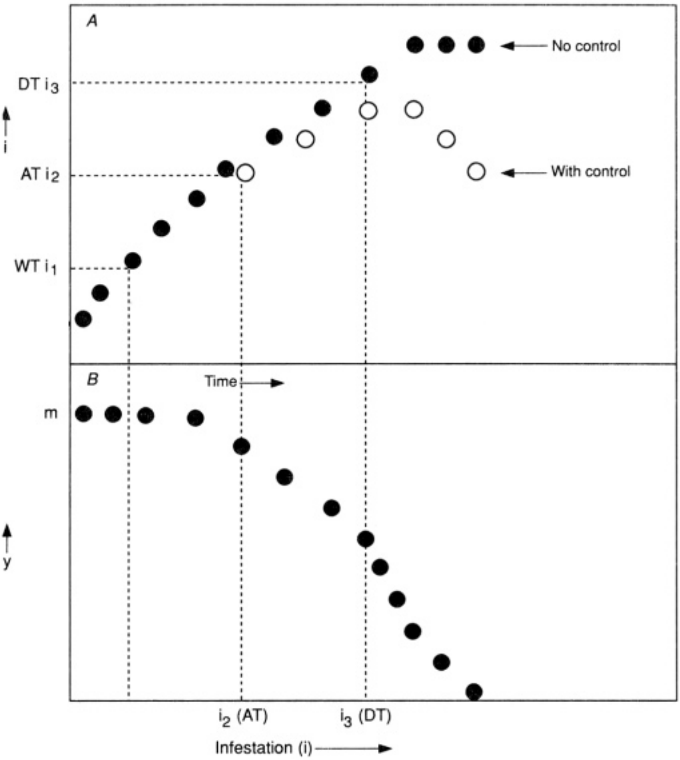
Different stages of threshold development can be seen in graph ( $A$ ), of increasing pest infestation ( $i$ ) with time, and in graph ( $B$ ), of yield ( $y$ ) reduction as infestation increases (Fig. 3). A warning threshold is reached at ( $i_1$ ) and an action threshold (AT) at ( $i_2$ ). AT is sometimes called the economic threshold, the level of pest infestation at which action must be taken to prevent the infestation rising to the damage threshold ( $i_3$ ) (DT) or economic injury level, where economic loss occurs. Economic loss must be defined, but is usually taken as when increased yield or quality, benefit (B), is greater, or at least not less than, the costs (C) of pest control. That is, $B/C > 1$.

Thus in B, there may be little loss of yield at the AT, but economic loss at the DT. The difference in time between AT and DT depends on how quickly the crop responds to attack; the thresholds may occur simultaneously.

### Economic action thresholds

The level of pest attack or damage chosen as an AT is not fixed, but is a dynamic value that can change with many factors. These can be expressed in a conceptual model (Chiang 1983).

$$\mathrm{AT} = \frac{\mathrm{t} \times \mathrm{T} \times \mathrm{P} \times \mathrm{B} \times \mathrm{S\,C} \times \mathrm{CF}}{\mathrm{Y} \times \mathrm{V} \times \mathrm{y/i} \times \mathrm{C} \times \mathrm{F} \times \mathrm{CE} \times \mathrm{R} \times \mathrm{S}}$$



**3.** Stages of threshold development. A shows increasing pest infestation with time, *B* shows yield reduction as infestation Increases.

Factors that favor a high AT and less control are
*t* = time between infestation, decision, control, and harvest;
*T* = temperature effect on infestation, control, and yield;
*P* = crop resistance to or tolerance of pest attack;
*B* = status of biological control of pests (Gonzalez and Wilson 1982);
*SC* = survival factor: pest development and survival; and
*CF* = critical factor: social attitude toward pests, food, chemicals, and the environment.

Factors favoring a low AT and more control measures are
*y* = amount of yield;
*V* = value of yield, which depends on y and the elasticity of demand;
*y/i* = relation of infestation to yield;
*C* = cost of control measures (Walker 1977);
*F* = profit margin;
*CE* = efficiency of pesticides, biocontrols, etc. in reducing pests;
*R* = farmer's perception of the effect of pests and their control, and his expectation of yield; and
*S* = crop stress: water, nutrients, soil, crop diseases, etc.

Another important factor is crop development. Hearn and Room (1979) included the number of cotton flowers and bolls in setting the AT, because a certain number are needed to get a good yield. In general, more complex models may, give better yield forecasts, but they will be more limited in application, measuring inputs will cost more, and farmers will need more technical ability to apply them. Cost and applicability are the critical factors in evaluating how useful a model is in practice.

## The gain threshold

One method for using crop loss information and economic thresholds to make control decisions is through use of a gain threshold (GT) (Bautista et al 1984). GT is yield in terms of the cost of pest control, or the amount of yield which must be produced to pay for pest control at the action threshold level of pest attack. Hence, it is the yield that must be produced to be economic.

$$\text{GT (kg/ha)} = \frac{\text{cost of control/ha}}{\text{unit price of yield/kg}}$$

GT can be calculated from the relationship between yield loss ($w$) and infestation ($i$)

$$w = a + b\,(i)$$

where $a$ is the loss in the absence of pests and $b$ the rate of loss. slope, or loss per unit of infestation. AT can be found from

$$\text{AT} = \frac{\text{GT}}{\text{b}}$$

## How to determine economic thresholds

There are three main ways to determine an economic threshold:

- A value is taken from elsewhere, tested, adapted, and changed until it works.
- A suitable value is estimated, tested, and adjusted until it is satisfactory.
- A value is calculated empirically from the effect of infestation on yield, control costs, and crop price and tested in farmers' fields for several years.

A threshold is acceptable if its use increases yield, saves money, and/or uses less pesticide (Herdt et a1 1964).

The farmer's perception of pest attack, his expectation of yield, and his use of economic thresholds need socioeconomic study, as described by Tait (1978) and applied to rice by Smith (1982). Farmers' actions depend on their background, experience with local conditions, and attitude toward risk.

## Decisions in pest management

Information on pest attack and yield loss and their economic effects can be used in deterministic, linear models or in stochastic, probability-based models (Austin 1982; Mumford 1987; Mumford and Norton 1984; Norton 1976a,b, 1982; Norton and Mumford 1983). Examples include linear programming in insect control (Watt 1963) and the costs and probabilities of different strategies in a decision tree (Valentine et al 1976), a pay-off, or a decision matrix. Shoemaker et al (1979) described a simulation model in which inputs can be varied. Other examples are given by Reichelderfer et al

(1984). The systems approach is reviewed by Ruesink (1976) and Getz and Gutierrez (1982). The management techniques of optimization and cost-benefit analysis are often used in project assessment, to compare different pest management actions, after future costs and benefits are discounted to net present values. The problems of food shortage, pesticides, health, and environment often remain.

Single observations on pests and yields are valuable, but a multivariate model of other factors over the yield response surface would add considerably to our knowledge. Computers make this increasingly possible, but good pest and yield data are still the basic essentials.

## References cited

Adams J M (1964) A review of the literature concerning losses in cereals and pulses since 1964. Trop. Sci. 19:1-28.

Adams J M (1976) A guide to the objective and reliable estimation of food losses in small farmer storage. Trop. Stored Prod. Inf. 32:5-12.

Adams J M (1977) A bibliography on post-harvest losses in cereals and pulses, with particular reference to tropical and sub-tropical countries. Report TDRI/G 10, Overseas Development Natural Resources Institute, Overseas Development Administration, London. 23 p.

Adam M J, Lapwood D H (1983) The effect of *Erwinia* on potato plants. 2. Compensatory growth. Ann. Appl. Biol. 103:79-85.

Ahrens C, Cramer H H, Mock M, Peschel H (1983) Economic aspects of crop losses. Proc. 10th Int. Congr. Plant Prot. Brighton 1:65-73.

Andow D H, Kiritani K (1983) The economic injury level and the control threshold in rice. Jpn. Pestic. Inf. 43:3-9.

Austin R B, ed. (1982) Decision-making in the practice of crop protection. Monograph 25. British Crop Protection Council, Bracknell. UK. 238 p.

Bardner R, Fletcher K E (1974) Insect infestations and their effects on growth and yield of field crops. Bull. Entomol. Res. 64:141-160.

Bautista R C, Heinrichs E A, Rejesus R S (1984) Economic injury levels for the rice leaffolder: insect infestation and artificial leaf removal. J. Econ. Entomol. 13:439-443.

Begon M, Mortimer M (1986) Population ecology: a unified study of plants and animals. 2d ed. Blackwell, Oxford. 204 p.

Chiang H C (1983) Factors to be considered in refining a general model of economic threshold. Entomophaga 27:99-103.

Chiarappa L, ed. (1971) Crop loss assessment methods: FAO manual on the evaluation and prevention of losses by pests, diseases, weeds. Food and Agriculture Organization and Commonwealth Agricultural Bureaux International, Slough, UK. 123 p.

Cramer H (1967) Plant protection and world crop protection. Pflanzenschutz Nachr. Bayer Leverkusen. 524 p.

Dyck V A (1974) Pest damage to plots and economic thresholds. Paper presented at the International Rice Research Conference, International Rice Research Institute, Los Baños, Laguna.

FAO — Food and Agriculture Organization (1967) Papers presented at the FAO Symposium on Crop Losses and background papers. Rome, Italy.

FAO — Food and Agriculture Organization (1977) Analysis of an FAO survey of post-harvest crop losses in developing countries. Rep. AGPP: MISC./27. Rome, Italy. 147 p.

Feldman R M, Curry G L (1982) Operations research for agricultural pest management. Operations Res. 30:601-618.

Gage S H, Mukerji M K (1971) A perspective of grasshopper population distribution in Saskatchewan and interrelations with control. Environ. Entomol. 6:469-479.

Getz W M, Gutierrez A P (1982) A perspective on systems analysis in crop production and insect pest management. Annu. Rev. Entomol. 27:447-490.

Gomez K A, Gomez A A (1984) Statistical procedures for agricultural research. 2d ed. Wiley, London and New York. 760 p.

Gonzalez D, Wilson L T (1982) A food web approach to economic thresholds: a sequence of pests/predaceous arthropods on California cotton. Entomophaga 27:31-43.

Hardwick R C, Andrews D J (1983) A simple model of the relationship between plant density, plant biomass and time. J. Appl. Ecol. 20:905-914.

Harper J L (1977) Population biology of plants. Academic Press, London and New York. 892 p.

Harris P (1974) Possible explanations of plant yield increases following insect damage. Agroecosystems 1:219-225.

Headley J C (1972a) Defining the economic threshold. Pages 100–108 *in* Pest control strategies for the future. National Academy of Science, Washington. D.C.

Headley J C (1972b) The economics of agricultural pest control. Annu. Rev. Entomol. 17:273-278.

Heam A B, Room P M (1979) Analysis of crop development for cotton pest management. Prot. Ecol. 1(4):265-277.

Herdt R W, Castillo L L, Jayasuriya S K (1984) Economics of insect control in rice in the Philippines. Pages 41-56 *in* Judicious and efficient use of insecticides on rice. International Rice Research Institute, P.O. Box 933, Manila. Philippines.

Hewitt G B, Onsager J A (1982) A method of forecasting potential losses from grasshopper feeding on northern mixed prairie forages. J. Grassland Manage. 35:53-57.

Hiebsch C (1978) Comparing intercrops with monoculture. Pages 187-200 *in* Annual report 1976-1977. Soil Science Department, Carolina State University, Raleigh, North Carolina, USA.

Judenko R (1983) Glossary of terms used in the application of the analytical method for assessing losses caused by pests. Rocz. Nauk. Roln. E. 10:9.

Justesen S H, Tammes P M L (1960) Studies of yield losses. 1. Self-limiting effects of injuries or competitive organisms on yield. Tijdschr. Plantenziehten. 66:281-287.

Khosla R K (1977) Techniques for assessment of losses due to pests and diseases of rice. Indian J. Agric. Sci. 47:171-174.

Killick R J (1979) The effect of infection with potato leaf roll virus on yield and some of its components. Ann. Appl. Biol. 91:67-74.

Lynch R E (1980) European corn borer: yield losses in relation to hybrid and stage of corn development. J. Econ. Entomol. 74:159-164.

Mumford J D (1987) Analysis of decision-making in pest management. Pages 201-208 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, St. Paul, Minnesota.

Mumford J D, Norton G A (1984) Economics of decision-making in pest management. Annu. Rev. Entomol. 29:157-174.

Mumford J D, Norton G A (1987) Economics of integrated pest management. Pages 191-200 in Crop loss assessment and pest management. P. S. Teng, ed. APS Press, St. Paul, Minnesota.

Norton G A (1976a) An analysis of decision making in crop protection. Agroecosystems 3:27-44.

Norton G A (1976b) Pest control decision-making, an overview. Ann. Appl. Biol. 84:444-447.

Norton G A (1982) A decision-analysis approach to integrated pest control. Crop Prot. 1:147-164.

Norton G A (1984) Economic considerations in IPM programmes. *In* Proceedings of seminar on IPM in Malaysia, Kuala Lumpur, Malaysia.

Norton G A, Mumford J D (1983) Decision-making in pest control. Ann. Appl. Biol. 8:87-117.

Ordish G (1952) Untaken harvest: man's loss of crops from pest, weed and disease. Constable, London. 171 p.

Pedigo L, Hutchins S H, Highley L G (1986) Economic injury levels in theory and practice. Annu. Rev. Entomol. 341-368.

Pimentel D, ed. (1981) Pest management in agriculture. 1. CRC Press, Boca Raton, Florida. 597 p.

Pimentel D. Andow A, Dyson-Hudson R, Gallahan D, Jacobson S, Irish M, Kroop S, Moss A. Schreiner I, Shepard M, Thompson T, Vinzant B (1980) Environmental and social costs of pesticides: a preliminary assessment. Oikos 34:126-140.

Pinstrup-Andersen P, de Londoño N, Infante M (1976) A suggested procedure for estimating yield and production losses in crops. PANS 22:359-365.

Reed W (1983) Crop losses caused by insect pests in the developing world. Proc. 10th Int. Congr. Plant Prot. Brighton 1:74-79.

Reichelderfer K H, Carlson G A, Norton G A (1984) Economic guidelines for crop pest control. Plant Prod. Prot. Pap. 58. Food and Agriculture Organization, Rome. Italy. 93 p.

Ruesink W (1976) Status of systems approach to pest management. Annu. Rev. Entomol. 21:27-37.

Shaw M J P (1980) Growth compensation for insect pest damage in field tobacco. Zimbabwe Sci. News 14:97-100.

Shoemaker C A, Huffaker C D, Kennet C E (1979) A systems approach to insect pest management of a complex of olive pests. Environ. Entomol. 8:162-189.

Solbrig O T (1980) Demography and evolution in plant populations. Pages 35-42 *in* Demography and evolution in plant populations. Botanical monograph 15. Blackwell, Oxford.

Southwood T R E, Norton G A (1973) Economic aspects of pest management strategies and decisions. *In* Insects: studies in population management. P. W. Geier, L. R. Clark, D. J. Anderson, and H. A. Nix, eds. Ecological Society of Australia. Mem. 1. Canberra.

Smith W H, ed. (1982) The role of anthropologists and other social scientists in interdisciplinary teams developing improved food production technologies. United Nations Development Programme/International Rice Research Institute, P.O. Box 933, Manila, Philippines. 101 p.

Stem V M (1973) Economic thresholds. Annu. Rev. Entomol. 18:258-280.

Tait E J (1978) Factors affecting the usage of insecticides and fungicides on fruit and vegetable crops in Great Britain. 1. Crop specific factors. 2. Farmer specific factors. J. Environ. Manage. 6:127-151.

Tammes P M L (1961) Studies of yield losses. 2. Injury as a limiting factor of yield. Tijdschr. Plantenziekten. 67:257-263.

Tanner C C ( 1962) The distribution of crop losses from pests around the average loss. PANS 8:110-117.

Thresh J M (1976) Gradients of plant virus diseases. Ann. Appl. Biol. 82:381-406.

Valentine H T, Newton C M, Talerico R M (1976) Compatible systems and decision models for pest management. Environ. Entomol. 5:891-900.

Waibel H (1986) The economics of integrated pest control in irrigated rice. Springer, Ijmuiden, Netherlands. 210 p.

Walker PT (1965) The distribution of loss of yield of maize and of infestations of the maize stem borer in East Africa. Meded. Landbouwhogesch. Gent. 30:1577-1587.

Walker P T (1975) Pest control problems, pre-harvest, causing major losses in world food supplies. FAO Plant Prot. Bull. 23:70-82.

Walker P T (1977) Crop losses: some relations between infestation, cost of control and yield in pest management. Meded. Landbouwwet. Gent. 42:419-426.

Walker P T (1983a) The assessment of crop losses in cereals. Insect Sci. Appl. 4:97-104.

Walker P T (1983b) Crop losses: the need to quantify the effects of pests, diseases and weeds on agricultural production. Agric. Ecosyst. Environ. 9:119-158.

Walker P T (1987) Losses in yield due to pests in tropical crops and their value in policy decision-making. Insect Sci. Appl. 8:665-671.

Watt K E F (1963) Dynamic programming, look-ahead programming and the strategies of insect pest control. Can. Entomol. 95:525-536.

Wheatley G A (1974) Insect problems in crops for processing. Pestic. Sci. 5:101-112.

Zandstra H G, Price E C, Litsinger J A, Morris R A (1981) A methodology for on-farm cropping systems research. International Rice Research Institute. P.O. Box 933, Manila, Philippines. 149 p.

## Notes

*Author's address:* P. T. Walker, 10 Cambridge Road, Salisbury, Wiltshire SP1 3BW, United Kingdom.

*Citation information;* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Empirical disease-yield loss models

R. E. Gaunt

Investigations of disease and yield relationships in field crops normally generate large amounts of data, especially when experiments and surveys are conducted in several sites and across several seasons. While single season experiments on one disease may be analyzed and interpreted to describe the relationship with yield without using models, such limited information has little practical value. Complex data from experiments involving several pests in multiple sites across seasons can be difficult to interpret. Modeling of yield responses to disease is a well-established technique. Models are available at several levels of complexity that encompass different methods and different philosophical approaches.

Modeling is a method of representing a system and of summarizing information. Models can be used to define or to test hypotheses. Empirical models are understood to be those derived using an experimental, often statistical, approach. For example, a relationship is defined by the regression or correlation of an independent variable (disease or other pest) with a dependent variable (yield or yield loss). Both the independent variable and the form of the relationship can be defined by the model. Theoretical or mechanistic models are derived from prior knowledge of the causal relationship between variables.

It is the structure of the model that is empirical, not the origin of the data. The distinction is important, because most models, whether empirical or theoretical, are likely to be based at least in part on experimental observations from trials designed specifically for the purpose.

## Objectives

Empirical models are developed and used for various purposes (Teng 1987). The primary use has been to define a simple relationship between disease and yield, which in turn is used in regional surveys to estimate overall yield reduction. The survey estimates can then be used in devising marketing strategies, for long-term records, or in assessing the importance of diseases and assigning research priorities. When used within the limitations of the specific model, the approach is very successful. Inappropriate uses, such as application to different production systems or in multiple-pest situations, has provoked criticism of the basic modeling approach, rather than of the method of application. Thus, in both model development and application, it is important to consider objectives carefully.

Empirical models also have been used to estimate yield response in specific fields for farm-level management, to identify likely control tactics, and to increase knowledge of the disease-yield relationship. Great care is required in selecting a model to meet these separate objectives. A model's use may be limited to only certain situations, such as a single-disease, short-duration epidemics. For management of specific farm fields, it can be argued that theoretical or mechanistic models are the most appropriate. An empirical model may be limited by the theoretical knowledge available. For example, the period of growth used for disease measurement in a model for disease management may be defined by theory, but the model may be selected empirically.

## Variables measured

Both dependent (yield) and independent (disease) variables can be measured in several ways. The choice of measurement is determined partly by the objective and partly by personal preference, in the absence of more precise knowledge. It is difficult to define all variables scientifically, but recent research is increasing our understanding.

The dependent variable can be defined as either yield or yield loss (the choice can be based on personal preference as well as on objectives). A more important, and related, choice is whether to use absolute units of yield (t/ha or $g/m^2$) or proportional (usually percent) yield. Absolute yield assumes that the actual yield per unit disease is the same, irrespective of the yield target in the absence of disease (Mackenzie and King 1980). Proportional yield is not constant, it increases with decreasing target yield. A proportional-yield model assumes that yield response in absolute units is dependent on target yield. Unfortunately, little experimental work has been done on this topic, but evidence suggests there is no generalized relationship between disease and yield. In most crops and regions, proportional yield loss models have been used more frequently than actual yield or yield loss models.

In some cases, biomass has been used as a yield variable, especially in hybrid models which are constrained by theoretical knowledge but defined empirically. This variable is unlikely to be commonly used in empirical models, except for crops where the whole plant is harvested or when the harvest index is very stable. However, biomass is often used as the most important variable in theoretical models. Its use in conjunction with yield component analysis in empirical modeling may be useful in increasing our understanding of relationships.

Methods of disease measurement, the independent variable, are reviewed elsewhere in this volume. It is relevant here to consider the choice of method. It is common to use a pathogen-based variable, such as disease incidence or severity, and to exclude effects on host senescence. For many objectives, such measurements are ideal for empirical models, especially because data can be produced rapidly, often with less training than is needed to collect data for other options. But such measurements only partly describe the effect of disease on the plant production system. That may limit the reliability of the model. More plant-oriented measurements of disease, such as percentage or actual green area remaining, improves the fit of a model and the amount of variation in the dependent variable explained by the model (Lim and Gaunt 1986; Rotem et al 1983a,b). Such measurements may be more time-consuming and require more training. Although they may not be justified, especially for single-disease, short-duration epidemics or for crops with a relatively stable production environment, they can be considered a valid option. Recent advances in remote measurement of canopy green area (Nutter, this volume) and the use of models for multiple disease and/or long-duration epidemics in less stable environments may increase the use of host-based measurements.

## Methods of model development

Most empirical models are based on regression analyses of the independent and dependent variables, although other statistical methods have been used (Teng 1985). Preferably, variables are selected before measurement, using prior knowledge of the physiological basis of the relationship. Or they may be preselected from a database. Variables usually are selected from a database by regression analysis, using stepwise methods. Alternatively, the researcher may choose variables on the basis of regression statistics.

The first decision in model development is usually the form of the regression analysis. Models can be described as single (critical)-point or multiple-point, depending on the number of variables in the equation.

$$\text{single-point } Y = a + bx$$

$$\text{multiple-point } Y = a + b_i x_i + b_2 x_2 \ldots b_1 x_1$$

In single-point models, the variables may be disease at a specific growth stage, time to first disease symptoms (disease-free period), or time to a specified disease level (threshold). All such models assume that single measurements of disease can adequately describe an epidemic and that the chosen disease measurement is the most appropriate. Neither assumption is likely to be true in all cases, but may well be true in some cases.

Definition of the limits within which the assumptions are reasonably true is an important aspect of model use. Sometimes it is assumed that growth stage or time period is causally important. If the variables are selected within limits set by prior physiological knowledge, this may be true. But if they are selected on purely statistical criteria, the assumption may not be valid. There are many reasons why a particular growth stage may be a good predictor of yield or yield loss without disease at that stage having a direct effect on yield. For example, disease at an early growth stage may be a good predictor of disease later in the season, with disease later in the season the cause of yield constraint. A knowledge of yield components and yield physiology can identify such circumstances.

Multiple-point models are often based on measurements of disease at several growth stages, on several plant parts, or a combination of the two. These models are developed to overcome problems of varying infection rates and periods of disease decline found in many field situations, especially with longer duration epidemics. Increasing the number of factors in regression equations often improves both the fit and the amount of variation explained. But it may cause some statistical problems, especially if more than three variables are used. A combination method using accumulated disease severity data, known as area under the disease progress curve (AUDPC), in a single-point model has been used successfully. AUDPC models do not account for variability in the time of disease presence in different epidemics. This is not necessarily a problem, if yield is related closely to accumulated photosynthetic area during the season irrespective of the time of maximum area.

A further variation in model type is the inclusion of nondisease variables to account for yield variation attributable to such factors as sowing date or rainfall. Yield variation from single field to regional levels in relation to disease constraints has been reviewed recently (Gaunt and Robertson 1989). In its simplest form, the inclusion of nondisease factors may be only cosmetic, with no enhancement of the relationship between disease and yield. In more complex models, nondisease factors may modify the effect of disease on yield. Such models would require prior knowledge of yield physiology and would be more theoretical than empirical.

Most empirical models are linear and assume a constant relationship between disease level and yield. But extensive evidence suggests that this assumption is not valid. Quadratic or other polynomial models have been used successfully. Teng (1985) suggested that there may be at least nine different responses of crops to disease, depending on growth stage of the crop, management strategy, and environmental factors. Caution is necessary in using nonlinear models, because statistical procedures can fit polynomial functions to almost any data set but may introduce spurious relationships which are unlikely to have any biological validity. In a truly empirical model, this may not be important. But it should be recognized that a model may reflect a particular characteristic of a data set and may have very little application to other data. Large databases may eliminate this type of problem and allow the use of linear or simple nonlinear functions.

A critically important aspect of modeling is evaluation of the model, both statistically and in practice. Data for regression models must meet certain criteria: lack of correlation of independent variables, uniform variability, and normal distribution of variation (Madden 1983). Models are evaluated using an F-statistic derived from the regression and error mean squares as a test of the overall significance of fit to the data. It is normally considered essential that this statistic be significant at a specified level of probability. The regression coefficient(s) also can be tested at defined probability levels by t- or F-statistics.

The coefficient of determination ($R^2$) derived from regression and error sums of squares defines the proportion (percentage) of total variation in the dependent variable explained by the independent variable(s). The $R^2$ value often is considered the most important in selecting from several regression models. It is judged subjectively by the researcher. The amount of variation not explained by the model can sometimes be attributed to known factors (e.g. sowing date, cultivar), in which case either the factors can be incorporated in the model or a model with a low $R^2$ value can be accepted.

The $R^2$ value also is used to determine the most appropriate number of factors in a multiple-point model. The number of factors needed is more correctly determined by examining the partial regression coefficients. The S-statistic, derived from the error mean square, provides a measure of the precision of the model in relation to the estimate of the dependent variable. Confidence intervals for estimates can be calculated from the model. But the S-statistic is not often used in crop loss modeling. Details of procedures are described by Gomez and Gomez (1984).

Field evaluation of models can be more important than statistical tests, but few examples of validation of models on independent data are found in the literature. Research in this area would be especially useful in defining the practical limits of model use.

## Applications

Empirical models may be used to test whether a previously determined functional form (prior physiological knowledge) provides a good relationship between variables. Alternatively, a model may be used to identify the form of a function where there is no previous knowledge. Great care and experience are needed in both cases, to guard against spurious biological conclusions. Preferably, specific physiological knowledge or experimentation should be used for verification.

More frequently, models are derived without too much consideration of their form. Care should be taken if they are used for survey or management purposes. For surveys, a model should not be used outside the range of the data from which it was derived. Extrapolation errors are likely if a model is used in different sites, with different management systems, or with different cultivars. The scope of the model selected should match closely the scope of the survey.

A common cause of error is the use of single-disease models in multiple-disease situations. Such use assumes independence of effect, which is unlikely and which commonly leads to overestimation of total losses, although underestimation also can occur.

There have been several attempts to derive multiple-pest empirical models, using regression (Johnson et a1 1987, Watts-Padwick 1956), synoptic (Stynes 1975), and other methods of analysis. The considerable problems with the development and use of such models reveal the limitations of applying currently available empirical approaches to complex relationships. Rouse (1988) argued that models for these purposes should be based on physiological concepts. The use of host-based measurements of disease may increase the value of empirical models of multiple pests, but additional data are needed to assign the proportions of estimated yield loss to specific diseases.

The use of empirical models for management purposes, especially for making decisions on the application of chemical controls, has proved to be satisfactory for short-duration epidemics of single diseases of crops in stable production environments. In these conditions, it is safe to assume that disease effects are relatively constant and decisions for individual fields are likely to be reasonably satisfactory. A model can be used to define a threshold, which may include a calculation of the cost:benefit of a control practice.

In less stable environments or with longer duration epidemics, empirical models are likely to be misleading unless they include some physiological criteria. Further work on crop growth-coupled models is needed for models to be adequate for management purposes. In the meantime, it is likely that control decisions will be based on epidemic models, on subjective thresholds, or on intuitive analyses.

## References cited

Gaunt R E, Robertson M J (1989) Yield variability and the impact on local and regional estimates of yield reductions caused by disease. In The spatial component of plant disease epidemics. M. J. Jeger, ed. Prentice Hall, UK.

Gomez K A, Gomez A A (1984) Statistical procedures for agricultural research. International Rice Research Institute, P.O. Box 933, Manila, Philippines. 680 p.

Johnson K B, Teng P S, Radcliffe E B (1987) Analysis of potato foliage losses caused by interacting infestations of early blight, *Verticillium* wilt, and potato leafhopper; and the relationship to yield. Z. Pflanzenkr. Pflanzenschutz. 94:22-33.

Lim L G, Gaunt R E (1986) The effect of powdery mildew (*Erysiphe graminis* DC. f. sp. *hordei*) and leaf rust (*Puccinia hordei* Otth.) on spring barley in New Zealand. I. Epidemic development, green leaf area and yield. Plant Pathol. 34:44-53.

Mackenzie D R, King E (1980) Development of realistic crop loss models for plant diseases. Pages 85-89 *in* Crop loss assessment. Proceedings of the Stakman commemorative symposium. P. S. Teng, ed. Miscellaneous Publications. Minnesota Agricultural Experiment Station, St. Paul, Minnesota. USA.

Madden L V (1983) Measuring and modelling crop losses at the field level. Phytopathology 73:1591-1596.

Nutter F W Jr. (1990) Remote sensing and image analysis for crop loss assessment. Pages 93-105 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Rotem J, Bashi E, Kranz J (1983a) Studies of crop loss in potato blight caused by *Phytophthora infestans*. Plant Pathol. 32:117-122.

Rotem J, Kranz J, Bashi E (1983b) Measurement of healthy and diseased haulm area for assessing late blight epidemics in potatoes. Plant Pathol. 32:109-115.

Rouse D I (1988) Use of crop growth-models to predict the effects of disease. Annu. Rev. Phytopathol. 26:183-201.

Stynes R A (1975) A synoptic study of wheat. Ph D thesis, University of Adelaide, South Australia. 291 p.

Teng P S (1985) Construction of predictive models. II. Forecasting crop losses. Pages 179-206 *in* Advances in plant pathology. Vol. 4. R. S. Ingram, ed. Academic Press, London.

Teng P S (1987) Quantifying the relationship between disease intensity and yield loss. Pages 104-113 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, Minnesota, USA.

Watts-Padwick G (1956) Losses caused by plant diseases in the colonies. Commonwealth Mycological Institute, Kew, Surrey, UK. 60 p.

## Notes

*Author's address:* R. E. Gaunt, Plant Protection Research Unit, Microbiology Department, Lincoln University College of Agriculture, Christchurch, New Zealand.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Yield losses due to weeds in rice in the Philippines

K. Moody

Weed management is perhaps the most important single element needed to improve crop stability in the humid tropics (Harwood 1979). The only universal pests in rice ( *Oryza sativa* L.) are weeds that exceed tolerable levels in all seasons (Moody and Cordova 1985). Because weeds are found in all fields in all crops, it is necessary to invest in control practices to reduce yield losses caused by weed competition.

Many factors cause loss of agricultural production, but there is little doubt that weeds are of major significance (Moody 1983). Because weeds are so common and widespread, people do not fully appreciate their importance in terms of the losses they cause and the cost of their control.

The total number of weed species in a field depends largely on the natural environment and the cropping system. The number is usually lower (10-15) in highly productive and intensive systems with a low diversity of crops grown in rotation, and higher (up to 50 or more) in extensively cropped fields in which a highly diversified crop rotation is practiced (Koch et al 1982). In either case, only a few species will account for most of the damage. The number of species that comprise the major portion of the weed flora in any ricefield is usually less than 10; rarely are more than 3 or 4 species important (Moody and Drost 1983).

The total monetary costs due to weeds are almost impossible to determine (Moody 1983). The whole system of weed control is so intermixed with so-called standard agricultural practices that accounting is difficult (Soerjani 1971). Factors that must be considered in determining total loss caused by weeds include land preparation, cultural practices pertaining to weed control, weed control expenses, and reduction in yield quantity and quality. Parker and Fryer (1975) stated that inadequate weeding results in serious yield reductions on most farms. Additional indirect losses are such that the total loss due to weeds on small-scale tropical farms may be as much as 25%.

Assuming that rice yields could be increased 10% by improved weed control practices, the increase in rice production throughout the world would be a staggering 46 million t. But increases mean little unless they can be achieved economically.

Maximizing crop yield without concurrently maximizing net revenue is rarely the objective of any producer. Herdt (1979) noted that farmers are unlikely to be impressed by yield gains equivalent to 5% of their current yields. He says that is obviously why farmers do not increase their level of weed control. However, Gomez et al (1979) reported that rather high returns were obtained from modest additional costs for weed control. The benefit-cost ratio of increased weed control was 4.2 in the wet season and 7.9 in the dry season.

## Yield losses

Rice grain yield losses due to weeds over the past 25 yr at IRRI have varied considerably from season to season and year to year. In irrigated transplanted rice in the dry season, yield reductions with uncontrolled weed growth compared to the best chemical weed control treatment ranged from 1.8 to 8.6 t/ha (data from IRRI annual reports). In the wet season, yield reductions ranged from 0.8 to 5.9 t/ha.

Yield losses due to weeds vary with such factors as type of rice culture, rice cultivar grown, plant spacing, amount of fertilizer applied, duration and time of weed infestation, weed species, amount of weed growth (this may be high in research station experiments due to the sowing of weed seeds), cropping season, and ecological and climatic conditions. Weed flora commonly change in response to changes in climate or cultural practices.

Numerous weed control trials have been conducted in rice in the Philippines during the past 20 yr. Few attempts have been made to summarize the available data. Mercado and Arceo (1980) reported a large increase in yield due to hand weeding and herbicide use in transplanted rice trials in 1975-78. Yields of hand-weeded and herbicide-treated plots were 1.5-2.0 times that of the unweeded plot.

Yield losses due to uncontrolled weed growth in different types of rice culture at IRRI are given in Table 1. The following conclusions can be made.

In terms of crop yield

- Yields were higher in the dry season than in the wet season.
- Yields for wet seeded rice were equal to or higher than those for transplanted rice.
- In the wet season, yields for upland and dry seeded rice were about 30% lower than those for wet seeded and transplanted rice.

In terms of percent yield loss

- The greatest yield losses occurred in upland and dry seeded rice, the least in transplanted rice.
- In transplanted rice, yield losses were greater in the wet season than in the dry season; in wet seeded rice, there was little difference between seasons.
- In rainfed conditions, losses were greater for wet seeded rice than for transplanted rice.
- Average yield losses were greater for wet seeded rice than for transplanted rice.

In terms of actual yield losses

- The greatest yield losses were in wet seeded rice, the least in dry seeded and upland rice.
- Yield losses were greater in the dry season than in the wet season for both transplanted and wet seeded rice.

**Table 1. Yield losses due to uncontrolled weed growth in different types of rice culture (IRRI, 1962-85).**

| Type of rice culture | Observations (no.) | Yield (t/ha) | | Yield loss | |
|---|---|---|---|---|---|
| | | Weeded | Not weeded | t/ha | % |
| Upland | 13 | 2.8 | 0.4 | 2.4 | 86 |
| Dry seeded | 8 | 2.7 | 0.4 | 2.3 | 85 |
| Wet seeded rainfed | 13 | 4.1 | 1.3 | 2.8 | 68 |
| Wet seeded irrigated (wet season) | 14 | 4.2 | 1.5 | 2.7 | 64 |
| Wet seeded irrigated (dry season) | 15 | 6.6 | 2.5 | 4.1 | 62 |
| Wet seeded av | | 5.0 | 1.8 | 3.2 | 64 |
| Transplanted irrigated (dry season) | 18 | 6.1 | 2.4 | 3.7 | 61 |
| Transplanted irrigated (wet season) | 19 | 4.1 | 1.8 | 2.3 | 56 |
| Transplanted rainfed | 14 | 3.7 | 1.7 | 2.0 | 54 |
| Transplanted av | - | 4.7 | 2.0 | 2.7 | 57 |
| Av | - | 4.5 | 1.6 | 2.9 | 64 |

- There was little difference in yield loss between irrigated and rainfed transplanted and wet seeded rice in the wet season.
- Yield losses were greater for wet seeded rice than for transplanted rice.
- Average yield loss due to uncontrolled weed growth across years and different types of rice culture was 2.9 t/ha (64%).

## Benefits of weed control

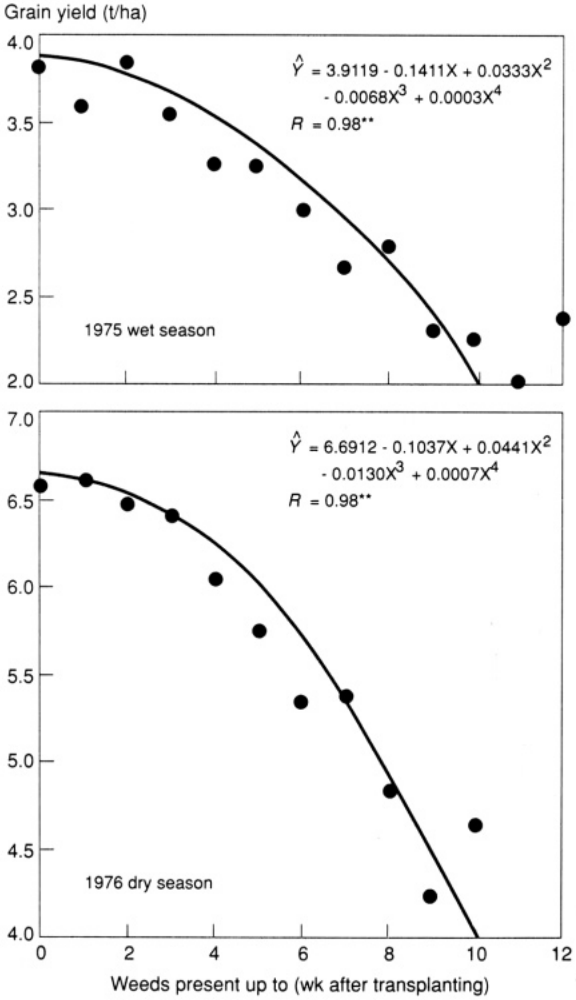
Losses caused by weeds in the absence of any weed control are unrealistic. Most farmers attempt to do some weed control. Therefore, comparing weeded and unweeded plots overstates the additional benefits of weed control. Also, losses reported for research station experiments are frequently higher than those in farmers' fields.

A more realistic approach is to compare the added benefits from additional weeding using farmers' weed control methods. However, little information is available on the actual extent of yield losses due to weeds in farmers' fields (Moody 1982).

De Datta (1980) reported that for 108 dry season trials of irrigated transplanted rice in farmers' fields in the Philippines, only 11% of the 1.9 t/ha yield gap between the best available cultural practices and farmers' cultural practices was accounted for by weed control. In 176 wet season trials, 13% of the yield gap was attributable to weed control. Mandac et al (1982) reported similar results for rainfed rice, implying in both cases that the best available weed control practices and the farmer's weed control practices were equally effective. However, they also pointed out that both appeared to be inadequate in fields subjected to severe early moisture stress.

## Weed control practices

Farmers' weed control practices usually are based on rational considerations, in that the levels of weed control inputs are largely determined by the expected levels of returns from those inputs. Thus, crops that are likely to give a good yield response are usually well weeded, those likely to give a poor response are often neglected. A farmer's level of weed control is often appropriate for the farming system he practices (Moody 1982). He would apply increased weed control measures if they were an integral part of improved and more remunerative farming systems (Moody 1983).



**1.** Grain yield of transplanted IR28 rice as affected by the presence of weeds for varying lengths of time after transplanting (Gomez, unpubl.).

Parker (1976) noted that a few studies might be valuable to show farmers how much yield they are losing as a result of poor weeding. The extent of yield loss due to delay in weeding is illustrated in Figure 1. In a study of four rainfed ricefields with moderate to heavy weed growth in Cagayan, Philippines, average yield was 1.3 t/ha where the farmers did no weeding (Table 2). Weeding the fields twice during the critical period of competition produced an average yield of 32 t/ha. In one field where the farmer weeded only once, at 40 d after transplanting (DT), the yield was 1.5 t/ha, compared to 2.2 t/ha when the field was weeded twice. Assuming that the farmer would have obtained only 1.3 t/ha if he had not weeded, his marginal increase was only 0.2 t/ha with one weeding, probably because the weeding was late (Navarez et al 1981).

In the same study, six farmers inirrigated areas used six different methods of weed control (Table 2). This indicates the difficulty in selecting a standard farmers' practice

**Table 2. Effect of farmers' weed control methods on grain yield and weed weights in transplanted rice (rainfed and irrigated areas). Cagayan, Philippines, 1980 wet season.**

| Weed control method [a] | Herbicide rate (kg/ha) | Fields (no.) | Weed wt (g/0.5 $m^2$) | Grain yield (t/ha) | Yield reduction (%) |
|---|---|---|---|---|---|
| Rainfed | | | | | |
| Fp: no weeding | - | 4 | 54.9 | 1.3 | 41 |
| Weeded check | - | | 0 | 2.2 | |
| Fp: hand weed 40 DT | - | 1 | 40.8 | 1.5 | 32 |
| Weeded check | - | | 0 | 2.2 | |
| Irrigated | | | | | |
| Fp: butachlor G fb spot weeding (9 DT fb 30 DT) | 0.8 | 1 | 6.8 | 4.1 | 2 |
| Weeded check | | | 3.6 | 4.2 | |
| Fp: butachlor EC fb hand weeding (4 DT fb 28 DT) | 0.46 | 1 | 17.7 | 4.2 | 18 |
| Weeded check | - | | 7.7 | 5.1 | |
| Fp: two rotary weedings (18 DT fb 35 DT) | -<br>- | 1 | 16.5 | 5.2 | 7 |
| Weeded check | - | | 4.3 | 5.6 | |
| Fp: one hand weeding (45 DT) | - | 1 | 105.9 | 3.6 | 10 |
| Weeded check | - | | 8.8 | 4.0 | |
| Fp: remove large weeds as needed | - | 1 | 20.0 | 3.3 | 21 |
| Weeded check | - | | 6.0 | 4.2 | |
| Fp: rotary weeding fb 2,4-D EC (18 DT fb 24 DT) | 0.24 | 1 | 5.2 | 5.1 | 16 |
| Weeded check | - | | 6.6 | 6.1 | |

[a] Fp = farmers' practice; fb = followed by; G = granular: EC = emulsifiable concentrate; DT = days after transplanting; weeded checks were hand weeded at 21 -25 DT and 35-40 DT in Solana and 15 and 30 DT in Alcala-Amulung.

as the weed control treatment in research-managed trials. Farmers' herbicide rates were less than those recommended, and the different methods resulted in varying degrees of weed control. Intensive weeding resulted in 2-27% yield increases, indicating that farmers were controlling weeds better in irrigated conditions than in rainfed conditions.

In another study in Guimba, Nueva Ecija, grain yield in the portions of rainfed fields weeded by farmers were 1.9-4.2 t/ha (av 3.0 t/ha) in the wet season and 2.0-4.4 t/ha in the dry season (Rao and Moody, unpubl.). When the fields were weeded twice during the critical period of competition, yields were increased 10-95% in the wet season and 14-75% in the dry season, indicating again that in most cases the farmers' weed control practices were not adequate to prevent yield losses. The farmers' weed control practices were characterized by herbicide rates lower than recommended and by late hand weeding.

The methodology used in these studies is described in the appendix. Garrity et al (unpubl.) developed a visual scoring system for assessing the weed suppression ability of upland rice cultivars. It is based on weed density and height of the weed canopy in relation to the rice crop canopy (Table 3). Weed suppression score was correlated positively with weed weight and negatively with plant height and grain yield.

Where total output value is low, farmers do not exert much effort on weed control. Farmers' weed control activities are guided by rational considerations (Binswanger and Shetty 1977). They will respond to improvements in their farming system with increased weed control.

**Table 3. Visual scoring system for assessing weed suppression ability (Garrity et al, unpubl.).**

| *Parameters* | |
|---|---|
| Weed density | Weed canopy height in relation to crop canopy height |
| L - Low | L - Lower |
| M - Moderate | S - Similar |
| H - High | H - High |
| *Scale* | |
| 1. Excellent | - No weeds to low weed density, with weed canopy height much below crop canopy height. |
| 3. Good | - Low to moderate weed density, with weed canopy lower than or equal to crop canopy height. |
| 5. Fair | - Moderate weed density, with weed canopy height lower or equal to crop canopy height. |
| 7. Poor | - Moderate to high weed density, with weed canopy height equal to crop canopy height. |
| 9. Unacceptable | - High weed density, with weed canopy height above crop canopy height. |

Estorninos et al (1982) stated that a farmer's weed control practices are determined largely by his concepts about weeds and their relationship with the crop, his resources, his knowledge of available technologies, and the environmental conditions in which the crop is grown.

