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Mechanisms of damage by stem borer, bacterial leaf blight and sheath blight, and their effects on rice yield

Proceedings of workshops in Khon Kaen, Thailand, 3-5 August 1992, and Cuttack, India, 3-5 March 1993

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Preface

This volume of the SARP Research Proceedings presents results of two workshops held as part of the SARP theme Crop Protection. During a workshop in Khon Kaen, Thailand, attention was focused on nature and extent of damage by stem borer, while a workshop in Cuttack, India, addressed similar topics for two diseases, bacterial leaf blight and sheath blight. The aim of the workshops was to review individual research of the participants in the past and to organize joint research for the next four years, comprising the third phase of SARP.

This volume is not a compilation of research papers. Rather, it presents the stepwise approach to analysis and synthesis of selected crop-pest systems to understand the major causes of damage.

The workshops were excellently organized by the SARP teams at Khon Kaen University, headed by team leader Dr. M. Keerati-Kasikorn, and the Central Rice Research Institute, with team leader Dr. P.R. Reddy, in collaboration with SARP staff at IRRI.

Thanks are due to Ms. J.P. Huisman (CABO-DLO) for preparing the final version of the manuscript, and to Ms. H.H. van Laar for advice and support during realisation of this volume.

Summary

Crop Protection is one of four themes in Systems Analysis and Simulation for Rice Production (SARP), a project in which 16 national agricultural research centres in South-east and East Asia, the Centre for Agrobiological Research in Wageningen, the Wageningen Agricultural University department of Theoretical Production Ecology and the International Rice Research Institute collaborate. Aim of the project is to build research capacity in the field of systems analysis and simulation at national agricultural research centres in south east Asia and at IRRI with the help of modern systems research techniques.

To develop a joint research approach aimed at understanding damage by stem borers, bacterial leaf blight and sheath blight in rice three-day workshops were organized in Khon Kaen, Thailand (stem borers), and Cuttack, India (bacterial leaf blight and sheath blight). The joint research agreed upon, including experimental work and modelling from a systems analytic point of view, is reported in this volume.

During the first day of the workshops the participants, entomologists and phytopathologists from 7 different SARP teams and 5 different countries, interested local researchers, IRRI researchers and SARP staff, exchanged information on progress of research in each of the teams (Chapter 3). To widen the perspective, general introductions were presented on crop physiology and ecology, and on the effects of pests and diseases on crop growth and production. The systems analytical approach was applied to stem borer research in a presentation of a detailed experiment on crop growth affected by stem borer infestations at different crop development stages (Chapter 2).

On the second day, concepts and experiences presented during the first day were translated into conceptual models of stem borer -, bacterial leaf blight -, and sheath blight - rice interactions. Using structured brainstorming, areas were identified where contradictory opinions on relations between stem borer and rice existed among the experts, indicating lack of empirical information (Chapter 4). To test the hypotheses on pest - rice interactions quantitative simulation models were presented which had been developed before the workshop using literature information. The participants evaluated the importance of various model assumptions by performing sensitivity analyses. Assumptions to which simulated yield was very sensitive were identified as topics for further experimental research (Chapter 5 stem borer, Chapter 6 bacterial leaf blight and sheath blight).

To test the models, i.e. the hypotheses on pest-rice interaction, proposals for joint experiments were discussed in detail. The proposals had been prepared in advance, and were adapted where necessary during the discussions (Chapter 7 stem borer, Chapter 8 bacterial leaf blight and sheath blight). SARP participants agreed on the importance of the joint experiments and drew up a time schedule accomodating experiments of each team (Chapter 9).

A follow-up workshop was planned during which results of the joint experiments will be presented. Analysis of the field experiments with the simulation models will show to which degree the system is understood. Such analysis provides a basis for developing tools for assessing the effect of different agronomic measures on crop response to pest attack (Chapter 10).