According to Vega (1983), there is no economic incentive for the complete removal of weed growth in most crops grown by small-scale farmers in developing countries. Doll (1976) proposed that "the maintenance of weed populations at levels which do not cause economic losses" was an appropriate definition of weed control for the traditional farmer.

## Conclusion

It is important for weed science researchers to develop alternative weed control practices. A farmer could then select one or more practices to solve his weed problems. Economic incentives would play an important role in such a selection (Vega 1983). Farmers, like all people, act on what they believe. That belief may differ from reality (Herdt and Capule 1983). If they believe the cost and yield response functions of a new technology will give lower benefits, they will not adopt the new technology, regardless of the objective reality. We must be sure our new alternatives are appropriate for the farmers' environments: agronomically, economically, and socially (Doll 1976).

## References cited

Binswanger H P, Shetty S V R (1977) Economic aspects of weed control in semi-arid tropical areas of India. Pages 75-91 *in* Proceedings of the Weed Science Society conference. Indian Society on Weed Science, Andhra Pradesh Agricultural University, Rajendranagar, Hyderabad, India.

De Datta S K (1980) Weed control in rice in south and southeast Asia. Ext. Bull. 156. Food and Fertilizer Technology Center, Taipei, China. 24 p.

Doll J D (1976) Reaching traditional farmers with improved weed management in Latin America. Pages 809-816 *in* Proceedings of the 1976 British crop protection conference on weeds. British Crop Protection Council. Brighton, England.

Estominos L E Jr., Navarez D C, Moody K (1982) Farmers' concepts about weeds and weed control practices in rainfed areas of the Philippines. Pages 507-518 *in* Report on a workshop on cropping systems research in Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Gomez K A, Lopez L, Novenario M J, Herdt R W, Marciano V P (1979) Constraints to high rice yields, Laguna, Philippines. Pages 173- 190 *in* Farm-level constraints to high rice yields in Asia: 1974-77. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Harwood R R (1979) Small farm development. Westview Press, Boulder, Colorado, USA. 160 p.

Herdt R W (1979) An overview of the constraints project results. Pages 395-411 *in* Farm-level constraints to high rice yields in Asia: 1974-77. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Herdt R W, Capule C (1983) Adoption, spread and production impact of modem rice varieties in Asia. International Rice Research Institute, P.O. Box 933, Manila, Philippines. 54 p.

Koch W, Beshir M E, Unterladstatter R (1982) Crop loss due to weeds. FAO Plant Prot. Bull. 30:103-111.

Mandac A M, Kalirajan K P, Flinn J C (1982) Economic limitations to increasing shallow rainfed rice productivity in Bicol, Philippines. IRRI Res. Pap. Ser. 80. 21 p.

Mercado G L, Arceo L M (1980) Cost effective weed control with butachlor in transplanted rice. Philipp. J. Weed Sci. 7:40-44.

Moody K (1982) The status of weed control in rice in Asia. Pages 114-118 *in* Improving weed management. FAO Plant Prod. Prot. Pap. 44. Rome, Italy.

Moody K (1983) Weeds: definitions, costs, characteristics, classification and effects. Pages 11-32 *in* Weed management in the Philippines. PLITS 1(1), H. Walter, ed. Institut fur Pflanzenproducktion in den Tropen and Subtropen. Universtat Hohenheim, Stuttgart, Federal Republic of Germany.

Moody K, Cordova V G (1985) Wet-seeded rice. Pages 467-180 *in* Women in rice farming. International Rice Research Institute. Cower Publishing Co.. Ltd.. England.

Moody K, Drost D C (1983) The role of cropping systems on weeds in rice. Pages 73-88 *in* Weed control in rice. International Rice Research Institute. P.O. Box 933, Manila, Philippines.

Navarez D C, Estaño D B, Moody K (1981) Preliminary evaluation of farmers' weed control practices in Cagayan, Philippines. Philipp. J. Weed Sci. 8:49-55.

Parker C (1976) Weed research requirements in developing countries. Pages 801-807 *in* Proceedings of the 1976 British crop protection conference on weeds. British Crop Protection Council, Brighton, England.

Parker C, Fryer J D (1975) Weed control problems causing major reductions in world food supplies. FAO Plant Prot. Bull. 23:83-95.

Soerjani M (1971) Present status of weed problem and the importance of weed dispersal in Indonesia. Paper presented at the 8th Session of the FAO Plant Protection Committee for Southeast Asia and Pacific Region, 4-11 Oct 1971, Jakarta, Indonesia.

Vega M R (1983) Crop production in the total absence of weed control. Pages 1-16 *in* Improving weed management. FAO Plant Prod. Prot. Pap. 44. Rome, Italy.

## Notes

*Author's address:* K. Moody, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

*Citation information;* International Rice Research lnstitute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

**Appendix.** A methodology for determining adequacy of farmer's weeding practices, abstracted from Moody (1988).

One of the simplest methods to determine if farmers are controlling weeds adequately, the actual crop yield losses that are occurring as a result of existing weed control practices, and the extent of weed control required, is to weed more extensively than usual in at least six randomly selected plots (Moody 1981). (For example, the plot scan be kept tree of weeds by handweeding when weeds are most competitive, during the first quarter to one-third of the crop life cycle.) Sufficient numbers of fields should be selected at random so that soil types, cropping systems, hydrological conditions, and weed flora of the area are adequately represented.

Plot size—which will vary depending on the uniformity of the crop, weed infestation, and the resources available—should be kept as small as possible to provide the desired information without excess variability. A plot size of 30-40 $m^2$ with a harvest area of 15-20 $m^2$ is usually adequate for rice.

Yields from plots weeded extensively should be compared with yields from adjacent plots where farmer's normal weeding took place. Sufficient distance should be provided between the harvest areas to avoid border effects. Comparisons between yields obtained in each area can be made using a paired *t*-test (Steel and Torrie 1960).

An example of the results using this methodology in transplanted rice in Guimba, Nueva Ecija, Philippines, and the methodology used to calculate *t* are given in Table 1. The observed value of *t* (8.59) must be compared with a theoretically derived value of determined statistical significance. Using the information provided in Table 2, it is found that 8.59 (df = 5) is greater than the theoretical value of 4.03 at the 1% level of probability. Therefore, the difference in yield between the two weeding regimes is highly significant.

If yields in the portions of the field receiving normal weeding are not significantly less than those where additional weeding took place, the farmer is controlling weeds adequately. In that case, it would be difficult to introduce a new method of weed control unless it has distinct advantages, such as saving time, labor, monetary inputs, or a combination of these, over what the farmer is currently doing (Moody 1981).

**Appendix Table 1. Statistical analysis of rice yield as affected by weeding treatment in Guimba, Nueva Ecija, Philippines.**

| | Yield (t/ha) | | |
|---|---|---|---|
| Plot no. (n) | Weeded ($X_1$) | Not weeded ($X_2$) | Difference (D) |
| 1 | 2.9 | 2.2 | 0.7 |
| 2 | 3.4 | 2.3 | 1.1 |
| 3 | 3.0 | 2.0 | 1.0 |
| 4 | 3.3 | 2.7 | 0.6 |
| 5 | 3.5 | 2.4 | 1.1 |
| 6 | 2.8 | 2.2 | 0.6 |
| Total | 18.9 | 13.8 | 5.1 (RD)<br>$RD^2 = 4.63$ |
| Mean | 3.15 | 2.3 | 0.85 ($\bar{d}$) |

$$S_{\bar{d}} = \sqrt{\frac{4.63 - (5.1)^2/n}{n\,(n-1)}} = \sqrt{\frac{4.63 - (5.1)^2 6}{6 \times 5}} = 0.099$$

$$t = \frac{\bar{d}}{S_{\bar{d}}} = \frac{0.85}{0.099} = 8.59$$

**Appendix Table 2. Distribution oft for six to ten replications at two probability levels (see Steel and Torrie 1960, p. 46).**

| Degrees of freedom (n - 1) | Value of *t* and probability levels | |
|---|---|---|
| | 0.05 | 0.01 |
| 5 | 2.51 | 4.03 |
| 6 | 2.45 | 3.71 |
| 7 | 2.31 | 3.50 |
| 8 | 2.26 | 2.25 |
| 9 | 2.23 | 3.17 |

If yield from the plots where additional weeding was done is significantly higher, the possibility of introducing a new weed control technology to the farmers or of improving their present techniques should be investigated (Moody 1981). The cost of the new method should not be appreciably greater than that of the currently used method unless returns from the new technology are sufficiently attractive to warrant the increase in cost. In all cases, records should be kept of the farmers' weeding practices so that necessary improvements can be suggested and monetary outlays can be determined.

## References cited

Moody K (1988) Developing appropriate weed management strategies for small-scale farmers. Pages 319-330 *in* Weed management in agroecosystems: ecological approaches. M. A. Altieri and M. Liebman, eds. CRC Press, Inc., Boca Raton, Florida.

Moody K (1981) Yield-loss studies for weed control recommendations. Pages 117-119 *in* A methodology for on-farm cropping systems research. H. G. Zandstra, E. C. Price, J. A. Litsinger, and R. A. Morris, eds. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Steel R G D, Torrie J H (1960) Principles and procedures of statistics. McGraw Hill, Inc., New York. 481 p.

# Assessing multiple pest populations and their effects on crop yield

K. B. Johnson

Increasingly, economical crop production requires quantitative information about how insect pests, weeds, and diseases affect crop productivity. A major objective of recent pest management research has been to study the relationship between pest intensity and loss of yield for selected pest problems. While this research has greatly, increased our knowledge of the effects of pests in solitary infestations, the complexities involved in studying pest intensity-field loss relationships has resulted in much less effort being directed toward studying the yield reductions caused by infestations of combinations of pests.

Research on multiple-pest effects is an important challenge. In many production systems, pest combinations are common. Decisions on the control of each pest often are economically and/or biologically intertwined.

For crop protection specialists interested in providing information on which to base control decisions, the problem of multiple-pest constraints to crop yield is twofold: first, understanding how combined pest infestations interact to affect yield. and second, providing management recommendations and decision aids that optimize profit for an acceptable level of risk. Research on multiple pests within specific systems has addressed both aspects of the problem (Johnson et al 1986, 1987; Keller et a1 1986; King 1982; Lamp et a1 1985; Lim et al 1985; Newsom and Boethel 1985; Noling et al 1983). However, often the work has been done without well-defined expectations or an extensive literature base upon which to base experimental design. Given the number of disease, weed, and insect pest permutations that can afflict crops, further development of general methodology, theory, and expectations for assessing and understanding the effects of multiple pests on crop yield has great potential. It can improve the design of experiments and collection of data, guide interpretation of results, accelerate research progress, and increase the pace of application of research findings in crop management programs.

Important considerations in the study of yield reductions caused by combined infestations in crops include the objectives of the study, the assessment of multiple pest populations and the damage they cause. the problem of interactions, pest competition and its effect on yield loss expectations, and new methodology for development of multiple-pest yield loss models and economic thresholds.

## Objectives in studying multiple-pest infestations

The objectives of a study of multiple-pest infestations usually can be divided into understanding and defining the combined effects of pest infestations on crop yield and providing recommendations or decision aids to manage multiple-pest problems. The distinction is made because the hypotheses and experimental designs for each differ.

The question of understanding multiple-pest effects requires tightly controlled field experiments, within which treatments representing relatively wide ranges of pest intensity must be attained, managed, and measured (Teng and Shane 1984, Walker 1987b). Factorial arrangements of pest infestations are used, along with the techniques used in single-pest experiments for creating and maintaining different pest infestation levels. Data collection centers on understanding crop response to damage and on the interactions that occur between the crop and the pests. Pest assessment methods and statistical yield loss models developed in these experiments are useful in further experimental work and in crop loss surveys (Teng 1987, Teng and Shane 1984, Walker 1987b).

Once the specific effects of combined infestations are understood, the question shifts to how best to manage a crop grown under combined infestation conditions. Experiments concerned with optimal control and with maximizing economic return often need to be more extensive than effects studies (i.e. cover a broader range of cropping conditions), but the complexity of the design and range of pest intensities examined within the experiment need not be as great. For example, depending on the type of interactions that occur, it may be possible to limit the range of pest treatments to intensities only slightly exceeding the economic threshold for each pest. Some questions to answer with this phase of experimentation include: Can the damage caused by subeconomic threshold populations of combined pests be considered additive? What are the economic benefits of controlling pests simultaneously through use of the same chemical or a tank-mix of two chemicals? How does the economic threshold for one pest change with increasingly higher levels of secondary but uncontrollable organisms?

The host and pest biology of the specific system also greatly influence objectives and experimental approach. The useful body of literature on multiple-pest effects is continually increasing. At the same time, the much larger body of literature on individual pests within specific cropping systems can provide many useful insights to be applied to the study of multiple-pest situations.

## Assessing multiple pests and their effects

Pest population measurement and damage assessment are critical to understanding how pests interact and how crop yield is being currently and/or will potentially be affected. Regardless of the objectives, three general types of assessments should be considered: measurement of the pest population, assessment of symptoms on plants, and assessment of damage to the crop.

Measurements of pest populations are the usual basis for decisionmaking within integrated pest control programs. In crop loss studies, incidence, counts, and pathogen isolations are used to determine if the treatments applied (pesticides, introductions, and inoculations) have had the desired effect of providing a range of pest intensities within the experiment (Teng and Shane 1984, Walker 1987a). In experiments, repeated sampling of pest populations allows for estimation of a pest intensity integral that can be correlated to yield. Repeated measures also provide timely information on management of infestation levels. When pests are combined, yield loss interactions may be attributable to one pest population having an effect at some point in time on the size of a second. The objectives of a study dictate the degree of detail necessary to quantify a pest population. However, if a study requires precise or sophisticated measurements, it may be desirable to make comparative assessments similar to those used by pest management scouts (Johnson et al 1988). Typical units for measuring populations include number or biomass per unit area, number per unit plant part, number per unit of capture (e.g. net sweeps), and proportional incidence (e.g. % plants infected). Crop growth stage should be recorded along with pest and damage assessments.

Within the crop loss assessment literature, measurement of percent damage or symptom expression on plant has been the variable most commonly related to yield reductions. Reasons for using damage and symptom assessments include the ease of using percentage scales, the relatively permanent nature of damage as an indicator of how much pest pressure a crop has experienced (in contrast to pest populations), and the often made, but rather loose assumption that observed plant damage is correlated linearly to reductions in crop productivity (Teng 1987, Teng and Shane 1984). Many types of aids to make these kinds of assessments have been published (Gaunt 1987, Walker 1987b). Standard area diagrams like those developed for rice by Chin and Ho (1973) and used in a multiple-pest survey by Teng (1975) probably provide the most rapid, accurate, and unbiased method for symptom and damage assessments.

Because of the potential for interactions to occur among pests, making assessments within multiple-pest infestations to relate pest damage to yield may require recording data in greater detail and possibly using more holistic and integrated approaches to measure pest damage.

As an illustration, suppose four pests were combined. Each pest could affect plant foliage by causing one of the following conditions—a mosaic symptom, shading (i.e. a weed), leaf skeletonizing, and a discrete leaf spotting lesion. Problems arise on how to measure and interpret the importance to yield of any one symptom if it is associated with another symptom. Is leaf skeletonizing important if it occurs on mosaic-affected leaves? If shading by weeds is extensive, will 10% lesion damage affect yield as much as it does on plants exposed to full sun?

Minimum data records should specify the degree to which symptoms are associated with one another. Integrated assessments made on a crop also may help to explain how pests interact. The kinds of assessments needed include leaf area index, percent green leaf area remaining, percent chlorosis, and total percent defoliation (Johnson et al 1987).

## The problem of interactions

Much of the interest in studying multiple-pest effects on crop yield focuses on the examination and interpretation of pest-pest and crop-pest interactions and what they mean in regard to crop management. There are three possible outcomes of combined pest infestations on crop yield: 1) no interaction, 2) greater-than-additive (synergistic) interactions, and 3) less-than-additive (antagonistic) interactions (Lamp et al 1985). With no interaction, the effects of multiple pests on crop yield are relatively independent and additive. With interaction, the effects of combined pest populations are greater or less than the summed effects of each single-pest infestation.

With any multiple-pest situation, the knowledge as to which outcome is likely can be very valuable. Greater-than-additive interactions are important because the economic injury threshold for each pest can be significantly lowered by the presence of the interacting pest. Less-than-additive interactions raise the economic injury threshold of a pest, given the presence of the interacting pest. Stated another way, what benefit is obtained from control of one pest if a second or third pest is present and allowed to damage the crop? Both biology and the context of the crop-pest system affect the importance of pest-pest interactions. The relative importance of an interaction depends on the perspective from which the pest-pest interaction is viewed and on the pest intensity levels within a crop.

Table 1 shows the results of an incomplete but representative survey of the literature on multiple-pest interactions. The relative frequencies of types of pest-pest interactions reported for studies of direct damage (disease, feeding damage, symptom expression, defoliation, etc.) are compared with interactions reported when the combined effects of pest infestations on yield were measured. In the literature concerned with direct pest damage, the number of reports of greater-than-additive (synergistic) interactions between pests about equal the number of reports of less-than-additive (antagonistic) interactions. Studies of the effects of multiple pests on crop yield mostly report antagonistic interactions; reports of synergistic effects are relatively rare.

**Table 1. A survey of literature showing the relative frequencies of reported interactions for damage responses and yield responses of plants/crops exposed to two or more plants.**

| Response | Reports surveyed (no.) | Relative frequency (%) of interaction type | | |
|---|---|---|---|---|
| | | Less-than-additive | Additive | Greater-than-additive |
| Damage[a] | 28 | 45 | 10 | 45 |
| Yield[b] | 14 | 57 | 21 | 21 |

[a] Literature surveyed: Barket et al 1972, Bisessar 1982, Chester 1944, Da Luz and Bergstrom 1987, Goodell et al 1982, Herzog et al 1975, Hyde 1978, Jenkins and Jones 1981, Johnson et al 1987, Karban et al 1987, Keller et al 1986, Lamp et al 1985, Lim et al 1985, Maier 1965, Manning 1975, Morton and Peterson 1960, Pietkiewicz 1974, Rowe et al 1985, Spadafora and Cole 1987, Stewart and Hill 1965, Summers and McClellan 1975, Thanassoulopolous 1976, Van der Wall et al 1970. [b] Literature surveyed: Coble 1985, Harrison 1974, Johnson et al 1986, Karban et al 1987, King 1982, Lamp et al 1985, Lim et al 1985, Manzer et al 1978, Noling et al 1984, Padwick 1956, Rowe et al 1985, Van der Wall et al 1970, Williams and Nyvall 1980.

Given that biologists usually are more fascinated with synergistic interactions between organisms, the relative rarity of studies of greater-than-additive yield loss interactions may appear at first to be paradoxical. An explanation, however, for the discrepancy in the types of interactions reported for direct plant damage and for yield losses can be based on the level of biological organization from which they are viewed.

Usually damage-type interactions are studied at the tissue and whole-plant levels of biological organization. Researchers are not as concerned with the response of the plant as they are with the response of the percent area diseased, damaged. or expressing symptoms. The reduced ability of the host to defend itself due to wounding and physiological stress is most often the explanation for synergistic damage (Datnoff and Sinclair 1988, Manning 1975, Rowe et al 1985, Van der Wall et al 1970). Less-than-additive interactions at this level are explained as direct antagonism between pests (Barker et al 1972, Da Luz and Bergstrom 1987) or as induced antagonism mediated through the host (Karban et al 1987).

In contrast, crop yield is an integrated measure of plant productivity. Under agricultural conditions, yield usually is measured at the population level of biological organization. At this level, the competition and mutual interference that occur among pest populations as they utilize or inflict damage to their host resource becomes an important less-than-additive interaction.

An illustration of how pests interact in damaging productive host organs is given in Figure 1.

## Pest competition and its effect on yield loss expectations

The idea that because of competition, less-than-additive yield loss interactions can be expected within multiple-pest infestations was recognized by Padwick (1956) and summarized in a model used in yield loss surveys. The model is

$$\text{Percent yield loss} = \{100 - [(100 - P_1)(100 - P_2)...(100 - P_n)]/100_{n-1}\}$$

$P_1$, $P_2$,..$P_n$ are percentages of yield losses caused by solitary infestations of each on n pests.

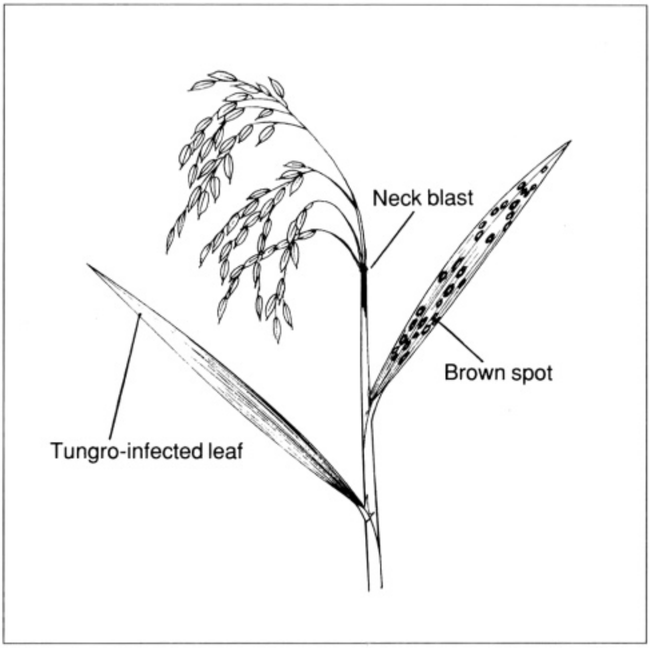
The supposition of this model is that, with regard to productivity, one pest cannot affect what another has already damaged. Thus, no matter how many pests are present, yield reductions are always limited to less than 100%. Two examples demonstrate the model.

In the first, infestations of pests $P_1$ and $P_2$ are at a level that would cause 10% yield loss if they were in solitary infestations. In a combined infestation, the yield loss expected from similar infestations of $P_1$ and $P_2$ would be

$$\{100 - [(100 - 10)(100 - 10)]/100\} = 19\%$$

Nineteen percent is slightly less than the 20% loss expected if the damage caused by both pests were additive.

In the second example, infestations of pests $P_1$ and $P_2$ are sufficient to cause 60 and 50% loss, respectively, if each were the only pest in a crop. If the loss is assumed to



**1.** A rice plant attacked by three diseases simultaneously. The neck blast lesion probably diminishes the impact of tungro and brown spot on yield of the plant. Similarly, on tungro-infected leaves, damage by brown spot potentially could be greater, given the stressed condition of this tissue. However, the impact of brown spot on yield of tungro-infected plants may be much less because the viral infection has reduced the efficiency of photosynthesis within the leaf.

be additive, it exceeds 100%. In a combined infestation, the yield loss expected from similar infestations would be

$$\{100 - [(100 - 60)\,(100 - 50)]/100\} = 80\%$$

An interpretation might have $P_1$ causing the first 60% loss and $P_2$ causing 50% loss of what is remaining.

To demonstrate that this type of interaction affects crop management and economic return, suppose that $P_1$ is not controlled. Then, the benefits received from complete control of $P_2$ (in harvested kg/ha) are roughly half the benefits received without a concurrent infestation of $P_1$.

This model was applied to experimental data from a factorially arranged study of the effects of three relatively dissimilar pest types on yield of potato. Maximum losses caused by individual infestations of the potato leafhopper, early blight, and *Verticillium* wilt were 54, 31, and 12%, respectively (Johnson et al 1986). Assuming the losses to be additive, the expectation for the total combined loss approaches 100%. In the experiment, when all three infestations were combined, the observed loss was 63%.

The model predicts a 72% loss. Pest-induced foliage loss in the combined infestation of this experiment also was less than the total amounts lost in the individual infestations (Johnson et al 1987).

These results show that, for relatively small yield losses, Padwick's model is not greatly different than the assumption of additive loss. When yield losses are higher, the less-than-additive competitive effects predicted by the model are more pronounced and, given the small amount of data presented, more realistic.

While less-than-additive yield loss interactions probably are a reasonable expectation within multiple-pest infestations, the practical significance of such interactions is dependent on a high level of intensity by at least one of the pest components. Most likely, these high pest intensities are well above economic thresholds, making this model more useful for interpretation of crop loss data than for tactical crop management. For combined pest infestations where all the components are at intensities below economic thresholds, the model indicates that additive loss may be the most reasonable assumption until further system-specific experimentation can evaluate antagonistic and synergistic effects.

## Methodology for modeling multiple-pest effects

A recent study on the effects of combined pests in soybean concluded that progress on understanding multiple-pest complexes is limited by inadequate methodologies and experimental approaches (Newsom and Boethel 1985). This statement can be seen to be even more important when it is considered in the context of a second conclusion reached within the same paper. The second conclusion stated that use of the economic threshold for an individual pest species clearly is an untenable concept for cropping areas where several major pests species occur simultaneously.

Recent developments in the research area of crop loss assessment may reduce current methodological inadequacies and improve theoretical approaches to pest management.

Over the last several years, the concept of biologically based economic thresholds (Stem et al 1959) has in part given way to the economic concepts of added value, profit maximization, decision analysis, and the risk adversity of producers as elements constituting a framework for integrated pest control (Blackshaw 1986, Mumford and Norton 1984, Zadoks 1987). As a consequence, the pest control question is more often stated as "what amount of control is necessary to optimize profit and minimize risk within a specific cropping scenario?" rather than "at what pest intensity level should control be applied?" This shift in thinking is the result of the recognition that economic thresholds are highly dynamic and that elements of uncertainty are inherent in pest control decisionmaking. Given that combined pest infestations are one of the factors that influence the economic thresholds of individual species, the integrated concepts of added value and profit optimization should lead to better management of crops subjected to multiple-pest pressures.

Blackshaw (1986) published multiple-pest economic decision models that combine the principles of economic threshold theory with the profit optimization approach.

The models require development of cost:benefit response planes or surfaces for given pest complexes. Benefit-of-control surfaces are dependent on the intensity level of the pests present; they incorporate the interactions of yield loss that occur with multiple organisms (additive losses being the simplest case). Cost planes are dependent on chemical dose/pest mortality functions, chemical and application costs, and the possibility that several pests can be controlled with the same chemical or mixtures of chemicals.

The difference between this approach and the single-species economic threshold is that pest effects are considered in an integrated manner. Presumably, populations of predators and parasites can be included within the benefit response surface. Experimental development of these benefit response surfaces represents a very important challenge for researchers (Palis et al, this volume).

With regard to the problem of understanding effects of multiple pests on yield, several statistical approaches (e.g. multiple regression, principal component analysis) have been used to correlate the combined effects of different pest ratings and other crop constraint variables with yield loss (King 1982, Teng 1987, Wiese 1980). Although these methods have provided models that usually explain a high proportion of the variation within a given data set, the results of the analyses have not led to models with high transportability (i.e. they are often experiment-specific), nor have the analyses provided much insight into how interactions among pests occur.

In contrast, a relatively simple approach to analyzing crop productivity is based on the concept that crop growth is the integral of the product of radiation interception and efficiency of radiation use (Monteith 1977). In this methodology, the analysis centers on correlating the amount of solar radiation caught by a crop's photosynthetic area to biomass produced. The advantage of this approach is it emphasizes understanding the mechanisms of productivity. Study of radiation interception also provides a common focal point between relatively simple empirical methods and more complex crop growth simulation models (Johnson 1987).

Waggoner and Berger (1987) showed that radiation interception models may be very useful in understanding the effects of pests on crop yield. In several pest and crop situations, a variable called healthy-area absorption (i.e. the amount of solar radiation absorbed by green area) was highly correlated with yield. Johnson (1987) suggested that pest effects can be divided into effects on radiation interception and effects on radiation-use efficiency. That method is particularly appropriate for studying multiple-pest problems.

In contrast to empirical methods that correlate pest damage (or % symptoms) with loss of yield, the radiation interception approach relates yield to the undamaged portion of the crop. Thus, how pest combinations interact mechanistically to limit a crop's productivity is the question of interest. As with other integrated approaches (Broscious et al 1987, Johnson et al 1987), radiation interception models may not lead to better partitioning of yield losses caused by individual pests. But the understanding and interpretation of how pests interact to affect yield should be much greater.

## References cited

Barker K R. Huisingh D, Johnston S A (1972) Antagonistic interaction between *Heterodera glycines* and *Rhizobium japonicum* on soybean. Phytopathology 53:1201.

Blackshaw R P (1986) Resolving economic decisions for the simultaneous control of two pests, diseases, or weeds. Crop Prot. 5:93-99.

Bisessar S (1982) Effect of ozone, antioxidant protection, and early blight on potato in the field. J. Am. Soc. Hortic. Sci. 107:597-599.

Broscious S C, Pataky J K, Kirby H W (1987) Quantitative relationships between yield and foliar diseases of alfalfa. Phytopathology 77:887-892.

Coble H D ( 1985) Development and implementation of economic thresholds for soybean. Pages 295-307 *in* CIPM- integrated pest management on major agricultural systems. R. E. Frisbie and P. L. Adkisson, eds. Texas Agricultural Experiment Station Miscellaneous Publication 1616. College Station, Texas.

Chester K S (1944) Low incidence of wheat leaf rust associated with unfavorable late winter weather and antagonism of *Septoria tritici.* Plant Dis. Rep. 28:280-287.

Chin K M, Ho B L (1973) Assessment keys for some rice diseases. MARDI Report No. 4. Malaysian Agricultural Research and Development Institute, Serdang, Malaysia. 9 p.

Da Luz W C, Bergstrom G C (1987) Interactions between *Cochlioholus sativus* and *Pyenophora tritici-repentis* on wheat leaves. Phytopathology 77:1355-1360.

Datnoff L E, Sinclair J B (1988) The interaction of *Fusarium oxysporum* and *Rhizocronia solani* in causing root rot of soybeans. Phytopathology 78:771-777.

Gaunt R E (1987) Measurement of disease and pathogens. Pages 6-18 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society. St. Paul, Minnesota.

Goodell J J, Powelson M L, Allen T C (1982) Interrelations between potatovirus X, *Veticillium dahliae,* and *Colletotrichum atramentarium* in potato. Phytopathology 72:631-634.

Harrison M D (1974) Interactions between foliar sprays and soil fumigation in the yield response of potatoes. Phytopathology 64:860-864.

Herzog D C, Thomas J W, Jensen RL, Newsom L D (1975) Association of sclerotial blight with *Spissistilus festinus* girdling injury on soybean. Environ. Entomol. 4:986-988.

Hyde P M (1978) A study of the effects on wheat of inoculation with *Puccinia recondita* and *Leptosphaeria nodorum.* Phytopathol. Z. 92:12-24.

Jenkins P D, Jones D G (1981) The effects of dual inoculation of wheat cultivars with *Septoria tritici* and *Septoria nodorum.* Phytopathol. Z. 101:210-221.

Johnson K B (1987) Defoliation, disease, and growth: a reply. Phytopathology 77:1495-1497.

Johnson K B, Radcliffe E B, Teng P S (1986) Effect of interacting populations of *Alternaria solani. Verticillium dahliae,* and the potato leafhopper (*Empoasca fabae*) on potato yield. Phytopathology 76:1046-1052.

Johnson K B, Teng P S, Radcliffe E B (1987) Analysis of potato foliage losses caused by interacting infestations of early blight, Verticillium wilt, and potato leafhopper; and the relationship to yield. Z. Pflanzenkr. Pflanzenschutz. 94:22-33.

Johnson K B, Watrin C G, Radcliffe E B (1988) Vertical distributions of potato leafhopper nymphs on potato relative to leaf position, plant age, and population size. J. Econ. Entomol. 81:304-309.

Karban R, Adamchak R, Schnathorst W C (1987) lnduced resistance and interspecific competition between spider mites and a vascular wilt fungus. Science 235:678-680.

Keller N P, Bergstrom G C, Carruthers R I (1986) Potential yield reductions in maize associated with an anthracnose/European corn borer pest complex in New York. Phytopathology 76:586-589.

King E D (1982) The effects of late blight, Colorado potato beetle, and weed populations on yield loss of potato. Ph D thesis, Pennsylvania State University, Stage College, Pennsylvania. 81 p.

Lamp W O, Yeargan K V, Nonis R F, Summers C G, Gilchrist D G (1985) Multiple pest interactions in alfalfa. Pages 345-364 *in* CIPM - integrated pest management on major agricultural systems. R. E. Frisbie and P. L. Adkisson, eds. Texas Agricultural Experiment Station Miscellaneous Publication 1616. College Station, Texas.

Lim S M, Appel J A, Noel G R, Edwards D I, Ford RE, Schmitt P, Coble H D (1985) Multiple pest effects in soybean. Pages 391-408 *in* CIPM - integrated pest management on major agricultural systems. R. E. Frisbie and P. L. Adkisson, eds. Texas Agricultural Experiment Station Miscellaneous Publication 1616. College Station, Texas.

Maier, C R (1965) The importance of *Alternaria* spp. in the cotton seedling disease complex in New Mexico. Plant Dis. Rep. 49:904-909.

Manning W J (1975) Interactions between air pollutants and fungal, bacterial, and viral plant pathogens. Environ. Pollut. 9:87-90.

Manzer F E, Memam D C, Hepler P R (1978) Effects of potato virus S and two strains of potato virus Xon yields of Russet Burbank, Kennebec, and Katahdin cultivars in Maine. Am. Pot. J. 55:601-609.

Monteith J L (1977) Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. London 281:277-294.

Morton D J, Peterson G A (1960) An inverse relationship between severities of *Helminthosporium* leaf blade and *Septoria* leaf sheath symptoms on barley. Plant Dis. Rep. 44:23-24.

Mumford J D, Norton G A (1984) Economics of decision making in pest management. Annu. Rev. Entomol. 29:157-174.

Newsom LD, Boethel D J (1985) Interpreting multiple pest interactions in soybean. Pages 232-255 *in* CIPM - integrated pest management on major agricultural systems. R. E. Frisbie and P. L. Adkisson, eds. Texas Agricultural Experiment Station Miscellaneous Publication 1616. College Station, Texas.

Noling J W, Bird G W, Grafius E J (1984) Joint influence of *Pratylenchus penetrans* and *Leptinotarsa decemlineata* on *Solanum tuberosum* productivity and pest population dynamics. J. Nematol. 16:230-234.

Padwick G W (1956) Losses caused by plant diseases in the colonies. Phytopathological Paper No. 1. Commonwealth Mycological Institute, Kew, Surrey, England. 60 p.

Pietkiewicz J (1974) Effect of viruses on the reaction of potato to *Phytophthora infestans.* Phytopathol. Z. 81:364-372.

Palis F, Pingali P L, Litsinger J A (1990) A multiple-pest economic threshold for rice (a case study in the Philippines). Pages 229-242 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Rowe R C, Riedel RM, Martin M J (1985) Synergistic interactions between *Verticillium dahliae* and *Pratylenchus penetrans* in potato early dying disease. Phytopathology 75:412-418.

Spadafora V J, Cole H (1987) Interactions between *Septoria nodorum* leaf blotch and leaf rust on soft red winter wheat. Phytopathology 77:1308- 1310.

Stem V M, Smith R F, Van den Bosch R, Hagen K S (1959) The integrated control concept. Hilgardia 29(2):81-101.

Stewart D M, Hill J H (1965) Toxicity of *Helminthosporium sorokinianum* and other fungi to *Puccinia graminis* var. *tritici* Plant Dis. Rep. 49:371-374.

Summers C G, McClellan W D (1975) Interaction between Egyptian alfalfa weevil feeding and foliar disease: impact on yield and quality in alfalfa. J. Econ. Entomol. 68:487-490.

Thanassoulopolous C C (1976) Symptom expression of tomato wilt fungi *Verticillum* and Fusarium as affected by the presence of tobacco mosaic virus. Phytoparasitica 4:137-140.

Teng P S (1975) A quantitative assessment of padi foliar diseases in the Tanjong Karang irrigation scheme, Selangor, Malays. Agric. J. 50:78-99.

Teng P S (1987) Quantifying the relationship between disease intensity and yield loss. Pages 105-113 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society, St. Paul, Minnesota.

Teng P S, Shane W W (1984) Crop losses due to plant pathogens. CRC Crit. Rev. Plant Sci. 2:21-47.

Van der Wall A F, Shearer B L, Zadoks J C (1970) Interactions between *Puccinia recondita* f. sp. *triticina* and *Septoria nodorum* on wheat, and its effects on yield. Neth. J. Plant Pathol. 76:261-263.

Waggoner P E, Berger R D (1987) Defoliation, disease, and growth. Phytopathology 77:393-398.

Walker P T (1987a) Measurement of insect pest populations and injury. Pages 19-29 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society, St. Paul, Minnesota.

Walker PT (1987b) Methods of studying the relation between different insect population levels, damage, and yield in experiments and surveys. Pages 97-104 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society, St. Paul, Minnesota.

Wiese M V (1980) Comprehensive andsystematic assessment of crop yield determinants. Pages 262-269 *in* Crop loss assessment. P. S. Teng and S. V. Krupa, eds. Miscellaneous Publication No. 7. University of Minnesota Agricultural Experiment Station, St. Paul, Minnesota.

Williams D J, Nyvall R F (1980) Leaf infection and yield losses caused by brown spot and bacterial blight diseases of soybean. Phytopathology 70:900-902.

Zadoks J C (1987) The concept of thresholds: warning, action, and damage thresholds. Pages 168-175 *in* Crop loss assessment and pest management. P. S. Teng, ed. American Phytopathological Society, St. Paul, Minnesota.

## Notes

*Author's address:* K. B. Johnson, Department of Plant Pathology, University of Minnesota, St. Paul, MN 55 108, USA. (Current address: Department of Botany, Oregon State University, Corvallis, OR 9733 1-2902, USA)

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Systems analysis and modeling in pest management

K. L. Heong

Widespread use of such terms as *systems approach, systems analysis,* and *systems modeling* has led to some confusion about the nature of the systems concept. In many fields of human endeavor, it has become fashionable to talk about systems—cropping systems, farming systems, transport systems, and social systems. In discussing systems analysis, one is faced with a semantic jungle.

Many biological scientists tend to associate the term *systems analysis* with the use of computers, complex mathematics, and modeling. Computer scientists, in fact, do use *systems analysis* only in reference to activities in electronic data processing.

But developing an understanding of systems analysis has more practical applications than its electronic data processing definition alone. Activities labeled *systems analysis* often have common elements, even though there are some differences in the scope and focus of the analytical activity. In practice, it is more useful to concentrate on the methodology rather than on the scope, leaving more precise definitions to those who practice in particular environments.

For our purposes, systems analysis refers to a systematic approach to investigating problems and identifying and selecting feasible options to arrive at better decisions.

## Definition of systems analysis

Systems analysis was developed during World War II as a means to consider military options (Hoag 1956, Quade 1966). The objective was to decide a course of action by systematically examining costs, effectiveness, risks, and alternative strategies. In a different context, systems analysis focuses on different classes of the work spectrum. At one end is the mathematically oriented analyst who uses complex mathematics and optimization techniques. In approaching a problem, this analyst defines a set of mathematical equations containing a set of variables and condition constraints. Using a set of defined objective functions, he determines the optimal solution. This approach, sometimes called *the mathematics of systems analysis* (Rudwick 1969) or the *hard systems analysis* (Bawden et al 1984, Checkland 1979), is suitable for systems with clear goals and predictable outcomes, as some pest management subsystems (Teng 1985).

At the other end of the work spectrum is the analyst faced with less structured problems. Here, the main objectives are to structure the problem at hand, identify decisionmakers and their goals, and examine the available options. When these objectives are met, the analyst proceeds to using mathematical techniques. This approach has been called *the logic of systems analysis* (Rudwick 1969) or the *soft systems approach* (Checkland 1979, Bawden et al 1984). The problem is structured through the process and the preferred solutions derived. This approach has proved to be extremely useful in designing management programs for specific pests and crops (FAO 1984, Norton 1982), in identifying research and extension needs for pest management (Johnson et al 1985, Norton and Heong 1988). and in evaluating projects (National Research Council 1976).

Because systems analysis is not a single method nor a set of techniques, practitioners have found it difficult to provide a brief definition. Quite often the techniques used differ from study to study, although the general philosophy is maintained. The form of the results also vary.

The definition that best fits our purpose is that given by Quade and Boucher (1968):

"Systems analysis is a systematic approach to helping a decisionmaker choose a course of action by investigating his full problem, searching out objectives and alternatives and comparing them in the light of their consequences using an appropriate framework—insofar as possible analytical—to bring expert judgment and intuition to bear on the problem."

## Systems analysis in pest management

Although a great deal of modern systems thinking was essentially derived from the biological sciences, systems thinking in agriculture did not begin until about two decades ago. Developments since that time have, in fact, led to polarization rather than integration of systems research in agriculture (Dent 1975). The impact on agriculture is still minimal, perhaps because of such factors as

- Lack of appreciation of the structure and functions of the various biological subsystems within a farm.
- Lack of liaison between systems researchers and decisionmakers.
- Overemphasis by systems researchers on model building.
- Uncertainty about how systems theory might be applied in agriculture.

These pitfalls in the systems approach were emphasized by Hoos (1972), Quade and Boucher (1968), and Majone and Quade (1980).

Developments of systems science techniques in pest management have followed a similar path. Most research papers exhibit *modelism* (Kahn and Mann 1957) or *modelitis* (Hoos 1972), apparently an occupational disease of modelers. This has led many authors (e.g. Norton 1977; Ruesink 1976; Way 1973, 1982; Watt 1970) to doubt the value of using systems analysis to improve pest management practices. Although systems analysis has made significant impacts in other fields, such as management (Cleland and King 1975, Kootz and O'Donnell 1976), military planning (Quade 1966), and policy planning (Quade and Boucher 1968), in pest management, it is difficult to say that significant improvements have resulted. This situation is likely to remain until a broader view of systems analysis for problem solving is applied.

The advantage of approaching any area of inquiry or any problem as a system is that it enables one to see the critical variables and constraints and their interactions. It forces scientists and field practitioners to be constantly aware that one single element, phenomenon, or problem should not be treated without regard for its interactions with other elements. Agricultural production systems, for instance, draw upon interrelated systems at the level of the crop, the farming community, and policymakers in agricultural authorities and governments.

Viewed in this context, it is clear that systems analysis applied to the management of pest problems is practical. It is of particular value in guiding policy decisions, defining research priorities, and improving research and extension roles. The value of systems analysis as an aid to pest management has been discussed by many authors (e.g. Getz and Gutierrez 1982, Huffaker 1980, Kranz and Hau 1982, Ruesink 1976, Stark and Smith 1971, Watt 1970). In many cases, emphasis has been on the biological and ecological relationships at the crop level, with little or no attention to the socioeconomic linkages between the farm and agricultural authorities. These linkages, however, often determine the success or failure of pest management (IOBC 1980, Kenmore et al 1985, Matteson et al 1984). Thus, it is argued that a systems approach directed at solving pest management problems should necessarily include these linkages.

As agricultural scientists became increasingly aware that real world problems usually are not structured and that at times institutional barriers are real constraints to solving pest problems, several conceptual approaches to problem solving were developed. These include the on-farm cropping systems approach pioneered by the International Rice Research Institute (Zandstra et al 1981), the farming systems research approach developed at the International Wheat and Maize Improvement Center (Byerlee and Collinson 1980, Collinson 1984, Remenyi 1985), the decision analysis approach (Norton 1982, Norton and Walker 1985), and the agroecosystem analysis and development approach (Conway 1985).

At the same time, recognition by scientists of the gaps that exist between technology, adoption, and practice resulted in the evolution of several important principles. Most notable were the appropriate technology principle (Schumacher 1973), the yield gap principle propounded by the cropping systems research program at IRRI, and the information gap principle propounded by Norton and Mumford (1982). These principles further illustrate the need to broaden the planning horizon of pest management research and extension programs to include the farming community.

## The analytical procedure in systems analysis

Agricultural research procedures are based on two important premises (Norton and Heong 1988):

1. That much greater research effort needs to be devoted to defining agricultural problems, if appropriate solutions are to be expected.

2. That those concerned with designing solutions are often overspecialized, both in a narrow discipline sense and in an institutional sense. Cooperation between disciplines and between research and extension workers is badly needed.

A general procedure for tackling pest management problems consists of four main stages (Fig. 1). In general, these stages are not rigid, but complementary and interactive. The stages should be taken as a guide to analysis of a problem. The stages are

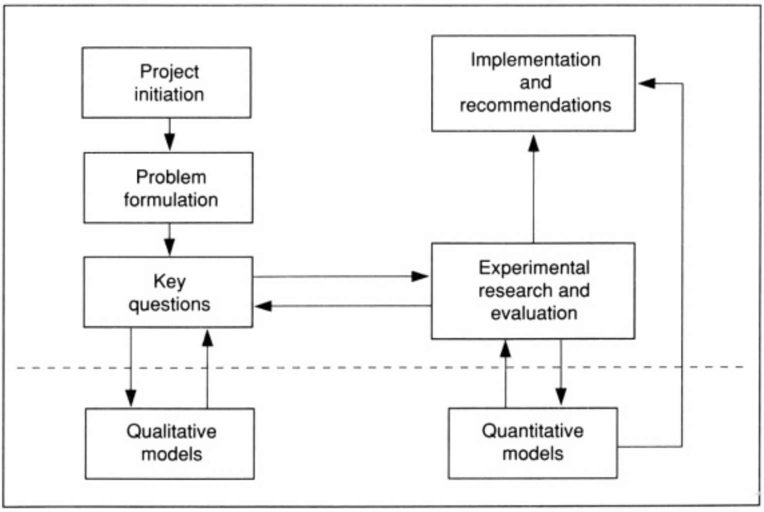
1. Formulating the problem. This involves identifying the relevant decision-makers and their options and objectives and describing the ecological and management components of the situation.
2. Identifying the key management questions.
3. Evaluating the various control options and their consequences.
4. Implementing the control options, policy decisions. and control strategies.

## Stage 1. Problem formulation

The problem formulation stage focuses on identifying the relevant decisionmakers, or clients, in the system, the ecological and technical aspects of the problem, and aspects relating to the management and control of the problem. The descriptive procedure can be summarized using the approach of Norton (1982).

Descriptions of the ecological and technical aspects relating to the pest problem provide the bases for selecting control options and the framework for research and incorporation of new information. The analysis proceeds with identification of the major components of the system and description of the systems' dynamics, focusing on the interactions of the components and their changes in the components with time.

Various descriptive techniques may be used to summarize the ecological aspects. For example, cropping patterns may be represented schematically (Fig. 2). Similarly,



**1.** Procedure for the systems approach.

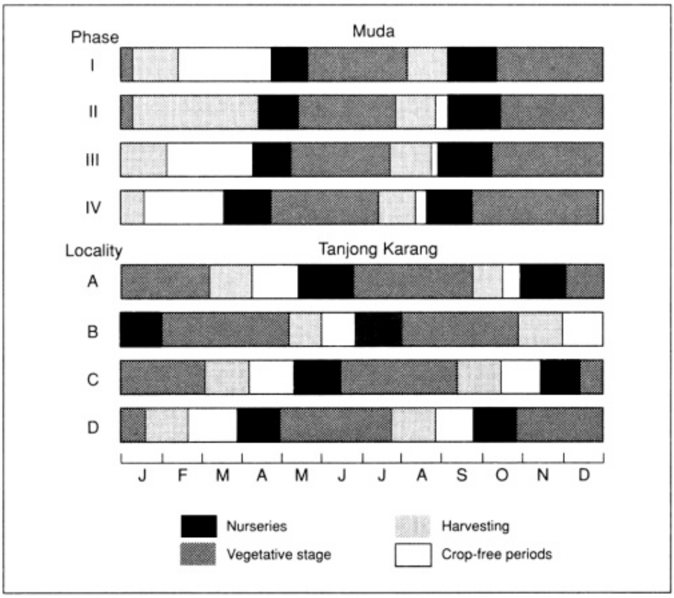
the time profile of the major pest components (Fig. 3) may be used to represent periods when pests are likely to be important. To give some idea of the damage relationships, a damage matrix (Fig. 4) can show attacks at various growth stages. An interaction matrix showing relationships between the major pest components and their natural enemies (Table 1) can summarize the important biological control agents.

At this stage, emphasis is on the objectives of the decision makers, factors affecting decisionmaking, and the options available and their consequences (Table 2). Farm surveys have been found valuable in identifying socioeconomic aspects of the problem (Heong 1984, Heong et al 1985, Heong and Ho 1987, Heong et al 1987, Mumford and Norton 1984, Norton 1982).

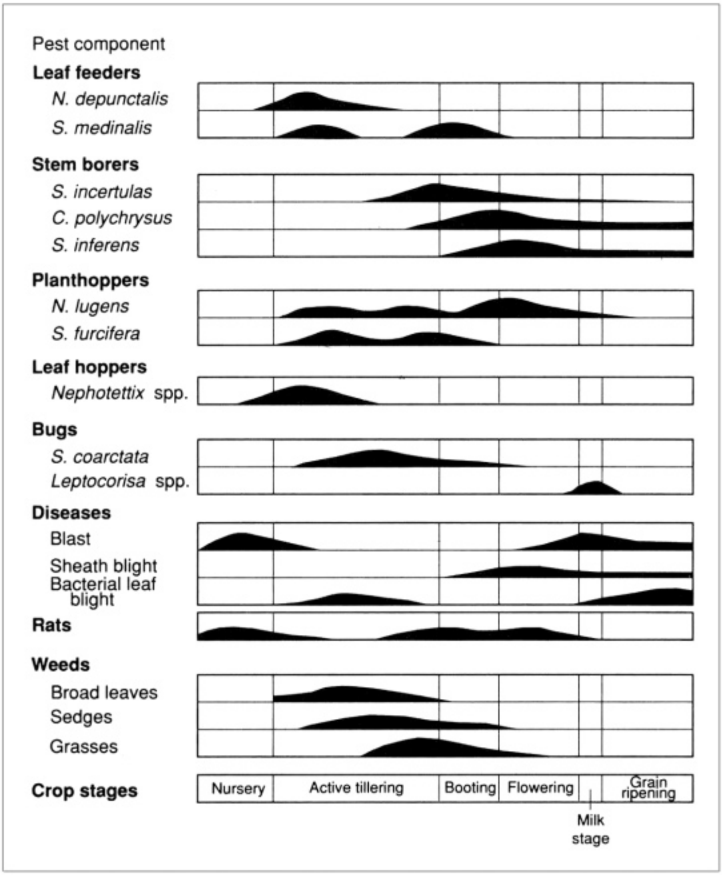
## Stage 2. Key questions

In the key questions stage, questions relating to the ecological and technical information required for resolving the problem are formulated and the important socioeconomic and management issues are identified. The questions normally relate to management of the problem and may be used as guidelines to further research and data analyses, and for improving extension and training efforts.

Key questions may relate to theoretical considerations of the impact of natural enemies, cultivation practices, pesticide resistance, and insecticide applications. In



**2.** Cropping patterns in the Muda and Tanjong Karang rice schemes, Malaysia. Muda Phases I-IV are determined by water release schedules. Locality A in Tanjong Karang is Sekinchan; B is Sungai Burong; C includes Sungai Leman, Sungai Panjang, and Sungal Nipah; D includes Sawah Sempadan and Bagan Terap.

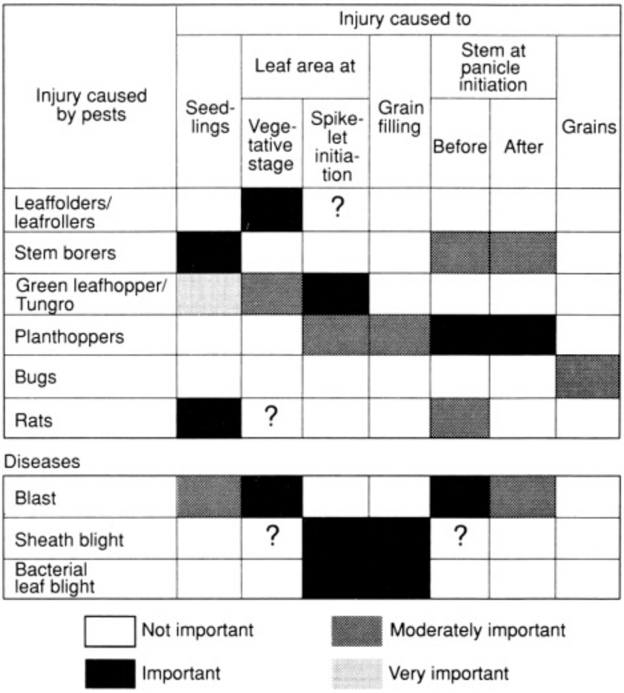


**3.** Time profile of major rice pests in Malaysia. In this schematic representation, bars indicate periods in which the pests are likely to be of economic importance; they do not necessarily indicate the size of the populations.

these cases, research and analytical models play a key role. For example, various models have been used to investigate the effects of cultural controls on pests (e.g. Shoemaker 1977), pesticide resistance (Comins 1977), biological control (Murdoch et al 1985, May and Hassell 1988, Hassell 1980), the effects of insecticides on natural enemies (Waage et al 1985), forecasting schemes (Cammell and Way 1977, Carlson 1970, Norton 1976), and insecticide application strategies (Birley 1977, Conway et al 1975, Heong 1988).

## Stage 3. Evaluation

Control options identified in the analysis need to be evaluated. Here, various techniques from management science, operations research, and empirical experiments can be used, depending on the nature of the control options. For those options that are less



| Injury caused by pests | Injury caused to | | | | | | |
|---|---|---|---|---|---|---|---|
| | Seedlings | Leaf area at | | Grain filling | Stem at panicle initiation | | Grains |
| | | Vegetative stage | Spikelet initiation | | Before | After | |
| Leaffolders/ leafrollers | □ | ■ | ? | □ | □ | □ | □ |
| Stem borers | ■ | □ | □ | □ | ▨ | ▨ | □ |
| Green leafhopper/ Tungro | ░ | ▨ | ■ | □ | □ | □ | □ |
| Planthoppers | □ | □ | ▨ | ▨ | ■ | ■ | □ |
| Bugs | □ | □ | □ | □ | □ | □ | ▨ |
| Rats | ■ | ? | □ | □ | ▨ | □ | □ |
| Diseases | | | | | | | |
| Blast | ▨ | ■ | □ | □ | ■ | ▨ | □ |
| Sheath blight | □ | ? | ■ | ■ | ? | □ | □ |
| Bacterial leaf blight | □ | □ | ■ | ■ | □ | □ | □ |

□ Not important
■ Important
▨ Moderately important
░ Very important

**4.** Damage matrix showing the importance of pest and disease attacks at the various growth stages of rice.

well defined, such as policy options and cultural practices, less formal, qualitative methods of evaluation can be used. These methods, which often rely on expert judgment, are used in management and project planning. Examples are the use of interaction matrices (Norton and Heong 1988, Quade and Boucher 1968), cause-effect matrices (Table 1) (Heong 1985), and the Delphi technique (Delbecq et al 1975).

For more well-defined options, such as the choice between insecticides, evaluations may be made through field or laboratory experiments. For more general control strategies, such as the optimal timing of sprays, using a biological control agent, and using the sterile male technique, research models have been shown to be useful (Conway et al 1975, Murdie and Campion 1972).

## Stage 4. Implementation

Implementation is an important, but often neglected component of many pest management programs. In investigating various control options, it is necessary to consider aspects of their implementation. Planning implementation strategies will depend on the knowledge and analysis carried out in the first three stages of the procedure. By emphasizing identification of gaps in the information flow from research to the farm and the form in which information can be received, suggestions for improvements

**Table 1. Interaction matrix between rice pests and their natural enemies (after Norton and Heong 1988).**

| | Pests[a] | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stem borers | | | | Leafrollers | | | | Leaffolders | | | | Green leaf-hopper | | | White-backed plant-hopper and brown plant-hopper | | | Rice bugs | | |
| Natural enemies | E | L | P | A | E | L | P | A | E | L | P | A | E | N | A | E | N | A | E | N | A |
| Parasitoids | | | | | | | | | | | | | | | | | | | | | |
| *Trichogramma* spp | 0 | | | | 0 | | | | 0 | | | | | | | | | | | | |
| *Telenomus* spp. | 0 | | | | | | | | | | | | | | | | | | | | |
| *Tetrastichus* spp. | | 0 | | | | | | | | | | | | | | | | | | | |
| *Paracentrobia* spp. | | | | | | | | | | | | | * | | | * | | | | | |
| *Oligosita* spp. | | | | | | | | | | | | | * | | | * | | | | | |
| *Anagrus* spp. | | | | | | | | | | | | | * | | | * | | | | | |
| *Gryon nixoni* | | | | | | | | | | | | | | | | | | | 0 | | |
| *Apanteles* spp. | | 0 | | | | 0 | | | | 0 | | | | | | | | | | | |
| *Bracon* spp. | | 0 | | | | | | | | | | | | | | | | | | | |
| *Xanthopimpla* spp. | | 0 | | | | | | | | | | | | | | | | | | | |
| *Temelucha* spp. | | 0 | | | | 0 | | | | 0 | | | | | | | | | | | |
| *Elenchus* spp. | | | | | | | | | | | | | | * | 0 | | * | | | | |
| *Elasmus* spp. | | 0 | | | | | | | | 0 | | | | | | | | | | | |
| *Mymar* spp. | | | | | | | | | | | | | * | | | * | | | | | |
| *Gonotocerus* spp. | | | | | | | | | | | | | 0 | | | 0 | | | | | |
| *Pipunculus* spp. | | | | | | | | | | | | | | 0 | | | 0 | | | | |
| Predators | | | | | | | | | | | | | | | | | | | | | |
| *Ropalidia* spp. | | | | | | | * | * | | | * | * | | | | | | | | | |
| *Conocephalus* spp. | 0 | | | | 0 | 0 | 0 | | 0 | | | | | | | | | | | | |
| *Cyrtorhinus* spp. | | | | | | | | | | | | | 0 | | | 0 | | | | | |
| *Ophinea* spp. | | | | | | 0 | 0 | | | 0 | 0 | | | 0 | 0 | | 0 | 0 | | | |
| *Paederus* spp. | | | | | | | | | | | | | | 0 | 0 | | 0 | 0 | | | |
| *Microvelia* spp. | | | | | | | | | | | | | | * | * | | | | | | |
| Spiders | | | | 0 | | | | 0 | | | | 0 | | * | * | | * | * | | | |

[a] Life stages parasitized or predated: E = egg; L = larval; P = pupal; N = nymphal; A = adult. 0 indicates important relationsip, * indicates very important relationship.

become more apparent. Such improvements form a guide for research and extension and for pest information systems (Heong 1988, Norton and Mumford 1982).

## The role of models

In many instances, carrying out all four stages in the systems analysis procedure will be sufficient. However, simple qualitative models often can be useful in refining the key questions and in defining the problem more precisely. Quantitative models are useful in describing interrelationships between various components. Often, the most powerful role is the modeling process that helps identify the variables, parameters, and

**Table 2. Some government policy options and their consequences in controlling the brown planthopper (BPH) problem (after Heong 1985).**

| Policy options | BPH and rice ecosystem | Farmers | Government |
|---|---|---|---|
| Warn and advise farmers | Good control if farmers follow advice | Constrained by finance, labor, time | No additional costs or functions |
| | BPH may spread due to delays in control | May not follow advice | BPH may spread to other areas |
| Distribute insecticides on credit and advise farmers | Better control likely | More likely to follow advice | High initial costs |
| | | Collect insecticides but may not pay debt | Problems in debt collecting |
| Distribute insecticides free of charge and advise farmers | Better control likely | More likely to collect chemicals | High costs |
| Distribute insecticides free of charge and supervise applications | Detrimental to natural enemies<br>Pollution to environment | Indiscriminate use of insecticides likely | High costs<br>High labor required |
| Treat infected fields and charge farmers | Better regional control<br>Detrimental to natural enemies | May not pay | High cost + labor required<br>Collection problems |
| Treat infected fields with no charge to farmers | Pollution to environment<br>Development of resistance to insecticide | Likely to be most happy<br>May grow dependent on government | High costs + labor required<br>Extension of pest control placed in jeopardy |

relationships (Heong 1985). Because models can, at best, only mimic real systems, their role as tools indecisionmaking will depend on the decisionmaker's questions. The answers can act as feedback to improve the descriptive analysis and to raise further key questions.

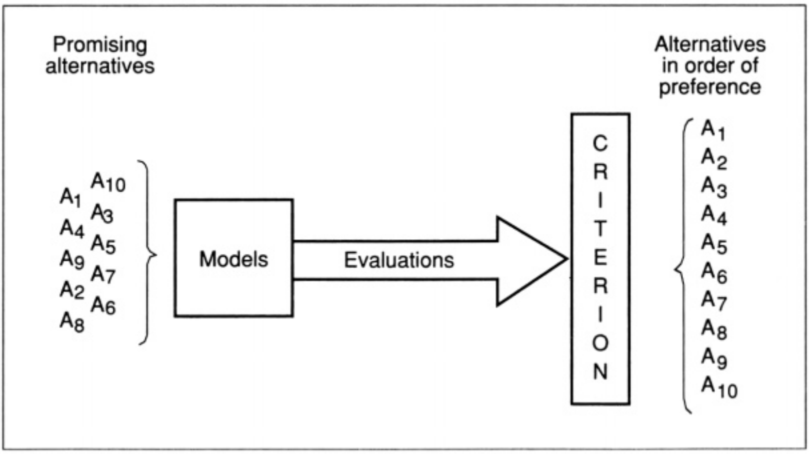
A model is the basic operating device used by the systems analyst. Models are a scaled-down representations of a real-world system. Many exterior features are completely excluded. A scientist's model is an abstraction of reality. Different models abstract different elements of the system. Thus, the structure of a model is determined by the applications anticipated. Models of pest management systems should be designed on the basis of their expected applications.

In the scientific sense, a model is a representation of a system which is used to predict the effect of changes in certain aspects of the system on its performance. Various alternatives can be examined by means of models that estimate the consequences or outcomes that can be expected from each alternative, such as the costs and extent to which each objective is attained (Fig. 5) (Quade and Boucher 1968). A criterion is used to weigh costs against performance, and alternatives can be arranged in order of the outcome.

Use of models in pest management was pioneered primarily by Watt (1961,1966, 1968) and Holling (1963,1966). A large literature now exists on models related to pest management (Conway 1973, Getz and Gutierrez 1982, Kranz and Hau 1982, Norton and Holling 1977, Ruesink 1976, Shoemaker 1977, Teng 1985). Much of the effort has concentrated on developing and refining models to describe existing systems; little time has been spent on evaluating alternate strategies (Ruesink 1976) or in answering management issues.

A few models have focused on evaluating control alternatives. Of particular importance are control of the sugarcane froghopper (Birley 1977, Conway et al 1975), the cattle tick (Sutherst et al 1979), the alfalfa weevil (Shoemaker 1977), the gypsy moth (Valentine et al 1976), and the coffee berry disease (Kranz and Hau 1982).

In improving pest management, models can be expected to perform several roles, including 1) improving the understanding of the pest, pest damage, and pest ecology and community; 2) evaluating control alternatives; 3) improving pest control decision-making; and 4) pest forecasting. By recognizing their limitations, we can further enhance their functions with more effort spent on defining the problem before models are considered. The need to obtain an appreciation of the overall pest situation is often of major importance.



**5.** Modeling in systems analysis (adapted from Quade and Boucher 1968).

## Conclusion

Systems analysis can help to define real-world details that affect pest management practice, and thus can identify possible management measures. For many of these measures, qualitative models will be sufficient for providing insights into relationships and evaluations. Consequences of alternative management strategies may be examined using such techniques as cause-effect matrices, nominal group techniques, and expert consensus. Models can be used to address key questions.

However, because at best they can only provide predictions within the conditions specified and cannot actually forecast the outcome, models should be developed for well-defined purposes. A model is a means to an end, not an end in itself. It is a major tool in analysis, but should not be viewed as identical with the analysis. Forgetting this function can trap analysts into treating the model they set out to build as more important than the question they set out to answer.

Pest problems are not static. They change as farmers' knowledge, attitudes, and practices change and as economic, technological, and political developments occur. To keep research and extension on target, it is important that the systems analysis process be carried out at intervals. This, in fact, is the real strength of systems analysis in solving pest management problems.

## References cited

Bawden R, Macadam R, Valentine I, Packham R (1984) Systems thinking and practices in the education of systems agriculturists. Agric. Syst. 13:200-225.

Birley M H (1977) A transfer function pest management model. Pages 201-216 *in* Proceedings of a conference on pest management. G. A. Norton and C. S. Holling, eds. International Institute for Applied Systems Analysis, A-2361. Laxenburg, Austria.

Byerlee D K, Collinson M P (1980) Planning technologies appropriate to farmers: concepts and procedures. International Wheat and Maize Improvement Center, Mexico.

Cammell M E, Way M J (1977) Economics of forecasting for chemical control of the black bean aphid, *Aphis fabae,* on the field bean, *Vicia fabae.* Ann. Appl. Biol. 85:333-343.

Carlson G A (1970) A decision theoretic approach to crop disease prediction and control. Am. J. Agric. Econ. 52:216-223.

Checkland P B (1979) Techniques in 'soft' systems practice. Part 2. Building conceptual models. J. Appl. Syst. Anal. 6:41-49.

Cleland D I, King W R (1975) Systems analysis and project management. McGraw Hill, Inc., New York.

Collinson M P (1984) Farm systems research: diagnosing the problem. Paper presented at the Annual Agricultural Symposium of the World Bank, 9-13 Jan 1984, Washington, D.C. 23 p.

Comins H N (1977) The control of adaptable pests. Pages 217-226 *in* Proceedings of a conference on pest management. G. A. Norton and C. S. Holling, eds. International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria.

Conway G R (1973) Experience in insect pest modelling: a review of models, uses and future directions. Pages 103-130 *in* Insects: studies in population management. Memoir I. P. W. Geier, L. R. Clark, D. J. Anderson, and H. A. Nix, eds. Ecological Society of Australia, Canberra.

Conway G R (1985) Agricultural ecology and farming systems research. Pages 43-59 *in* Agricultural systems research for developing countries. J. V. Remenyi, ed. ACIAR Proceedings No. 11. Australian Centre for International Agricultural Research, Canberra.

Conway G R, Norton G A, Small N J, King A B S (1975) A systems approach to the control of the sugarcane froghopper. Pages 193-229 *in* Study of agricultural systems. G. E. Dalton, ed. Applied Science Publishers, Ltd., London.

Delbecq A L, van den Ven A H, Gustafson D H (1975) Group techniques for program planning: a guide to nomical group and delphi processes. Scott, Foreman and Co., Glenview, Illinois.

Dent J B (1975) The application of systems theory in agriculture. Pages 107-127 *in* Study of agricultural systems. G. E. Dalton, ed. Applied Science Publishers, Ltd., London.

FAO (1984) Analysis and design of integrated crop management programmes (with particular reference to Africa). FAO Committee of Experts on Pest Control. Paper No. AGP:PES/84/ WP/3:4. FAO, Rome. 18 p.

Getz W M, Gutierrez A P (1982) A perspective on systems analysis in crop production and insect pest management. Annu. Rev. Entomol. 27:447-466.

Hassell M P (1980) Foraging strategies, population models, and biological control: a case study. J. Anim. Ecol. 45:471-486.

Heong K L (1984) Pest control practices of rice farmers in Tanjong Karang, Malaysia. Insect Sci. Appl. 5:221-226.

Heong K L (1985) Systems analysis in solving pest management problems. Pages 133-149 *in* Integrated pest management in Malaysia. B. S. Lee, W. H. Loke, and K. L. Heong, eds. Malaysian Plant Protection Society, Kuala Lumpur.

Heong K L (1988) A simulation approach to evaluating insecticides for brown planthopper control. Res. Pop. Ecol. 30:165-176.

Heong K L, Ho N K (1987) Farmers' perceptions of the rice tungro virus problem in the Muda Irrigation Scheme, Malaysia. Pages 165- 174 *in* Management of pests and pesticides. J. Tait and B. Napompeth, eds. Westview Press, Boulder and London.

Heong K L, Ho N K, Jegatheesan S (1985) The perception and management of pests among rice farmers in the Muda Irrigation Scheme, Malaysia. MARDI Report No. 105. Malaysian Agricultural Research and Development Institute, Serdang.

Heong K L, Yahya H, Tee S P (1987) Pest management practices of tobacco farmers in Bachok (Kelantan), Peninsular Malaysia. MARDI Report No. 116. Malaysian Agricultural Research and Development Institute, Serdang.

Hoag M W (1956) An introduction to systems analysis. The RAND Corporation. Pages 1-21 *in* Systems analysis. S. L. Optner, ed. Penguin Books Ltd., Middlesex, England.

Holling C S (1963) An experimental component analysis of population processes. Mem. Entomol. Soc. Can. 32:22-32.

Holling C S (1966) The strategy of building models of complex ecological systems. Pages 195-214 *in* Systems analysis in ecology. K. E. F. Watt, ed. Academic Press, New York and London.

Hoos I R (1972) Methodology, methods, and models. *In* Systems thinking. F. E. Emery, ed. Penguin Books Ltd., Middlesex, England.

Huffaker C B, ed. (1980) New technology of pest control. John Wiley and Sons, New York.

IOBC — International Organization for Biological Control (1980) Conference on future trends of integrated pest management. Bellagio, 30 May - 4 June 1980. IOBC special issue. Centre for Overseas Pest Research, London.

Johnson K B, Teng P S, Bird G W, Grafius E, Nelson D, Rouse D (1985) Analysis of potato production systems and identification of IPM research needs. Final Report of the Potato Task Force, NC-166. Technical Committee on Integrated Pest Management, USDA, Washington, D.C. 145 p.

Kahn H, Mann I (1957) Techniques of systems analysis. RAND Corporation. 13 p.

Kenmore P E, Heong K L, Putter C A J (1985) Political, social and perceptual aspects of integrated pest management programmes. Pages 47-66 *in* Integrated pest management in Malaysia. B. S. Lee, W. H. Loke, and K. L. Heong, eds. Malaysian Plant Protection Society, Kuala Lumpur.

Koontz H, O'Donnell L (1976) Management: a system and contingency analysis of managerial function. 6th ed. McGraw Hill, Tokyo.

Kranz J, Hau B (1982) Systems analysis in epidemiology. Annu. Rev. Phytopathol. 18:67-81.

Majone G, Quade E S, eds. (1980) Pitfalls in analysis. International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria.

Matteson PC, Altieri MA, Gagne W C (1984) Modification of small farmer practices for better pest management. Annu. Rev. Entomol. 29:383-402.

May R M, Hassell M P (1988) Population dynamics and biological control. Phil. Trans. R. Soc. Lond. B. 318:129-169.

Mumford J D, Norton G A (1984) Economics of decision making in pest management. Annu. Rev. Entomol. 29:157-174.

Murdie G, Campion D G (1972) The use of computer simulation of cotton red bollworm (*Diparopsis castanea* Hmps.) populations to investigate the potential value of sterile male release and sex attractants in control programmes. Cotton Growers' Rev. 49:276-284.

Murdoch W W, Chesson J, Chesson P L (1985) Biological control in theory and practice. Am. Nat. 125:344-366.

NRC — National Research Council (1976) Systems analysis and operations research: a tool for policy and program planning for developing countries. National Academy of Sciences, Washington, D.C.

Norton G A (1977) Background to agricultural pest management modelling. Pages 161-176 *in* Proceedings of a conference on pest management. G. A. Norton and C. S. Holling, eds. International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria.

Norton G A (1976) Analysis of decision making in crop protection. Ago-Ecosystems 3:37-44.

Norton G A (1982) A decision-analysis approach to integrated pest control. Crop Prot. 1:147-164.

Norton G A, Heong K L (1988) An approach to improving pest management: rice in Malaysia. Crop Prot. 7:34-90.

Norton G A, Holling C S, eds. (1977) Proceedings of a conference on pest management. International Institute for Applied Analysis, A-2361, Laxenburg, Austria.

Norton G A, Mumford J D (1982) Information gaps in pest management. Pages 589-598 *in* Proceedings of the international conference on plant protection in the tropics. K. L. Heong, B. S. Lee, T. M. Lim, C. H. Teoh, and Y. Ibrahim, eds. Malaysian Plant Protection Society. Kuala Lumpur.

Norton G A, Walker B H (1985) A decision analysis approach to savanna management. J. Environ. Manage. 21:15-31.

Quade E S (1966) Military systems analysis. The RAND Corporation. Pages 121-140 *in* Systems analysis. S. L. Optner, ed. Penguin Books Ltd., Middlesex, England.

Quade E S, Boucher W I, eds. (1968) Systems analysis and policy planning: applications in defense. Elsevier Publishing Co., New York.

Remenyi J U, ed. (1985) Agricultural systems research for developing countries. Proceedings of an international workshop held at Hanvkeshury Agricultural College, Richmond, N.S.W., Australia, 12-15 May 1985. ACIAR Proceedings No. 11. Australian Centre for International Agricultural Research, Canberra. 189 p.

Rudwick B H (1969) Systems analysis for effective planning: principles and cases. John Wiley and Sons, Inc., New York.

Ruesink W G (1976) Status of the systems approach to pest management. Annu. Rev. Entomol. 21:27-44.

Shoemaker C A (1977) Optimal management of an alfalfa ecosystem. Pages 301-316 *in* Proceedings of a conference on pest management. G. A. Norton and C. S. Holling, eds. International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria.

Shumacher E F (1973) Small is beautiful: a study of economics as if people mattered. Blond and Briggs, Ltd., London.

Stark R W, Smith R F (1971) Systems analysis and pest management. Pages 331-342 *in* Biological control. C. B. Huffaker, ed. Plenum, New York.

Sutherst R W, Norton G A, Barlow N D, Conway G R, Birley M, Comins H N (1979) An analysis of management strategies for cattle tick ( *Boophilus microplus* ) control in Australia. J. Appl. Ecol. 16:359-382.

Teng P S (1985) Integrating crop and pest management: the need for comprehensive management of yield constraints in cropping systems. J. Plant Rot. Trop. 2:15-26.

Valentine H T, Carlton M N, Talevico R L (1976) Compatible systems and decision models for pest management. Environ. Entomol. 5:891-900.

Waage J K, Hassell M P, Godfray H C J (1985) The dynamics of pest-parasitoid-insecticide interactions. J. Appl. Ecol. 22:825-838.

Watt K E F (1961) Use of a computer to evaluate alternative insecticidal programs. Science 133:706-777.

Watt K E F, ed. (1966) Systems analysis in ecology. Academic Press, New York and London.

Watt K E F (1968) Ecology and resource management. McGraw Hill, New York.

Watt K E F (1970) The systems point of view in pest management. Pages 71-79 *in* Concepts of pest management. R. L. Rabb and F. E. Guthrie, eds. North Carolina State University, Raleigh, North Carolina, USA.

Way M J (1973) Objectives, methods and scope of integrated control. Pages 137-152 *in* Insects: studies in population management. P. W. Geier, L. R. Clark, D. J. Anderson, and H. A. Nix, eds. Ecological Society of Australia, Canberra, Australia.

Way M J (1982) Practical realities of integrated pest control. Pages 121-128 *in* Proceedings of the international conference on plant protection in the tropics. K. L. Heong, B. S. Lee, T. M. Lim, C. H. Teoh, and Y. Ibrahim, eds. Malaysian Plant Protection Society, Kuala Lumpur.

Zandstra H G, Price E C, Litsinger J A, Morris R (1981) A methodology for on-farm cropping systems research. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

## Notes

*Author's address:* K. L. Heong, Entomology Department, IRRI, P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# A multiple-pest economic threshold for rice (a case study in the Philippines)

F. Palis, P. L. Pingali, and J. A. Litsinger

Economic threshold (ET) is defined as the pest population that produces incremental damage equal to the cost of controlling or preventing that damage (Headley 1972a). It is the level of pest population where the benefit of pest control is equal to its cost (Norton 1976). Here we define ET as the pest damage level where the value of incremental reduction in yield is equal to the cost of preventing its occurrence.

Economic thresholds are important decisionmaking tools in integrated pest management (IPM). They enable strategic timing of pest control action, particularly chemical control. Their usefulness is related to the application of pesticides on the basis of need, in order to minimize such negative externalities as harmful effects of agricultural chemicals to the environment and public health.

The economic threshold concept is based on the assumption that farmers are profit maximizers (Headley 1972b), that they will make pest management decisions on the basis of the profit to be derived from a particular pest control activity. Such farmers operate where marginal revenue equals marginal cost. A profit-maximizing farmer would likely make his pest management decisions on the basis of threshold values.

Many farmers, however, continue to apply pest control measures earlier than called for. Perhaps they perceive that a recommended ET is higher than it should be. Currently, ETs assume only one pest, when in fact an array of pest species are usually present in a field at the same time. Cumulative damage caused by a combination of pests may be above an economic level, even though each pest is below its individual ET. The interaction or synergistic effect could cause the presence of one pest to enhance the damage inflicted by another pest: although there may be no significant reduction in yield caused by a single pest, with joint infestations, there is.

The effect of organisms preying on or parasitizing insect pests also is not considered in a single-pest ET. A population of predators and parasites could provide effective natural control.

ETs are thought to be location specific. The severity of pest infestation, degree of crop response to pest damage and control, and effectiveness of control differ across locations. Market prices of chemicals, labor, and rice also vary.

An ET also changes with time, as pest populations fluctuate. Different insects attack the rice plant at different growth stages. As rice matures, its response to pest attacks changes.

These factors make it inappropriate to establish a blanket ET for a particular pest at all stages of a crop and across all locations.

In the Philippines, several scientists have worked on estimating economic thresholds for different insect pests, to serve as bases for field recommendations. The 1985 Masagana 99 Interagency Insect Control Guide for the Philippines recommended the application of insecticide to control rice stem borers if deadhearts reach 10% when rice is at the tillering stage. Pathak and Dyck (1973) suggested 10% deadhearts as the ET during maximum tillering. (It is believed that the rice plant produces enough new tillers to compensate if less than 10% of the tillers are damaged.) In 1986, Waibel estimated the ET for stem borer during the reproductive phase as 15% deadhearts in the wet season and 13% in the dry season (Table 1).

Our estimates are slightly lower—8% at both the vegetative and reproductive phases. Leaffolder ETs estimated from greenhouse trials were 9% damaged leaves for the wet season and 7% for the dry season. Leaffolder did not cause significant reductions in rice yield and no leaffolder ET was established. For caseworm, ETs estimated in greenhouse trials were 19% for the wet season and 21% for the dry season, higher than our recent estimate of 9% at the vegetative phase.

But commonly used procedures for estimating ET cannot cope with situations where a combination of pests attack a crop simultaneously (Zadoks 1985). At IRRI, researchers found that at increasing intensities of infestation, no one test insect (rice caseworm, rice whorl maggot, and yellow stem borer) significantly reduced yield by itself (Table 2). However, combinations of two or more pests caused economic losses, even when each was below its individual ET (IRRI 1983).

Because crops are often attacked simultaneously by two or more insect pest species, it seems more realistic to calculate multiple-pest thresholds. We present here a methodology for determining a multiple-pest ET. It is basically a modified version of the methodology for determining a single-pest ET. The methodology considers both simultaneous attack and aggregate effects.

The literature on multiple-pest ETs is sparse. Johnson and Teng (1987) presented evidence showing significant effects of multiple diseases and insects on potato yield. Blackshaw (1986) developed ET models for a two-pest/two-pesticide situation on spring barley. Hutchkins et al (1988) used an injury equivalency system: he converted larval size to leaf consumption to develop a multispecies economic injury equivalency for determinate soybeans.

**Table 1. Economic threshold values in Nueva Ecija, Philippines (Waibel 1986).**

| Pest | Threshold value | |
|---|---|---|
| | Wet season | Dry season |
| Rice whorl maggot | 48 | 42 |
| Rice caseworm - vegetative phase | 19 | 21 |
| Rice leaffolder - reproductive phase | 9 | 7 |
| Stem borer - reproductive phase | 7 (15%) | 6 (13%) |

**Table 2. IR36 yield as affected by rice caseworm (RCW), rice whorl maggot (RWM), or yellow stem borer (YSB), alone and in double and triple pest combinations, at four infestation levels in the field.[a] IRRI, 1982 wet season.**

| | Grain yield (g/m) at infestation level | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| RCW | 519.2 | 539.3 | 526.8 | 474 |
| RWM | 541.2 | 554.8 | 508.4 | 451.4 |
| YSB | 473.5 | 485.9 | 443.2 | 42426.6 |
| RCW + RWM | 481.3 | 495.2 | 343.3 | 385.4 |
| RCW + YSB | 461.5 | 434.9 | 396.3 | 360.5 |
| RWM + YSB | 397.9 | 423.2 | 460.9 | 392.9 |
| RCW + RWM + YSB | 447.4 | 416.7 | 426.6 | 318.9 |
| Control (unprotected) | 487.6 | 487.6 | 487.6 | 487.6 |
| Control (protected) | 501.9 | 501.9 | 501.9 | 501.9 |

[a] Av of four replications. Level 1 = 200 RCW, RWM, and YSB/2.25 $m^2$, Level 2 = 400 RCW, RWM, and 300 YSB. Level 3 = 600 RCW and RWM and 400 YSB. Level 4 = 900 RCW 2nd-instar larvae, RWM adults and 500 YSB 1st-instar larvae.

In a 1982 IRRI study, crop damage (% deadhearts, % damaged leaves, etc.) was used to index pest infestation. Monitoring damage is less difficult than monitoring egg, larva, pupa, and moth populations. For example, to monitor stem borers, rice tillers must be pulled out and dissected to count the larvae boring inside the stalks. In addition, estimates of pest populations should also consider the effects of natural enemies on insect growth (e.g. the number of parasitized egg masses).

## Estimating multiple-pest ET

We used data from on-farm field verification trials to develop formulas for estimating multiple-pest ETs.

### Materials and methods

The data were collected from IPM on-farm trials conducted by IRRI in Zaragoza, Nueva Ecija, Philippines. Five farms were monitored weekly during the 1988 wet season. All farms were in the same environment and farmers used the same levels of farm inputs and management. All hills used in the analyses were untreated. In each of three farms, 25 hills were monitored; in each of the two other farms, 105 hills were monitored. The 285 hills were marked, numbered, and checked at the vegetative, reproductive, and ripening phases, at 35, 49, and 70 d after transplanting (DT). Pest infestation ranged from 0 to 82% (Table 3).

*Insect damage.* The sample unit used to measure insect damage was one hill. Leaves damaged by leaffolder, caseworm, whorl maggot, and defoliators (particularly *naranga* and *rivula*); deadhearts (dead tillers) or whiteheads (empty panicles) due to stem borer; and flag leaves damaged by leaffolder were counted. Damage was computed as

**Table 3. Pest damage (%) at different crop growth phases. Zaragosa, Nueva Ecija, 1982.**

| Pest | Mean | SD | Min | Max |
|---|---|---|---|---|
| | *Vegetative phase* | | | |
| Whorl maggot | 23.06 | 13.97 | 1.4 | 75.0 |
| Caseworm | 6.06 | 4.77 | 0.0 | 20.2 |
| Defoliators | 1.32 | 2.27 | 0.0 | 16.7 |
| Leaffolder | 4.71 | 6.06 | 0.0 | 33.3 |
| Deadhearts | 5.80 | 8.30 | 0.0 | 41.2 |
| | *Reproductive phase* | | | |
| Whorl maggot | 22.48 | 11.33 | 28 | 78.2 |
| Defoliators | 6.75 | 5.74 | 0.0 | 32.4 |
| Caseworm | 0.56 | 1.36 | 0.0 | 9.5 |
| Leaffolder | 7.30 | 8.00 | 0.0 | 42.5 |
| Deadhearts | 7.39 | 10.20 | 0.0 | 56.3 |
| | *Ripening phase* | | | |
| Whorl maggot | 13.05 | 7.98 | 0.0 | 66.6 |
| Defoliators | 3.09 | 4.72 | 0.0 | 30.0 |
| Caseworm | 0.32 | 1.17 | 0.0 | 8.9 |
| Leaffolder | 14.92 | 12.09 | 0.0 | 61.5 |
| Flag leaf | 12.80 | 13.29 | 0.0 | 62.5 |
| Whiteheads | 5.87 | 10.08 | 0.0 | 82.0 |

N = 285.

$$\%\ \text{leaffolder} = \frac{\text{no. of leaffolder-damaged leaves}}{\text{total no. of leaves}} \times 100 \qquad (1)$$

$$\%\ \text{deadhearts} = \frac{\text{no. of deadhearts}}{\text{total no. tillers}} \times 100 \qquad (2)$$

$$\%\ \text{caseworm} = \frac{\text{no. of caseworm-damaged leaves}}{\text{total no. of leaves}} \times 100 \qquad (3)$$

$$\%\ \text{defoliation} = \frac{\text{no. of defoliated leaves}}{\text{total no. of leaves}} \times 100 \qquad (4)$$

$$\%\ \text{whiteheads} = \frac{\text{no. of whiteheads}}{\text{total no. of leaves}} \times 100 \qquad (5)$$

Damage by deadheart, leaffolder, caseworm, whorl maggot, and defoliators was calculated for the vegetative, reproductive, and ripening phases. Percent whitehead and percent damaged flag leaves were calculated at ripening.

*Yield.* Filled and unfilled grains were weighed separately. Yield was corrected to 11.5% moisture.

## Formulas for estimating ET

Separate multiple regression equations were estimated for each phase (35, 49, and 70 DT). Yield, in grams per hill, was the dependent variable; infestation by whorl maggot, caseworm, defoliators *naranga* and *rivula,* stem borer, and leaffolder the independent variables.

*Single-pest ET.* The working formula for the single-pest ET (Norton 1976) was

$$\text{ET} = \frac{c}{pdk} \tag{6}$$

where

c = costs of pest control (material, labor, credit charge);

p = output (market price of rough rice);

d = damage coefficient (% yield reduction per % increase in pest infestation level); and

k = % control efficacy (pest kill), effectivity of pesticide in controlling the pest.

*Multiple-pest ET.* The operational formula for a multiple-pest ET (the simultaneous occurrence of two or more insect pests) was

$$\begin{gathered}(\text{rough rice} \times \%\ \text{control efficacy}) \times (\text{d1* pest1} + \text{d2* pest2} + \text{d3 pest1* pest2}) \geq \\ \text{control cost} \quad \text{monetary loss prevented} \geq \text{control cost} \quad \text{benefit} \geq \text{cost}\end{gathered} \tag{7}$$

The benefit (value of loss prevented) is the product of the price of rough rice, the relative effectivity of control, and the cumulative damage due to pests and their interactions, if any. Coefficients d1, d2, and d3 were estimated by multiple regression. Combinations of damage due to pest 1 and pest 2 would give the estimated cumulative damage due to the two pests together.

If there is no significant interaction between two pests, the multiple-pest ET equation can be rearranged as

$$\text{Pest1:ETpest1} = \frac{c}{p \times \text{dpest1} \times k} = \frac{\text{dpest2} \times \text{pest2}}{\text{dpest1}} \tag{8}$$

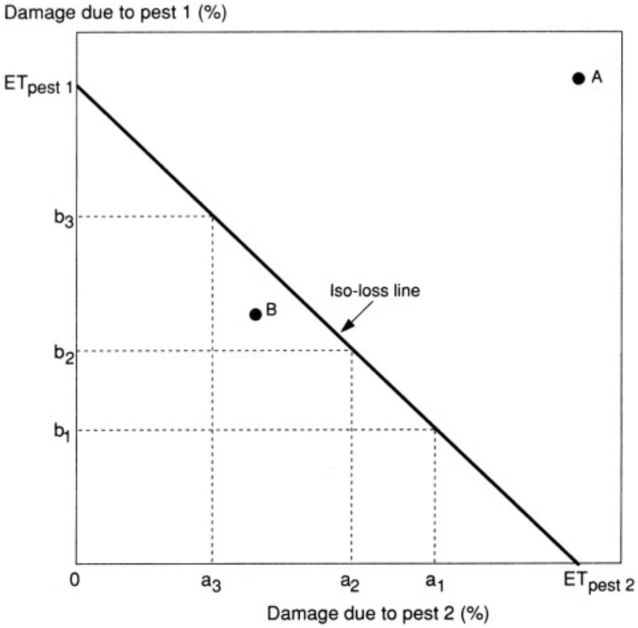
$$\text{Pest2:ETpest2} = \frac{c}{p \times \text{dpest2} \times k} = \frac{\text{dpest1} \times \text{pest1}}{\text{dpest2}} \tag{9}$$

Note that the ET of one pest is determined by the other pest.

*Iso-loss line.* An iso-loss line shows the different combinations of damage by pest 1 and pest 2 that result in the same reduction in yield. The intercepts of the line are the sum of the single-pest ETs.

The various combinations of pests 1 and 2 that result in equal profitabilities of control can be plotted on a 2-dimensional graph (Fig. 1). The locus of points (the iso-loss line) indicates that the benefit of pest control is equal to the cost of control for any combination of pest 1 and pest 2, such as a1b1, a2b2, and a3b3. Combinations falling below the line, such as at point B, are at subeconomic thresholds and control is unnecessary. Point A indicates when both pest 1 and pest 2 reach their thresholds and pest control is warranted.

Iso-loss lines need not be straight. When there is an interaction between two pests, the line can curve. For simplicity and clarity, we consider iso-loss lines here as straight lines.