Contents

1 Introduction

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SARP

In 1992, the SARP project, short for Systems Analysis and simulation for Rice Production, entered its third phase. The project was started in 1984 by national agricultural research centers (NARCs) in south east Asia, the Centre for Agrobiological Research in Wageningen and the Department of Theoretical Production Ecology of the Wageningen Agricultural University, in collaboration with the International Rice Research Institute. Aim of the project is to build research capacity in the field of systems analysis and simulation at the national agricultural research centers and at IRRI with the help of modern systems research techniques. The long-term goal is to further enhance sustainable productivity of rice-based systems. Staff time is contributed by participating institutes. Funds for training, exchange of scientists, and coordination are contributed by the Directorate General for International Cooperation (DGIS) of the Dutch Ministry of Foreign Affairs.

Until 1991, three training programs were held under SARP auspices. In total 92 researchers from 16 NARCs throughout south-east Asia were trained in the use of the systems approach and computer simulation modelling as a tool in their research activities. Some of these teams have later organized their own national training courses for sister institutes. Training was followed by case studies within the informal SARP network, to actively introduce the approach in the NARC's research programs. Case study topics were selected by the participants in accordance with ongoing research at their institutes. During the case studies the teams were visited by SARP staff for technical and scientific support.

Trainees were always part of a team of at least four researchers from the same NARC. Each team had the support of a senior scientist, the team supervisor who maintained close links with the NARC's research policies. One of the scientists in the team was selected to be team leader. Each team consisted of different disciplines to ensure a focus on the rice system, rather than carrying out research in the traditional disciplines, with a major risk of neglecting important system aspects. Various workshops and a closing conference in Bangkok were organized. A substantial number of publications show the results of the period 1984-1991.

SARP's third phase will last until 1995. Emphasis will be put on collaborative research. From the training programs four themes emerged as a framework for collaborative research:

1. Agro-ecosystems (agro-ecological zonation, timing of crops and crop sequences, optimization of regional water use);
2. Potential Production (crop responses to light and temperature, development and morphogenesis);
3. Crop and Soil Management (water and nitrogen management for different soils, rice varieties, plant spacing, plant establishment);
4. Crop Protection (damage mechanisms by pests and diseases).

The aims in the third phase of SARP are

- to reinforce the teams and to support joint research programs within the informal network;
- to develop applications at the crop and agro-ecosystem level aimed at both policy makers (e.g. through studies on agro-ecological zonation), and extension workers and farmers (e.g. by directing research to development of tools for advice on nitrogen and pest and disease management);
- to support national training programs when they arise;
- to transfer coordination of the project to NARCs and IRRI.

In March 1992 a workshop was held at IRRI to organize research in the informal network. All team supervisors and team leaders were invited. Research priorities were established for each of the four themes in the project. The kick-off for joint research activities was to be given in workshops per theme.

In the theme Crop Protection the earlier case studies had shown teams to be interested in research on a range of pathosystems. To optimally utilize the network character of research in SARP, selection of a limited number of pathosystems was needed. During the planning workshop the insect pathosystem rice-stem borer (SB, five species are of economic importance), the bacterial pathosystem rice-bacterial leaf blight (BLB, *Xanthomonas campestris* pv. *oryzae*), and the fungal pathosystem rice-sheath blight (ShBl, *Rhizoctonia solani*) were identified as highly conducive to a systems analytic approach within the context of the informal SARP network. Criteria used in the selection procedure included the number of teams that was actively involved in research on the pathosystem (reflecting, among others, the economic importance of the pest and the disease), the current state of knowledge on mechanisms of damage, and the scientific support available at IRRI and in Wageningen. An overview of teams working on rice-stem borer, rice-bacterial leaf blight and rice-sheath blight is given in Table 1.1.

The kick-off for joint research on SB damage was given at a workshop held in Khon Kaen, Thailand, from 3 to 5 August 1992. Joint research on damage by the diseases was discussed at a workshop in Cuttack, India, from 3 to 5 March 1993. This volume of the SARP Research Reports summarizes the common approaches developed at these workshops.

Table 1.1. Teams and researchers in the SARP project working on rice-stem borer, and rice- bacterial leaf blight and rice-sheath blight.