**1.** The iso-loss line for indicating benefit of pest control equal to the cost of pest control (the economic threshold-ET) for any combination of damages due to pest 1 and pest 2.

## Results and discussion

We made separate estimates of single-pest and multiple-pest ETs for the vegetative, reproductive, and ripening phases of the rice crop.

*Vegetative phase.* The estimated damage function at the vegetative phase is

$$\begin{aligned}\text{Yield} = {} & \underset{(1.13)}{17.83^{**}} + \underset{(0.03)}{0.02^{ns}}\ \text{whorl maggot} - \underset{(0.09)}{0.16^{*}}\ \text{caseworm} + \\ & \underset{(0.16)}{0.30^{*}}\ \text{defoliators} + \underset{(0.08)}{0.05^{ns}}\ \text{leaffolder} - \underset{(0.04)}{0.18^{**}}\ \text{deadheart}\end{aligned} \tag{10}$$

Casewonn and stem borers significantly reduced grain weight at maximum tillering. Yield decreased by 0.16 g/hill per unit increase in percent leaves damaged by caseworm and 0.18.g/hill per unit increase in percent deadhearts due to stem borer. Defoliators *naranga* and *rivula,* however, increased yield by 0.30 g/hill per unit increase in percent defoliated leaves. This could be attributed to the capacity of the young plants to compensate (Rubia and Shepard 1987). Whorl maggot- and leaffolder-damaged leaves did not significantly affect yield. In general, the standard errors are small, indicating low variability in the damage coefficients.

Because only caseworm and stem borer damage significantly reduced yield, these two pests become eligible for threshold analyses. Interaction terms were dropped because no significant interactions between pests were detected.

Monocrotophos is the chemical most commonly used by farmers in Nueva Ecija. Average chemical control efficacy is 60% (Litsinger et ai 1987). To achieve 60% control for 1 ha, a farmer needs 2.5 liters of monocrotophos at US$7.80/liter, or US$19.50/ha. The average wage rate for the 1987 dry season crop was US$1.15/person per d. Assuming one labor day per pesticide application, the cost of chemical pest control was US$20.65/ha. The average price of rough rice was US$0.16/kg. The damage coefficient, *d,* per hill corresponds to the slope for each pest estimated in equation 10. Crop density was assumed to be 152,000 hills/ha at 16- × 16-cm spacing.

The single-pest thresholds for stem borer (deadheart) and caseworm are therefore

$$\mathrm{ETL}_{dh} = \frac{\$20.65}{\$0.16 \times (0.18 \times 152000)/1000 \times 0.60} = 8\% \qquad (11)$$

$$\mathrm{ETL}_{cw} = \frac{\$20.65}{\$0.16 \times (0.16 \times 152000)/1000 \times 0.60} = 9\% \qquad (12)$$

Pest control action is warranted when deadhearts reach 8% or when caseworm-damaged leaves reach 9%. Table 4 shows a 0.28 probability of sampling a hill with at least 8% stem borer damage at 35 DT, and a 0.25 probability of getting a hill with at least 9% caseworm-damaged leaves. Hence, using single-pest ET as the decision criterion for timing pest control application would imply no spraying at early growth stages (particularly not at 35 DT) 75% of the time. This confirms most observations of field researchers, that spraying is not necessary during the vegetative phase.

However, when the joint effects of the two pests are considered, spraying may be required even when infestations of caseworm and stem borer are below their respective single ETs. Iso-loss equations for caseworm and stem borer were derived:

$$\%\ \text{deadheart} = 7.83 - 0.89\ \text{caseworm} \qquad (13)$$

$$\%\ \text{caseworm} = 8.81 - 1.12\ \text{deadhearts} \qquad (14)$$

Table 5 shows iso-loss summaries that indicate the minimum percent damage combinations of deadhearts and caseworm that would require treatment. The iso-loss line (Fig. 2) indicates that at 5% deadhearts, spraying is needed when damage due to caseworm reaches 3.2%. Note that both damage levels are below the single-pest ETs.

The probability of attaining the multiple-pest ET depicted by the iso-loss line is 0.51, which is greater than the single-pest ETs (0.28 for stem borer and 0.25 for caseworm). Thus, a decision to spray is more likely when we use the multiple-pest ET rather than single-pest ETs as the decision criterion for pest control. However, pest damages and their combinations are below the multiple-pest threshold 49% of the time. Hence, we may infer an equal chance of reaching a decision to spray or not to spray using the multiple-pest ET.

Similar ET loci can be drawn for the reproduction and ripening phases of rice. The multiple-pest ETs could be below or above the line for the vegetative phase, depending on the seventy of the pests during each phase.

*Reproductive phase.* Crops respond differently to pest damage as they mature. Thus, damage functions and ETs differ for each growth stage of the plant.

**Table 4. Probability of single-pest damage below, above, or equal to their economic thresholds.**

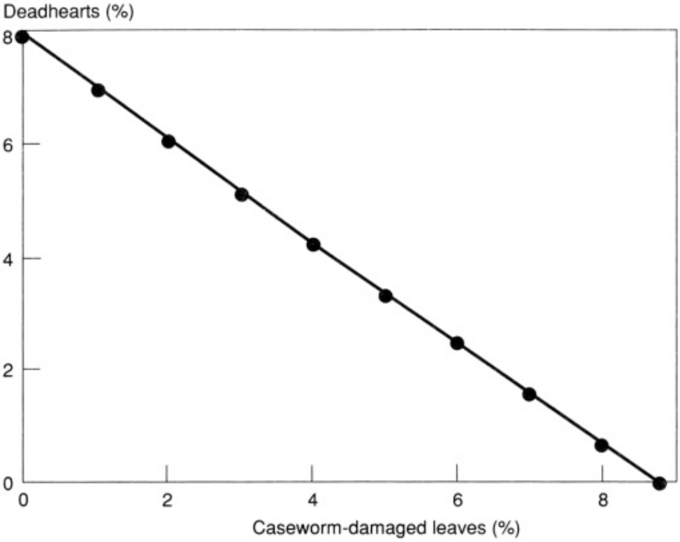
| Pest | Class[a] | % probability |
|---|---|---|
| | *Vegetative phase* | |
| Deadhearts | 0 | 0.48 |
| | 0 < VDH < 5 | 0.12 |
| | 5 = < VDH < 8 | 0.12 |
| | VDH > = 8 | 0.28 |
| Caseworm | 0 | 0.12 |
| | 0 < VRCW < 5 | 0.37 |
| | 5 = < VRCW < 9 | 0.26 |
| | VRCW > = 9 | 0.25 |
| | *Reproductive phase* | |
| Deadhearts | 0 | 0.46 |
| | 0 < REDH < 5 | 0.04 |
| | 5 = < REDH < 8 | 0.13 |
| | REDH > = 8 | 0.37 |
| | *Ripening phase* | |
| Whiteheads | 0 | 0.57 |
| | 0 < RWH < 5 | 0.01 |
| | 5 = < RWH < 7 | 0.11 |
| | RWH >= 7 | 0.31 |
| Leaffolder | 0 | 0.10 |
| | 0 < RLF < 5 | 0.15 |
| | 5 = < RLF < 9 | 0.14 |
| | RLF > = 9 | 0.61 |

[a] VDH = vegetative deadheart. VRCW = vegetative rice caseworm REDH = reproductive deadheart. RWH = ripening whitehead RLF = ripening leaffolder.

**Table 5. Iso-loss points of vegetative-phase deadheart- and caseworm-damaged leaves.**

| Caseworm-damaged leaves (%) | Deadhearts (%) 8.0-0.89 VRCW[a] | Deadhearts (%) | Caseworm-damaged leaves (%) 9-1.12 VDH[b] |
|---|---|---|---|
| 0 | 8.0 | 0 | 9.0 |
| 1 | 7.1 | 1 | 7.9 |
| 2 | 6.2 | 2 | 6.8 |
| 3 | 5.3 | 3 | 5.6 |
| 4 | 4.4 | 4 | 4.5 |
| 5 | 3.6 | 5 | 3.4 |
| 6 | 2.7 | 6 | 2.3 |
| 7 | 1.8 | 7 | 1.2 |
| 8 | 0.9 | 8 | 0.0 |
| 9 | 0.0 | | |

[a] VRCW =vegetative caseworm. [b] VDH = vegetative deadhear.



**2.** Multiple-pest economic threshold (iso-loss line) for deadheart and caseworm at the vegetative phase.

The damage function at the reproductive phase (56 DT) is estimated as

$$\begin{array}{l}
\text{Yield} = 18.34^{**} + 0.09^{ns}\text{leaffolder} - 0.18^{*}\text{ deadheart} + \\
\qquad\quad (0.62) \qquad (0.06) \qquad\qquad\quad (0.07) \\
\qquad\quad 0.006^{ns}\text{ leaffolder}^{*}\text{ deadheart} \\
\qquad\qquad\qquad\qquad (0.006)
\end{array} \tag{15}$$

Stem borer damage again significantly reduced yield, by 0.12 g/hill per unit increase in percent deadheart. Leaffolder damage and its interaction with stem borer did not significantly affect yield.

The reproductive-phase ET for stem borer damage is the same as estimate for the vegetative phase. Pest control is required only when deadhearts reach 8%. The probability of reaching this threshold is 0.37. Using single-pest ET would imply no spraying during the reproductive phase 63% of the time. We were unable to calculate a multiple-pest ET at this stage because no other pest damage significantly affected yield.

*Ripening phase.* The estimated damage function at the ripening phase (70 DT) is

$$\begin{array}{l}
\text{Yield} = 19.54^{**} - 0.15^{**}\text{ leaffolder} - 0.21^{**}\text{ whitehead} + \\
\qquad\quad (0.60) \quad (0.05) \qquad\qquad\quad (0.04) \\
\qquad\quad 0.06^{ns}\text{ leaffolder}^{*}\text{whitehead} \\
\qquad\quad (0.04)
\end{array} \tag{16}$$

Stem borer and leaffolder damage significantly reduced yield by 0.21 g/hill per unit increase in percent whitehead and percent damaged leaves. Damaged flag leaves did not affect yield.

Using the same assumptions, the single-pest thresholds are

$$\mathrm{ET}_{wh} = \frac{\$20.65}{\$0.16 \times (0.21 \times 152000)/1000 \times 0.60} = 7\% \qquad (17)$$

$$\mathrm{ET}_{lf} = \frac{\$20.65}{\$0.16 \times (0.15 \times 152000)/1000 \times 0.60} = 7\% \qquad (18)$$

Pest control is warranted when whiteheads reach 7% or when leaffolder-damaged leaves reach 9%. The probability of sampling a hill with 7% whiteheads is only 0.30; the probability of sampling a hill with 9% leaffolder damage is a high 0.61. Thus, during ripening, leaffolder damage would most likely reach its threshold earlier than whiteheads would.

The iso-loss equations for whiteheads and leaffolder were derived as follows:

$$\%\ \text{whitehead} = 67 - 0.71\ \text{leaffolder} \qquad (19)$$

$$\%\ \text{leaffolder} = 9.4 - 1.40\ \text{whitehead} \qquad (20)$$

The minimum percent damage by whitehead and leaffolder combinations that warrants pest control is presented in Table 6. These combinations are plotted in Figure 3, which shows that at 5% whiteheads, spraying is needed when concurrent damage due to leaffolder reaches 2.4%. Note that both damage levels are below their respective single-pest ETs.

The probability of attaining the multiple-pest ET is 0.75 (Table 7), which is larger than the probability of reaching the single-pest ET. A decision to spray is more probable using a multiple-pest ET than it is using a single-pest ET. Insecticide application would be needed at 70 DT 70% of the time.

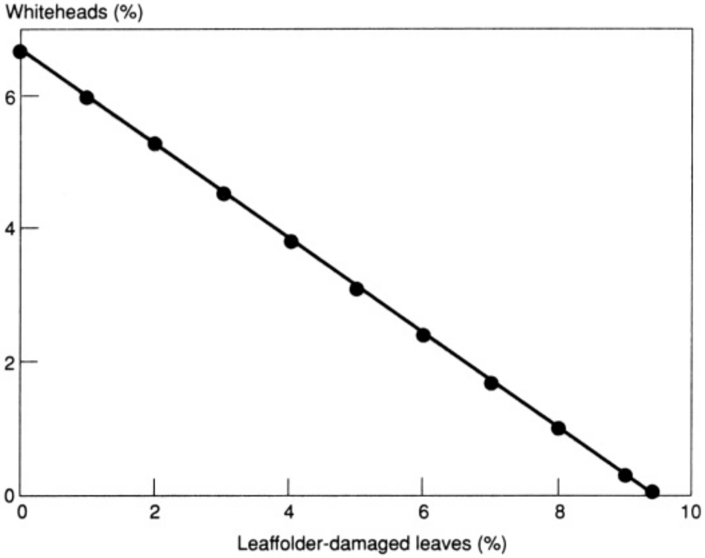
## Comparison of thresholds

The ET for stem borer damage at the vegetative phase is the same as at the reproductive phase (8%). But it decreases to 7% at ripening. This could imply that at 35 and 49 DT,

**Table 6. Iso-loss points of whitehead- and leaffolder-damaged leaves at ripening phase.[a]**

| Leaffolder-damaged leaves (%) | Whiteheads (%) 6.7-0.71 RLF | Whiteheads (%) | Leaffolder-damaged leaves (%) 9.4-1.4 RWH |
|---|---|---|---|
| 0 | 6.7 | 0 | 9.4 |
| 1 | 6.0 | 1 | 8.0 |
| 2 | 5.3 | 2 | 6.6 |
| 3 | 4.6 | 3 | 5.2 |
| 4 | 3.9 | 4 | 3.8 |
| 5 | 3.2 | 5 | 2.4 |
| 6 | 2.4 | 6 | 1.0 |
| 7 | 1.7 | 6.7 | 0.0 |
| 8 | 1.0 | | |
| 9 | 0.3 | | |
| 9.4 | 0.0 | | |

[a] RLF = ripening leaffolder, RWH = ripening whitehead.



**3.** Multiple-pest economic threshold (iso-loss line) for leaffolder and whitehead at the ripening phase.

**Table 7. Probability distribution of multipest thresholds across plant growth stages.**

| Pest damage | Observations (no.) | % probability |
|---|---|---|
| | *Vegetative phase* | |
| < Multipest ET | 139 | 0.49 |
| ≥ Multipest ET | 146 | 0.51 |
| | *Ripening phase* | |
| < Multipest ET | 72 | 0.25 |
| ≥ Multipest ET | 213 | 0.75 |

the plant has greater capacity to recover, but at 70 DT it becomes more susceptible. Caseworm damage is critical only at the vegetative phase (ET 9%). Leaffolder damage is significant only at the ripening phase (ET 9%). These ETs are reflected in the intercepts of the iso-loss equations.

Using a multiple-pest ET would result in recommending more insecticide applications than using the single-pest ET, because the threshold is reached earlier. However, most farmers already apply insecticides before the crop reaches the single-pest ET. Multiple-pest ET should be a better pest control decision aid because it incorporates the appropriate time to spray to control pest combinations.

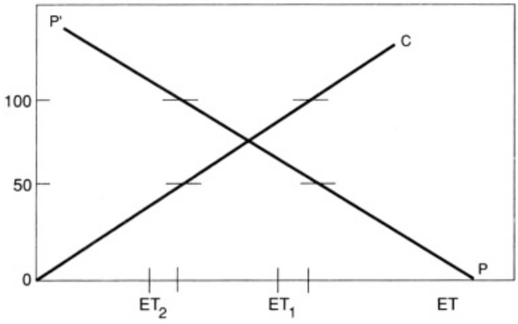
The multiple-pest ETs presented here are ready for field verification, validation, and refinement.

## Input and output price effects

Economic thresholds are sensitive to the level of the damage coefficient, to the control efficacy of the insecticide used, and to the prices of chemicals and rough rice. A reduction in chemical prices or an increase in rice prices will lower the ET (Fig. 4). An increase in control costs or a decrease in rice prices would increase the ET.

The degree to which an increase or decrease in input and output prices will affect ET are presented in Tables 8 and 9. Suppose that pest control cost is reduced 50%. The ET for each pest would also be reduced 50% (i.e. from 8% deadhearts to 4% deadhearts during the vegetative phase). Similarly, if the price of rough rice decreases 50%, ET would increase 50% (i.e. 8% deadhearts to 16% deadhearts). However, a 50% increase in the cost of chemicals or a 50% decrease in rough rice price would not change the ET as much. ET is more sensitive to decreases in costs and prices.

Government price policies for inputs and outputs directly affect the profitability of IPM. Thus, when a government buys rough rice at higher prices than the market



**4.** Relationship between input and output prices and economic threshold (ET). OC = input price related to ET, PP = output price related to ET.

**Table 8. Economic thresholds with changes (percent increase or decrease) in input prices.**

| Pest | ET | Increase in price of chemical | | | | | Decrease in price of chemical | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 50% | 10% | 20% | 30% | 40% | 50% |
| | | | | *Vegetative phase* | | | | | | | |
| Deadhearts | 8 | 8.6 | 9.4 | 10.2 | 11.0 | 11.7 | 7.0 | 6.3 | 5.5 | 4.7 | 3.9 |
| Caseworm | 9 | 9.7 | 10.6 | 11.5 | 12.3 | 13.2 | 7.9 | 7.0 | 6.2 | 5.3 | 4.4 |
| | | | | *Reproductive phase* | | | | | | | |
| Deadhearts | 8 | 8.6 | 9.4 | 10.2 | 11.0 | 11.7 | 7.0 | 6.3 | 5.5 | 4.7 | 3.9 |
| | | | | *Ripening phase* | | | | | | | |
| Whiteheads | 7 | 7.4 | 8.1 | 8.7 | 9.4 | 10.1 | 6.0 | 5.4 | 4.7 | 4.0 | 3.4 |
| Leaffolder | 9 | 10.3 | 11.3 | 12.2 | 13.2 | 14.1 | 8.5 | 7.5 | 6.6 | 5.6 | 4.7 |

**Table 9. Economic thresholds at different (percent increase or decrease) output prices.**

| Pest | ET | Increase in rough rice price | | | | | Decrease in rough rice price | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 50% | 10% | 20% | 30% | 40% | 50% |
| | | | | | *Vegetative phase* | | | | | | |
| Deadhearts | 8 | 7.12 | 6.53 | 6.02 | 5.59 | 5.22 | 8.70 | 9.79 | 11.19 | 13.05 | 15.66 |
| Caseworm | 9 | 8.01 | 7.34 | 6.78 | 6.29 | 5.87 | 9.79 | 11.01 | 12.59 | 14.69 | 17.62 |
| | | | | | *Reproductive phase* | | | | | | |
| Deadhearts | 8 | 7.12 | 6.53 | 6 02 | 5.59 | 5.22 | 8.70 | 9.79 | 11.19 | 13 05 | 15.66 |
| | | | | | *Ripening phase* | | | | | | |
| Whiteheads | 7 | 6.10 | 5.59 | 5.16 | 4.80 | 4.48 | 7.46 | 8.39 | 9 59 | 11.19 | 13.43 |
| Leaffolder | 9 | 8.54 | 7.83 | 7.23 | 6.71 | 6.27 | 10.44 | 11.75 | 13.43 | 15.66 | 18.80 |

price. ETs would be low and the profitability of control would increase (a higher yield would mean a higher return). If a government subsidizes the cost of chemicals. ETs also would be low and chemical control more profitable.

## Conclusion

Economic threshold is a useful tool in IPM, in warranting control. especially pesticide application. But the single-pest ETs developed so far have limitations. Because crops often are infested by groups of insect pest species, multiple-pest thresholds are more appropriate to use in timing insecticide application because they account for the cumulative damage done by pests.

A single-pest ET is determined solely by the damage coefficient of one pest. A multiple-pest ET determines various combinations of two pests that would cause the same amount of yield loss. The damage coefficients for each pest partially determine the multiple-pest ET, their values are the intercepts of the multiple-pest equations, the iso-loss lines. The probability of reaching a multiple-pest ET is greater than the probability of reaching a single-pest ET.

Economic thresholds, whether for single or multiple pest species, are location specific. A particular ET depends on the damage coefficient, which is a function of the severity of pest damage. Pest damage itself is a function of biotic (pests, predators, parasites, variety) and abiotic (weather, topography, synchronous or asynchronous cropping system, environment as a whole) factors.

Economic thresholds also are directly related to chemical costs and inversely related to rice prices. As the price of chemical control decreases, the ET decreases; as the price of rice increases, the ET decreases.

Using predators for biological control is an ideal substitute for chemical control. Obviously, that practice does not leave chemical residues on food and does not contribute to pollution. Incorporation of predators into ET calculations would be beneficial.

A word of caution: in developing countries such as the Philippines, the majority of farmers are not mathematically literate. Economic threshold technology might be more effectively used by agricultural technicians, as a basis for their pest control recommendations to farmers.

## References cited

Blackshaw R P (1986) Resolving economic decisions for the simultaneous control of two pests, diseases or weeds. Crop Prot. 5(2):93-99.

Headley J C (l972a) Defining the economic thresholds. Pages 100-108 *in* Pest control strategies for the future. Agricultural Board, National Academy of Sciences. Washington, D.C.

Headley JC (1972b) Economics of agricultural pest control. Annu. Rev. Entomol. 17:273-286.

Hutchkins S H, Highley L G, Pedigo L P (1988) Injury equivalency as a basis for developing multi-species economic injury levels. J. Econ. Entomol. 81(1):1-8.

IRRI — International Rice Research Institute (1982) Annual report for 1981. P.O. Box 933, Manila, Philippines.

IRRI — International Rice Research Institute (1983) Annual report for 1982. P.O. Box 933, Manila, Philippines.

Johnson K B, Teng P S (1987) Analysis of potato foliage losses caused by interacting infestations of early blight, verticillium wilt, and potato leafhopper; and the relationship to yield. J. Plant Dis. Prot. 94(1):22-23.

Norton G A (1976) Analysis of decision making in crop protection. Agro-ecosystems 3:27-44.

Litsinger J L, Canapi B L, Bandong J P, De la Cruz C G, Apostol R F, Pantua P C, Lumaban M D, Alviola A L, Raymundo F, Libetario E M, Loevinsohn M E, Joshi R C (1987) Rice crop loss from insect pests in wetland and dryland environments of Asia with emphasis on the Philippines. Insect Sci. Appl. 8 (4/5/6):677-692.

Pathak M D, Dyck V A (1973) Developing an integrated method of rice insect pest control. PANS 19(4):534-544.

Rubia E, Shepard B M (1987) Simulation of insect damage on rice. Entomology Department, International Rice Research Institute, P.O. Box 933, Manila, Philippines. (Unpubl. paper)

Waibel H (1986) The economics of integrated pest control in irrigated rice. Crop protection monograph. Springer-Verlag, Berlin.

Zadoks J C (1985) On the conceptual basis of crop loss assessment: threshold theory. Annu. Rev. Phytopathol. 23:455-473.

## Notes

*Authors' address:* F. Palis, P. Pingali, and J. Litsinger, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Methodology used in the IRRI integrated pest survey

F. A. Elazegui, J. Soriano, J. Bandong, L. Estorninos, I. Jonson, P. S. Teng, B. M. Shepard, J. A. Litsinger, K. Moody, and H. Hibino

Field surveys are an integral part of activities to determine the importance of pests in farmers' fields. However, methodologies for surveying rice pests are relatively underdeveloped, compared with methodologies for other aspects of field assessment of pests and losses caused by pests (James and Teng 1979). Reliable methods are central to pest surveillance and early warning systems in several Southeast Asian countries (Teng and Heong 1988) and to attempts at improving the reliability of crop loss data (Teng, this volume).

Sporadic reports on pest occurrences in certain areas, with associated yield loss. have been mentioned in unrelated crop years in the Philippines. In the Surveillance and Early Warning System Project of the Philippine-German Crop Protection Programme conducted through the Philippine Bureau of Plant Industry, major crop pests (tungro, armyworm, locust, corn stalk borer, rats, golden snail) were monitored yearly, nationwide, by listing the region and hectarage affected (BPI 1983, 1986, 1987, 1988). There were no reports, however, on factors that could have caused pests to occur in an area, except for tungro in 1987. The report stated: "Tungro upsurges have been drought-related and associated with poor water management and nonsynchronous plantings." Rice insect pests were monitored in the 1982 wet season in Maguiapo, Guagua, Pampanga, and in 1983 and 1984 in Famy, Lumban, Pila, and Siniloan in Laguna (NCPC 1983, 1984, 1985). However, there is no information on actual pest infestations on a crop-to-crop or year-to-year basis. Even without formal surveys, pest occurrences in certain years may still be documented by interviewing farmers (Zadoks and Schein 1979). The reliability of that subjective information, however, depends on the accuracy with which farmers perceive pests in their fields.

The Integrated Pest Survey Project reported here aims to provide such information, to better understand the effect of the physical environment and cultural practices on pest dynamics. With this understanding, we hope that pest events can be predicted, pest management measures undertaken, and crop losses prevented.

We attempted to determine the distribution and severity and farmers' perceptions of pests; to relate pest distribution and severity to crop management practices, rainfall, soil types, and other factors; and to establish pest zone areas that favor certain pests because of a combination of particular environmental characteristics, crop management practices, and other factors.

The survey covered three provinces in Central Luzon with major areas planted to rice (Bulacan, Pampanga, and Nueva Ecija). Scientists from three disciplines at IRRI were involved: entomology, agronomy, and plant pathology.

## Field methodology

### Selecting fields

Initially the plan was to categorize patterns of rainfall, water control, soil type, crop establishment methods, cropping patterns, and planting dates, in order to select about 60 fields for each class.

Actual field identification started in June, when fields were still fallow. Soil maps were obtained from regional government offices in each province, from which villages with soil types highly suitable for rice were identified and visited. However, some villages were too far from main roads or from the town proper. Some more accessible fields had been converted into residential lots. Some villages with vast rice areas (and therefore soils highly suitable for rice) were not indicated on the maps. Only a few fields were selected using the soil maps.

To identify additional fields, we asked employees in Municipal Agriculture Offices to identify villages with large rice areas. The employees could specify which areas or villages in towns were rainfed or irrigated, planted early or late, with plains or terraces. In addition, they could suggest names of farmers. Those offices often were deserted, however, as the employees were mostly out in the field. We had to visit other offices in the Municipal Hall to obtain a town map and to ash the employees about villages where rice was widely grown.

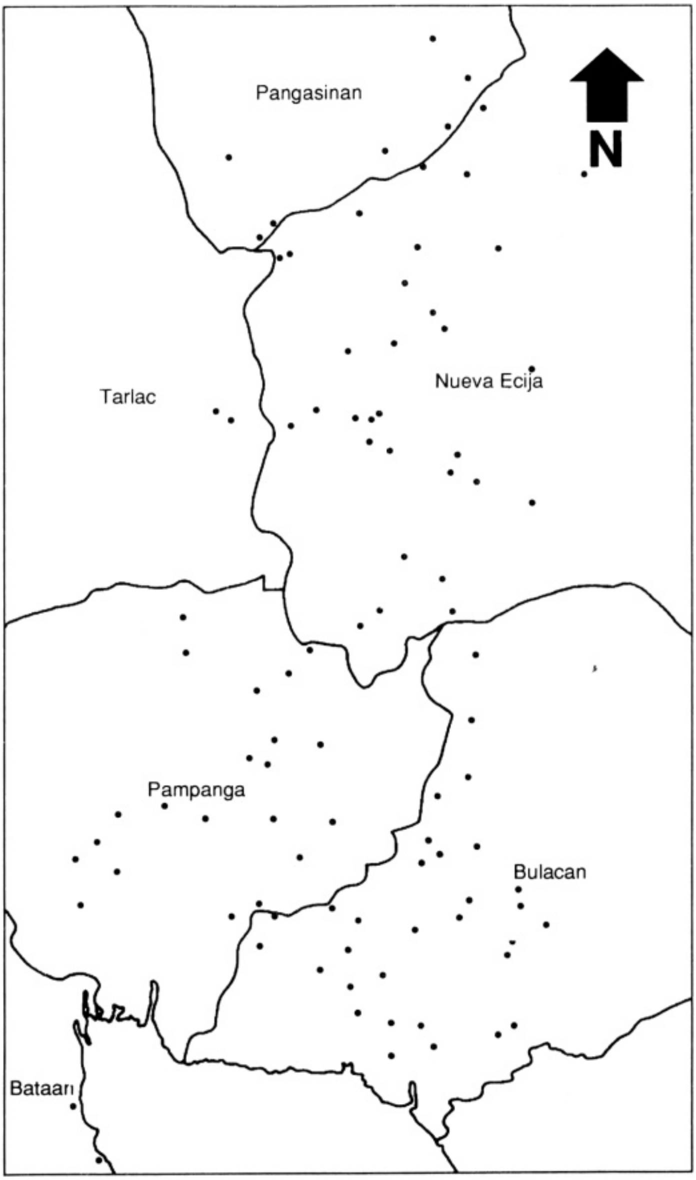
In the villages, carabao (water buffalo) or farm implements in front or haystacks nearby were taken to indicate a farmer home. We found it important to clearly identify ourselves to the farmers, so that they would not think we were government technicians or representatives of chemical companies promoting pesticides. Sometimes, despite our introductions, the farmers would still be suspicious, and would refer us to their *pangulo,* the president of a farmers' organization, or the head of the village. When the *pangulo,* usually an above-average or wealthy farmer, was informed of our purpose, he often would offer his field. That created another problem: survey fields should be those cultivated by average or small-scale farmers representative of the majority of the farmers in the region. The same problem occurred with farmers suggested by the Municipal Agriculture Office: employees would name larger-scale farmers.

In a village, we selected fields that were approximately 1 ha in size, where the variety planted, the planting method, and the planting date represented most fields in the area. If a village had two classes of fields (e.g. upper and lower strata), two fields were selected. Care was taken to ensure that fields in one locality were dispersed.

The location of the fields surveyed is shown in Figre 1.

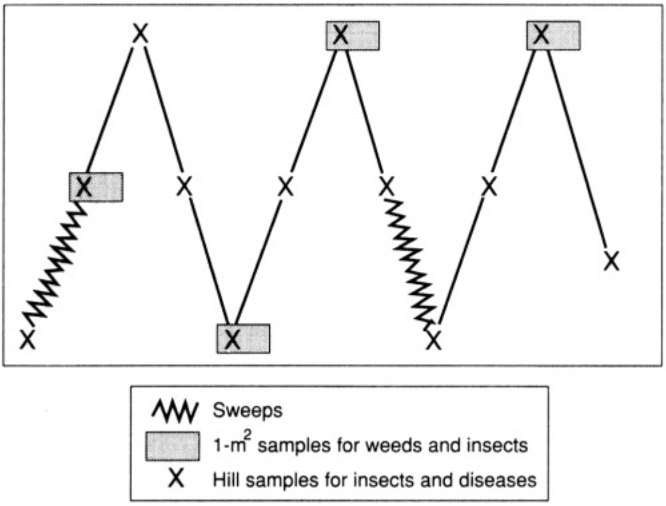
### Sampling pattern

A zigzag pattern was used to sample a field for weeds, insects, and diseases (Fig. 2). This pattern can account for random, regular, or aggregate pest distributions in a field



1. Map showing location of fields (dots) used in Integrated Pest Survey.

(Lin et a1 1979). Twelve hills and four 1-m$^2$ areas were sampled in each field. Transplanted fields were sampled at 21 d after sowing (DAS) (seedbed), 30 d after transplanting (DT), 60 DT, and at harvest. Direct seeded fields were sampled about 21 DAS and at 30-d intervals until harvest.



**2.** Zigzag pattern of sampling used in IRRI Integrated Pest Survey.

The zigzag sampling pattern can be used only at 30 DT and 51 DAS. Later, plants have closed their canopies, making it difficult to walk through a field. Also, farmers did not want their fields to be disturbed, particularly at heading. Samples then had to be taken only from borders.

The field data on each pest were entered on a form designed to facilitate transferal to computer data management (Fig. 3).

## Pest assessment

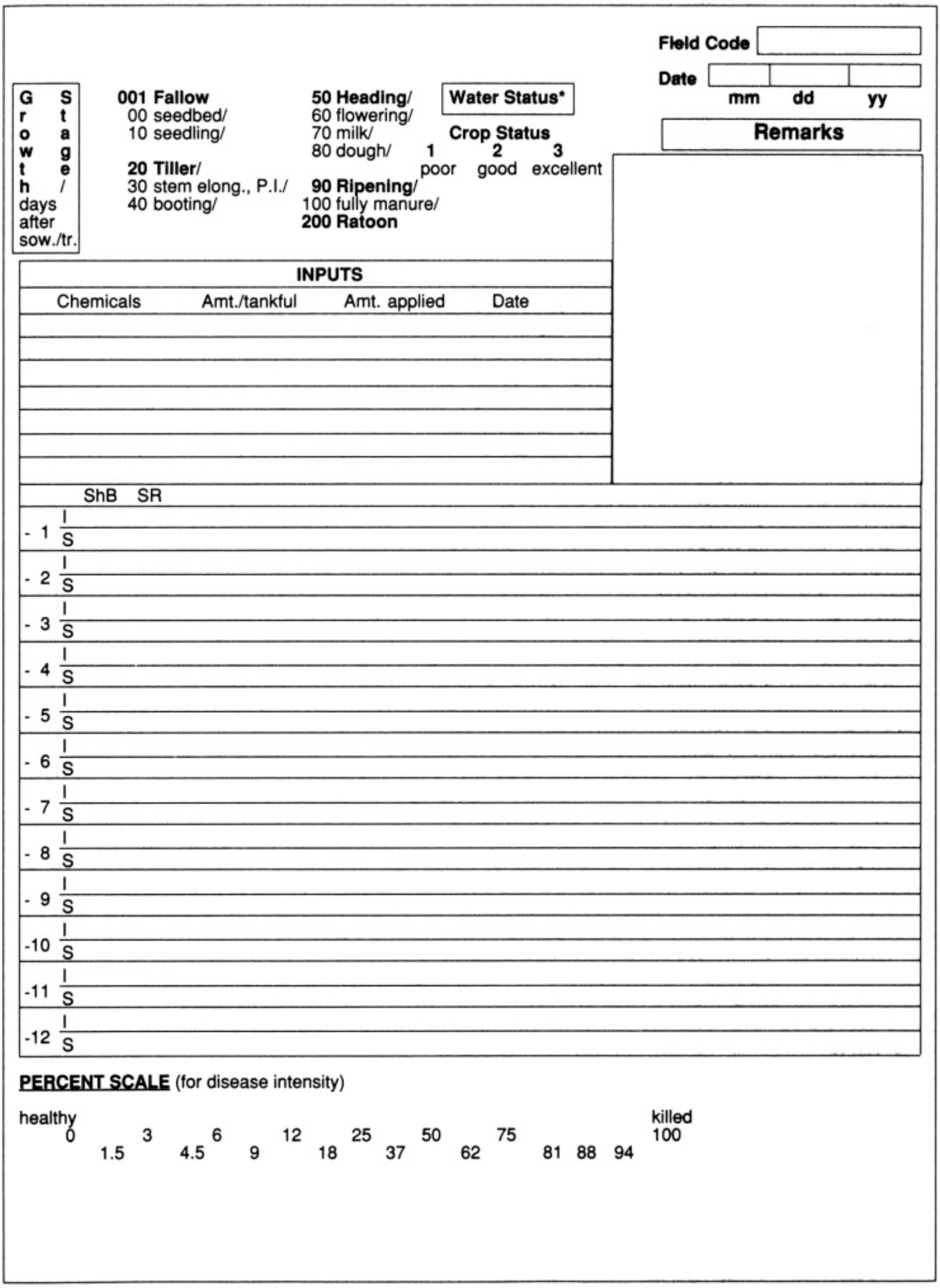
*Disease.* Observations were taken from 12 hills in each field. For leaf diseases (leaf blast, brown spot, narrow brown spot, leaf scald, bacterial blight, and bacterial leaf streak), two tillers/hill were randomly selected (24 tilles/field). Each leaf in each tiller was rated by % area affected.

Data were summarized as

$$\begin{array}{c}\text{Incidence/field}\\ \text{by tiller}\end{array} = \frac{\text{No. of tillers infected}}{24} \times 100$$

$$\text{Severity} = \frac{\text{Sum of \% leaf area affected/tiller}}{\text{No. of tillers infected}}$$

$$\text{\% leaf area affected/tillers} = \frac{\text{Reading for leaf 1} + \text{reading for leaf 2} + \ldots}{\text{No. of leaves in tiller}}$$



**Field Code**

**Date**

mm dd yy

**Remarks**

**Growth Stage/**
days after sow./tr.

**001 Fallow**
00 seedbed/
10 seedling/
**20 Tiller/**
30 stem elong., P.I./
40 booting/
**50 Heading/**
60 flowering/
70 milk/
80 dough/
**90 Ripening/**
100 fully manure/
**200 Ratoon**

**Water Status***

**Crop Status**

| **1** | **2** | **3** |
|---|---|---|
| poor | good | excellent |

**INPUTS**

| Chemicals | Amt./tankful | Amt. applied | Date |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

| | | ShB | SR |
|---|---|---|---|
| - 1 | I | | |
| | S | | |
| - 2 | I | | |
| | S | | |
| - 3 | I | | |
| | S | | |
| - 4 | I | | |
| | S | | |
| - 5 | I | | |
| | S | | |
| - 6 | I | | |
| | S | | |
| - 7 | I | | |
| | S | | |
| - 8 | I | | |
| | S | | |
| - 9 | I | | |
| | S | | |
| -10 | I | | |
| | S | | |
| -11 | I | | |
| | S | | |
| -12 | I | | |
| | S | | |

**PERCENT SCALE** (for disease intensity)

healthy 0 1.5 3 4.5 6 9 12 18 25 37 50 62 75 81 88 94 100 killed

**3.** Integrated Pest Survey Form B: Diseases

**Fig. 3 continued**

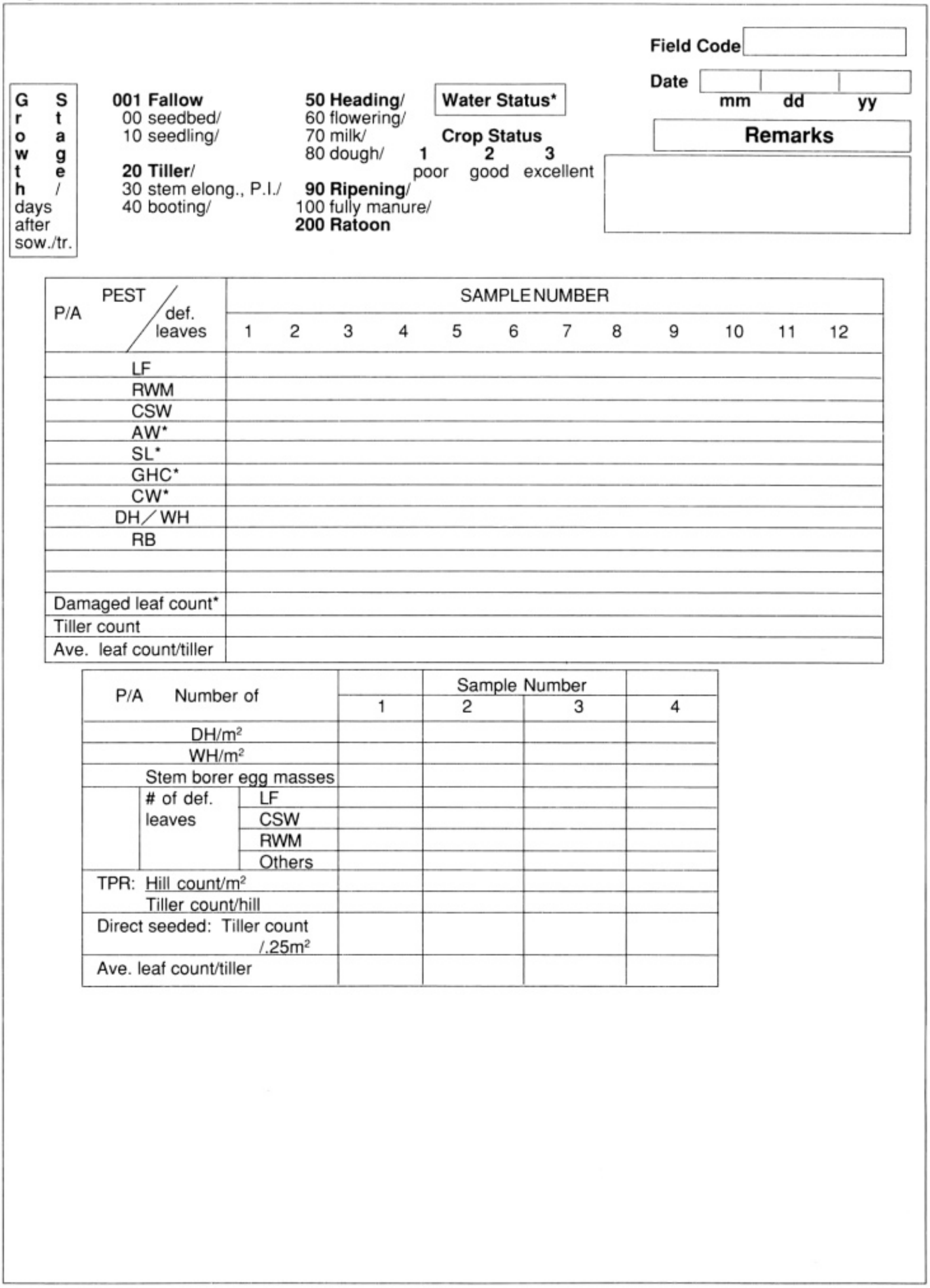
## WATER STATUS

| Description | | Score |
|---|---|---|
| Without standing water | | |
| soil dry and hard | ________________ | 1 |
| soil moist and hard | ________________ | 2 |
| soil moist and soft | ________________ | 3 |
| soil wet and hard | ________________ | 4 |
| soil wet and soft | ________________ | 5 |
| With little standing water | | |
| soil hard | ________________ | 6 |
| soil soft | ________________ | 7 |
| With adequate water | | |
| soil hard | ________________ | 8 |
| soil soft | ________________ | 9 |
| With too much water | | |
| soil hard | ________________ | 10 |
| soil soft | ________________ | 11 |

## DISEASE ABBREVIATIONS

ShB = sheath blight
SR = stem rot
LB = leaf blast
PB = panicle blast
BS = brown spot
NBS = narrow brown spot
LS = leaf scald
ShR = sheath rot
Bk = bakanae
BB = bacterial blight
BLS = bacterial leaf streak
RTV = rice tungro virus
GS = grassy stunt

Fig. 3 continued



**Field Code** ☐

**Date** ☐ ☐ ☐
mm dd yy

**Growth Stage/** days after sow./tr.

**001 Fallow**
00 seedbed/
10 seedling/
**20 Tiller/**
30 stem elong., P.I./
40 booting/
**50 Heading/**
60 flowering/
70 milk/
80 dough/
**90 Ripening/**
100 fully manure/
**200 Ratoon**

**Water Status***

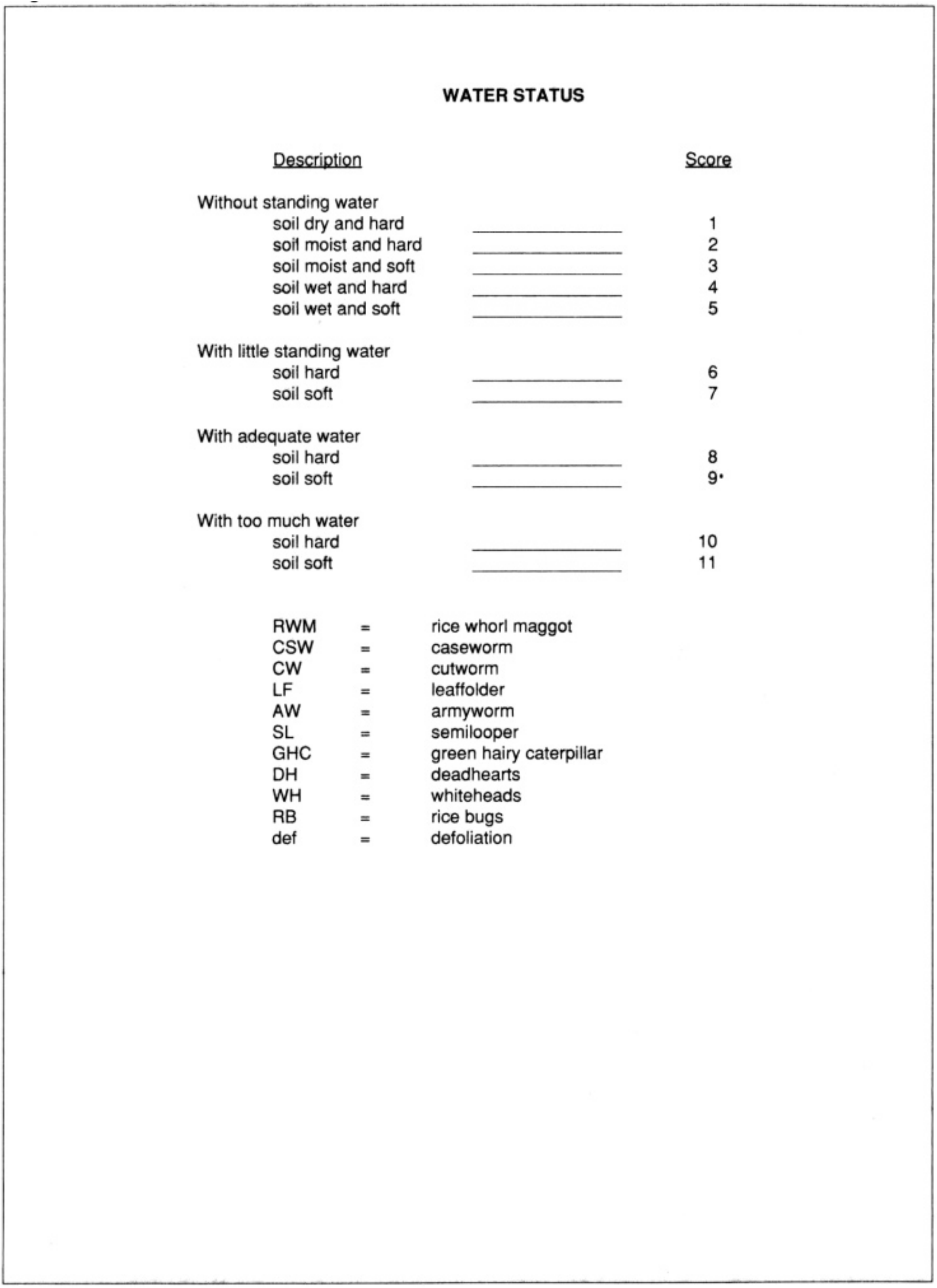
**Crop Status**
**1** poor **2** good **3** excellent

**Remarks**

| P/A PEST / def. leaves | SAMPLE NUMBER 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LF | | | | | | | | | | | | |
| RWM | | | | | | | | | | | | |
| CSW | | | | | | | | | | | | |
| AW* | | | | | | | | | | | | |
| SL* | | | | | | | | | | | | |
| GHC* | | | | | | | | | | | | |
| CW* | | | | | | | | | | | | |
| DH/WH | | | | | | | | | | | | |
| RB | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Damaged leaf count* | | | | | | | | | | | | |
| Tiller count | | | | | | | | | | | | |
| Ave. leaf count/tiller | | | | | | | | | | | | |

| P/A Number of | | Sample Number 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| DH/$m^2$ | | | | | |
| WH/$m^2$ | | | | | |
| Stem borer egg masses | | | | | |
| # of def. leaves | LF | | | | |
| | CSW | | | | |
| | RWM | | | | |
| | Others | | | | |
| TPR: Hill count/$m^2$ | | | | | |
| Tiller count/hill | | | | | |
| Direct seeded: Tiller count /.25$m^2$ | | | | | |
| Ave. leaf count/tiller | | | | | |

Fig. 3 continued



## WATER STATUS

| Description | | Score |
|---|---|---|
| Without standing water | | |
| soil dry and hard | ________________ | 1 |
| soil moist and hard | ________________ | 2 |
| soil moist and soft | ________________ | 3 |
| soil wet and hard | ________________ | 4 |
| soil wet and soft | ________________ | 5 |
| With little standing water | | |
| soil hard | ________________ | 6 |
| soil soft | ________________ | 7 |
| With adequate water | | |
| soil hard | ________________ | 8 |
| soil soft | ________________ | 9 |
| With too much water | | |
| soil hard | ________________ | 10 |
| soil soft | ________________ | 11 |

RWM = rice whorl maggot
CSW = caseworm
CW = cutworm
LF = leaffolder
AW = armyworm
SL = semilooper
GHC = green hairy caterpillar
DH = deadhearts
WH = whiteheads
RB = rice bugs
def = defoliation

For sheath blight (ShB), stem rot (SR), sheath rot (ShR), and panicle blast (PB), the following system was adopted:

For ShB, each hill was rated as follows (Ahn and Mew 1986):

| Rating | Leaf blade or leaf sheath position[a] | Affected area (%) | | |
|---|---|---|---|---|
| | | Leaf blade | | Leaf sheath |
| 0 | 3 | < 5 | and | < 5 |
| 1 | 3 | 5-25 | and/or | 5-25 |
| 3 | 3 | >25 | and/or | >25 |
| | 2 | 5-25 | and/or | 5-25 |
| 5 | 2 | >25 | and/or | >25 |
| 7 | 1 | 5-25 | and/or | 5-25 |
| 9 | 1 | >25 | and/or | 25 |

[a] 3 = third leaf, counting from flag leaf (1).

Data were summarized as follows:

$$\text{Incidence} = \frac{\text{No. of infected hills}}{12} \times 100$$

$$\text{Severity index} = \frac{1\ (N1) + 5\ (N3) + 20\ (N5) + 50\ (N7) + 100\ (N9)}{12}$$

where N1 is the hill count with rating of 1,
N2 is the hill count with rating of 2,

N9 is the hill count with rating of 9.

For SR, each hill was rated based on modification of the scale by Jackson et al (1977) as follows:

1 = with few, small lesions <1 cm long, limited to outer sheaths
3 = with few well-defined lesions limited to outer sheaths
5 = with more extensive lesions extending through the sheaths to the culms without killing the tillers
7 = with rotting of the stem killing <30% of the tillers
9 = with rotting of the stem killing >30% of the tillers.

$$\text{SR incidence} = \frac{\text{No. of infected hills}}{12} \times 100$$

$$\text{SR severity} = \frac{\text{Sum of all ratings/field}}{\text{No. of infected hills}}$$

For ShR, infected and total tillers/hill were counted; each infected tiller was rated (Estrada et a1 1984) as follows:

1 = small brown lesions covering about 1/10 of leaf sheath, panicle exsertion normal, few grains discolored

2 = larger lesions which tend to coalesce and may cover half the leaf sheath, about 65% or more panicle exsertion, moderate grain discoloration

3 = lesions have coalesced and may cover entire leaf sheath, no exsertion to slight exsertion of about 30%, severe grain discoloration

$$\text{ShR incidence} = \frac{\text{Sum of \% infection/hill}}{12}$$

where

$$\text{\% infection/hill} = \frac{\text{No. of infected tillers}}{\text{Total tillers}} \times 100$$

$$\text{ShR severity} = \frac{\text{Total ratings from each tiller in all hills}}{\text{No. of infected tillers in whole field}}$$

For PB, infected and total panicles/hill were counted, and each infected panicle was rated (Ahn and Mukelar 1986) as follows:

1 = lesions on a few secondary branches and pedicels

3 = lesions on several secondary or primary branches

5 = partial infection on the panicle axis or base, or total infection around panicle base but without unfilled grains

7 = total infection around panicle axis or base with >30% of filled grains

9 = total infection around panicle base or uppermost internode with <30% of filled grains

$$\text{PB incidence} = \frac{\text{Sum of \% infection/hill}}{12}$$

where

$$\text{\% infection/hill} = \frac{\text{No. of infected panicles}}{\text{Total panicles}} \times 100$$

$$\text{PB severity index} = \frac{10\,(n1) + 20\,(n3) + 40\,(n5) + 70\,(n7) + 100\,(n9)}{N}$$

where n = no. of panicles in each rating,
N = total panicles.

Using scales for severity was unsatisfactory, due to difficulties with panicles that fell between scores. Instead, we suggest using a rating system of 0-100, where 0 =none, 10 = 10% infection or 10% area affected, 20 = 20%, etc., with 100 = total infection, plant killed, no yield; 5% can be used to interpolate between two points on the scale. ShB and SR are still rated by hill, ShR by tiller hill, and PB by panicle/hill.

For tungro, the enzyme-linked immunosorbent assay test is used to detect the presence of tungro virus particles in infected leaves. Seedbed samples consisted of 5 seedlings each from 20 random spots in the seedbed. Samples are bulked. Direct seeded samples consisted of 21-d-old seedlings taken from 12 spots in a zigzag pattern. Later samples consisted of 2 leaves/hill for transplanted rice or 2 leaves/25 $m^2$ for direct seeded rice; one leaf should be the 2d youngest leaf. All field samples are packed separately by hills and transported to the laboratory in ice chests.

For nematodes, populations were monitored only in the first crop, 1987-88. Soil and root samples (roots and rhizosphere soil from 1/4 of a hill) were taken at tillering and at flowering to milk stage. Samples from a field were collected in plastic bags, hills 1, 3, 5, 7, 9, and 11 in bag 1, and hills 2, 4, 6, 8, 10, and 12 in bag 2, and transported to the laboratory in an ice chest. They were processed using the Baermann funnel technique.

*Insects.* Figure 2 shows the path that the sampler followed. Sampling units were (1) 10 sweeps in each of two locations, (2) 1 $m^2$ in each of 4 locations, and (3) 12 transplanted hills or 12-$cm^2$ direct seeded area.

Sweep net catches were sorted and counted in the laboratory (Fig. 4). Before transplanting, each seedbed is sampled by sweeping 10× at 3 different locations.

Four 1-$m^2$ areas were estimated for sampling yellow stern borer (YSB) egg masses and deadhearts (before panicle formation) and rice bug, *Conocephalus, Oxya,* and whiteheads (after panicle formation).

Insects, particularly planthoppers (brown planthopper/whitebacked planthopper), were dislodged and collected from each hill into a water pan. Fast moving/flying arthropods not caught in the pan were recorded. Each hill was further examined for water bugs and spiders. Insects caught in the water pan were taken back to the laboratory to be identified and counted. Each hill sample was counted and recorded separately as shown in the data sheet in Figure 4.

Defoliation was recorded for each hill sample as the number of damaged leaves by whorl maggot, caseworm, leaffolder, or *other defoliators* (cutworm, armyworm, green hairy caterpillar, green semilooper). *Other defoliators* were lumped into one group since the damage they cause is more or less similar in nature.

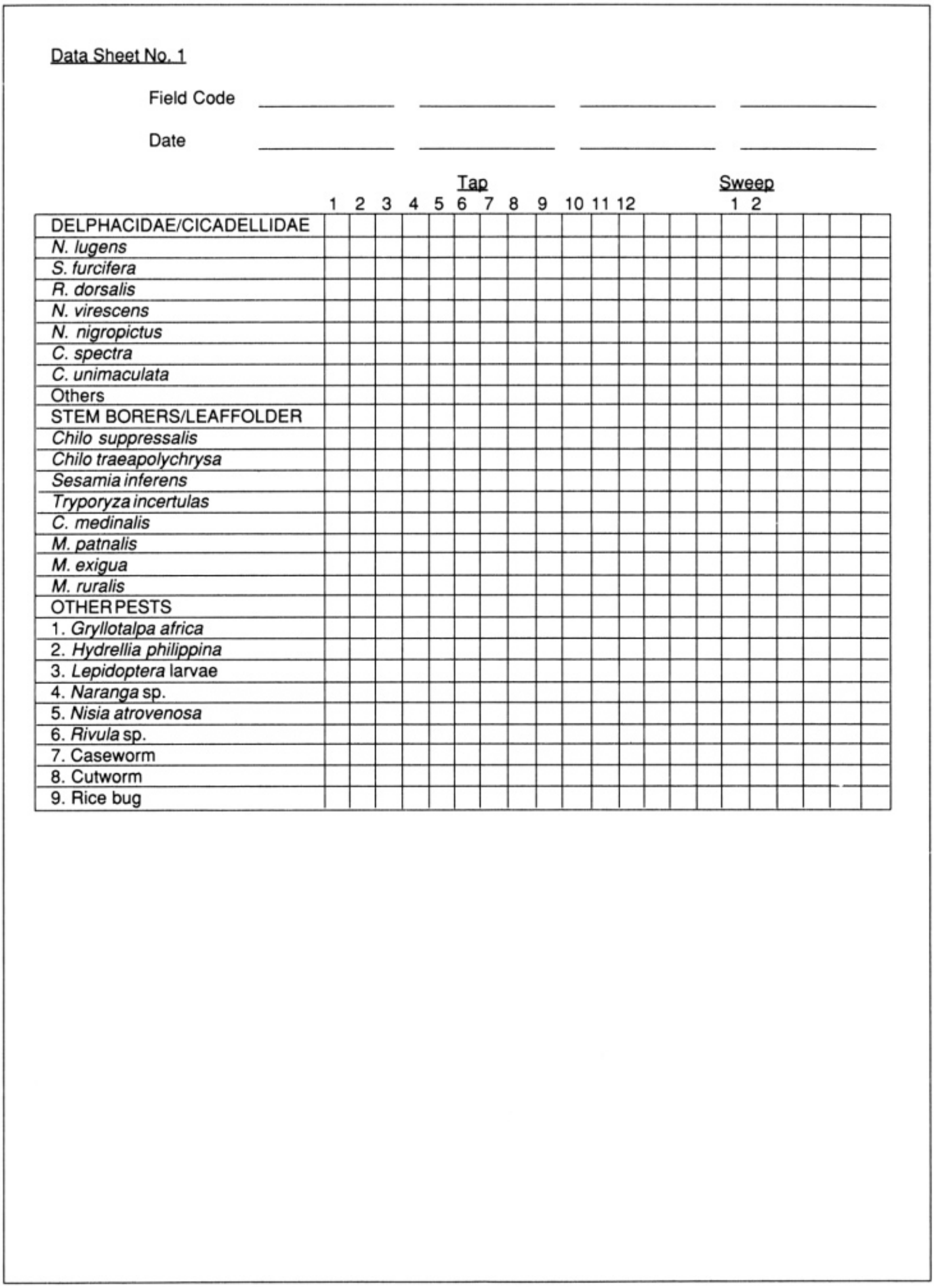
Data on insects were summarized as incidence of damaged leaves by insect type in each hill or $m^2$ observation, i.e.

$$\begin{array}{c}\text{\% leaffolder-}\\ \text{damaged leaves}\end{array} = \frac{\text{No. of leaffolder-damaged leaves}}{\text{Total leaves}} \times 100$$

*Weed scoring.* At first, observations (Weed Form B1, Fig. 5) were divided into three data points:

1. Above canopy cover of the whole field or seedbed.

   The whole field or seedbed was viewed as one big sampling unit. Weed species that towered over the canopy of rice were rated according to the area they cover (percent cover) using the weed code and weed rating scale (included in the data form).



Data Sheet No. 1

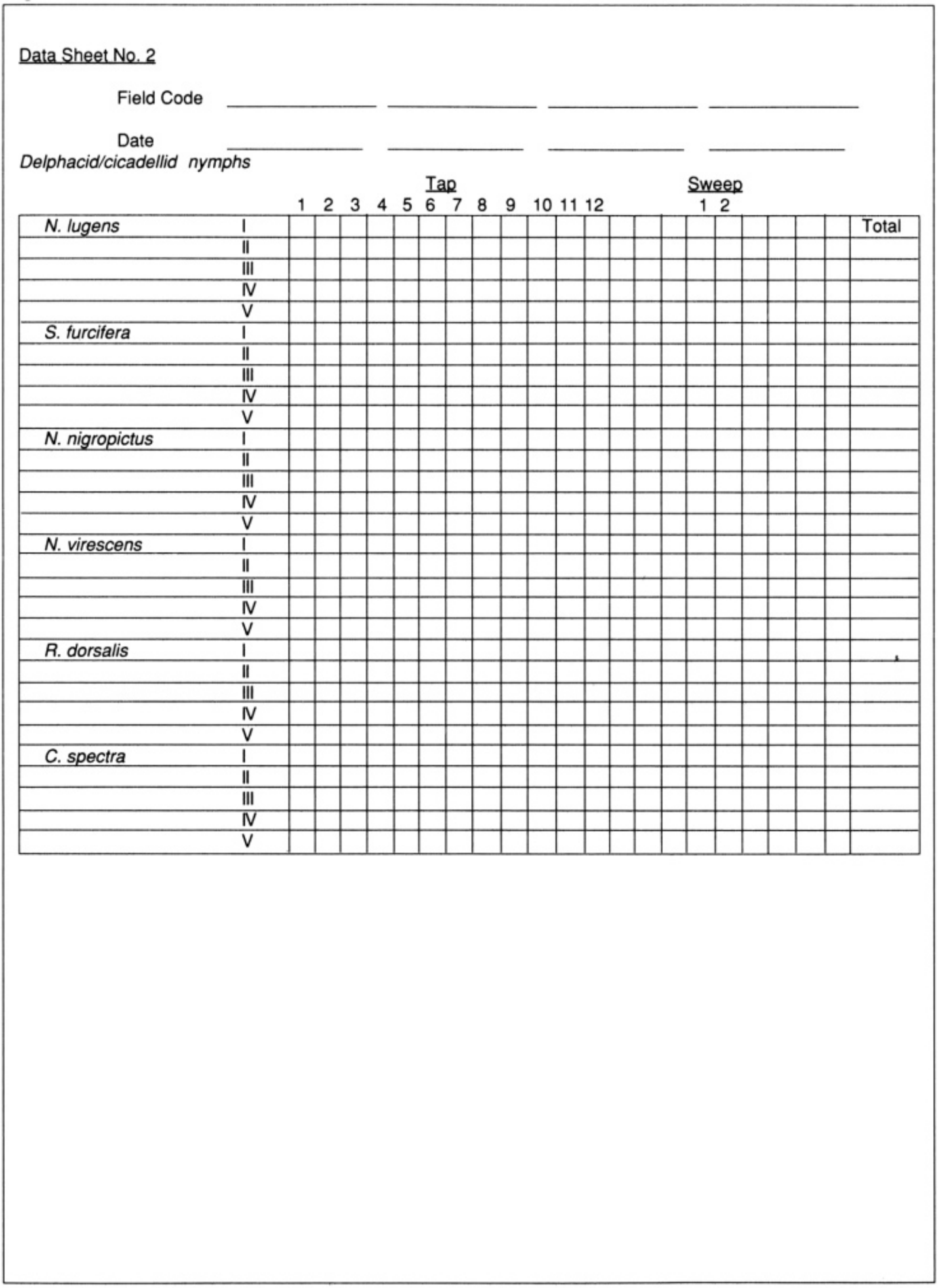
Field Code __________ __________ __________ __________

Date __________ __________ __________ __________

| | Tap | | | | | | | | | | | | | | | Sweep | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | | | 1 | 2 | | | | |
| DELPHACIDAE/CICADELLIDAE | | | | | | | | | | | | | | | | | | | | |
| *N. lugens* | | | | | | | | | | | | | | | | | | | | |
| *S. furcifera* | | | | | | | | | | | | | | | | | | | | |
| *R. dorsalis* | | | | | | | | | | | | | | | | | | | | |
| *N. virescens* | | | | | | | | | | | | | | | | | | | | |
| *N. nigropictus* | | | | | | | | | | | | | | | | | | | | |
| *C. spectra* | | | | | | | | | | | | | | | | | | | | |
| *C. unimaculata* | | | | | | | | | | | | | | | | | | | | |
| Others | | | | | | | | | | | | | | | | | | | | |
| STEM BORERS/LEAFFOLDER | | | | | | | | | | | | | | | | | | | | |
| *Chilo suppressalis* | | | | | | | | | | | | | | | | | | | | |
| *Chilo traeapolychrysa* | | | | | | | | | | | | | | | | | | | | |
| *Sesamia inferens* | | | | | | | | | | | | | | | | | | | | |
| *Tryporyza incertulas* | | | | | | | | | | | | | | | | | | | | |
| *C. medinalis* | | | | | | | | | | | | | | | | | | | | |
| *M. patnalis* | | | | | | | | | | | | | | | | | | | | |
| *M. exigua* | | | | | | | | | | | | | | | | | | | | |
| *M. ruralis* | | | | | | | | | | | | | | | | | | | | |
| OTHER PESTS | | | | | | | | | | | | | | | | | | | | |
| 1. *Gryllotalpa africa* | | | | | | | | | | | | | | | | | | | | |
| 2. *Hydrellia philippina* | | | | | | | | | | | | | | | | | | | | |
| 3. *Lepidoptera* larvae | | | | | | | | | | | | | | | | | | | | |
| 4. *Naranga* sp. | | | | | | | | | | | | | | | | | | | | |
| 5. *Nisia atrovenosa* | | | | | | | | | | | | | | | | | | | | |
| 6. *Rivula* sp. | | | | | | | | | | | | | | | | | | | | |
| 7. Caseworm | | | | | | | | | | | | | | | | | | | | |
| 8. Cutworm | | | | | | | | | | | | | | | | | | | | |
| 9. Rice bug | | | | | | | | | | | | | | | | | | | | |

**4.** Integrated Pest Survey Form C: Laboratory count of insects.

Fig. 4 continued



Data Sheet No. 2

Field Code ____________ ____________ ____________ ____________

Date ____________ ____________ ____________ ____________

*Delphacid/cicadellid nymphs*

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Tap | | | | | | | | | | Sweep | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | | | 1 | 2 | | | | | |
| *N. lugens* | I | | | | | | | | | | | | | | | | | | | | | | Total |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |
| *S. furcifera* | I | | | | | | | | | | | | | | | | | | | | | | |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |
| *N. nigropictus* | I | | | | | | | | | | | | | | | | | | | | | | |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |
| *N. virescens* | I | | | | | | | | | | | | | | | | | | | | | | |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |
| *R. dorsalis* | I | | | | | | | | | | | | | | | | | | | | | | |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |
| *C. spectra* | I | | | | | | | | | | | | | | | | | | | | | | |
| | II | | | | | | | | | | | | | | | | | | | | | | |
| | III | | | | | | | | | | | | | | | | | | | | | | |
| | IV | | | | | | | | | | | | | | | | | | | | | | |
| | V | | | | | | | | | | | | | | | | | | | | | | |

**Fig. 4 continued**

Data Sheet No. 3

Field Code __________ __________ __________ __________

Date __________ __________ __________ __________

| | | | | | | | | Tap | | | | | | | | | | | Sweep | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | | | | 1 | 2 | |
| PREDATORS | | | | | | | | | | | | | | | | | | | | | Total |
| *Microvelia atrolineata* | A/N | | | | | | | | | | | | | | | | | | | | |
| *Cyrtorhinus lividipennis* | A/N | | | | | | | | | | | | | | | | | | | | |
| *Micraspis crocea* | A/L | | | | | | | | | | | | | | | | | | | | |
| Carabid beetle | | | | | | | | | | | | | | | | | | | | | |
| Staphylinid beetle | | | | | | | | | | | | | | | | | | | | | |
| *Conocephalus longipennis* | | | | | | | | | | | | | | | | | | | | | |
| *Agriocnemis* sp. | | | | | | | | | | | | | | | | | | | | | |
| *Metioche vittaticollis* | | | | | | | | | | | | | | | | | | | | | |
| *Anaxipha longipennis* | | | | | | | | | | | | | | | | | | | | | |
| Spiders | | | | | | | | | | | | | | | | | | | | | |
| *Atypena* (Callitrichia) *formosana* | A/J | | | | | | | | | | | | | | | | | | | | |
| *Tetragnatha* sp. | A/J | | | | | | | | | | | | | | | | | | | | |
| *Lycosa pseudoannulata* | A/J | | | | | | | | | | | | | | | | | | | | |
| *Oxyopes* sp. | A/J | | | | | | | | | | | | | | | | | | | | |
| *Araneus inustus* | A/J | | | | | | | | | | | | | | | | | | | | |
| *Argiope* sp. | A/J | | | | | | | | | | | | | | | | | | | | |
| Salticids | A/J | | | | | | | | | | | | | | | | | | | | |
| Dyschiriognatha | A/J | | | | | | | | | | | | | | | | | | | | |
| Other Araneae | A/J | | | | | | | | | | | | | | | | | | | | |
| PARASITES | | | | | | | | | | | | | | | | | | | | | |
| *Tetrastichus* sp. | | | | | | | | | | | | | | | | | | | | | |
| *Telenomous* sp. | | | | | | | | | | | | | | | | | | | | | |
| *Gonatocerus* sp. | | | | | | | | | | | | | | | | | | | | | |
| *Oligosita* sp. | | | | | | | | | | | | | | | | | | | | | |
| Other Hymenopterans | | | | | | | | | | | | | | | | | | | | | |

2. Below canopy cover.
   Weed species present in each of the 3 sampling points (1.0 $m^2$) below the rice canopy were rated according to their percent cover (using the rating scale).

   The method was used for both transplanted and wet seeded rice (broadcast or row-seeded).
3. Weed species present in each of the 12 sampling points.
   For transplanted rice, weed species in each of 12 sampled hills which could have been transplanted together with the rice seedlings were recorded using the weed code.

   For wet seeded rice, a 25- × 25-cm quadrant was used in each of the 12 sampling points. Percent cover of the weed species present within each of the points was recorded in decreasing order of dominance, The weeds could be either above or below the canopy of rice.

These 3 data points were later simplified into 2: weed cover of whole field and weed cover of four 1-$m^2$ areas (Weed Form B2, Fig. 5). Note that weed rating was changed from percent weed cover to no. of plants/$m^2$. The weed cover of four 1-$m^2$ areas was not only confined to weeds below canopy, but included those above and the same height as crop canopy, as shown in the scale.

For weed cover of whole field, the weed species with highest rating was written in the first box under weed code and the score was written in the visual rating box. Other weed species observed were listed in order of decreasing dominance, but were not rated. Similar rating was done for each 1-$m^2$ area.

Weed data were summarized by determining average rating by weed species.

*Other data.* The general stand of the crop (poor, good, or excellent), water status (without, with little, adequate, or too much water), and soil condition (hard or soft) were recorded for each sampling time. Each farmer was asked about inputs applied between visits (fertilizer and pesticides, rates of application, total amount applied, and date applied). Other stresses, such as Zn deficiency, chlorosis due to N deficiency, phytotoxicity, rat damage, snail damage, and lodging, were also noted.

Grain yield was taken from 3 random 5-× 2-$m^2$ area in the 1 -ha sample field. Data were reported at 14% moisture content.

## Farmer interview

Interviews to determine farmers' knowledge about pests and their responses to pests are ongoing. Data on this aspect are being entered in the farmer pest recognition/ perception form (Fig. 6).

## Data management

All data are being entered into a database using RBASE system V on IBM-PC AT. Systematic field documentation containing field code, name of farmer, location, field feature or characteristics, and planting date can be generated easily. A summary of what weeds are predominant, what insects are abundant, and what diseases are

**Field Code** ☐

**Date** ☐ ☐ ☐
**mm** **dd** **yy**

**Growth Stage/**
days after sow./tr.

**001 Fallow**
00 seedbed/
10 seedling/
**20 Tiller/**
30 stem elong., P.I./
40 booting/

**50 Heading/**
60 flowering/
70 milk/
80 dough/
**90 Ripening/**
100 fully manure/
**200 Ratoon**

**Water Status**

**Crop Status**
**1** poor
**2** good
**3** excellent

**Remarks**

A. Above canopy cover (whose seedbed or field)

| Weed Sp. (just indicate no. as stated below) | Rating |
|---|---|
| | |
| | |
| | |
| | |

B. Below canopy cover (each of four 1.0-m² areas)

| | | Rating |
|---|---|---|
| Area | Weed Sp. | |
| a | | |
| b | | |
| c | | |
| d | | |

C. Weed Species (each of 12 hills)

| Hill | Rating |
|---|---|
| | Weed Sp. |
| a | |
| b | |
| c | |
| d | |
| e | |
| f | |
| g | |
| h | |
| i | |
| j | |
| k | |
| l | |

Rating Scale

0 = no weed
tr = a few scattered plants
1 = 1-10% weed cover
2 = 11-20% weed cover
3 = 21-30% weed cover
4 = 31-40% weed cover
5 = 41-50% weed cover
6 = 51-60% weed cover
7 = 61-70% weed cover
8 = 71-80% weed cover
9 = 81-90% weed cover
10 = 91-100% weed cover

Weed Species

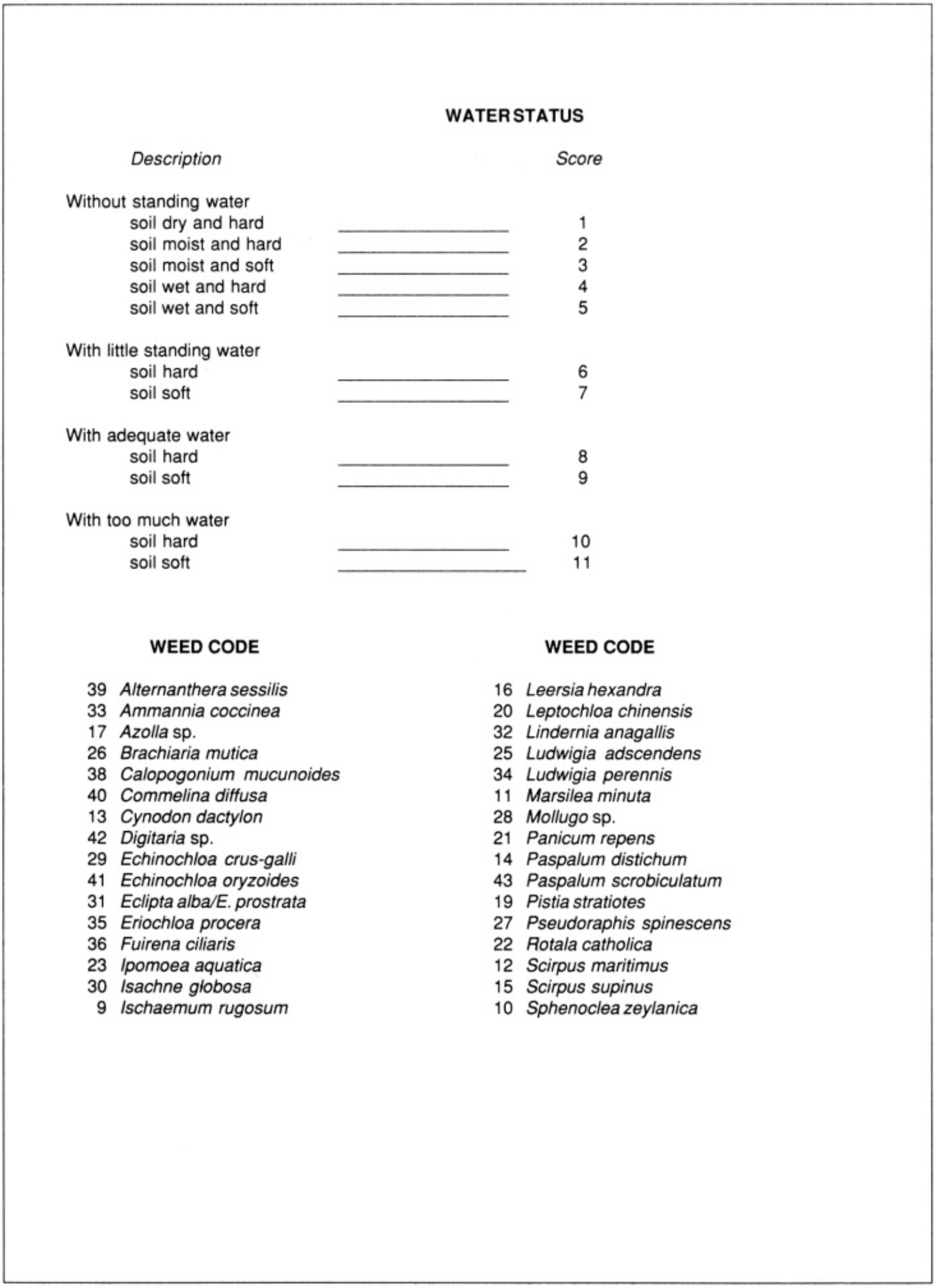
1. *Echinochloa glabrescens*
2. *Echinochloa colona*
3. *Monochoria vaginalis*
4. *Ludwigia octovalvis*
5. *Fimbristylis miliacea*
6. *Cyperus rotundus*
7. *Cyperus iria*
8. *Cyperus difformis*

---

*For transplanted rice, indicate which weed species occur in the hill sample.

**5.** Integrated Pest Survey Form B1: Weeds.

**Fig.** 5 continued



### WATER STATUS

| *Description* | | *Score* |
|---|---|---|
| Without standing water | | |
| soil dry and hard | ____________ | 1 |
| soil moist and hard | ____________ | 2 |
| soil moist and soft | ____________ | 3 |
| soil wet and hard | ____________ | 4 |
| soil wet and soft | ____________ | 5 |
| With little standing water | | |
| soil hard | ____________ | 6 |
| soil soft | ____________ | 7 |
| With adequate water | | |
| soil hard | ____________ | 8 |
| soil soft | ____________ | 9 |
| With too much water | | |
| soil hard | ____________ | 10 |
| soil soft | ____________ | 11 |

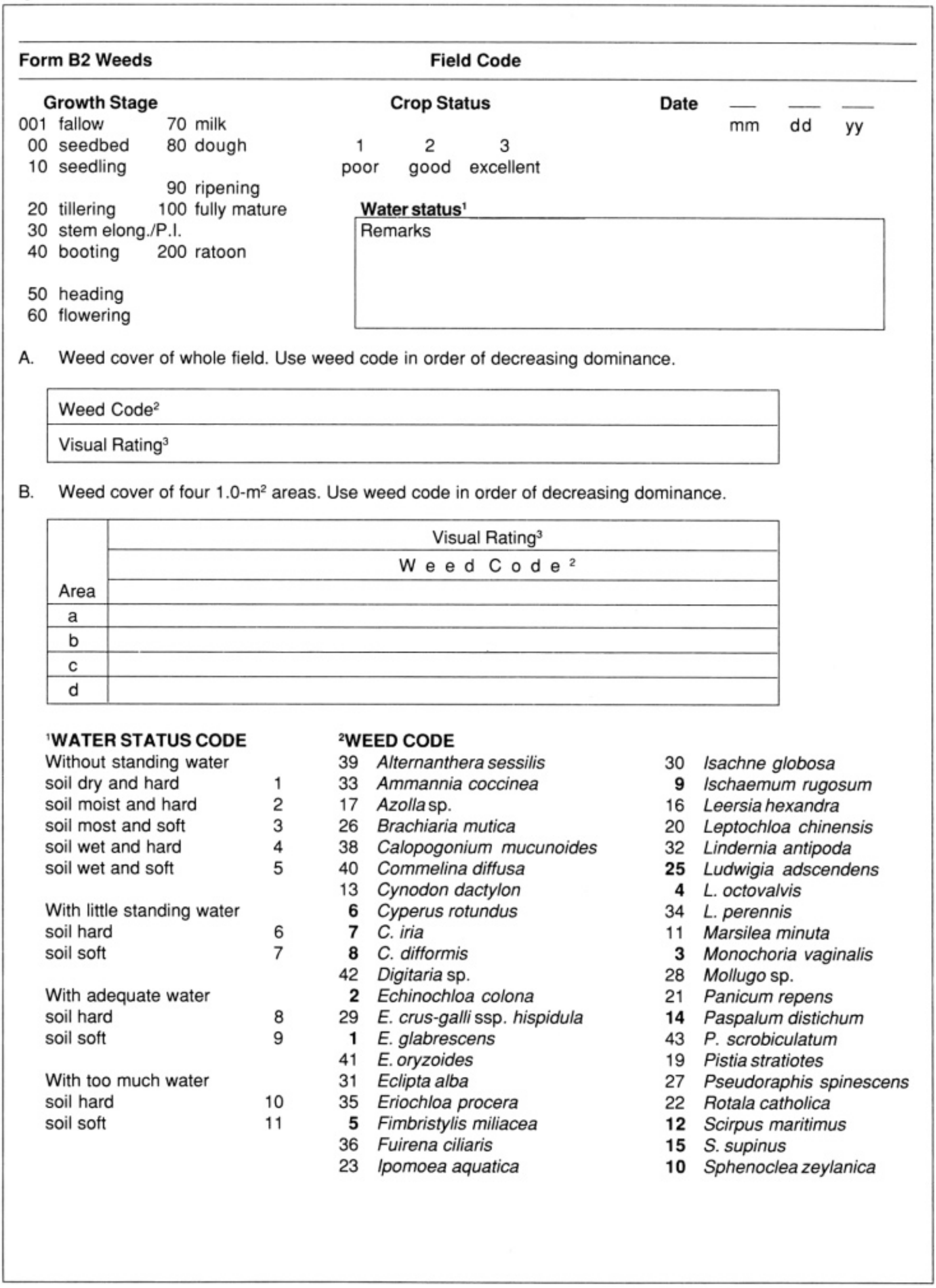
### WEED CODE

| | |
|---|---|
| 39 | *Alternanthera sessilis* |
| 33 | *Ammannia coccinea* |
| 17 | *Azolla* sp. |
| 26 | *Brachiaria mutica* |
| 38 | *Calopogonium mucunoides* |
| 40 | *Commelina diffusa* |
| 13 | *Cynodon dactylon* |
| 42 | *Digitaria* sp. |
| 29 | *Echinochloa crus-galli* |
| 41 | *Echinochloa oryzoides* |
| 31 | *Eclipta alba/E. prostrata* |
| 35 | *Eriochloa procera* |
| 36 | *Fuirena ciliaris* |
| 23 | *Ipomoea aquatica* |
| 30 | *Isachne globosa* |
| 9 | *Ischaemum rugosum* |

### WEED CODE

| | |
|---|---|
| 16 | *Leersia hexandra* |
| 20 | *Leptochloa chinensis* |
| 32 | *Lindernia anagallis* |
| 25 | *Ludwigia adscendens* |
| 34 | *Ludwigia perennis* |
| 11 | *Marsilea minuta* |
| 28 | *Mollugo* sp. |
| 21 | *Panicum repens* |
| 14 | *Paspalum distichum* |
| 43 | *Paspalum scrobiculatum* |
| 19 | *Pistia stratiotes* |
| 27 | *Pseudoraphis spinescens* |
| 22 | *Rotala catholica* |
| 12 | *Scirpus maritimus* |
| 15 | *Scirpus supinus* |
| 10 | *Sphenoclea zeylanica* |

**Fig. 5 continued**



**Form B2 Weeds** **Field Code**

**Growth Stage**

001 fallow
00 seedbed
10 seedling
20 tillering
30 stem elong./P.I.
40 booting
50 heading
60 flowering
70 milk
80 dough
90 ripening
100 fully mature
200 ratoon

**Crop Status**

1 poor 2 good 3 excellent

**Date** ___ ___ ___
mm dd yy

**Water status**[1]

Remarks

A. Weed cover of whole field. Use weed code in order of decreasing dominance.

| | |
|---|---|
| Weed Code[2] | |
| Visual Rating[3] | |

B. Weed cover of four 1.0-m² areas. Use weed code in order of decreasing dominance.

| | |
|---|---|
| | Visual Rating[3] |
| | Weed Code[2] |
| Area | |
| a | |
| b | |
| c | |
| d | |

**[1]WATER STATUS CODE**

| | |
|---|---|
| Without standing water | |
| soil dry and hard | 1 |
| soil moist and hard | 2 |
| soil most and soft | 3 |
| soil wet and hard | 4 |
| soil wet and soft | 5 |
| With little standing water | |
| soil hard | 6 |
| soil soft | 7 |
| With adequate water | |
| soil hard | 8 |
| soil soft | 9 |
| With too much water | |
| soil hard | 10 |
| soil soft | 11 |

**[2]WEED CODE**

| | |
|---|---|
| 39 | *Alternanthera sessilis* |
| 33 | *Ammannia coccinea* |
| 17 | *Azolla* sp. |
| 26 | *Brachiaria mutica* |
| 38 | *Calopogonium mucunoides* |
| 40 | *Commelina diffusa* |
| 13 | *Cynodon dactylon* |
| **6** | *Cyperus rotundus* |
| **7** | *C. iria* |
| **8** | *C. difformis* |
| 42 | *Digitaria* sp. |
| **2** | *Echinochloa colona* |
| 29 | *E. crus-galli* ssp. *hispidula* |
| **1** | *E. glabrescens* |
| 41 | *E. oryzoides* |
| 31 | *Eclipta alba* |
| 35 | *Eriochloa procera* |
| **5** | *Fimbristylis miliacea* |
| 36 | *Fuirena ciliaris* |
| 23 | *Ipomoea aquatica* |
| 30 | *Isachne globosa* |
| **9** | *Ischaemum rugosum* |
| 16 | *Leersia hexandra* |
| 20 | *Leptochloa chinensis* |
| 32 | *Lindernia antipoda* |
| **25** | *Ludwigia adscendens* |
| **4** | *L. octovalvis* |
| 34 | *L. perennis* |
| 11 | *Marsilea minuta* |
| **3** | *Monochoria vaginalis* |
| 28 | *Mollugo* sp. |
| 21 | *Panicum repens* |
| **14** | *Paspalum distichum* |
| 43 | *P. scrobiculatum* |
| 19 | *Pistia stratiotes* |
| 27 | *Pseudoraphis spinescens* |
| 22 | *Rotala catholica* |
| **12** | *Scirpus maritimus* |
| **15** | *S. supinus* |
| **10** | *Sphenoclea zeylanica* |

**Fig.** 5 continued

[3] Visual scoring scale in assessing weed infestation.

I. Weed density

N = nil — no weed
L = low — weed density is <5 plants/$m^2$
M = moderate — weed density is 5-20 plants/$m^2$
H = high — weed density is 21-50 plants/$m^2$
VH = very high — weed density is 51 plants or more/$m^2$

II. Scale

1 = no weed
3.1 = low weed density, weed canopy lower than crop canopy.
3.2 = low weed density, weed canopy about as high as crop canopy.
3.3 = low weed density, weed canopy higher than crop canopy.
5.1 = moderate weed density, weed canopy lower than crop canopy.
5.2 = moderate weed density, weed canopy about as high as crop canopy
5.3 = moderate weed density, weed canopy higher than crop canopy.
7.1 = high weed density, weed canopy lower than crop canopy.
7.2 = high weed density, weed canopy about as high as crop canopy.
7.3 = high weed density, weed canopy higher than crop canopy.
9.1 = very high weed density, weed canopy lower than crop canopy.
9.2 = very high weed density, weed canopy about as high as crop canopy
9.3 = very high weed density, weed canopy higher than crop canopy.

**Fig. 5 continued**

**Form B3 Weeds** **Field Code**

**Growth Stage**

| | | | |
|---|---|---|---|
| 001 | fallow | 70 | milk |
| 00 | seedbed | 80 | dough |
| 10 | seedling | | |
| | | 90 | ripening |
| 20 | tillering | 100 | fully mature |
| 30 | stem elong./P.I. | | |
| 40 | booting | 200 | ratoon |
| 50 | heading | | |
| 60 | flowering | | |

**Crop Status**

| 1 | 2 | 3 |
|---|---|---|
| poor | good | excellent |

**Date** ___ ___ ___
mm dd yy

**Water status**[1]

Remarks

A. Weed cover of whole field. Use weed code in order of decreasing dominance.

| Visual Rating[3] | Weed Code[2] | | | | |
|---|---|---|---|---|---|
| | | | | | |

B. Weed cover of four 1.0-m² areas. Use weed code in order of decreasing dominance.

| Area | Visual Rating[3] | Weed Code[2] | | | | |
|---|---|---|---|---|---|---|
| a | | | | | | |
| b | | | | | | |
| c | | | | | | |
| d | | | | | | |

**[1]WATER STATUS CODE**

| | |
|---|---|
| Without standing water | |
| soil dry and hard | 1 |
| soil moist and hard | 2 |
| soil moist and soft | 3 |
| soil wet and hard | 4 |
| soil wet and soft | 5 |
| With little standing water | |
| soil hard | 6 |
| soil soft | 7 |
| With adequate water | |
| soil hard | 8 |
| soil soft | 9 |
| With too much water | |
| soil hard | 10 |
| soil soft | 11 |

**[2]WEED CODE**

| | |
|---|---|
| 39 | *Alternanthera sessilis* |
| 33 | *Ammannia coccinea* |
| 17 | *Azolla* sp. |
| 26 | *Brachiaria mutica* |
| 38 | *Calopogonium mucunoides* |
| 40 | *Commelina diffusa* |
| 13 | *Cynodon dactylon* |
| 6 | *Cyperus rotundus* |
| 7 | *C. iria* |
| 8 | *C. difformis* |
| 42 | *Digitaria* sp. |
| 2 | *Echinochloa colona* |
| 29 | *E. crus-galli* ssp. *hispidula* |
| 1 | *E. glabrescens* |
| 41 | *E. oryzoides* |
| 31 | *Eclipta alba* |
| 35 | *Eriochloa procera* |
| 5 | *Fimbristylis miliacea* |
| 36 | *Fuirena ciliaris* |
| 23 | *Ipomoea aquatica* |
| 30 | *Isachne globosa* |
| 9 | *Ischaemum rugosum* |
| 16 | *Leersia hexandra* |
| 20 | *Leptochloa chinensis* |
| 32 | *Lindernia antipoda* |
| 25 | *Ludwigia adscendens* |
| 4 | *L. octovalvis* |
| 34 | *L. perennis* |
| 11 | *Marsilea minuta* |
| 3 | *Monochoria vaginalis* |
| 28 | *Mollugo* sp. |
| 21 | *Panicum repens* |
| 14 | *Paspalum distichum* |
| 43 | *P. scrobiculatum* |
| 19 | *Pistia stratiotes* |
| 27 | *Pseudoraphis spinescens* |
| 22 | *Rotala catholica* |
| 12 | *Scirpus maritimus* |
| 15 | *S. supinus* |
| 10 | *Sphenoclea zeylanica* |

**Fig. 5** continued

[3] Visual scoring scale in assessing weed infestation.