Stem borer	
CRRI, Cuttack, India	Dr. R.C. Dani
IRRI, Los Baños, Philippines	Ms. E.G. Rubia
KKU, Khon Kaen, Thailand	Dr. M. Keerati-Kasikorn
PUAT, Pantnagar, India	Dr. P.K. Pathak
TNAU-TRRI, Aduthurai, India	Mr. N. Raju
UPM, Serdang, Malaysia	Dr. Md. Norowi Hamid
ZAU, Hangzhou, China	Mr. Xu Zhihong
Bacterial leaf blight	
CRRI, Cuttack, India	Dr. P.R. Reddy
TNAU-TRRI, Aduthurai, India	Dr. V. Narasimhan
Sheath blight	
CRRI, Cuttack, India	Dr. P.R. Reddy
	Dr. U.D. Singh
PUAT, Pantnagar, India	Dr. R.A. Singh
	Mr. B. Das

Research approach in the SARP Crop Protection theme

Joint research in the Crop Protection theme focuses on quantitatively explaining effects of the selected pests and diseases on growth and production of rice, based on insights in the effects on physiological processes. Although attention is focussed on SB, BLB and ShBl, the research approach is applicable to any growth reducing factor (Rabbinge et al., 1989). The crop growth model L1D (Penning de Vries et al., 1989), recently succeeded by ORYZA1 (Kropff et al., 1993), is used as an instrument for integrating effects on physiological processes at the crop level. The approach consists of several steps. Following identification of all possible effects of a growth reducing factor on plant and crop physiology (step 1), the effects, or damage mechanisms, which are hypothesized to be the most important for explaining damage (step 2: ranking) are quantified (step 3) and introduced into the crop growth model (step 4). The crop growth model extended with the damage mechanisms represents the hypothesis to be tested. Quantitative comparison with holistic field experiments (step 5) is carried out to evaluate to which extent damage is understood, and whether additional damage mechanisms need to be quantified and included in the model before proceeding to (step 6) application of the model.

For the Crop Protection theme this crop-centered approach implies that the emphasis should be on effects of pests and diseases on the crop, i.e. damage, rather than on their population dynamics. The focus on effects of pests and diseases on crop growth enables efficient exchange of information among members of a team who are working in different themes, since all are using the crop growth model as a vehicle for integrating hypotheses on plant-environment interactions. In addition, the crop growth model provides a framework for evaluating hypotheses on damage in different environments by performing joint experiments, and may therefore also contribute to increasing research efficiency within the theme.

Research activities in the third phase of SARP have been divided into process research and applied research. Process research aims at identification and quantification of the major mechanisms which cause damage. This phase should result in a model of crop growth combined with mechanisms of damage which performance has been tested in standardized experiments at different locations. When sophisticated techniques are needed to quantify damage mechanisms, experiments may be carried out by participants at appropriately equiped institutes. Validation experiments should preferably be carried out by all participating teams to utilize the network to its full potential in speeding up research. Applied research uses the model developed during the phase of process research to evaluate management alternatives with respect to their effect on damage, and to contribute to design of rice ideotypes. Management alternatives comprise e.g. the effect of cultivar choice, nitrogen fertilizer rate, and plant density on damage, and the optimal timing of chemical control, represented by damage thresholds. In this phase experiments with the simulation model are supplemented with testing of the model with additional field experiments. Applied research questions to be answered will be formulated in the course of the project, after identification of the demand for specific end-products.

Workshop objectives

The overall objective of the workshops in Khon Kaen (SB) and Cuttack (BLB and ShBl) was to develop a joint research approach aimed at understanding insect and pathogen damage in rice, to ultimately be able to derive recommendations for crop management. Joint research includes experimental work and modelling, from a systems analytic point of view.

A number of partial objectives were distinguished:

1. To exchange information on the current state of knowledge on SB, BLB and ShBl damage in rice among SARP participants;
2. To develop a common concept of the damage mechanisms of SB, BLB and ShBl resulting in growth reduction and yield loss in rice;
3. To understand how SB, BLB and ShBl damage mechanisms can be introduced into a rice growth model, and to be able to use the model for analysis of field experiments;

4. To develop a joint experimental approach to improve and test the model (= the hypothesis);
5. To agree upon joint output, and a realistic time-table.

Outline of the report

The chapters of these proceedings roughly follow the programmes of the workshops. In Chapter 2 introductions are given on physiological processes of crop growth and the way they can be affected by insects and pathogens, adopting a systems view. The approaches are applied to the rice - stem borer system in a detailed case study of crop growth analysis after stem borer infestations at different crop development stages. In Chapter 3 previous research on SB, BLB and ShBl by the SARP participants is reviewed. Chapters 2 and 3 set the scene for the development of conceptual models of pest damage using brainstorm (Chapter 4). In Chapters 5 and 6 the sets of hypotheses on the causes of pest damage which constitute the conceptual models, are translated into quantitative simulation models. Experiments are designed to test various assumptions in the models, and to evaluate the models as a whole (Chapters 7 and 8). The workplans that the participants agreed upon are presented in Chapter 9. Chapter 10 addresses short-term and long-term research goals of the theme.

2 Review of crop physiology and crop ecology in relation to pest damage

2.1 Physiological processes of crop growth and production and their relationships to damage by stem borer, bacterial leaf blight and sheath blight [1]

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Introduction

As the world population continues to grow, agricultural scientists are facing the challenge to further increase food production. Crop yield has been improved through plant breeding, water and fertilizer management, and pest control. Further increases in yield potential will rely on understanding physiological processes of crop growth and production.

At least 90 % of the biomass of higher plants is derived from photosynthesis (Zelitch, 1982). Total biomass accumulation is a function of the rate of biomass production and growth duration. Further, harvestable yield is the product of total biomass produced times harvest index. It is doubtful whether the harvest index for many cereals can be further increased (Austin, 1981), implying that further increases in production will be attained through increased CO_2 fixation (Coombs, 1984). Therefore, photosynthesis is a major physiological process of crop growth and production.

In this section, a short review is given of major physiological processes underlying crop growth, and the way they are influenced by environmental factors. First the processes involved in fixation of CO_2 are discussed. Then, utilization of the assimilates by various crop organs is addressed. Finally, the effects of injury by stem borer, bacterial leaf blight and sheath blight on these processes are assessed and possibilities for management of the pests are put forward.

[1] Sections on BLB and ShBl added by W.A.H. Rossing, in consultation with S. Peng

Photosynthesis

Photosynthesis is a process through which plants capture solar energy and convert it into chemical energy stored in the form of carbohydrate. Photosynthesis can be divided into two groups of processes:

Light reaction. Chlorophyll pigments capture PAR photons (400-700 nm) which are used to split water and produce intermediate carriers of energy (ATP) and reducing power (NADPH):

$$2H_2O + 2ADP + 4NADP + 2P_i \xrightarrow[\text{Chloroplasts}]{\text{Light}} O_2 + 2ATP + 4NADPH$$

Dark reaction. The NADPH and ATP produced in the light reaction are used to reduce CO_2 to carbohydrates and other compounds through the Calvin Cycle (Figure 2.1):

$$CO_2 + 2ATP + 4NADPH \xrightarrow{\text{Rubisco}} (CH_2O)_n + H_2O + 4NADPH + 2P_i + 2ADP$$

Three photosynthetic systems exist in crop plants: C3 plants, C4 plants, and CAM system. In C3 pathway, CO_2 is fixed by RuBP carboxylase enzyme into a 3-carbon acid (PGA) as the first product. Rice is a C3 plant with following photosynthetic characteristics:

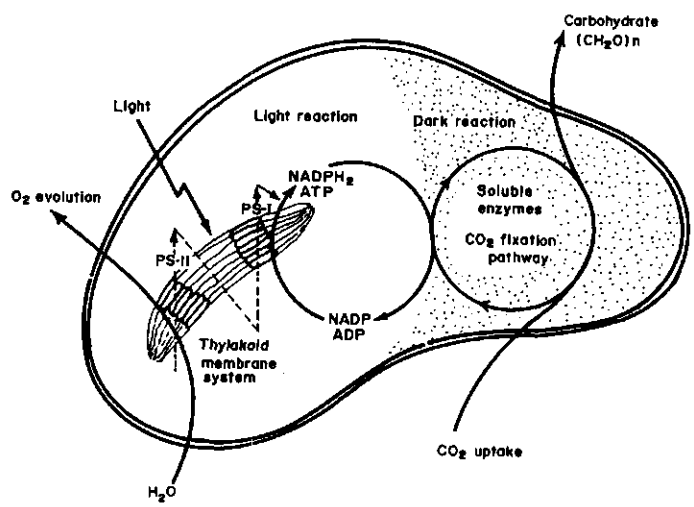

Figure 2.1. Photosynthetic function in chloroplast (redrawn from Saka and Chisaka, 1985).

light compensation point 15-38 μmol m^{-2} s^{-1} (PAR), light saturation 1710^{-2} 280 μmol m^{-2} s^{-1} (PAR), optimum temperature 20-33 °C for japonica and 25-35 °C for indica varieties, CO_2 compensation point 55 ppm, and maximum net photosynthetic rate 25-32 μmol CO_2 m^{-2} s^{-1} (Yoshida, 1981).