I. Weed density

Nil = no weed
Low = weed density is <5 plants/$m^2$
Moderate = weed density is 5-20 plants/$m^2$
High = weed density is 21-50 plants/$m^2$
Very high = weed density is 51 plants or more/$m^2$

II. Scale

0 = no weed
1 = low weed density, weed canopy lower than crop canopy.
2 = moderate weed density, weed canopy lower than crop canopy.
3 = high weed density, weed canopy lower than crop canopy.
4 = very high weed density, weed canopy lower than crop canopy.
5 = low weed density, weed canopy about as high as crop canopy.
6 = moderate weed density, weed canopy about as high as crop canopy.
7 = high weed density, weed canopy about as high as crop canopy.
8 = very high weed density, weed canopy about as high as crop canopy.
9 = low weed density, weed canopy higher than crop canopy.
10 = moderate weed density, weed canopy higher than crop canopy.
11 = high weed density, weed canopy higher than crop canopy.
12 = very high weed density, weed canopy higher than crop canopy.

**6.** Integrated Pest Survey Form A: Farm data and farmer pest recognition/perception.

**Fig. 6 continued**

## C. Farmer's Perceptions of Pests and Pest Control

Do you have any pest (insect, disease, or weed) problems on your farm?
☐ YES ☐ NO
If *YES*, what pest problems did you have

last year?

| SEASON TYPE/ type of planting | PEST PROBLEMS | CAVANS LOST |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

in previous years?

| SEASON TYPE/ type of planting | PEST PROBLEMS | CAVANS LOST |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Did you try to practice pest control? ☐ YES ☐ NO
If *YES*, what did you do?

Did you succeed? ☐ YES ☐ NO
Why?

What are the important RICE pests on your farm?
(Ask specifically about insects, diseases, and weeds.)
**Record in order of importance**

| | English Name | Local Name | Part of plant affected |
|---|---|---|---|
| Seedbed | | | |
| | | | |
| | | | |

**Fig. 6 continued**

Maximum tillering

| | | |
|---|---|---|
| ________ | ________ | ________ |
| ________ | ________ | ________ |
| ________ | ________ | ________ |
| ________ | ________ | ________ |

Flowering/ripening

| | | |
|---|---|---|
| ________ | ________ | ________ |
| ________ | ________ | ________ |
| ________ | ________ | ________ |
| ________ | ________ | ________ |

How do you control each of the above pests (if chemical, state which)?
1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________
6. ____________________
7. ____________________
8. ____________________
9. ____________________
10. ____________________
11. ____________________
12. ____________________
13. ____________________
14. ____________________
15. ____________________
16. ____________________

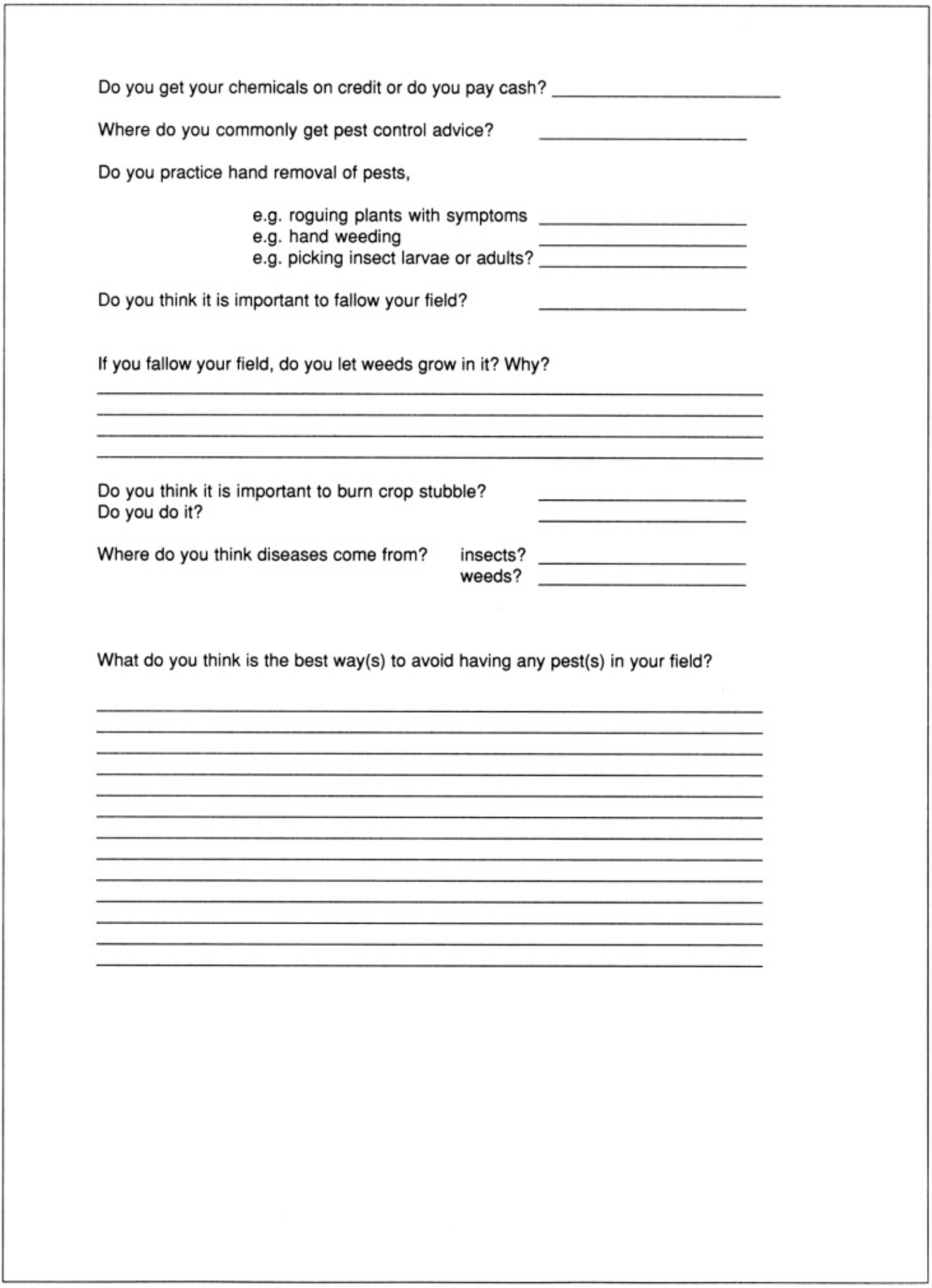
When do you usually apply pesticides?
1. When you see insect
2. When you see symptoms of injury
3. When you are free
4. When chemicals are available
5. ON a certain day each month, each week, which day
6. When advised by Department of Agriculture persons
7. When your neighbor sprays
8. When the chemical salesman recommends it
9. I do not apply any chemical
10. I apply only to control weeds, as recommended by manufacturer.

What kind of formulation do you prefer? ☐ powder ☐ liquid ☐ granule

Where do you buy pesticides?____________________

How much (in pesos) do you usually spend on herbicides? ____________ insecticides? ________ fungicides? ____________. Do you think it is worth it? ☐ Yes ☐ No

**Fig. 6 continued**



Do you get your chemicals on credit or do you pay cash? ________________________

Where do you commonly get pest control advice? ______________________

Do you practice hand removal of pests,

e.g. roguing plants with symptoms ______________________
e.g. hand weeding ______________________
e.g. picking insect larvae or adults? ______________________

Do you think it is important to fallow your field? ______________________

If you fallow your field, do you let weeds grow in it? Why?

______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________

Do you think it is important to burn crop stubble? ______________________
Do you do it? ______________________

Where do you think diseases come from? insects? ______________________
weeds? ______________________

What do you think is the best way(s) to avoid having any pest(s) in your field?

______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________

Fig. 6 continued

**D. Farmer's Pest Recognition Abilities**

| What is (Disease) | Important? | Cause? | Frequency? | Action? | Favored by? |
|---|---|---|---|---|---|
| Photo **A** | | | | | |
| **B** | | | | | |
| **C** | | | | | |
| **D** | | | | | |
| **E** | | | | | |
| **F** | | | | | |
| **G** | | | | | |
| **H** | | | | | |
| **I** | | | | | |
| **J** | | | | | |

For Rice Tungro Virus, ask if he has observed the symptoms before in the field (or adjacent fields) we will be sampling.

| | | | | | |
|---|---|---|---|---|---|
| What is (Insect) **A** | | | | | |
| **B** | | | | | |
| **C** | | | | | |
| **D** | | | | | |
| **E** | | | | | |
| **F** | | | | | |
| **G** | | | | | |
| **H** | | | | | |
| **I** | | | | | |
| **J** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| What is (Weed) **A** | | | | | |
| **B** | | | | | |
| **C** | | | | | |
| **D** | | | | | |
| **E** | | | | | |
| **F** | | | | | |
| **G** | | | | | |
| **H** | | | | | |
| **I** | | | | | |
| **J** | | | | | |

**Fig.** 6 continued

What varieties do you grow that are resistant to any of these pests?

| Pest | Varity |
|---|---|
| ____________ | ____________ |
| ____________ | ____________ |
| ____________ | ____________ |
| ____________ | ____________ |
| ____________ | ____________ |
| ____________ | ____________ |

For any pest, which of the following practices do you prefer to follow?

___ 1. Plant a resistant variety
___ 2. Plant different crop
___ 3. Fallow during dry season
___ 4. Remove plants (weeds/fested hills) by hand
___ 5. Spray chemical when pest or symptom is first observed
___ 6. Spray chemical only if threshold is exceeded
___ 7. Spray chemical according to manufacturer's label
___ 8. Burn stubble
___ 9. Hire a trained person to help you decide what to do
___ 10. Cut weed "heads" off to reduce future seeding
___ 11. Cut weed foliage for animal feed

common or severe at a particular growth stage in a particular province can be obtained. Also, relationships between pests and certain features such as method of planting, variety grown, planting date, date of sampling, water status of the field, pesticide use pattern, and grain yield can be determined.

## Remarks

The methodology described here is still undergoing refinement and field testing. No results are presented, although we have been collecting data since 1987 wet season. Analyses will be reported after the fourth survey (1989 dry season). However, we feel that the interdisciplinary team approach adopted for this survey is unique in determining pest problems in farmers' fields.

## References cited

Ahn S W, Mew T W (1986) Relation between rice sheath blight and yield. Int. Rice Res. Newsl. 11(5):21-22.

Ahn S W, Mukelar A (1986) Rice blast management under upland conditions. Pages 363-374 *in* Progress in upland rice research. Proceedings of the 1985 Jakarta conference. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

BPI — Bureau of Plant Industry (1983) Annual report 1982. San Andres, Manila.

BPI — Bureau of Plant Industry (1986) Annual report 1985. San Andres, Manila.

BPI — Bureau of Plant Industry (1987) Annual report 1986. San Andres, Manila.

BPI — Bureau of Plant Industry (1988) Annual report 1987. San Andres, Manila.

Estrada B A, Torres C Q, Bonman J M (1984) Effects of sheath rot on some yield components. Int. Rice Res. Newsl. 9(2):14.

Jackson L F, Webster R K, Wick C M, Bolstad J, Wilkerson J A (1977) Chemical control of stem rot of rice in California. Phytopathology 67:1155-1158.

James W C, Teng P S (1979) The quantification of production constraints associated with plant diseases. Appl. Biol. 4:201-267.

Lin C S, Poushinsky G, Mauer M (1979) An examination of five sampling methods under random and clustered disease distributions using simulation. Can. J. Plant Sci. 59:121-130.

NCPC — National Crop Protection Center (1985) Annual report 1984. U.P. at Los Baños, Laguna, Philippines.

NCPC — National Crop Protection Center (1984) Annual report 1983. U.P. at Los Baños, Laguna, Philippines.

NCPC — National Crop Protection Center (1983) Annual report 1982. U.P. at Los Baños, Laguna, Philippines.

Teng P S (1990) Crop loss assessment: a review of representative approaches and current technology. Pages 19-37 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Teng P S, Heong K L, eds. (1988) Pesticide management and integrated pest management in Southeast Asia. Consortium for International Crop Protection, College Park, Maryland 20740, USA.

Zadoks J C, Schein R D (1979) Epidemiology and plant disease management. Oxford University Press, New York.

# Notes

*Authors' address:* F. A. Elazegui, J. Soriano, J. Bandong, L. Estorninos, I. Jonson, P. S. Teng, B. M. Shepard, J. A. Litsinger, K. Moody, and H. Hibino, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Information management systems in rice pest surveillance

K. L. Heong

During the last decade, Integrated Pest Management (IPM) programs in rice have been emphasizing decisionmaking. Most rice production systems have three groups of decisionmakers: farmers, agricultural extension officers, and policymakers (Heong 1988a, Norton 1982). The types of information and the forms in which information is delivered to each group depend on their needs. A surveillance system can only be effective if it has been designed to address the problems of all three groups, to provide them with relevant information in time to be useful.

Most rice pest surveillance systems have been designed to address the problems of policymakers, extension officers, and researchers. Many countries have not yet been able to provide farmers with appropriate real-time information for pest management.

## Rice pest surveillance systems

Rice pest surveillance systems in Asia began as early as the 1940s, after heavy pest infestations in Japan led to food shortages (Yoshimeki 1967). Pest surveillance was started in India in 1969, after a widespread epidemic of tungro. In Malaysia, a pest surveillance system was established in 1979, following outbreaks of the brown planthopper (Ooi 1982). Pest surveillance and early warning systems began in the Philippines in 1975 and in Thailand in 1983, through the German Agency for Technical Cooperation. In Indonesia, pest surveillance started in 1975; there are now more than 2,000 pest observation units. Pest surveillance in South Korea started in 1958; today, 151 observation units are used to collect rice pest and disease information (Song and Park 1985). In China, pest surveillance is an important component of rice pest management (Lewis 1983); more than 4,000 pest observers are said to be employed by general plant protection stations throughout the country.

A typical pest surveillance system consists of the basic components of an information management system: data collection, data processing and storage, information synthesis, and information delivery. While a few countries (South Korea, Malaysia) have begun using computerized systems, most still carry out their activities manually. Pests and diseases in the fields are assessed by various procedures or sampling techniques from observation plots or randomly selected plots. The procedures differ markedly among national systems, although they are usually standardized within a country.

Field data usually are summarized, often manually, before they are delivered to the head office. In Malaysia, for example, the data summaries are typed and several duplicates are mailed to headquarters and various departments (Heong 1986a). Such delays confine data use to generating historical information. The data play a limited role in pest forecasting, although historical information has been used for some decisions. In Japan, mean pest populations over a number of years have been used as guides to decide whether an action is needed (Hirao 1979). Migration patterns of the brown planthopper in Japan and China have been established from historical records (Cheng et al 1979, Kisimoto 1976). Some researchers have built time-series models from historical data (Ono 1965, Torii 1967).

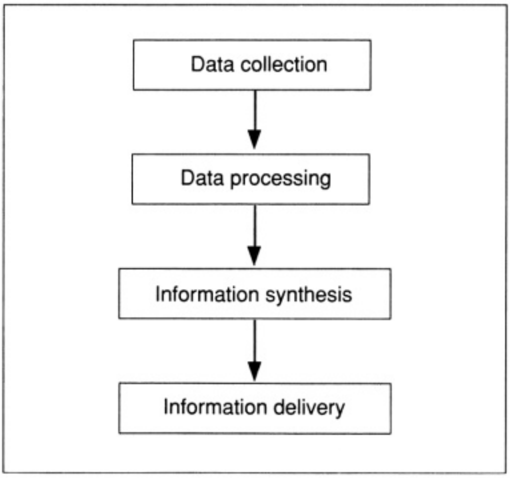
In temperate countries such as Japan, Korea, and China, real-time information is important in preventing pest outbreaks. Other countries in Asia, however, have not fully utilized such systems. In many cases, survey data processing and information synthesis need to be decentralized. Local pest surveillance officers in Malaysia, for instance, usually scan their data before mailing the reports. An officer will convene a meeting of the local pest control committee if the pest situation is abnormally high (Heong 1988b).

## Management of pest surveillance information

An information management system for pest surveillance has four basic components (Fig. 1).

### Data collection

Most pest surveillance systems adopt one or several methods to record rice pests and diseases (Benigno 1978; Dyck 1978; Gomez 1972; Heong 1981, 1986b; Kiritani 1972;



**1.** Basic components of an information management system for pest surveillance.

Nishida and Torii 1970). Light traps, in a variety of designs. are the most common. The type of insects and numbers caught depend on the trap design, operating procedures, and weather. At best, they can only provide rough trends of insect abundance (Wolda 1978). Nevertheless, they are convenient and easy to run. One problem in synthesizing data from light traps is that the traps have to be of the same design and operated in the same manner for the data to be comparable.

Absolute number methods of surveying, such as direct counting, are laborious. The *sticky board* method (Heong 1981) and the water pan sampler (Ferrer and Shepard 1987) have proved to be easier to manage while yielding reliable results. Methods such as yellow pan traps, sticky traps, sweep nets, and aerial nets yield only relative abundance and are prone to errors similar to those with light traps.

For insects that cause visible damage symptoms on plants, such as stem borers, gall midge, leaffolders, caseworms, and whorl maggots, visual scores or direct counts of damaged leaves may be used. Such methods have been used successfully in disease assessments (Gaunt 1987, Teng 1984) but they still lack standardization among observers.

The lack of suitable methods to rapidly acquire and synthesize pest data is a major obstacle in many pest surveillance systems. Traditionally, data are recorded in the field by the paper-and-pencil method and later keyed into computers for analyses. In South Korea, data from pest surveillance observation plots are recorded onto cards which are posted to the central office, where they are entered into a minicomputer (Song 1986). This is time-consuming and there is high chance of error in data transcription.

Several methods are now available by which data can be directly recorded electronically. Use of the paper grid/digitizer, voice recordings, data loggers, electronic notebooks, and portable computers has been discussed by Teng and Rouse (1984), Heong (1986a), and Bowen and Teng (1987). There is potential for developing use of these data-collecting devices. With rapid advancements in microprocessor technology, cheaper, morerobust, and more efficient instruments are likely to become available for pest surveillance.

## Data processing

Data can be processed very rapidly with modern electronic computers. A computerized database system can provide decisionmakers with centralized control of operational data. In pest surveillance, data on pest and disease infestations, weather, localities, and agronomic practices form the operational database. It is important that the various data sets be interrelated, to facilitate retrieval. Most pest surveillance systems adopt a database management system (DBMS) which enables the user to query the database for specific answers. For example, a decisionmaker may want to know the localities where high densities have been observed, to pinpoint the areas where action is required.

The DBMS may be written in a high-level programming language, such as PL/1, COBOL, or BASIC. Perhaps a more efficient way is to use a DBMS procedural language, like dBASE III, RBASE V, or FOXBASE, which requires fewer programming steps and less run time. Several such programs for rice are being developed at

IRRI, in Thailand (H. Weibel, Thai-German Plant Protection Project, Bangkok, Thailand, 1988, pers. comm.), and in China (J. Cheng, Zhejiang Agricultural University, Hangzhou, China, 1988, pers. comm.). Because surveillance system requirements differ in different countries, it is often necessary to rewrite the codes for each country. A more efficient way would be to develop software with a DBMS shell that would allow users to define their own database requirements.

In many developing countries, however, adoption of computers in managing pest surveillance data still lags. Despite the widespread use of computers in business, its use has not spread to the agricultural sector. One reason is the lack of qualified personnel, another is the lack of software designed for agricultural use. This is expected to change as computer application courses are introduced to agriculture students in many colleges and universities.

## Information synthesis

An important component of an information management system is information synthesis. The types of information required depend on who will use the information. That determines the synthesis. Regional summaries of pests and diseases often are useful for policymakers to plan their control strategies. Farmers, on the other hand, require early warning of potential pest attacks, followed by advice on what to do. Different analytical tools are required for the different information requirements.

Density maps of pests are excellent tools for both strategy planning and early warning. They provide the policymaker with trends and geographical distributions of high-risk areas. When these maps are generated in a time sequence, visual progress of pest development can be obtained. Such techniques have been developed for rice in South Korea (Song et al 1982). In Japan, weather information received by radio facsimile recorder is being used to generate maps of low-level jet streams that are related to long-distance displacements of rice planthoppers (Watanabe et al 1988). These maps are used to provide early warning of potential planthopper migrations into Japan.

## Information delivery

For pest surveillance systems to be useful in pest management, the pest information generated has to be delivered to the relevant decisionmakers. In South Korea, pest summaries are used in the weekly pest surveillance meetings at the headquarters from which warnings are sent out. Pest surveillance officers receiving these warnings then warn farmers by planting red flags carrying advisory messages in their fields. Pest reports are also delivered through billboards, local newspapers, radio, television, and village public address systems.

To benefit from such warnings, farmers need to be armed with basic pest management knowledge and the skills to respond to the warnings. They should understand that the warnings are for the region and that their own fields might not require any treatment. Among the basic skills needed are the ability to recognize pests, natural enemies, and damage due to pests and diseases; the ability to monitor their abundance; and the ability to make rational decisions based on these observations.

Often, pest information delivery from headquarters to regional stations is through the postal service or by telephone or telegram. Facsimile transmission is potentially useful, especially in Japan, Korea, and China, where nonromanized characters are used. Even for countries using romanized characters, facsimile is likely to revolutionize information delivery. Another form of delivery uses a videotex and data communications network (Heong 1988b). Although such systems are being utilized in business, their application to pest surveillance networks still awaits further development.

## Future developments

Rice pest surveillance activities will continue to be part of rice production systems in many countries. Often they are designed as information systems for policymakers. As such, emphasis has been placed on improving data collection, analysis, and retrieval, with little attention paid to synthesizing the data and delivering information to farmers.

With the increasing availability of modem computer technology and developments in information management, it is likely that national pest surveillance systems will adopt such technology. Many national agricultural programs maintain centralized data management systems. Advancements in microcomputers can be expected to decentralize data management and improve information delivery. To speed improvements in farmers' pest management decisionmaking, the farmers need to be trained in the basic skills that will enable them to respond to pest warnings. As research efforts improve information technology, there is an even stronger need to increase farmers' ability to utilize pest information efficiently.

## References cited

Benigno E A (1978) Pest damage assessment and sampling. *In* Proceedings of the regional training seminar on integrated pest control for irrigated rice in South and Southeast Asia, Oct 16-Nov 18, 1978, Philippines. Food and Agriculture Organization, United States Agency for International Development, and Philippine Bureau of Plant Industry. 11 p. (mimeo.)

Bowen K L, Teng P S (1987) Methods of field data collection and recording in experiments and surveys. Pages 76-81 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Cheng S N, Chen J C, Yam S H, Chu L M, Wu T L, Wu C T, Chien J K, Yau C S (1979) Studies on the migrations of brown planthopper *Nilaparvata lugens* Stal. Acta Entomol. Sin. 22:1-21.

Dyck V A (1978) Sampling rice insects. *In* Proceedings of the regional training seminar on integrated pest control for irrigated rice in South and Southeast Asia, Oct 16-Nov 18. 1978, Philippines. Food and Agriculture Organization, United States Agency for International Development, and Philippine Bureau of Plant Industry. 12 p. (mimeo.)

Ferrer E R, Shepard B M (1987) Sampling planthoppers and predators on direct-seeded and transplanted rice. J. Agric. Entomol. 5:199-204.

Gaunt R E (1987) Measurement of disease and pathogens. Pages 6-18 *in* Crop loss assessment and pest management. P. S. Teng, ed. APS Press, The American Phytopathological Society, St. Paul, Minnesota.

Gomez K A (1972) Techniques for field experiments with rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Heong K L (1981) The uses and management of pest surveillance data. Malays. Agric. J. 52:65-89.

Heong K L (1986a) Database management for pest management. MARDI Report No. 108. Malaysian Agricultural Research and Development Institute, Serdang, Malaysia.

Heong K L (1986b) Quantitative evaluations in biological control. Pages 87-106 *in* Biological control in the tropics. M. Y. Hussein and A. G. Ibrahim, eds. Penekit Universiti Pertanian Malaysia, Selangor.

Heong K L (1988a) Computerized surveillance systems in pest management. Pages 375-386 *in* Movement of pests and control strategies. ASEAN Plant Quarantine Centre and Training Institute, Serdang, Malaysia.

Heong K L (1988b) The surveillance and forecasting of insect populations in rice pest management. Pages 55-65 *in* Pesticide management and integrated pest management in Southeast Asia. P. S. Teng and K. L. Heong, eds. Consortium for International Crop Protection, Maryland, USA.

Hirao J (1979) Forecasting brown planthopper outbreaks in Japan. Pages 101-112 *in* Brown planthopper: threat to rice production in Asia. International Rice Research Institute, P.O. Box 933, Manila.

Kiritani K (1972) Strategy in integrated control of rice pests. Rev. Plant Prot. Res. 5:76-104.

Kisimoto R (1976) Synoptic weather conditions inducing long distance immigration of planthoppers, *Sogatella furcifera* Horv. and *Nilaparvata lugens* Stal. Ecol. Entomol. 1:95-109.

Lewis T (1983) Insect pest monitoring in China. Chem. Ind. 20:463-464.

Nishida T, Torii T (1970) A handbook of field methods for research on rice stem borers and their natural enemies. International Biological Program Handbook No. 14. Blackwell Scientific Publications, Oxford, USA.

Norton G A (1982) Crop protection decision making - an overview. Pages 3-11 *in* Decision making in the practice of crop protection. R. B. Austin, ed. British Crop Protection Council, London.

Ono K (1965) Principles, methods, and organization of blast disease forecasting. Pages 173-194 *in* The rice blast disease. The Johns Hopkins Press, Baltimore, Maryland.

Ooi PA C (1982) A surveillance system for rice planthoppers in Malaysia. Pages 551-565 *in* Proceedings of the international conference on plant protection in the tropics. K. L. Heong, B. S. Lee, T. M. Lim, C. H. Teoh, and Y. Ibrahim, eds. Malaysian Plant Protection Society, Kuala Lumpur.

Song Y H (1986) A general system analysis for a computer-based pest forecasting information management system [in Korean, English summary]. Pages 401-417 *in* Research report. Rural Development Administration, Suweon.

Song Y H, Kim C H, Choi J S (1982) Development of computer mapping system MAPSYS for pest management research [in Korean, English summary]. Korean J. Plant Prot. 21:142-145.

Song Y H, Park Y D (1985) A computer-based pest forecasting information management system. Pages 163-174 *in* Symposium: hi-technologies in agricultural sciences andcoming agriculture [in Korean, English summary]. The Association of Korean Agricultural Science Societies, Seoul, S. Korea.

Teng P S (1984) Surveillance systems in disease management. FAO Plant Prot. Bull. 32:51-60.

Teng P S, Rouse D I (1984) Understand computers: applications in plant pathology. Plant Dis. 68:539-543.

Torii T (1967) Statistical methods in rice stem borer research. Pages 127-167 *in* The major insect pests of the rice plant. The Johns Hopkins Press, Baltimore, Maryland.

Watanabe T. kino H, Hirai Y (1988) Computer program for forecasting the overseas immigration of long distance migratory rice planthoppers [in Japanese, English summary]. Jpn. J. AppI. Entomol. Zool. 32:82.85.

Wolda H (1978) Fluctuations in abundance of tropical insects. Am. Kat. 112:1017-1045.

Yoshmeki M (1967) A summary of the forecasting program for rice stern borer control in Japan. Pages 181-193 *in* The major insect pests of the rice plant. The Johns Hopkins Press. Baltimore, Maryland.

## Notes

*Author's address:* K. L. Heong, International Rice Research Institute. P.O. Box 933, Manila, Philippines.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933. Manila, Philippines.

# EPIPRE: research - development - application of an integrated pest and disease management system for wheat

J. C. Zadoks

EPIPRE (Epidemiology for Prediction and Prevention) is a disease and pest warning system for wheat developed in the Netherlands. It is an early example of attempts worldwide to develop computerized systems for integrated pest management (IPM) (e.g. CIPM 1983, Ives et al 1984). EPIPRE integrates various aspects of chemical control, crop husbandry, varietal choice, and farm economics in relation to five fungal diseases and several aphid pests (Zadoks 198l). This is a kind of postmortem analysis of the development of EPIPRE (Zadoks 1989).

At the initiation of the project in 1976, there was both occasion and motive. The occasion was rising interest among Dutch wheat farmers in intensive wheat growing, in response to the example of northern Germany where 10 t/ha yields could be obtained by applying some 10 chemical treatments.

The motive was more complex. On the one hand, there was the strong desire to do “something useful” with existing knowledge of plant disease epidemiology and computer science. On the other hand, there was serious concern about the environmental effects of frequent applications of systemic chemicals (still new in 1976) over large areas. The motive, activated by the occasion. induced a project proposal to the Netherlands Grain Centre (Zadoks 1976), which accepted it for funding. The project began in April 1977; its execution was entrusted to Mr. F. H. Rijsdijk.

## Scientific aspects of EPIPRE

The sequence Research - Development - Application is well-known from industry. The project proposal made it clear that EPIPRE was not a research project, but a development project that should lead to widespread application of existing knowledge.

### Phytopathological knowledge

The proposal stated that sufficient phytopathological knowledge was available to develop a disease warning system specifically for yellow rust caused by *Puccinia striilformis,* which is well-known in the Netherlands (e.g. Hogg et al 1969, Zadoks 1961). In retrospect, this statement is no more than a hypothesis, which turned out to be not supported. For practical application of existing knowledge, the literature abounded in redundant information but revealed few useful facts.

### Economic knowledge

Economic knowledge was found to be inadequate. The costs of treatment were known but little information on the benefits of treatment was available. Some information was misleading (Rijsdijk 1979). Damage thresholds in use had no scientific foundation. A rough-and-ready approach was chosen for EPIPRE. Detailed examination of results from experiments on chemical control led to workable initial figures which gradually were improved. The objective was not to predict benefits precisely, but to see whether a treatment would or would not produce profit at a given production level.

### Computer knowledge

Computer knowledge seemed adequate. Dynamic simulation models of plant pests (Carter et al 1982, Rabbinge et al 1979) and disease (Kampmeijer and Zadoks 1977, Rijsdijk and Rappoldt 1979, Waggoner et al 1972, Zadoks 1979) were known. The programming languages CSMP (IBM 1975) and FORTRAN held no secrets. But we soon found that dynamic simulation models applied a hundred times a day were too slow for EPIPRE, even on Wageningen University's then modem DEC 10 computer. The beautifully dressed simulation models had to be subjected to a striptease: the bare results consisted only of exponential equations.

Modeling was one thing, data handling another. Again, the premise of satisfactory knowledge, as stated in the project proposal, was wrong. Great effort and much time had to be invested in data handling. The 1978 version of EPIPRE used a primitive, homemade database constructed in FORTRAN. Later versions of EPIPRE used a formal Data Base Management System (Ratcliff 1982) compatible with FORTRAN.

### System design

The separation of phytopathological knowledge, economic knowledge, and computer knowledge was essentially wrong. "Development" implies integration of all relevant knowledge into one operational system (Rabbinge and Rijsdijk 1984, Rijsdijk 1980, Zadoks 1984). We had no notion of system development methodology (Rice et al 1978).

The system design was simple. Inputs are transformed into outputs. Inputs are the field-specific data provided by participants. Outputs are the field-specific recommendations given to participants. The transformation was accomplished by means of a set of rules representing our phytopathological and economic knowledge (Zadoks 1984).

Because EPIPRE was intended to serve hundreds of individual fields, the problem of handling large masses of data outweighed any scientific problem, at least in the beginning. On peak days, some 300 postcards with field data arrived with the morning mail. The recommendations were computer-printed and dispatched by the afternoon mail the same day.

### Counterscientific approach

Scientifically, the problem was in the rules that contain our phytopathological and economical knowledge in algorithmic form. The rules are equations with variables and constants. usually called parameters. Parameters, in turn, may be variables to be calculated by specific algorithms. The literature furnished few good rules, and let us down completely in parameter estimation. There was neither intention nor opportunity to engage in research: the task was development. The approach chosen was pragmatic, opportunistic, and in a way, counterscientific.

Several shortcuts were taken. One was in the area of rules. Consider the frequency distribution of fields against the intensity of a disease in those fields. The zone of low disease intensities, where no treatment is needed, was disregarded. So was the zone of high disease intensities, where the need for treatment was obvious. Attention was concentrated on the intermediate zone of uncertainty, where decision support might be welcome. Another shortcut was in parameter estimation. Scores of trial data were scrutinized for varietal resistance, fungicide effectiveness, etc. Conclusions were laid down in three classes: dangerous, not so dangerous, and not dangerous. The method allowed the systems engineer two degrees of freedom: changing the class attribution and changing the parameters attached to the classes.

An information vacuum existed on the epidemiological effects of fungicides (Zadoks 1977). Two types of data had to be entered for every fungus and active ingredient combination: the fraction of the fungus killed and the duration of protection provided by the fungicide. To complicate matters, trial data indicated that these parameters interacted with cultivars. Here, common sense was the only guide (Rijsdijk 1983, Zadoks 1984b).

Weather data were not used (Zadoks 1984c). One reason was that no good quantitative rules were available linking weather data to future disease intensities. Another was that the field data provided by the participants already were in a way an integration of the effect of past weather on disease. Because weather forecasts were too poor to be useful, the decision was made to skip weather as an input.

## Forward flight

The 1978 participants were benevolent but critical. They did not want a one-disease-only warning system, and they said so. Farmers face several diseases at a time, and they were beginning to use broad-spectrum fungicides. Obviously, broad-spectrum problems controlled by broad-spectrum fungicides required a broad-spectrum EPIPRE. This created a dilemma. Diseases could be handled in depth, one by one as was originally planned, but interest of the participants would be lost in the process. Or a broad, but superficial EPIPRE could be assembled, and participants' interest retained. The broad approach was chosen, with reliance on year-to-year improvement.

In later years, advances were technical rather than fundamental, with one exception. In 1979, Dr. R. Rabbinge contributed his knowledge on cereal aphids (Carter et al 1982; Rabbinge et al 1979, 1981). EPIPRE was updated annually after detailed discussions with representatives of the Extension Service and of research institutes. As recommendations were improved, they became more contentious, in that they showed the losses and gains expected from different harmful agents and various control options. They ended with a summary recommendation: do not treat, wait and see, treat.

## Human aspects of EPIPRE

The elementary system design was prepared in 1977. In 1978, EPIPRE was tested in practice. The cooperation of many people was needed. Whatever the intricacies of the system, it is made for human beings. Without good user relations, even the best system will fail. The actors belonged to two groups: the domestic EPIPRE team and its supervising committee, and the target group, the participants.

### Domestic forces

The EPIPRE team, with warm support from the sponsor, was enthusiastic and self-confident. The team worked assiduously and accomplished the impossible within a limited time and with a limited budget. The Supervising Committee was composed of all interested representatives of farmers, Extension Service, sponsor, colleagues, and team members. With this support, the team had to approach target group farmers and recruit participants.

### Participants

*Recruitment.* The team was convinced that doing something for farmers implied doing it with farmers; they had to be involved from the start. The term participant seemed to characterize that involvement. Participants were made partners, with the obvious implication of avoiding claims for legal liability. Participants were expected to criticize the team freely, and they did.

The public was sensitized by an information campaign in the rural press. Actual recruitment was done annually by the Extension Service. In 1978, more than 300 farmers across the Netherlands subscribed.

### Interaction

The problem was not recruitment, but interaction of the team with the participants. Interaction needed to be sufficiently frequent to exchange the necessary information, but it should not let the work be drowned in the social activities prescribed by rural protocol.

Interaction with participants took the forms of regional sessions, field instructions, printed instructions, mail, telephone, and field sorties by team members. Regional sessions of participants, local extension agents, and the EPIPRE team took place in early spring, for registration and instruction, and in the autumn, for evaluation. Annual reports were distributed among participants and other interested parties.

Essential information was exchanged by means of postcards, to the team with field observations, back to participants with recommendations. Mail services at the time were adequate. Turnaround time, from participant to team and back to participant, was three working days, at most. Turnaround time, weekend delays, and holiday delays were incorporated in the computer programs and thus were dealt with in the recommendations. The telephone answering service, which began in 1979, was much appreciated by participants because they had missed the personal touch.

In 1978 and 1979, all registered fields were visited by a team member at least once, some were visited six times. In this way, the team did a great deal of troubleshooting. The number of problems was amazingly low. Warnings were wrong in less than 0.5% of the cases. Corrections usually could be applied at the next round of interaction. without financial loss to the farmer.

### Yield monitoring

EPIPRE's comparative advantage was its field specificity (Zadoks 1984a). Each field, with its own peculiarities, was registered separately and monitored for pests and diseases. EPIPRE required the participant to do the monitoring, for two reasons.

- The participant should be trained to diagnose his own situation.
- The participant is responsible for providing good input data, the team is responsible for providing good output data.

### Reactions of participants

Participants registered one or more fields. Although computers were not yet popular. no participant objected to recommendations coming from the computer. The source of recommendations was not of concern, so long as Rijsdijk, whom they trusted, handled the instrument. This was in contrast to the attitude of some researchers who had strong opposition to using computers.

Participants' comments were both negative and positive. The two most frequent negative reactions were too long turnaround time (a technical objection that is more a matter of feeling than of fact) and they felt they did not earn money by participating (Blokker 1983). Again, that is not quite true (Zadoks 1984a). On average, earnings were positive, but the lowest earnings were too small to give the farmer a feeling of earning extra income (Rossing et al 1985).

Positive reactions were both specific and general. One specific reaction was "EPIPRE compelled me to go out and look at the crop. I found a severe attack by eyespot. It was a narrow escape." More general reactions centered on two points: "I was forced to go out and look at the crop myself" and "I learned so much about pest and disease control in wheat" (Blokker 1983). Both reactions had the sense of "and I liked it."

## Transfer of EPIPRE

The final step in a development project is its transfer to the user. Once more we come back to Research - Development - Application. Research is an important task of the University. Development, according to some, is not. Certainly, routine application is beyond the terms of reference of a Dutch university.

In 1980, negotiations were started with a few interested parties to transfer EPIPRE. After an extra trial year to test EPIPRE's performance, the request was granted by the sponsor.

The Ministry of Agriculture became interested for its own reasons, supposedly:

- EPIPRE provided a certain alibi for the Ministry's apparent lack of environmental concern.
- EPIPRE (the only computerized management system in arable crop husbandry) could serve as a bridge toward more general computerized crop management systems.
- EPIPRE had introduced a new principle into agricultural extension, which might be useful in restructuring the Extension Service.

The Ministry decided to continue EPIPRE for at least one more experimental year (1982) with a new team at the Research Institute for Arable Crops (RAGV) at Lelystad. The new team was instructed by the old team, and that was the end of the development phase. The application phase began in 1982 and continued (Reinink 1984).

## Results

What are the results of the EPIPRE development project? There are several criteria:

- Were hypotheses (statements in project proposal) confirmed?
- Have attitudes changed?
- Were innovations realized?

### Statements in the project proposal

The implicit hypothesis that an IPM system for wheat could be constructed in a relatively short time was confirmed. EPIPRE covers more diseases and pests and is more integrated than was ever expected.

The explicit hypothesis that the literature provided sufficient information was rejected (at least for diseases). Procedures had to be adapted to a degree that I call counterscientific.

The idea that the target group (farmer participants) should be involved from the beginning was correct and fruitful.

The promise to transfer the system to an appropriate institution for application was kept.

The claim that EPIPRE was to be financially self-supporting could not be substantiated. At the national level, the project was profitable (Zadoks 1984a).

### Changes in attitude

Evaluation studies (Blokker 1983) indicated that participants almost unanimously were appreciative of the learning effect. As a spin-off, EPIPRE farmers also looked more critically at crops other than wheat.

The author believes that EPIPRE has influenced the Extension Service, which shows less interest in risk avoidance (Rijsdijk 1979) and cosmetic effects and more interest in profitability of treatments than before.

Step by step, EPIPRE and standard recommendations converged, so that the comparative advantage of EPIPRE decreased.

Interest in intensive wheat farming in the Netherlands, which was the stimulus that triggered the conception of EPIPRE, dwindled. EPIPRE, with its emphasis on benefit-cost relations in crop protection, probably contributed to that effect.

### Innovations

EPIPRE was the first operational computerized IPM scheme in Europe, and possibly in the world. It demonstrated that such schemes are feasible.

EPIPRE was one of the first IPM scheme with explicit benefit-cost calculations. It moved from the critical period approach toward the threshold approach (Zadoks 1984c, 1985).

Routine use of EPIPRE in Belgium, England (to a limited extent), northern France (served from Belgium), Sweden, and Switzerland are spin-off benefits (Zadoks 1983).

EPIPRE obviously affected research in Wageningen, which became more practically oriented.

Students became more interested in farmer problems.

## Conclusion

Within the crop protection sciences, the development of EPIPRE was a medium-sized project. But it had ramifications in many segments of society in the Netherlands and beyond. The idea to distinguish research, development, and application and to maintain that distribution was effective. Development clearly delineated the project from other activities and gave it acceptability, purpose, and impetus.

However, a rigid distinction of research, development, and application is artificial and unjustified. Research without development can become a sterile exercise, producing more of the same instead of new information. Application reorients research and continuously questions development. Development without research can be innovative but risky, as EPIPRE convincingly showed. Development needs guidance from research as well as from the society which it serves.

## References cited

IBM–International Business Machines (1975) Continuous system modeling program III (CSMP III). Program reference manual. SH 19-7001-3. IBM Technical Publication Department, White Plains, USA. 206 p.

Blokker K J (1983) Computergesteunde voorlichting. Een decisiegericht voorlichtingskundig onderzoek naar EPIPRE en andere geautomatiseerde informatiesystemen. (Decision-oriented extension research). Ph D thesis, Wageningen Agricultural University. 389 p.

Carter N, Dixon A F G, Rabbinge R (1982) Cereal aphid populations: biology, simulation and prediction. Simulation Monographs. Pudoc. Wageningen. 91 p.

CIPM—Consortium for Integrated Pest Management (1983) Success stories. Texas A&M University, Bryan, Texas. 198 p.

Hice G F. Turner W S, Cashwell L F (1978) System development methodology. 2d ed. North-Holland Publishing Co., Amsterdam. 449 p.

Hogg W H, Hounam C E. Mallik A K, Zadoks J C (1969) Meteorological factors affecting the epidemiology of wheat rusts. Technical Note No. 99. World Meteorological Organization, Geneva, Switzerland. 113 p.

Ives P M, Wilson L T, Cull P O, Palmer W A, Haywood C, Thomson N J, Hearn A B, Wilson A G L (1984) Field use of SIRATAC: an Australian computer-based pest management system for cotton. Prot. Ecol. 6(1):1-21.

Kampmeijer P, Zadoks J C (1977) EPIMUL, a simulator of foci and epidemics in mixtures, multilines and mosaics of resistant and susceptible plants. Simulation Monographs. Pudoc. Wageningen. 50 p.

Rabbinge R, Ankersmit G W, Pak G A (1979) Epidemiology and simulation of population development of *Sitobion avenae* in winter wheat. Neth. J. Plant Pathol. 85:197-220.

Rabbinge R, Drees E M, Van der Graaff M, Verberne F C M, Wesselo A (1981) Damage effects of cereal aphids in wheat. Neth. J. Plant Pathol. 87:217-232.

Rabbinge R, Rijsdijk F H (1984) Epidemiological and crop physiological foundation of EPIPRE. Pages 227-235 *in* Cereal production. E. J. Gallagher, ed. Butterworths, London.

Ratcliff W (1982) dBase II assembly-language relational database management system. User manual. Ratcliff Software Production, Ashton Tate, Culver City, California. 186 p.

Reinink K (1984) Recent experiences in computerized pest and disease control in the Netherlands. Pages 685-690 *in* Proceedings of the British Crop Protection Council Conference. British Crop Protection Council, Brighton, England.

Rijsdijk F H (1979) Verliezen in de nederlandse tarweteelt. Gewasbescherming 10:196-199.

Rijsdijk F H (1980) Systems analysis at the cross-road of plant pathology and crop physiology. Z. Pflanzenkr. Ptlanzenschutz 87:404-408.

Rijsdijk F H (1983) Decision making in the practice of crop protection. The EPIPRE system. Pages 65-76 *in* Proceedings of the British Crop Protection Council Symposium. British Crop Protection Council, Brighton, England.

Rijsdijk F H, Rappoldt K (1979) A model evaluation of sport, dispersal inside and above canopies. Pages 407-410 *in* Proceedings of the 1 st International Conference of Aerobiology. Munich. Erich Schmidt Verlag, Berlin. 471 p.

Rossing W A H, Schans J. Zadoks J C (1985) Het project Epipre, project analyse in de gewasbescherming. Landbouwk. Tijdschr. 97:29-33.

Waggoner P E, Horsfall J G, Lukens R J (1972) EPIMAY, a simulator of southern corn leaf blight. Bull. 729. Connecticut Agricultural Experiment Station, New Haven. 84 p.

Zadoks J C (1961) Yellow rust on wheat, studies in epidemiology and physiologic specialization. Tijdschr. Plantenziekten (Neth. J. Plant Pathol.) 67:69-256.

Zadoks J C (1976) Project proposal EPIPRE. 7 p. (unpubl.)

Zadoks J C (1977) On the epidemiological evaluation of fungicide action. Neth. J. Plant Pathol. 83 (supplement 1):417-426.

Zadoks J C (1979) Simulation of epidemics: problems and applications. EPPO Bull. 9:227-234.

Zadoks J C (1981) EPIPRE: a disease and pest management system for winter wheat developed in the Netherlands. EPPO Bull. 11:365-369.

Zadoks J C (1 983) An integrated disease and pest management scheme. EPIPRE, for wheat. Pages 116-129 *in* Better crops for food. Ciba Foundation Symposium 97. J. Nugent and M. O'Connor, eds. Pitman, London.

Zadoks J C (1984a) Analyzing cost-effectiveness of EPIPRE. EPPO Bull. 14:61-65.

Zadoks J C (1984b) EPIPRE, a computer-based scheme for pest and disease control in wheat. *In* Cereal production. E. J. Gallagher, ed. Butterworths. London. 354 p.

Zadoks J C (1984c) A quarter century of disease warning, 1958-1983. Plant Dis. 68:352-355.

Zadoks J C (1985) On the conceptual basis of crop loss assessment: the threshold theory. Annu. Rev. Phytopathol. 23:455-473.

Zadoks J C (1989) EPIPRE: research, development and application of an integrated pest and disease management system for wheat. Plant Dis. Epidemiol. 2:3-29.

Zadoks J C, Rijsdijk F H, Rabbinge R (1984) EPIPRE: a systems approach to supervised control of pests and diseases of wheat in the Netherlands. Pages 344-351 *in* Pest and pathogen control. Strategic, tactical and policy models. G. R. Conway, ed. Wiley, Chichester. 488 p.

## Notes

*Acknowledgments:* Thanks are due to IOBC Bulletin for the permission to reprint this paper and to Dr. D. J. Royle for the careful revision of the text.

*Author's address:* J. C. Zadoks, Department of Phytopathology, Wageningen Agricultural University, P.O. Box 2025, 6700 EE Wageningen, The Netherlands.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice, P.O. Box 933, Manila, Philippines.

# Using pest surveillance data in Thailand

P. Menakanit, A. Upanisakorn, L. Menakanit,
S. Sri-arunothai, and U. Dechmani

The Pest Surveillance and Warning System in Thailand was implemented in 1981, and modified in 1984. Pest surveillance data are taken from on-farm trials. Results of a 4-yr analysis in Chachoengsao Province, Central Thailand, show that only brown planthopper is a major rice pest. Several pests reached their economic threshold (ET) levels, but in only a few fields. Considering net returns, it appeared that ETs are acceptable, from the point of view of risk, as indicators of need to control and to generate additional income for the farmer.

Pest surveillance activities were done through Plant Protection Service Units in surveillance crop loss fields (SCF). Farmers were asked to define SCF plots of approximately 0.16 ha (1 rai) each. Pest control decisions in an SCF were made based on ETs for insects and diseases. If a pest reached its threshold, a portion of the plot was left unsprayed.

Data collection involved pest sampling weekly, data on the development stage of the crop, and agronomic and economic data of each farmer's pest control practices. If a control treatment was applied, chemical and labor costs were included. Theoretically, three factors are involved: the farmer, the ET for each pest, and control.

Each farmer carried out his regular pest control practices in his remaining fields. which served as a comparison for the SCF plot.

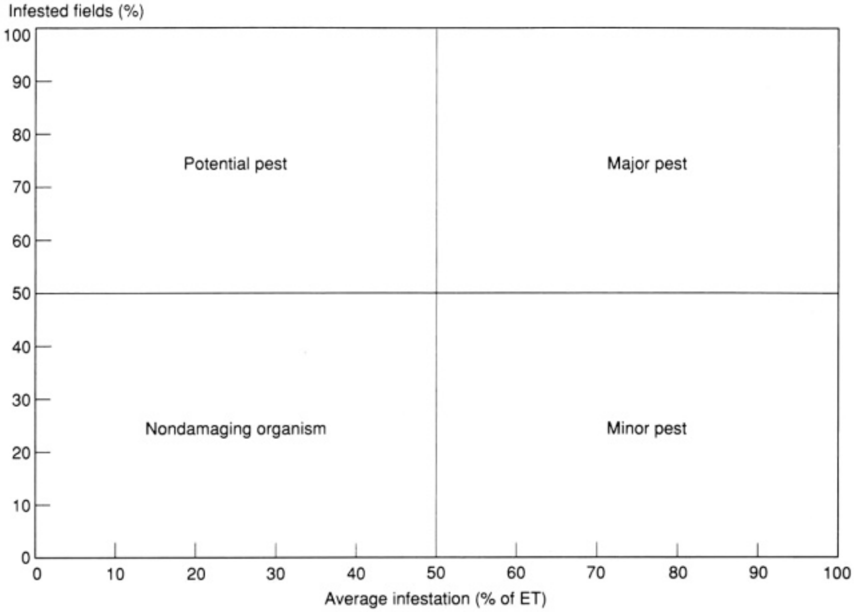
The objectives were

- To test the validity and reliability of recommended thresholds.
- To assess the benefit of the ET strategy, which then could indicate farmer willingness to adopt the strategy.
- To work out the status of the economic importance of various pests and diseases.

## Data analysis

Field data were stored and processed in a microcomputer using the Pest Surveillance Information System (PSIS) developed on dbase III+ program (Dias et al 1988).

The pest situation for 1984-87 wet and dry seasons was extracted. The frequency of pest occurrence and average infestation levels, expressed as percent of ET, were related in a pest classification scheme produced by the program. This allowed classification of pests into potential, major. and minor (Fig. 1).



**1.** Pest classification scheme.

**Table 1. Method for calculating partial budget of surveillance crop loss fields.**

| Parameter | Treatment | | |
|---|---|---|---|
| | Farmer A | Economic threshold B | Control C |
| Yield (1) | | | |
| Price (2) | | | |
| Gross returns (3) | (1) x (2) | | .. |
| Cost of chemical (4) | | | |
| Cost of labor (5) | | | |
| Cost of credit (6) | | | |
| Cost of additional harvest (7) | | | |
| Total cost of control (8) | Sum (4) - (7) | .. | .. |
| Net returns (9) | (3) - (8) =Aa | Ba | Ca |
| Marginal net returns: | | | |
| Farmer - Control | Aa-Ca | | |
| ET - Farmer | | Ba-Aa | |
| ET - Control | | | Ba-Ca |

Net returns were computed by partial budget analysis (Table 1) to assess the relative advantage of using ET as a treatment decision aid.

It is widely accepted that farmers will accept new farming methods as long as they find them economically attractive. In a number of studies in developing countries,

Table 2. **Pest situation, 1984-87 wet and dry seasons.**

| Pest | 1984 | | 1985 | | 1986 | | 1987 | |
|---|---|---|---|---|---|---|---|---|
| | Wet | Dry | Wet | Dry | Wet | Dry | Wet | Dry |
| Brown planthopper | 2 | 1 | 5.5 | 2.5 | 10.8 | 61.8 | 6 | 0.5 |
| Whitebacked planthopper | 33 | 0.2 | 4 | 0.5 | 25 | 0.5 | 08 | 05 |
| Green leafhopper | 13.1 | 9 | 1.3 | 1.3 | 1.1 | 1 | 1.1 | |
| Rice leaffolder | 8 | 2.3 | 16 | 8 | 5.4 | 2.8 | 7.4 | 21 |
| Stem borer | 0.6 | 2.3 | 0.3 | 1 | 2 | 0.4 | 0.5 | 0.4 |
| Blast | 20 | 3.2 | 9.5 | 20.6 | 50 | 1.8 | 0.5 | 12 |
| Neck blast | 0.9 | 1 | 12 | 2.4 | 0.6 | 6 | 0.3 | 0.6 |
| Bacterial blight | 4 | 1.2 | - | 6.3 | - | - | | |
| Sheath rot | - | - | - | - | - | - | 0.6 | |
| Sheath blight | - | - | - | - | - | - | 2.3 | 2 |

**Table 3. Relative importance[a] of the most common pests in Chachoengsao Province, Thailand, 1984-86.**

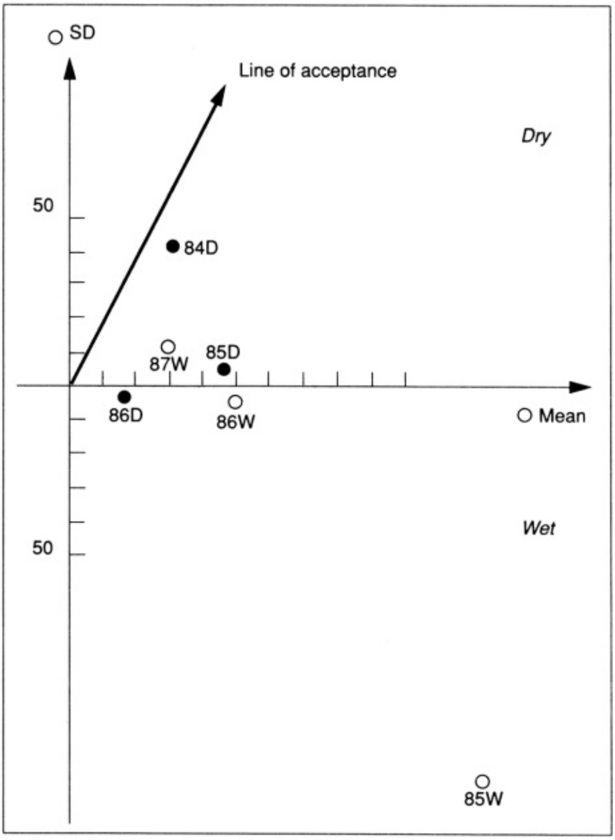
| Year | Season | Brown planthopper | Green leafhopper | Rice leaffolder | Stem borer | Whitebacked planthopper | Neck blast |
|---|---|---|---|---|---|---|---|
| 1984 | Wet | N | P | P | N | P | N |
| 1984-85 | Dry | N | P | N | N | N | P |
| 1985 | Wet | P | P | P | N | P | N |
| 1985-86 | Dry | N | N | N | N | N | N |
| 1986 | Wet | P | P | P | P | P | P |
| 1986-87 | Dry | M | P | P | P | | P |
| 1987 | Wet | P | P | P | P | N | N |

[a] N = no damage. P = potential pest, M = major pest.

**Table 4. Mean and standard deviation of net returns of economic thresholds and farmers' practices, in baht/rai, 1984-87 wet and dry seasons (Menakanit 1985).[a]**

| | | Economic threshold | Farmers' practices | Difference $\overline{X}$ | Difference SD |
|---|---|---|---|---|---|
| 1984 Dry | $\overline{X}$ | 1802.76 | 1773.56 | 29.1 | 43.2 |
| | SD | 326.59 | 283.39 | | |
| 1985 Wet | $\overline{X}$ | 1274.86 | 1105.11 | 169.75 | -123.9 |
| | SD | 372.12 | 496.02 | | |
| 1985 Dry | $\overline{X}$ | 1105.5 | 1061.6 | 47.37 | 15.55 |
| | SD | 270.2 | 254.65 | | |
| 1986 Wet | $\overline{X}$ | 1122.98 | 1071.26 | 51.72 | -3.02 |
| | SD | 263.27 | 266.29 | | |
| 1986 Dry | $\overline{X}$ | 1558.91 | 1542.8 | 16.11 | -4.03 |
| | SD | 241.94 | 245.97 | | |
| 1987 Wet | $\overline{X}$ | 1662.49 | 1630.8 | 31.69 | 11.02 |
| | SD | 345.08 | 334.06 | | |

[a] US$1 = about 25 baht; 1 rai = 0.16 ha.



**2.** Risk assessment of the performance of economic threshold levels, Chachoengsoa, 1985-87 wet and dry seasons.

including Thailand, farmers have been found to be moderately risk averse. They are willing to accept a new technology if the standard deviation of additional income is not more than two times the amount of additional income (Ryan 1984).

## Results and discussion

Table 2 shows the maximum infestation level of pest population each season, 1984-87. During the 1984 wet season, the following pests reached ET: whitebacked planthopper, green leafhopper, rice leaffolder, stem borer, brown planthopper, rice blast, and neck blast. Brown planthopper, stem borer, and neck blast were most dominant; their infestation levels reached ET almost every year. However, even though populations of pests were high, when we classified pests by relating population levels with the occurrence to their thresholds, only brown planthopper was a major pest, in 1983 (Fig. 1, Table 3). Neck blast and stem borer were potential pests in some areas.

When net returns of SCF and farmer plots are compared (Table 4), net return of ET technology on average is higher than that of farmer's practices. Risk (measured in terms of the standard deviation of net returns) shows that increases in average net returns are accompanied by an acceptable increase in variation of net returns (Fig. 2).

## References cited

Dias A, Gonzales R, Menakanit P, Waibel H (1988) User's manual on pest surveillance information system for rice-based cropping systems. Asian Institute of Technology, Bangkok, Thailand. 99 p.

Menakanit P (1985) Economic analysis of surveillance crop loss field in the surveillance pilot area. Surveillance in rice based cropping systems. Pages 153-157 *in* Proceedings of a workshop at Khonkaen. Department of Agricultural Extension, Bangkok, Thailand.

Ryan J G (1984) Efficiency and equity considerations in the design of agriculture technology in developing countries. Aust. J. Agric. Econ. 28:109-135.

## Notes

*Authors' addresses:* P. Menakanit, Vertebrate and Other Pests Control Group, Plant Protection Service Division, Department of Agricultural Extension (DAE), Phaholyotin Rd., Bangkok 10900, Thailand; A. Upanisakorn and L. Menakanit, Regional Plant Protection Service Office, Central Region, DAE, Phaholyotin Rd., Bangkok 10900, Thailand; S. Sri-arunothai, Vertebrate and Other Pests Control Group, Plant Protection Service Division, DAE, Phaholyotin Rd., Bangkok 10900, Thailand; and U. Dechmani, Plant Protection Service Division, DAE, Phaholyotin Rd., Bangkok 10900, Thailand.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Genetically sound strategies for disease management

K. M. Chin

Other papers in this volume are concerned primarily with the assessment of disease and its consequences, so that appropriate control strategies can be selected. An implicit assumption is that any control tactic applied will be effective. Experience, however, has shown that often, the efficacy of a control tactic cannot be sustained in the face of pathogen evolution.

Many farmers in the developing world have inadequate food security. Crop failures can have disastrous consequences for many farmers in less developed countries who have inadequate food security. As a result, farmers prefer crop production and protection techniques that minimize risks, rather than those that maximize yield. This makes it particularly important that tactics to control pests and diseases work as and when they are supposed to. For economic and technical reasons, alternative measures may not be available immediately. Measures that help maintain the efficacy of control tactics, thereby reducing yield fluctuations, are of special significance to farmers in South and Southeast Asia.

Four major approaches are available for disease control — host resistance, pathogen-disruptive chemicals, cultural practices, and biological control agents. The first two have been the most used in recent years, but their extensive use also has revealed the innate ability of pathogen populations to adapt genetically to a host plant resistance or to chemical toxicants, resulting in an apparent breakdown of control.

## Pathogen evolution

There are many examples of host resistance becoming ineffective as a result of the development of virulent pathotypes capable of overcoming the resistances. *P. oryxae,* the causal agent of blast disease, is particularly well known for its great capacity to change in response to selection pressures.

For example, when rice varieties Improved Mahsuri, Jaya, and Setanjung first became available to farmers in Malaysia, they were highly resistant to blast. Within 2-5 seasons, their popularity had resulted in rapid selection of the corresponding virulences, and widespread damage occurred (Chin 1985). Many other rice-growing countries have reported similar experiences (Ezuka 1979, Ou 1985).

Similarly, intensive use of certain fungicides in a number of crops has resulted in the selection of insensitive genotypes, and loss of control (Dekker 1976, Delp 1980, Staub and Sozzi 1984). Examples on rice have been documented by Uesugi (1979) and Katagiri et a1 (1980).

Many pathogen populations are large enough to allow them to produce a virtually unlimited range of mutants (Wolfe and Schwarzbach 1978). Assuming that the mutation rate of *P. oryzae* is similar to that of other organisms ($10^{-6}$ - $10^{-8}$/locus per day and a spore production rate of $5 \times 10^3$ conidia/lesion per day [ Ou 1985]), it seems likely that mutants matching most *R* genes or toxicants will exist over even small, moderately infected fields. Whether these mutants increase enough to become detectable using conventional sampling methods or to assume economic importance depends on a number of factors, including the genetic penalty paid for acquiring new attributes.

Initially, when a cultivar with a new resistance Fene (say *R1* ) is introduced into a region, it may be assumed that the corresponding virulence ( *V1* ) is rare in the pathogen population—otherwise, the resistance gene would not confer resistance. Because VI is rare, it is likely to be less fit than *V0* (the virulence that is only able to attack cultivars without *R1* ) on *R0.* But because *V1* can attack both *R0* and *R1* (whereas *V0* can only attack *R0* ), it has a selective advantage over *V0.* That advantage increases as the proportion of *R1* increases (i.e. as the new resistant cultivar increases in popularity). Whether *V1* or *V0* predominates (the outcome of selection) therefore depends on a fine balance between the relative fitnesses of *V1* and *V0* and the extent of cultivars with the *R1* gene for resistance.

Similarly, selection for insensitivity against a toxicant depends on the relative fitnesses of insensitive and sensitive strains of the pathogen and the effective area covered by the chemical used. Effective area is a function of spray coverage and chemical systemicity and persistence.

These changes were modeled by Chin (1987) as

$$\frac{\alpha t}{\beta t} = \frac{\alpha_o w^t}{\beta_o \theta^t}$$

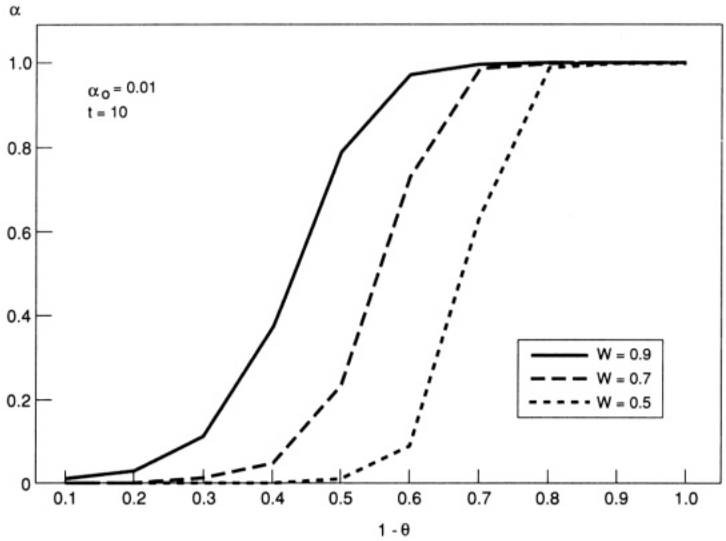
where $a_0$ and $a_t$ are the initial and final frequencies *V1* and $b_0$ and $b_t$ are the initial and final frequencies of *V0,* after t cycles of selection; *w* is the relative fitness of *V1;* and 8 is proportion of host area devoted to *R0.*

They are described in Figures 1 and 2.

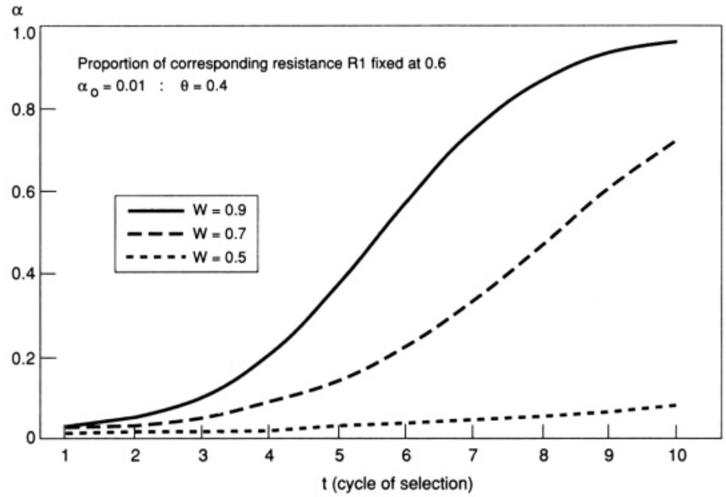
The following is an example of the rapidity with which pathogen populations can respond. If 60% of an area is planted to a variety with a new *R* gene (or treated with a new, specific fungicide) and if the relative fitness of the corresponding virulence (or insensitive genotype) is 0.9, then virulence (or insensitive genotype) will increase from an initial level of 0.01 to 0.97 in ten cycles of selection.

## Genetically sound strategies

Genetic strategies to improve the longevity of control tactics involve two types of durability: inherent durability and systems durability (Wolfe 1983).



**1.** Frequencies a of virulent genotype *V1* after 10 cycles of selection on increasing proportions of resistant hosts (R1).



**2.** Change in frequency a of virulence genotype *V1* with time (t) for different relative fitness (w) values.

## Inherent durability

In this strategy, two forms of resistance may be used. For pathosystems where race nonspecific resistance (Scott et al 1978) or other forms of durable resistance (Johnson

1981) are available, these may be used. Where these forms are not available, pyramiding *R* genes has been advocated to reduce the probability of matching pathogen genotypes (Nelson 1978). There is, in fact, no *a priori* reason to assume a gene-for-gene relationship. What is intended is that there should be a demand for a multigenic response from the pathogen.

### Systems durability

Systems durability operates by encouraging disruptive selection in the pathogen population (Mather 1957). By introducing diversity into crops or cropping systems, selection is directed toward different optima in time or space.

Systems that have been suggested (e.g. Wolfe 1983) include

1. Diversity between crops
   a. Deployment in time (e.g. sowing cultivars with different *R* genes in different seasons)
   b. Deployment in space (e.g. sowing cultivars with different *R* genes in different areas/fields
2. Diversity within crops (e.g. multilines and varietal mixtures). Effective and durable control of *P. oryzae* has been demonstrated using an appropriate blend of rice cultivars (Chin and Ajmilah 1982, Chin et al 1985).
3. Diversity between and within crops (e.g. different mixtures at different times and different regions).

## Strategies for using pathogen-disruptive chemicals

### Compounds apparently beyond pathogen adaptation

This strategy is identical to that using durable resistance. Typically, compounds with multisite action have been less susceptible to adaptation by pathogens. Compounds that select for pathotypes with poor fitness and those that are not systemic or lack persistence are also likely to be more durable.

However, even among systemic, single-site compounds, the rate of adaptation by pathogens has varied. For example, there has been rapid, massive adaptation to some phenylamides and benzimidazoles, but slower adaptation to ergosterol biosynthesis inhibitors or EBIs (Georgopoulos 1987). While the difference may be due largely to the number of genes in the pathogen that determine its response to a particular fungicide, fitness levels of adapted pathotypes that may also be implicated are at the moment unclear. Selection of modifier genes that increase the fitness of insensitive genotypes, allowing them to compete better with sensitive genotypes, cannot be ruled out.

### Deployment in time or space

This strategy also is based on encouraging disruptive selection in the pathogen population. Examples include alternating different fungicides, using different fungicides in different seasons, or using fungicides in alternate seasons.

**Mixtures**

This strategy parallels the use of pyramiding genes in host resistance. Urech and Staub (1985) considered this the only practical strategy for minimizing resistance risks to phenylamide fungicides. Considerable success in preventing the buildup of resistance against metalaxyl in the Oomycetes has been achieved by mixing metalaxyl with protective, multisite fungicides like mancozeb.

## Integrated approach

Integration of host resistance with fungicides may have both tactical and strategic advantages. Wolfe (1982) considered that combining low levels of varietal resistance with fungicide application could provide adequate protection and extend the durability of both measures. Williams (1986) suggested that integrating fungicide seed treatment with moderate host resistance could provide adequate and durable protection against leaf blast on upland rice, where it is needed most.

## Conclusion

As production technology for rice and rice-based systems improves in South and Southeast Asia, the tools to control diseases become increasingly refined and selective. That selectivity has elicited equally sophisticated responses from pathogen populations. Tactics need to be complemented by strategic considerations if we are not to waste valuable genetic and chemical resources.

Surveys of plant diseases should assess not only the size of pathogen populations (amount of disease), but also their quality (virulence/insensitivity gene frequencies, fitnesses of pathotypes), to provide the basis for informed disease management. Where apparently durable resistance or fungicides are used, it is important to monitor the pathogen population so that the continuing efficacy of the control measure can be evaluated. When new host plant resistances or fungicides of unknown durability become available, baseline information on corresponding variations in the pathogen population should be determined so that changes can be assessed. Virulence and sensitivity analyses are needed to determine the best genetic strategies for delaying pathogen evolution. Following implementation of the chosen strategy, monitoring of its success is needed.

## References cited

Chin K M (1985) Virulence analysis as a tool in disease management. Pages 392-401 *in* Progress in upland rice research. Proceedings of the 1985 Jakarta conference. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Chin K M (1987) A simple model of selection for fungicide resistance in plant pathogen populations. Phytopathology 77:666-669.

Chin K M, Ajmilah B N H (1982) Rice variety mixtures in disease control. Pages 241-246 *in* Proceedings of the international conference on plant protection in the tropics. Kuala Lumpur, Malaysia.

Chin K M, Bonman J M, Mew T W (1985) Alternative methods for the control of blast and sheath blight diseases of rice. Paper presented at the 25th Anniversary of the International Rice Research Institute, 1-5 Jun 1985, Los Baños, Laguna, Philippines.

Dekker J (1976) Acquired resistance to fungicides. Annu. Rev. Phytopathol. 14:405-428.

Delp C J (1980) Coping with resistance to plant disease control agents. Plant Dis. 64:652-657.

Ezuka A (1979) Breeding for and genetics of blast resistance in Japan. Pages 27-48 *in* Proceedings of the rice blast workshop. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Georgopoulos S G (1987) The development of fungicide resistance. Pages 239-251 *in* Populations of plant pathogens — their dynamics and genetics. M. S. Wolfe and C. E. Caten, eds. Blackwell, Oxford.

Johnson R (1981) Durable resistance: definition of, genetic control, and attainment in plant breeding. Phytopathology 71:567-568.

Katagiri M, Uesugi Y, Umehara Y (1980) Development of resistance to organophosphorus fungicides in the field. Pestic. Sci. 5:417-421.

Mather K (1957) The genetical structure of populations. Symp. Soc. Exp. Biol. 1:66-95.

Nelson R R (1978) Genetics of horizontal resistance to plant diseases. Annu. Rev. Phytopathol. 16:359-378.

Ou S H (1985) Rice diseases. Commonwealth Agricultural Bureaux, Kew, Surrey, England. 380 p.

Scott P R, Johnson R, Wolfe M S, Lowe H J B, Bennet F G A (1978) Host specificity in cereal mildews. Pages 27-62 *in* Plant Breeding Institute annual report 1978. Plant Breeding Institute, Cambridge, UK.

Staub T, Sozzi D (1984) Fungicide resistance: a continuing challenge. Plant Dis. 68:1026-1031.

Uesugi Y (1979) Resistance of phytopathogenic fungi to fungicides. Jpn. Pestic. Inf. 35:5-9.

Urech P A, Staub T (1985) The resistance strategy for acylalanine fungicides. Bull. OEPP 15:8.

Williams R J (1986) Prospects for integrated disease management in food crops in developing countries. Paper presented at the Annual Residential Conference on Plant Pathology in a Developing World, 16-18 Dec 1986, British Society for Plant Pathology, London.

Wolfe M S (1982) Dynamics of the pathogen population in relation to fungicide resistance. Pages 139-149 *in* Fungicide resistance in crop protection.
J. Dekker and S. G. Georgopoulos, eds. Centre for Agricultural Publishing and Documentation, Wageningen. 265 p.

Wolfe M S (1983) Genetic strategies and their value in disease control. *In* Challenging problems in plant health. T. Kommendahl and P. H. Williams. eds. American Phytopathological Society, St. Paul, Minnesota.

Wolfe M S, Schwarzbach E (1978) Patterns of race changes in powdery mildews. Annu. Rev. Phytopathol. 16:159-180.

## Notes

*Author's address:* K. M. Chin, Ciba-Geigy Agricultural Experiment Station, Locked Bag, 71309 Rembau, West Malaysia.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Using historical weather and pest data for pest zoning

S. M. Coakley

The average weather (climate) conditions in a given geographical region determine the agricultural crops that can be grown in that area. But unexpected meteorological conditions can greatly reduce yields. Unusual weather may affect the crop plant directly (e.g. flooding, frost damage, etc.) or indirectly, through its effects on crop pests (e.g. pathogens, insects, vertebrates, weeds). In either case, understanding the role of both long-term climate and current meteorological conditions is important in managing crops for optimum yields (Coakley 1988, 1989; Jeger 1987).

Information in Coakley (this volume) can help in planning the collection of meteorological data for specific purposes. Here, I describe the use of weather and pest data already collected (historical data) to better understand pest-weather interactions.

Although a favorable climate is critical in the development and survival of natural populations of many types of organisms, quantifying the effects of climatic factors to identify which factors are most important has been difficult. The computer program WINDOW has been developed to help identify the climatic factors that are important in the development of a disease. The programmers used case studies of two different foliar fungal diseases of winter wheat in two geographically distinct regions in the USA (Coakley et al 1985, 1988a). The analysis procedure (described in detail in Coakley et al 1988a,b) is examined here, using one disease as an example.

Although WINDOW has been used on only two diseases so far, it should be applicable in identifying and quantifying relationships between pests and climatic conditions using other historical databases.

## Identifying the important climatic factors

Stripe rust of wheat caused by *Puccinia striiformis* West. primarily attacks the foliage, but sometimes attacks the wheat head. It reduces both the quantity and quality of grain yield. A 19-yr disease database for multiple cultivars and sites in the U.S. Pacific Northwest is available. Analysis of the cultivar Gaines at Pullman, Washington, is presented here; similar results were obtained for other cultivars and sites.

The Disease Index (DI) on winter wheat Gaines was recorded on a 0-9 scale at the dough stage (growth stage 8). From 1968 to 1984, disease ranged from 0 to 7.5, with

**Table 1. Meteorological factors calculated for each window.**

| |
|---|
| *Standard* |
| Temperature (°C) |
| Mean max |
| Mean min |
| Mean av |
| Precipitation |
| Total (cm) |
| Frequency (d) |
| Total consecutive days with |
| Total consecutive days without |
| |
| *Variable* [a] |
| Positive degree days (7 °C base) |
| Negative degree days (7 °C base) |
| Total consecutive days with min temp <7 °C |
| Total days with av temp <0 °C |
| Total days with max temp >25 °C |

[a] These factors are set according to type of disease being studied.

a 4.5 average (corresponding to 40% of the foliage covered with rust). This average is considered moderate disease severity, resulting in 10-20% yield losses.

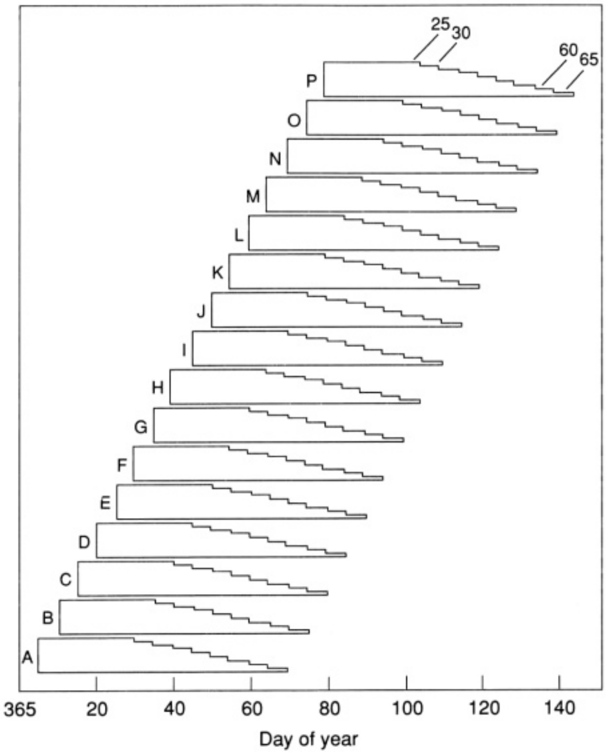
Daily maximum and minimum temperature and precipitation data are routinely collected. Each meteorological factor considered (Table 1) was averaged or summed for sequential time periods. (The number of factors that can be considered is infinite and can be set by the investigator.) The computer program is iterative; it can essentially exhaust the information available in the weather data. The analysis can begin or end as appropriate and is not tied to a calendar year.

For stripe rust, we began our analysis on day of year (DY) 210 (28 Jul) and ended on DY 205 the following year. Wheat was planted normally in early October and harvested in August.

Figure 1 shows the sequence used to summarize the data for each of the 17 yr used in developing the model. In Window A, data are summed (e.g. total precipitation) for 9 time segments, each 5 d longer than the previous segment. Each segment of Window A begins on DY 5 and ranges from 25 to 65 d long. After the factor is summed for Window A, the start advances 5 d and data arrays are built for Window B, with each time segment beginning on DY 10. This process is repeated until the entire time period has been analyzed.

For each time segment, correlation analysis is done between the DI for each year and each meteorological factor. If a factor correlation is significant, the data for all factors in that window are printed out. Printouts are examined for increases and decreases in correlation coefficients within a single window and between windows.

Table 2 gives a portion of the printout for the total precipitation (TPREC) factor in the window that began on DY 75 (16 Mar). The correlation coefficients between DI and TPREC are shown on the line labeled CORR (second to bottom). The highest correlation ($r$ = 0.71) of DI was with the 25-d-long window that began on DY 75.



**1.** Sequence of windows used to summarize data across time.

The time periods for the factors with the highest correlations with DI are further examined using 1-d differences between window lengths and increments. Figure 2 gives an example of the TPREC factor; Window A would begin on DY 71, and Window J would begin on DY 80. Each window had segments 21-29 d long, to allow identification of the particular factors that were correlated most highly with final DI. Table 3 gives a portion of the printout that shows TPREC in the window that began on DY 73 and was 23 d long. The TPREC-DI correlation coefficient was 0.75, significant at $P \leq 0.001$.

Two temperature and three precipitation factors were correlated most highly with disease on Gaines (Table 4). The factors can be identified using the following example, taken from the first entry in Table 4: MMAX 004 (21) is the mean maximum temperature factor that began on 4 Jan, was 21 d long, and had a correlation coefficient with DI of 0.71.

Of these five factors, all but DG25C accumulate early enough in the season to be used in predictive models to aid control decisions. It should be stressed that correlation between meteorological factors and DI does not imply a causal relationship, nor explain how climate may affect the biology of the organisms involved.

**Table 2. Correlation coefficients between total precipitation (TPREC) and disease severity for a Window that begins on DY 75 (16 Mar) and has subsets 65, 60, ..., 25 d long (excerpt of a printout).**

| Year | Total precipitation (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Window length (d) | | | | | | | | |
| | 65 | 60 | 55 | 50 | 45 | 40 | 35 | 30 | 25 |
| 1967 | 11.69 | · | · | · | · | · | · | · | 3.78 |
| 1968 | 3.80 | · | · | · | · | · | · | · | 3.26 |
| 1969 | 10.12 | · | · | · | · | · | · | · | 2.92 |
| 1970 | 5.10 | · | · | · | · | · | · | · | 2.31 |
| 1971 | 12.39 | · | · | · | · | · | · | · | 6.68 |
| 1972 | 9.39 | · | · | · | · | · | · | · | 3.33 |
| 1973 | 3.83 | · | · | · | · | · | · | · | 0.96 |
| 1974 | 9.68 | · | · | · | · | · | · | · | 4.34 |
| 1975 | 9.86 | · | · | · | · | · | · | · | 5.19 |
| 1976 | 10.82 | · | · | · | · | · | · | · | 4.88 |
| 1977 | 5.00 | · | · | · | · | · | · | · | 0.66 |
| 1978 | 10.89 | · | · | · | · | · | · | · | 4.39 |
| 1979 | 14.11 | · | · | · | · | · | · | · | 5.28 |
| 1980 | 9.44 | · | · | · | · | · | · | · | 2.98 |
| 1981 | 14.55 | · | · | · | · | · | · | · | 8.76 |
| 1982 | 9.34 | · | · | · | · | · | · | · | 2.65 |
| 1983 | 9.91 | · | · | · | · | · | · | · | 4.46 |
| 1984 | 11.39 | · | · | · | · | · | · | · | 6.83 |
| Mean | 9.39 | · | · | · | · | · | · | · | 4.11 |
| S.D. | 3.14 | · | · | · | · | · | · | · | 2.03 |
| Corr | 0.38 | 0.38 | 0.36 | 0.39 | 0.41 | 0.47 | 0.51 | 0.49 | 0.71 |
| P | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.05 | 0.05 | 0.01 |

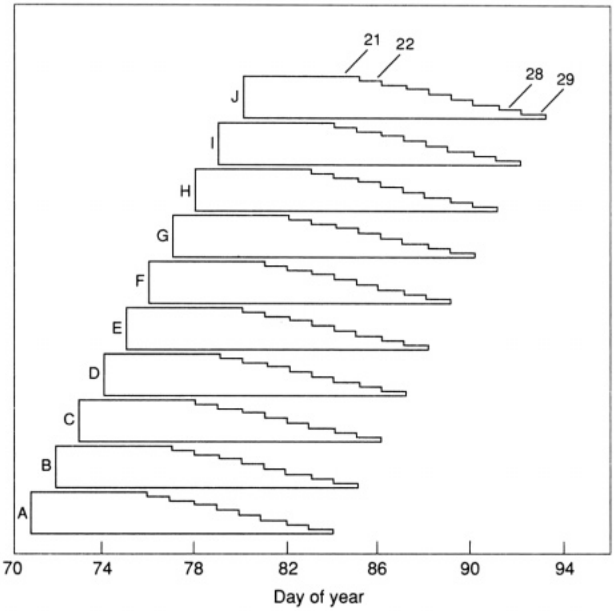
Mean = TPREC mean for 17 yr for that subset, S.D. = standard deviation, Corr = correlation coefficient, P = significance of correlation coefficient at <0.05.

## Quantifying how climatic factors affect disease

The meteorological factors that are highly correlated with disease are used in regression analysis as the independent variables, with DI the dependent variable. Other independent variables also can be included (e.g. time of planting, growth stage, etc.) We have used the Statistical Analysis System (SAS) program package (SAS Institutes, Inc. 1985), which includes a variety of regression techniques (Maximum $R^2$, stepwise, backward, forward) to evaluate all models to a maximum of three factors. Care is taken to ensure that the factors included in a single model are not correlated with each other and that similar factors do not overlap significantly in time.

### Model evaluation

The models developed are evaluated using a variety of techniques: a) minimization of standard errors of prediction; b) stability of sign in the regression coefficients; c) random distribution of studentized residuals plotted against predictions and time (patterns of residuals can be used to diagnose the type of error in the model); d)



**2.** Sequence of windows summarizing data on total precipitation across time.

examination of variance inflation factors of coefficients; and e) accuracy of predictions.

Accuracy of prediction is evaluated using a contingency table of severity classes (Fig. 3) to separate times when disease was severe (DI > 5.3, and times when disease was moderate or light (DI ≤ 5.5). In Quadrant 1, actual and predicted DI are light or moderate; in Quadrant 4, actual and predicted DI are severe. In Quadrant 2, actual disease is underpredicted and in Quadrant 3, it is overpredicted. Accuracy is calculated as

$$\%\ \text{Accuracy} = \frac{\text{Quadrant 1} + \text{Quadrant 4}}{\text{total years}}$$

Model accuracy was used to compare these models with some earlier models developed using other meteorological criteria. The models developed using WINDOW were more accurate and should be more useful in developing strategies to manage stripe rust.

## Model validation

Models are validated using a) Allen's PRESS statistic as a form of data splitting (Coakley et al 1988b); b) application of the models to new data (e.g. 1985 and 1986); c) analysis of model coefficients and predicted values; and d) examination of the biological reasonableness of the equations.

**Table 3. Correlation coefficients between total precipitation (TPREC) and disease severity for a Window that begins on DY 73 (14 Mar) and has subsets 29, 28, ..., 21 d long (excerpt of a printout).**

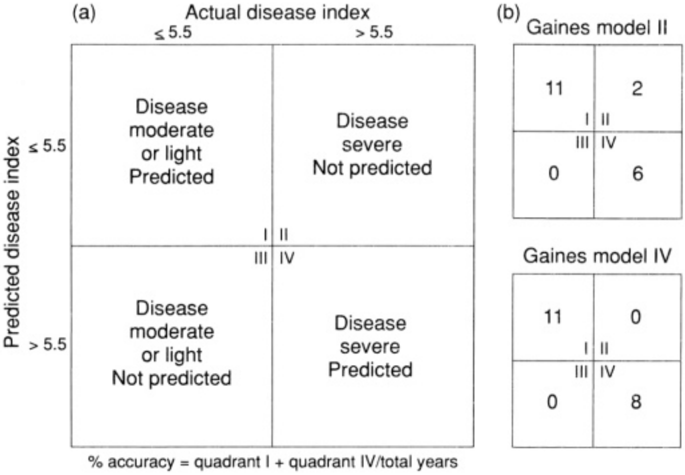
| Year | Total precipitation (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Window length (d) | | | | | | | | |
| | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 |
| 1967 | 4.07 | . | . | . | . | . | 4.03 | . | . |
| 1968 | 3.59 | . | . | . | . | . | 2.88 | . | . |
| 1969 | 4.24 | . | . | . | . | . | 2.03 | . | . |
| 1970 | 3.63 | . | . | . | . | . | 2.67 | . | . |
| 1971 | 6.92 | . | . | . | . | . | 5.12 | . | . |
| 1972 | 5.36 | . | . | . | . | . | 3.75 | . | . |
| 1973 | 0.96 | . | . | . | . | . | 0.95 | . | . |
| 1974 | 5.69 | . | . | . | . | . | 3.91 | . | . |
| 1975 | 5.19 | . | . | . | . | . | 4.58 | . | . |
| 1976 | 5.04 | . | . | . | . | . | 4.66 | . | . |
| 1977 | 0.69 | . | . | . | . | . | 0.69 | . | . |
| 1978 | 4.49 | . | . | . | . | . | 3.33 | . | . |
| 1979 | 5.61 | . | . | . | . | . | 3.93 | . | . |
| 1980 | 5.24 | . | . | . | . | . | 3.99 | . | . |
| 1981 | 8.77 | . | . | . | . | . | 7.03 | . | . |
| 1982 | 4.35 | . | . | . | . | . | 3.03 | . | . |
| 1983 | 5.59 | . | . | . | . | . | 5.31 | . | . |
| 1984 | 8.78 | . | . | . | . | . | 6.51 | . | . |
| Mean | 4.95 | . | . | . | . | . | 3.79 | . | . |
| S.D. | 2.08 | . | . | . | . | . | 1.67 | . | . |
| Corr | 0.63 | 0.68 | 0.70 | 0.71 | 0.70 | 0.73 | 0.75 | 0.75 | 0.72 |
| P | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.001 | 0.001 | 0.001 | 0.01 |

Mean = TPEC mean for 17 yr for that subset, S.D. = standard deviation, Corr = correlation coefficient, P = significance of correlation coefficient at 50.05.

**Table 4. Meteorological factors correlated with disease index on winter wheat Gaines. DY = day of year.**

| Factor | DY | Length (d) | Time period | r[a] |
|---|---|---|---|---|
| Mean max temp | MMAX 004 | (21) | [04 Jan-24 Jan] | 0.71 |
| Total days with max temp >25 °C | DG25C 113 | (66) | [23 Apr-27 Jun] | -0.88 |
| Total precipitation | TPREC 073 | (23) | [14 Mar-05 Apr] | 0.75 |
| Precipitation frequency | PFREQ 080 | (38) | [21 Mar-27 Apr] | 0.64 (a) |
| Precipitation frequency | PFREQ 095 | (59) | [05 Apr-02 Jun] | 0.70 (a) |

[a] Correlation coefficients ( *r* ) are significant at P ≤ 0.001, or ≤ 0.01 (a).