Radiation, temperature, humidity, CO_2 concentration affect photosynthetic rate. Stomatal conductance, internal CO_2 concentration, Rubisco concentration and activity largely control photosynthetic rate.

Respiration

Photorespiration. The carboxylating enzyme (Rubisco) can also act as an oxygenase, using O_2 to oxidize sugars to CO_2 in a process called photorespiration. Photorespiration, a characteristic of C_3 plants, represents a great loss of energy which the plant can not avoid. As much as 20 % of all C fixed in the Calvin cycle may be lost as CO_2 evolved in the process.

Dark respiration. Photorespiration occurs in peroxisomes, whereas dark respiration takes place in mitochondia. Dark respiration involves the oxidation of carbon compounds with the release of energy and reductant which can be used in the maintenance, growth, ion movements and other transport processes of the plant. There is no growth without respiration. Growth is achieved by use of intermediates and the energy produced by respiration. Sugars are the principal substrates. One molecule of glucose will yield 24 e^- (24 reducing equivalents or 36 ATP).

Knowing what the energy is used for allows us to distinguish between growth and maintenance respiration. McCree (1974) proposed following model:

$$R = kPg + cW,$$

where
- R = 24 h total dark respiration for the whole plant,
- W = plant dry weight,
- Pg = gross photosynthetic rate,
- k = growth respiration coefficient, and
- c = maintenance respiration coefficient.

It has been found that maintenance mostly involved the cost of protein turnover. Growth respiration involves the formation of new biomass, and that means new cells with new cellulose, proteins, lipids and others. When a plant is young and growing actively, growth respiration is the major component of total respiration. With a mature plant, however, maintenance respiration becomes a substantial fraction of total respiration (Yoshida, 1981).

Canopy photosynthesis

Plant productivity is more closely related to canopy photosynthesis than to single leaf photosynthesis. Leaf photosynthesis measurements usually estimate the maximum potential of a genotype because the uppermost fully expanded leaves (optimum physiological conditions and plant position) are examined (Elmore, 1980). Canopy photosynthesis measurements, on the other hand, measure the carbon uptake of the whole stand. This measurement more accurately describes the photosynthetic activity per unit ground area and combines genotype efficiency, leaf morphology, and canopy architecture (Wells et al., 1986). However, it is impossible to use canopy photosynthesis as selection criteria in the germplasm screening program because the measurement of canopy photosynthesis is laborious, time consuming, and costly.

Canopy photosynthesis is primarily determined by incident solar radiation, photosynthetic rate per unit leaf area, leaf area index, and leaf orientation (through canopy light interception). We have no control on the solar radiation. However, there are genotypic differences in the shading tolerance. In addition, we can manipulate leaf area distribution and leaf orientation to maximize the light interception. Accumulated radiation intercepted by canopy is highly correlated with biomass and yield production in many crops (Monteith, 1969). Genotypic variation in single leaf photosynthesis has been reported. Its magnitude may be too small to mean anything at the whole-plant level.

Translocation and partitioning of newly fixed C

Once C is fixed in the chloroplast, new assimilates (sugars) are stored as starch for later export or transferred to the cytoplasm where most are converted to sucrose and exported from the cell. Sucrose will be translocated from source to sink through phloem for the growth of various plant organs or storage. The source is the site where carbon assimilates are produced, while the sink is the site where carbon assimilates are utilized.

The sucrose concentration gradient between source and sink determines the rate of translocation. The source and sink activity (strength) controls the sucrose concentration gradient. Sink activity depends on sink size and the rate of assimilate utilization. The rate of translocation can be determined by measuring ^{14}C movement through the system, dry weight gain in sinks, or loss in dry weight from leaf sources.