**3.** Contingency table of severity classes to separate periods of relative disease severity.

**Table 5. Equations for predicting stripe rust index (DI) on winter wheat Gaines (X-variables are defined in Table 4).**

*Predictive Model II*

DI = -1.344 + 0.182 PFREQ + 0.406 MMAX + 0.315 TPREC

Adjusted-$R^2$ = 0.76, PRESS = 24.2

Accuracy = 89%

*Late-season Model IV*

DI = 5.940 - 0.256 DG25C + 0.309 MMAX + 0.039 PFREQ

Adjusted-$R^2$ = 0.88, PRESS = 11.2

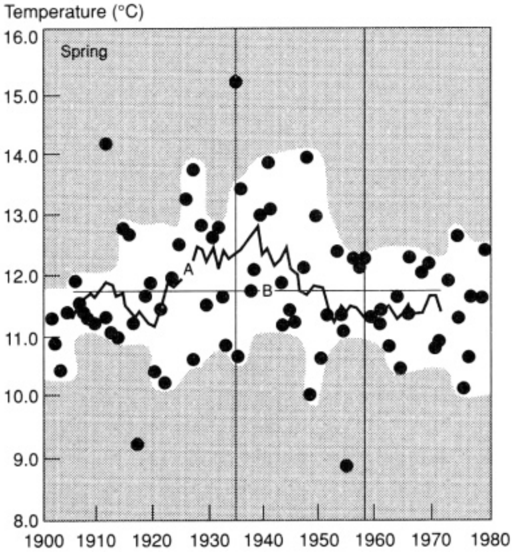
Accuracy = 100%

Table 5 lists the best predictive and late-season models for winter wheat Gaines. The late-season model could be useful in designing disease control if an accurate seasonal forecast for temperature were available.

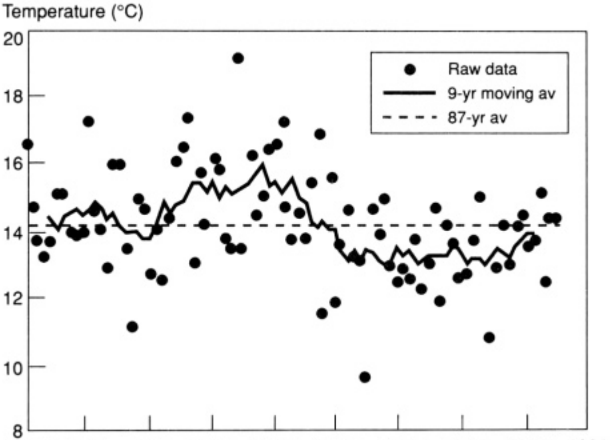
## Summary

WINDOW allows a) identification of meteorological factors that may need further study of their roles in the epidemiology of a disease; b) prediction of DI to facilitate control decisions; c) comparison of cultivar sensitivity to climatic conditions; and d) evaluation of the possibility that a disease will spread into new areas or will increase in importance under changing climatic conditions.

If the resources are not available to do such an extensive analysis of meteorological-disease interactions, as we have done using WINDOW, it is possible to gain significant insight into the possible role climate may play in the epidemiology of a



**4.** Long-term plot of spring temperatures showing trends and patterns.



**5.** Long-term temperature data showing climatic trends (av maximum temperature for spring at Spokane).

particular disease by examining some relatively simple analyses of historical data. Monthly data can be plotted directly or averaged for a season. Weather trends can be examined in those plots that coincide with disease change.

Figure 4 shows a plot of spring temperature that revealed a great deal of information about long-term trends of temperature. It confirmed the association of severe disease with below-normal spring temperatures. Figure 5 gives an additional 7 yr of temperature data. The plot suggests that average spring temperature may be increasing. If this is true, stripe rust may not continue to be so severe so frequently.

It is possible that meteorological conditions limit pest population development much more than previously thought. Consideration of climatic factors in research directed toward management of losses in rice and rice-based agroecosystem could be useful.

## References cited

Coakley S M (1988) Variation in climate and prediction of disease in plants. Annu. Rev. Phytopathol. 26:163-181.

Coakley S M (1989) Historical weather data: its use in epidemiology. Pages 54-83 *in* Plant disease epidemiology. Vol. II. K. Leonard and W. Fry, McGraw-Hill Publishing Co., New York.

Coakley S M (1990) Monitoring the physical environment for yield loss studies. Pages 87-91 *in* Crop loss assessment in rice. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Coakley S M, Line R F, McDaniel L R (1988a) Predicting stripe rust severity on winter wheat using an improved method for analyzing meteorological and rust data. Phytopathology 78:543-550.

Coakley S M, McDaniel LR, Line R F (1988b) Quantifying how climatic factors affect variation in plant disease severity: a general method using a new way to analyze meteorological data. Climatic Change 12:57-75.

Coakley S M, McDaniel L R, Shaner G (1985) Model for prediction of *Septoria tritici* blotch severity on winter wheat. Phytopathology 75:1245-1251.

Jeger M J (1987) Meteorology and plant disease. Pages 255-276 *in* International conference on agrometeorology. F. Produ, F. Rossi, and G. Cristoferi, eds. Fondazione Cesena Agriculture Publications, Cesena, Italy.

SAS Institutes, Inc. (1985) SAS user's guide: statistics version 5. Cary, North Carolina.

## Notes

*Author's address;* S. M. Coakley, Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon 97331, USA.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Requirements for an economic interpretation of crop losses

H. Waibel

Detailed information about crop losses is the basis for any valid economic analysis of pest management measures. Because pest control inputs do not increase yields but rather reduce crop losses, information on two relationships, control measure - pest and pest - yield, is indispensable in decisionmaking in pest management. More and more, this fact is being recognized, as is shown in the increasing number of activities and publications. Crop loss information is likely to improve decisions in the following three areas (Carlson 1980):

- Farm management decisionmaking using short-term pest information.
- Pesticide regulatory decisions using crop loss information.
- Research funding using information on relative crop losses.

The discussion here concentrates on short-term pest information for farm management decisionmaking because this is where information derived from crop loss assessment is most needed.

Although many crop loss studies have been carried out, results are not always useful in farm management decisionmaking because the main focus had been to provide information for research funding. Also, farm management decisionmaking requires pest-specific information (i.e. damage coefficients showing the relationship between pest populations and expected yield loss).

## Sources of crop loss information

In rice farming in Asia, crop loss assessment studies that provide quantitative information have been carried out only over the last few years. Cramer's global crop loss estimates are probably the most widely used source (Cramer 1967).

Many reports of studies on pest control start with the phrase “It is known that crop losses worldwide amount to X%” (with a variety of figures given), and cite Cramer's work. Although those figures can be regarded as historical (Reed 1986), the question is whether the crop loss assessment data being collected in the less developed countries now are useful in updating Cramer's estimates. Because of the ultimate importance of crop loss information in the economic analysis of pest management, it is useful to review the available sources of information.

## The farmer

Simply to ask a farmer what he thinks the magnitude of crop loss due to a pest in his crop is likely to be cannot be expected to elicit a precise response. It is difficult for a farmer to single out one factor, such as loss due to insects, from the many factors that may cause a low yield. It is equally difficult to estimate the impact of a not-yet-applied pesticide. Data accumulated in this manner must be treated with care.

Studies indicate that farmers' perceptions of crop losses, even in industrialized countries, have a historical component. Farmers tend to base their loss estimates on those caused by severe outbreaks experienced in the past. In less developed countries, where farmers are less well informed, perceptions are likely to be much more problem than option oriented (Mumford and Norton 1984). For example, by comparing perceptions of pest problems of farmers in Thailand with actual yields of rice, yields did not differ between fields of farmers who reported pest problems and those who did not (Stone 1983). A study now underway in Thailand is investigating farmers' decisionmaking in controlling rice pests (H. Tuettinghoff, 1986, pers. comm.). Preliminary results indicate that farmers estimate the yield loss from missing an insecticide application as about 1/3 higher than that from not applying fertilizer. In a survey of farmers in the Philippines and in Thailand, the vast majority of respondents expected losses to pests of more than 35% in the Philippines and more than 50% in Thailand (Table 1). These data clearly underline the dimension of the problem: pest losses are perceived to be at intolerable levels.

These figures also explain why pesticides, especially insecticides, are regarded as indispensable for rice production. Simply weighing the value of the expected loss (which can be avoided by applying appropriate control measures) against the actual expenditure for pest control (which will rarely exceed 10% of the variable cost of production) yields a rate of return not reached by most of the technology components in rice.

It should be mentioned that farmers made their loss estimates in the absence of any recent severe pest outbreak. One might have expected them to provide more relaxed estimates. On the other hand, little is being done to encourage farmers looking at pests more rationally, to tell them that pest A at level X is not dangerous. Consequently, most farmers' perceptions lead to overestimations of yield losses.

**Table 1. Rice farmers' loss estimates in Thailand and the Philippines.**

| Loss estimate (%) | Philippines | Thailand |
|---|---|---|
| <25 | 36.7 | 15.5 |
| 25-50 | 38.6 | 19.9 |
| >50 | 22.7 | 64.7 |
| $\overline{x}$ | 36.08 | 57.9 |

Source: Surveys conducted by H. Waibel in 1980 (Philippines) and 1986 (Thailand).

## Policymakers and administrators

Policymakers and administrators who decide upon government interventions with regard to pest control are another interesting source of crop loss information. This group cannot be ignored because of the implications of perceptions. Although not quantifiable, their perceptions of crop losses tend to be even higher overestimations than those of farmers, because their control costs are zero, as long as they stay within budget limits (Kenmore et al 1985). It is difficult to convince these persons to adopt objective standards for an economic evaluation of the impact of government-induced actions on yield and profit. On the other hand, it is astonishing that up to now, no formal study has been made of the many pesticide subsidy programs in less developed countries (Repetto 1985), even though free distribution of pesticides or pesticide subsidies are often supported by donor countries.

The rationale of a government‘s plant protection services is, to a major degree, to continue to play the role of “fire brigade,” to prevent pest outbreaks which they associate with severe crop losses. Yet, there is no statistically or economically valid definition of outbreak. “Crop loss” usually is replaced by the term “area infested by pests.” Considerable budgetary resources are spent to collect, compile, and analyze data on pest infestations; the validity of those data is highly questionable.

## Controlled experiments

Various types of experiments may provide crop loss information, although many are not designed for the particular purpose of crop loss assessment.

First, there are pesticide evaluation trials conducted primarily at experiment stations, often on behalf of the chemical industry. In a 12-yr span in the Philippines, relative differences between no treatment and the treatment pesticide that resulted in the highest yield averaged 33-40%, depending on the season (Waibel 1986).

Next, there are the “yield constraint” trials IRRI carries out as on-farm trials to determine by how much farmers’ yields can be increased when more insecticides are used. Results over 7 yr show that an additional 0.5 t/ha in the wet season and 0.8 t/ha in the dry season are obtained with higher levels of insect control (Herdt et al 1984). In relative terms, yield loss would be in the order of 10-20% (based on a yield level of 4-5 t/ha). However, the yield loss calculated is not comparable to farmers’ estimates of losses because they represent a kind of residual loss.

Since 1978, IRRI has been conducting insect control experiments in different provinces in the Philippines. These trials were set up in connection with a new procedure for developing recommendations (Litsinger et al 1980). Yield loss was defined as the relative difference between the yield obtained under maximum protection and no treatment. For 1978-80, average loss was computed at 8.6%. Similar trials, conducted by Waibel in cooperation with Regional Crop Protection Centers, showed almost the same result, an average 8.9% loss. Although these experiments are not necessarily comparable because of the different varieties used and location in which they were conducted, two observations can be mentioned:

- The relatively high proportion of trials with nonsignificant yield differences.
- A somewhat decreasing trend as one moves from experiment station to farmers’ field trials.

We can conclude that the crop loss estimates given by Cramer (1967) can be updated, at least for rice in tropical Asia. Such revised loss data can be the basis for further economic calculations. What is needed in addition is an adequate framework for crop loss assessment that will facilitate economic interpretations for farm management decision making.

## Economic aspects of crop loss assessment

### Current definitions of loss

Various definitions of crop loss can be found in the literature, often with large differences. To government agencies, crop loss is what would be lost if no control programs were carried out. For the farmer, crop loss might be what is lost despite his control efforts (i.e. the difference between actual and expected yields).

A useful concept of yield levels and derived losses was presented by Zadoks and Schein (1979). They defined various levels of yield and classified crop loss according to the differences between yield levels. For example, the highest possible yield, called primitive yield, was defined as the yield without any control measures. The technically maximum yield under experimental conditions and the actual yield reached under a farmer's conditions, was defined as attainable yield. This was designated the “FAO definition of crop loss.”

Clearly, this definition of crop loss does not have an economical base. It ignores the costs of existing control techniques. The scheme of Zadoks and Schein (1979) can be used, in a modified way, to further explore the consequences of ignoring economic aspects in the definition of crop loss. Yield levels can be presented in a matrix that shows the possible interactions between levels (Table 3). That results in different definitions of loss.

The bottom row indicates the yield levels relevant to the different parties concerned with crop loss assessment — researcher, extension worker, and farmer. This

**Table 2. Yield levels and yield losses (modified from Zadoks and Schein 1979).** [a]

| Kind of yield | Theoretical | Attainable | Economic | Actual | Primitive |
|---|---|---|---|---|---|
| Theoretical | * | - | - | - | - |
| Attainable | Unavoidable loss | * | -<br>* | -<br>- | -<br>- |
| Economic | - | (Residual loss)[a] | * | - | - |
| Actual | Theoretical loss | Crop loss "FAO" | * | Economic loss | - |
| Primitive | - | Avoidable loss | (Potential economic loss)[a] | - | - |
| Whose yield | Laboratory researcher's | Field researcher's | Extension worker's | Farmer's | Untreated control |

[a] Terms in parentheses are farmer interpretations.

illustrates that the crop loss assessment of a researcher will not necessarily provide an answer to a farmer's pest control decision problems.

In doing a short-term economic analysis, only some yield levels are of interest. For example, we do not care about theoretical yield—it is beyond reach in farmers' fields. We also do not care about attainable yield—the farmer would lose money if he tried to achieve this level. What is relevant is economic yield, the yield obtained under what is believed to be the most profitable control strategy.

This would be the extension worker's target; the farmer's yield is the "control plot." Loss assessment as a basis for economic decisionmaking is concerned with the economic loss, the difference between the economic yield and the farmer's yield.

## Economic definition of crop loss

Loss always refers to the difference between the outcome of an action taken and the outcome if the action had not been taken. Given the variation of pests over time, an outcome will depend on the pest situation. Crop loss in economic terms can be one of the following:

- The value of yield lost due to insufficient control measures.
- No significant difference in yield was achieved with the control carried out — the money invested in control measures was lost.

These two aspects of loss in pest management decisionmaking were first formulated within the economic threshold concept (Stem et al 1959). Crop loss assessment studies were seldom based on these principles. This contributes in part to the overestimations of loss by the various parties interested in loss assessment. This in turn leads to the uneconomical application of loss prevention measures and results in suboptimal use of resources (Headley 1982). For example, if the level of such inputs as fertilizer is based on attainable yield, the level of pest control and other inputs used could be beyond the economic optimum.

Carrying out an economic analysis on the basis of available crop loss data requires that a large number of assumptions be made. The most important are the costs and the effectiveness of alternative control measures. This illustrates the need to develop an economically based scheme of crop loss assessment (Waibel and Engelhardt 1988).

The primary factor distinguishing conventional crop loss assessment from the scheme proposed is that loss would be based on net returns rather than on yield. Since we defined loss in general terms as the difference between the outcomes of two possible actions (i.e. spray and nospray), under a given situation (pest or no pest) the scheme proposed uses the concept of a payoff matrix.

In pest management, a payoff matrix would list possible actions associated with various states of nature (i.e. various levels of pest attack). In its simplest form, 'spray' or 'no spray' action can be associated with two pest levels, 'below' and 'above' economic threshold. The cells of the matrix contain the net returns (payoffs) for an action taken in a given situation. Table 3 shows an example based on results of on-farm trials in Central Thailand.

Various parameters relevant to crop loss assessment can be derived from the matrix. First, what might be called the potential loss can be defined as the difference

**Table 3. Payoff matrix, with results from on-farm trial in Thailand (Waibel and Engelhardt 1988).**[a]

| Event (E) | Probability (E)[b] | Action | |
|---|---|---|---|
| | | Control (a1) | No control (a2) |
| Threshold reached (z1) | 0.5 | (a1 z1)<br>448.0 | (a2 z1)<br>439.5 |
| Threshold not reached (z2) | 0.5 | (a1 z2)<br>471.5 | (a2 z2)<br>476.6 |

[a] Payoff values in \$/ha. [b] Hypothetical values.

between the economically most favorable situation (a2 z1), no pest and no control measure, and the least favorable situation (a2 z2), pest and no control. The potential loss will describe the economic dimension of the pest problem. Based on empirical data, this turned out to be 7.8%, which is lower than the levels using current definitions of loss.

The difference in net return between pest and no pest conditions, with control, can be defined as the residual loss. The maximum possible improvement with optimal control was less than 5%. Of course, this is a theoretical value which assumes 100% effectiveness of control at zero cost. This definition, however, is close to the FAO crop loss definition.

The success of an existing control measure is defined as the quotient of residual loss and potential loss. It can be used to measure the efficiency of existing control strategies. In this case, it was calculated at 37%, which indicates that existing control measures do not perform satisfactorily.

Finally, economic loss is calculated as the difference between net returns for treated and untreated fields, weighted with the probabilities of a pest or no pest situation. If we assume the probability of 'pest' and 'no pest' to be equal ($p = 0.5$), the economic loss to a farmer who routinely uses pesticides would be \$2.25/ha. This loss is equivalent to 0.55% when based on the maximum net returns. It becomes obvious that economic loss depends on the pest situation and the control method being used. If the farmer practice is calendar-based pesticide application and the probability of pest occurrence is low, the economic loss will be high.

This shows that the value of crop loss assessment is in predicting loss rather than in proving that losses are intolerable. Crop loss assessment studies for this purpose need to be done on the farm level. On-farm trials for this purpose need only three treatments:

- farmer’s control practice.
- presently recommended practice.
- no control (i.e. natural control).

If pest data are recorded and yield measurements as well as input prices are taken, the economic loss can be identified and damage coefficients derived. It then will be possible to express pests in units of economic loss rather than in units of populations.

Such loss assessment activities should be carried out as an ongoing activity of the plant protection organization of the government.

## Summary

Crop loss assessment in rice has reached a stage which allows us to update initial estimates based on Cramer (1967). However, their usefulness in economic interpretations is limited, because crop loss assessment seldom deals with economic loss but tends to place more emphasis on researcher's loss. This means that losses turn out to be high. That risks indirect and unintentional promotion of noneconomic use of pesticides.

From an economic point of view, it is of secondary concern whether losses are high or low. It is more important to predict losses with a reasonable degree of accuracy, to allow the appropriate economic decision to be made. For example, if in a given year, loss is predicted to be low (i.e. below threshold), resources which would have gone into control measures can be diverted to more productive use. The net gain with the alternative use of resources is the value of crop loss information. To achieve this, crop loss assessment studies need to be carried out under real farm conditions. This activity should become the prime task of the national plant protection service. If resources used for large-scale pest control were shifted to farm-level assessment, the contribution of crop loss assessment to on-farm decisionmaking in pest management would increase significantly. The type of studies initiated by Litsinger et al (1980) can be used as a framework, but need to be adjusted to enable a plant protection service to design a permanent program.

## References cited

Carlson G A (1980) Economic aspects of crop loss information. Crop loss assessment. Proceedings of E. C. Stakman Commemorative Symposium. University of Minnesota, Minneapolis, Minnesota.

Cramer H H (1967) Pflanzenschutz and Weltemte. Pflanzenschutz Nech. Bayer 20:1-523.

Headley J C (1982) The economics of pest management. *In* Introduction to insect pest management. R. S. Metcalf and W. H. Luckmann, eds. John Wiley and Sons, New York.

Herdt R W, Castillo L L, Jayasuriya S (1984) The economics of insect control in rice in the Philippines. Pages 41-56 *in* Judicious and efficient use of insecticides. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Kenmore P E, Heong K L, Putter C A J (1985) Political, social and perceptual aspects of integrated pest management programs. Pages 47-66 *in* Integrated pest management in Malaysia. B. S. Lee, W. H. Loke, and K. L. Heong, eds. MAPPS, Malaysia.

Litsinger J A, Lumaban M D, Bandong J P, Pantua P C, Barrion AT, Apostol R F, Ruhendi (1980) A methodology for determining insect control recommendations. IRRI Res. Pap. Ser. 46.

Mumford J D, Norton G A (1984) Decision making in pest management. Annu. Rev. Entomol. 29:157-174.

Reed W (1986) Crop losses caused by insect pests in the developing world. Proceedings of the British crop protection conference. British Crop Protection Council, Brighton, England.

Repetto R (1985) Paying the price: pesticide subsidies in developing countries. World Resources Institute, Washington, D.C.

Stem V M, Smith R F, Van den Bosch R, Hagen K S (1959) The integrated control concept. Hilgardia 29:81-101.

Stone F D (1983) Agricultural changes as an adaptive process: adoption of modem methods and responses to pest outbreaks by rice farmers in Chachoengsao Province, Central Thailand. Ph D thesis, University of Hawaii, Honolulu. 474 p.

Waibel H (1986) The economics of integrated pest control in irrigated rice. Crop protection monographs. Springer-Verlag, Berlin.

Waibel H, Engelhardt T (1988) Criteria for the economic evaluation of alternative pest management strategies in developing countries. FAO Plant Prot. Bull. 36(1):27-33.

Zadoks J C, Schein R D (1979) Epidemiology and disease management. Oxford University Press, New York.

## Notes

*Author's address:* H. Waibel, Asian Institute of Technology, Bangkok. Thailand.

*Citation information:* International Rice Research Institute (1990) Crop loss assessment in rice. P.O. Box 933, Manila, Philippines.

# Recommendations

These recommendations were made after approximately 7 h of discussion held over several days by members of the five working groups of the workshop. In addition, the national program leaders of the Food and Agriculture Organization (FAO) Intercountry Program on Integrated Pest Control (IPC) met to discuss issues of mutual concern. Recommendations from all six groups were adopted during the Plenary Session of the workshop. Although there was some disagreement over specifics, participants agreed on the broad outline.

Participants represented researchers, extension workers, crop protection technical specialists in national programs, and scientists from private industry. Participants agreed to consider the term *PEST* as all-encompassing, to include insects. diseases (pathogens), weeds, and vertebrates.

## Working group on pest assessment and sampling

Most policymakers rely on research and extension for data, and pest assessment information should be presented in a form appropriate for their use. The needs of different users of pest assessment and sampling methodology will differ, and the accuracy and precision they need also will differ. However, for IPC implementation, the immediate need is to focus on the training of extension staff and farmers to recognize pests and natural enemies, rather, than to develop precise counting and complicated sampling techniques.

Tables 1 and 2 summarize various methods used by research and extension.

### Recommendation 1

*That efforts be made to develop standardized methods and formats for collecting data on the following parameters: size and composition of pest and natural enemies populations, incidence and severity, host growth and development, climate, and yield.*

Sample number, size, and location can be critical and guides such as FIELDRUNNER: A disease incidence, severity and spatial pattern assessment system (B. R. Delp, L. J. Stowell, and J. J. Marois [1986] Plant Disease 70:954-957) should be used in situations where they may be helpful.

**Table 1. Pest assessment and sampling for research.**

| Methodology | Parameters available/ required | Comments |
|---|---|---|
| Pest/natural enemies population<br>- size/ratio<br>- composition | Densities (absolute, relative) | Every method has inherent limitations.<br>Standardization and validation of proven methods will be helpful. |
| | Natural enemies/pest ratios | |
| | Pest virulence | Pest population size may be corrected for natural enemies and competitive organism incidence.<br>There is a need to determine virulence in addition to numbers. |
| Incidence/severity | Damage expressed as % of plants or plant area attacked | The need is for more objective instrumentation to assess severity. Remote sensing should be considered when available. |
| | Use of keys and scales | |
| Host growth | Plant growth keys | Satisfactory system widely adopted. |
| Climate | Meteorological | Use standardized, simple instrument stations that are maintained and calibrated, located in an area appropriate to trial sites. |
| Yield<br>- quality<br>- quantity | | Sampling techniques are available from IRRI. |

## Recommendation 2

*That efforts be made to, develop common or standard methods and formats for managing the data collected in pest assessment and sampling activities (see recommendations by the Working Group on Databases)*

The types of data management needed by researchers and extension workers will differ (Tables 1 and 2). Methodologies should account for the difference but also should establish common ground between the two user groups.

## Recommendation 3

*That programs to encourage exchange of data collected by various groups be developed within the South and Southeast Asia region.*

**Table 2. Pest assessment and sampling for extension.**

| Methods | Parameters available/required | Comments |
|---|---|---|
| Pest/natural enemies populations<br>- size<br>- composition | | Methods should be standardized and simplified to produce consistent and verifiable results. |
| Incidence/severity | Quantitative scales and keys | The IRRI Standard Evaluation System (SES) should be improved or modified to relate it to yield losses.<br>SES growth stages of hosts are generally adequate. |
| Climate | Meteorological stations | There is a need for more precise forecasting information. |
| Cultivar | | A key to identify cultivars commonly grown is needed. |
| Yield | Crop cutting from farmers' fields | It is usually Inaccurate. |

Data exchange could be facilitated by creating user groups or by developing computer software that national programs can share. International organizations, such as the FAO and IRRI, are urged to investigate existing national database management systems and examine the feasibility of implementing this recommendation.

## Working group on thresholds and intensity/loss relationships

Before economic thresholds can become widely adopted, damage functions for major pests of rice need to be developed and validated. Pest thresholds are variable and affected by environment, cropping season, crop growth stage sensitivity, multiple pests and natural enemies, cultivar, government policy, and risk perceptions of farmers. A network among national programs is needed to facilitate the exchange of information, methodology, and ideas for establishing and implementing thresholds and intensity/loss relationships for all pests in South and Southeast Asia on the lines of the FAO *Crop loss manual* and this workshop.

### Recommendation 1

*That the current state of development and use of pest thresholds and damage functions for pests in rice-based farming systems in South and Southeast Asia be determined, using such resources as the International Rice Research Newsletter, summaries of workshops, surveys of research and national program staff, and personal contacts.*

Existing damage functions and/or economic thresholds of pests of rice should be documented and, where possible, characteristics of the production systems described. This information should be compiled and disseminated as rapidly as possible.

**Recommendation 2**

*That standard protocols for conducting pest intensity/yield loss experiments to determine damage functions of rice pests be established through joint efforts of research centers and national Departments or Ministries of Agriculture.*

National program staff should be involved in efforts to devise standardized methodologies.

**Recommendation 3**

*That methods of calculating economic thresholds be as easy to implement as possible.*

Economic thresholds based on damage functions should be calculated and correlated decision aids (such as incidence/ severity relationships) developed. Farmer education programs, including development of local language materials, should accompany the decision aids.

## Working group on aids to farm-level decision making

**Preamble**

Decision aids should be developed to increase the self-reliance in making appropriate pest management decisions by farmers, extension workers, crop protection specialists, and trainers. The most important channel to achieve this is education and training. The decision aids should recognize farmers' ability to make decisions and their needs. They should be simple, concrete, and precise; in guideline form; qualitative rather than quantitative; positive; and provide feedback.

Group members feel strongly that the skills to be developed are recognition of key pest damage disorders and natural enemies, field checking, decision making, safe handling of pesticides, and cultural control practices.

**Recommendation**

*That decision aids should he developed for specific, activities, taking into account the relationships shown in Table 3.*

## Working group on pest/crop loss databases

This working group strongly endorses the recommendations of the Southeast Asian Pesticide Management and IPM Workshop at Pattaya, Thailand, 23-27 Feb 1987, urging that an information system on crop pests (insects, diseases, weeds, and other organisms) be developed, as an aid to regional planning and for other purposes.

Such a system of linkages among national databases would be of great benefit in the following areas of activity (although it is appreciated that the value to a country will vary with its size, climate, and communication facilities):

**Table 3. Decision aids in relation to implementation activities.**

| ACTIVITIES<br>Pest zoning | Sampling technique | Pest/natural enemy interaction | Pest combination | Pest-weather interaction | Village ranking of pests by approximate losses | DECISION AIDS | |
|---|---|---|---|---|---|---|---|
| X | X | X | | | X | Pests | SPECIMEN |
| X | X | X | | | | Natural enemies | |
| X | | X | X | | X | Pests | PICTORIAL GUIDES |
| X | | X | | | X | Natural enemies | |
| X | | X | | | X | Diagnostic key | |
| X | X | | | X | X | Records of outbreaks and incidences | |
| | X | | | | X | Individual field boards | |
| | X | | X | | X | Signal flags | |
| X | X | X | X | X | | Community pest board | |
| X | X | | X | | X | Pest maps | |
| | | X | X | X | X | Results | DEMONSTRATION |
| | x | x | | x | x | Methods | |
| x | x | x | x | x | x | Tours | |
| x | x | x | x | | x | Public quiz | |
| x | x | x | x | | x | Drama, songs, trailers, comic books | |
| x | x | x | x | | x | Flip charts | |
| x | | x | x | | x | Posters | |
| x | x | x | x | | | Tools, pegboard, nets, traps | |
| x | | ? | | | x | Pesticide wheels guide | |
| | | ? | | | | Measuring cup | |

- To identify the distribution and changes in the status of and the importance of pests on crops in the region. This information is often demanded by administrators to guide resource allocation, but is often difficult to obtain from neighboring countries.
- In IPC programs, to provide information on infestations in farmers' fields, yields, and pesticide use and effectiveness.
- To provide current information on policy decisions and planning on food and other crops.
- To inventory pesticides logistics to improve supply in relation to outbreaks of pests.
- To research modeling and to forecast pests outbreaks.
- To evaluate crop germplasm in relation to pests in different areas.
- To provide information to improve quarantine in a region.

Collection of meteorological data and information on pesticides associated with pests and crop data would be valuable to many users, as would be associated crop yield reduction information (when reliable assessment methods become available).

### Recommendation 1

*That an external resource group be organized to assist national programs in improving their databases.*

One or more resource persons could assume responsibility for the following tasks:

- To evaluate the content and reliability of existing national databases and other sources of information and to determine the need for a regional pest/crop loss database.
- To assess national and regional requirements for computer hardware and software.
- To coordinate development, data collection, and utilization of personnel in a regional effort to improve the exchange of pest and loss information.
- To coordinate the frequency of observations and the means of data transmission.
- To determine the training needed to develop computer-based pest/crop loss databases.
- To assess the funding needed to develop pest/crop loss databases.

### Recommendation 2

*That standardized information (with objectives, methods of analysis, and format of output) as far as practicable be the aim throughout the region, to avoid difficulties in incompatibility when the information is used for comparisons.*

The information collected should follow the recommendations of the Working Group on Pest Assessment and Sampling and should include the following, with its location and an estimate of its reliability (it is realized that the collection of some of these data may be impossible or impractical at the present time):

- Pest and natural enemy status (the criteria depend on the species). Ideally, this information should come from fields not treated with pesticides.
- Crop information — growth stage, cultivar, cropping season, area on which grown, yield, production, and yield reduction associated with pests. Data on crop rice would also be valuable.
- Meteorological data associated with pests, natural enemies, and crops not already collected by National Departments. The parameters needed are discussed by the Working Group on Pest Assessment and Sampling (Table 1, 2).
- The type and amount of pesticides used, with costs when available.
- Farming type, farmers' status, farm size, income range, and other appropriate socioeconomic information.

It is not expected that a database can immediately be compiled for all pests, crops, and countries. Exploration on limited key organisms in a few countries would be advisable.

## Working group on economics and utilization of pest/loss data

Group members agreed that methods of rice pest assessment are inadequate and not standardized for economically based decisionmaking in the region. They expressed concern that the data collected for establishing policy in plant protection may be unreliable. Attention needs to be increased on farm-level socioeconomic factors that influence farmer decisionmaking.

**Recommendation 1**

*That national workshops be convened to achieve the following objectives: to present country procedures, to identify success cases, to establish guidelines for practical pest assessment in rice, to identify procedures for overcoming constraints in the implementation of guidelines, and to establish working teams to sustain data collection in support of decisionmaking.*

Organizations such as the German Agency for Technical Cooperation, IRRI, Consortium for International Crop Protection, and Food and Agriculture Organization are urged to facilitate the arrangement of donor support for such workshops.

**Recommendation 2**

*That a training program on the economics of pest management be established for plant protection specialists in national programs.*

The outputs expected from such a training program would include increased use of socioeconomic tools in pest management decisionmaking, establishment of a network of pest management economists in the region, country studies of the impact of national pest and pesticide policies on the economic feasibility of IPC at farmers' level, country-specific training on the economics of pest management for plant protection specialists, and determination of country-specific economic parameters that would provide support for policy decisionmaking.

# Participants

## Australia

John Martin

Australian International Development
Assistance Bureau
Canberra

Douglas Waterhouse

Australian International Development
Assistance Bureau
Canberra

## Bangladesh

M. A. Taher Mia

Department of Plant Pathology
Bangladesh Rice Research Institute
G.P.O. Box 64
Ramna, Dhaka

## Burma

Maung Maung Lay

Plantation Crops Division
Agriculture Corporation
Rangoon

Moe Hein

Research Division
Agriculture Corporation
Rangoon

## Germany

Volkmar Hasse

Deutsche Gesellschaft fur Technische
Zusammenarbeit

## India

M. C. Diwakar

Directorate of Plant Protection, Quarantine
and Storage
N.H. IV, Faridabad
New Delhi

A. D. Pawar

Directorate of Plant Protection, Quarantine
and Storage
N.H. IV. Faridabad
New Delhi

V. Ragunathan

Directorate of Plant Protection, Quarantine
and Storage
N.H. IV. Faridabad
New Delhi

R. L. Rajak

Directorate of Plant Protection, Quarantine
and Storage
N.H. IV. Faridabad
New Delhi

Harikesh B. Singh

North-Eastern Hill
University of Medziphema

R. S. Singh
Department of Plant Pathology
Ludhiana

R. S. Upadhyay

Department of Botany
Banaras Hindu University

## Indonesia

Djafar Baco
Maros Research Institute for Food Crops

Mas Haeruddin Taslim
Food Crop Protection
Direktorat Perlindungan Tanaman Panpan
Jalan Ragunan, Pasar Minggu
Jakarta Selatan

Wolfgang Linser
c/o Departemen Keuangan R.I.,
Gedung Utama, Lantai 5 km 502,
Jln. Lapangan Banteng Timur no. 4
Jakarta Pusat

Yadi Rusyadi
Directorat Perlindungan Tanaman Pangan
Jalan Ragunan, Pasar Minggu
Jakarta Selatan

Sunoto
Directorat Perlindungan Tanaman Pangan
Jalan Ragunan, Pasar Minggu
Jakarta Selatan

V. L. Tjandrakirana
Directorat Perlindungan Tanaman Pangan
Jalan Ragunan, Pasar Minggu
Jakarta Selatan

Pius Sunarjo
UNHAS

## Italy

C. A. J. Putter
Plant Protection Service
FAO, AGPP
Via delle Terme di Caracalla
00100 Rome

## Malaysia

Supaad bin Mohd Amin
Rice Research Division
Malaysian Agricultural Research and
Development Institute
P.O. Box 12301, G.P.O.
50774 Kuala Lumpur

Asna Booty-Othman
Department of Agriculture -
Crop Protection Branch
Cawangan Perlindungan Tanaman
Jabatan Pertanian
Jalan Gallagher
Kuala Lumpur

K. M. Chin
Disease Control Group
CIBA-GEIGY Agricultural
Experiment Station
Locked Bag 71309 Rembau
Negeri Sembilan

Abdul Halim Nik
Department of Agriculture -
Plant Protection Branch
Cawangan Perlindungan Tanaman
Jabatan Pertanian
Jalan Gallagher
Kuala Lumpur

K. L. Heong
Malaysian Agricultural Research and
Development Institute
P.O. Box 12301
Kuala Lumpur 50774

Lim Guan Soon
Central Research Laboratories Division
Malaysian Agricultural Research and
Development Institute
P.O. Box 12301
G.P.O. Kuala Lumpur
50714 Selangor

## Netherlands

J. C. Zadoks

Laboratory of Phytopathology
Wageningen Agricultural University
Binnenhave 9/6709 PD
Wageningen

## New Zealand

Roy E. Gaunt

Department of Agricultural Microbiology
Lincoln College
Canterbury

## Philippines

Mary Jean Calipayon

Agricultural Promotion Center
Bohol

Damaso P. Callo, Jr.

Integrated Pest Management (IPM) Program
Department of Agriculture
Diliman, Quezon City

Ester R. Carpio

Philippine Council for Agriculture,
Forestry, and Natural Resources
Research Development
Los Baños, Laguna

Norberto O. Chingcuanco

Distributed Processing Systems, Inc.
3rd Floor, Casmer Building
Salcedo Street, Legaspi Village
Makati, Metro Manila

Cristeta A. Cueto

University of the Philippines at Los Baños
Los Baños, Laguna

Lolita Dolores

Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

Rodrigo L. Embajador

RSO, Region XII
Department of Agriculture

Nelson J. Esteban

Philippine-German Biological Plant
Protection Project, Crop Protection
Division,
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Marcelino M. Guevarra

Sugar Regulatory Administration
Pampanga

Maria Luz C. Josue

Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

George S. Karganilla

Philippine-German Biological Plant
Protection Project, Crop Protection
Division,
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Peter E. Kenmore

FAO Inter-Country Programme for
Integrated Pest Control in Rice
P.O. Box 1864
Manila

Merdelyn C. Lit

Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

Orlando J. Lorenzana

RCPC, Region II
Department of Agriculture

Edwin D. Magallona

University of the Philippines at Los Baños
Los Baños, Laguna

Herondino T. Mandao
Philippine-German Biological Plant Protection Project, Crop Protection Division,
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Fe L. Mangaban
Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

Jose R. Medina
University of the Philippines at Los Baños
Los Baños, Laguna

Jorge D. Melchor
RCPC, Region X
Department of Agriculture

Marissa Nate
University of the Philippines at Los Baños
Los Baños, Laguna

Peter Ooi
(CIBC)
FAO-IPC, Manila

Oscar S. Opina
Department of Plant Pathology
University of the Philippines at Los Baños
Los Baños, Laguna

Ester P. Pacumbaba
Philippine Coconut Authority
Albay Research Center
Guinobatan, Albay

Cecilia Pascual
Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

Cornelio A. Peralta
FAO/IPM
Department of Agriculture
Manila

Edmundo S. Quinit
Philippine-German Biological Plant Protection Project, Crop Protection Division,
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Avelino D. Raymundo
Department of Plant Pathology
University of the Philippines at Los Baños
Los Baños, Laguna

Manuel B. Rondon
RCPC, Maligaya Rice Research Training Center
Department of Agriculture
Ilagan, Isabela

Teodoro N. Ruiz
RCPC, Region VIII
Department of Agriculture

Napoleon T. Saavedra
National Crop Protection Center
University of the Philippines at Los Baños
Los Baños, Laguna

Fernando F. Sanchez
National Crop Protection Center
University of the Philippines at Los Baños
Los Baños, Laguna

Nemesia C. San Juan
Philippine Coconut Authority
Davao Research Center
Davao

Solita R. Sicat
Philippine-German Biological Plant Protection Project, Crop Protection Division,
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Jesus P. Sumangil
Crop Protection Division
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Evangeline C. dela Trinidad
Region V
Bureau of Plant Industry
Department of Agriculture
692 San Andres Street, Malate, Manila

Tatsui Tsuboi
Bohol Agricultural Promotion Center
Bohol

Leopoldo C. Valdez
Institute of Plant Breeding
University of the Philippines at Los Baños
Los Baños, Laguna

Siew-Fing Wong
International Staff Housing #26
International Rice Research Institute
Los Baños, Laguna

## Sri Lanka

P. O. S. Abeywardena
Department of Agriculture
P.O. Box 18
Peradeniya

W. N. S. Bowatte
Department of Agriculture
P.O. Box 18
Peradeniya

C. Kudagamage
Department of Agriculture
P.O. Box 18
Peradeniya

Rohan Rajapakse
University of Ruhuna
Matara

## Thailand

Chantana Boonprapapitak
Plant Protection Service Division
Department of Agricultural Extension
Ministry of Agriculture and Cooperatives
2143/1 Paholyothin Road
Khet, Bangkhen
Bangkok

Chalerm Sindhusake
Entomology and Zoology Division
Department of Agriculture

Arunee Surin
Department of Agriculture
Bangkhen, Bangkok

Areepan Upanisakom
Plant Protection Service Division
Department of Agricultural Extension
Ministry of Agriculture and Cooperatives
Amphor Muang, Chainat Province

Hermann Waibel
GTZ-Thai German Plant Protection Program
P.O. Box 9-100
Bangkok 10900

## United Kingdom

Peter T. Walker
10 Cambridge Road
Salisbury
Wiltshire SPl 3BW

## USA

Dale D. Bottrell
University of Maryland
Consortium for International
Crop Protection (CICP)
4321 Hartwick Road, Suite 404
College Park, Maryland 20740

Angel Chirri
USAID/San Jose
Agency for International Development
Washington, D.C. 20520

Stella Melugin Coakley
National Center for Atmospheric Research
P.O. Box 3000
Boulder, Colorado 80307-300

Harold D. Coble
Department of Crop Science
North Carolina State University
Raleigh, North Carolina 27650

Charles J. Delp
APS Office of International Programs
145 Kentucky Ave. SE
Washington DC 20003

Kenneth B. Johnson
University of Minnesota
Department of Plant Pathology
495 Borlaug Hall
1991 Buford Circle
St. Paul, Minnesota 55108

Forrest W. Nutter, Jr.
Department of Plant Pathology
The University of Georgia
College of Agriculture
Athens, Georgia 30602

Donald W. Roberts
Boyce Thompson Institute
Cornell University
Ithaca, New York

## Vietnam

Le Van Thuyet
Plant Protection Department
Ministry of Agriculture and Food Industries
189B Tay son, Dong da
Hanoi

Pham Thi Nhat
Plant Protection Department
Ministry of Agriculture and
Food Industries
189B Tay son, Dong da
Hanoi

## INTERNATIONAL RICE RESEARCH INSTITUTE

S. W. Ahn
Alicia Amante
Gerardo N. Aquino
Maria Austria
Jovito Bandong
Marietta Baraoidan
John Michael Bonman
Emerlito Borromeo
Pepito Cabauatan
Rogelio Cabunagan
Silvino B. Calvero, Jr.
Bernard Canapi
Noel Chua
Francisco A. Elazegui
Leopoldo Estorninos
Bienvenido S. Estrada
Nestor G. Fabellar
Ferdinand Fajardo
Eleanor R. Ferrer
Zenaida Flores
S. S. Gnanamanickam
Kwanchai A. Gomez
Gilda Jonson
Ekkehard Kurschner
Edgar M. Libetario
James A. Litsinger
Rosario Lubigan
Alita Mackill
Amable Jose P. Magnaye
Danilo Matias
Edward Medalla
Elizabeth Mesina
T. W. Mew
Keith Moody
Faustino L. Nuque
Pat Pantua
Robert dela Peña

Prabhu L. Pingali
Avelita Rosales
Edward Roumen
Leandro Sanchez
B. Merle Shepard
Jose Soriano, Jr.
Paul S. Teng
Casiana Vera Cruz

**Fellows and Scholars**

Tika Adhikari (Nepal)
K. K. Baloch (India)
Edwin Benigno (Philippines)
Ganesh Dahal (Nepal)
M. A. Gill (India)
Xia Jingyuan (China)
Buddhi Khadge (Nepal)
Margery Koch (Netherlands)
Imke Schloesser (Germany)
Claro Q. Torres (Philippines)
Peter Van Duin (Netherlands)

**IPM Trainees**

Idris Ali M. Ahamed (Sudan)
Gurusamy Alagarsamy (India)
Ephraim O. Bright (Nigeria)
Jin-Yun Jiang Changsha (China)
Benigno Cruz (Philippines)
I. G. P. A. Diratmaja (Indonesia)
S. K. I. Fernando (Sri Lanka)
M. N. Lal (India)
Pham Lan La (Vietnam)
Sittichai Limrateepong (Thailand)
Birang A. Madong (Cameroon)
Loku Banda Mahagedara (Sri Lanka)
Lixing Mao (China)
Ajit K. Pal (India)
Shree Baba Pradhan (Nepal)
Ying Tang (China)
Somchai Tangpoonpol (Thailand)
Vu Thi Hoi (Vietnam)
Xiaoming Zhang (China)

ISBN 971-22-0001-9