The term "partitioning" is used to describe how a crop uses newly formed photosynthates. The morphological aspects of partitioning consider which parts are capable of growing and which actually grow (leaves, stems, roots, etc.). Root : shoot ratio (functional balance) and harvest index are morphological expressions of carbon partitioning. The physiological aspects of partitioning consider separation between respiration associated with growth and maintenance.

Carbon remobilization

Fixed CO_2 is used in the processes of growth and development, or is accumulated as sugars and starch in the storage organs, mainly in the leaf sheath and stem. Carbohydrate accumulation reaches a maximum concentration at around heading. These stored carbohydrates can be translocated into grain. The amount translocated can be estimated by the ^{14}C labeling technique. Cock and Yoshida (1972) estimated that 68 % of the accumulated carbohydrates was translocated into the grain, 20 % was respired during the grain-filling period, and 12 % remained in the vegetative parts. In the grain at maturity, 26 % of its carbohydrate was translocated from storage organs and 74 % was contributed by photosynthesis after flowering. Flag leaf contributes relatively more carbohydrate to the grain than other leaves.

Translocation of C can occur from main stem to tiller. During the tillering stage, the main stem translocates about 35 % of its total assimilates into young tillers (Mar, 1964). This percent decreases to 3.8 % at heading. Carbohydrates can also be translocated from tiller to main stem. At heading, 3.6 % of tiller carbohydrate can be transported to the main stem, whereas after mid-grain filling, 38.2 % of tiller carbohydrate can be translocated to the main stem. The carbohydrates of non-productive tillers (25.5 to 36.1 %) can be translocated to productive tillers.

The C and N of dying shoots can also move into the rest of the plant. Thorne and Wood (1987) labeled tillers of winter wheat with $^{14}CO_2$ and examined the remaining ^{14}C after death of the tillers. They found that 55-7 % of the ^{14}C supplied to living tillers had been transferred, 9-21 % was in the root, and the rest remained in the shoots. The ^{14}C which was not retained in the dead tillers was found in all parts of the plant, including about 7 % in grain. However, this amount of C translocated to other parts of the plant represented only a small proportion of total plant dry weight. For a crop with 6 t ha^{-1} grain yield and 12 t ha^{-1} aboveground biomass, if we assume that dying shoots represent 10 % of total biomass, 70 % of C in dying shoots move to the rest parts of plant and of which 7 % in the grain, and dying shoots and grain contain 41 % C, the contribution of remobilized C from dying shoots to grain yield is:

$12 \times 10\ \% \times 41\ \% \times 70\ \% \times 7\ \% / 41\ \% = 0.06$ t ha^{-1}.

Therefore, the direct translocation of C from dying shoot to grain is not important. The translocation of mineral nutrients such as N and P from dying shoot to the other part of plants may help plants to maintain the nutrient status and photosynthesis at late growth stage, which will indirectly contribute to grain yield.

Measuring photosynthesis and respiration

Measurements of photosynthesis and respiration usually involve monitoring CO_2 or O_2 exchange rates. Exchange of CO_2 can be measured by a infrared gas analyzer or ^{14}C method. Exchange of O_2 can be determined by oxygen electrode. Though many

photosynthesis systems have been developed, the majority utilize a closed or open system (Field et al., 1989).

Closed or transient system

We place a photosynthesizing leaf in a closed chamber and monitor the change in CO_2 concentration over a short period of time (usually 20 s). The rate of CO_2 depletion is the photosynthesis rate. The amount of CO_2 depletion is the product of concentration and system volume. To express photosynthesis on a leaf-area or dry-weight basis, simply divide total photosynthesis by the area or weight of photosynthesizing tissue (Figure 2.2).

Open or steady-state system

Differential system. When an air steam is passed continuously through the chamber with a photosynthesizing tissue enclosed, the CO_2 in the air leaving the chamber will be depleted relative to the air entering the chamber. Photosynthetic rate can be determined by the difference in CO_2 concentrations and air flow rate.

Compensating system. In a compensating system, the CO_2 depleted by photosynthesis is replaced by injecting CO_2 into the chamber. When the rate of CO_2 injection is adjusted such that the CO_2 concentration in the air entering and leaving the chamber is the same, photosynthesis is equal to the rate of CO_2 injection.

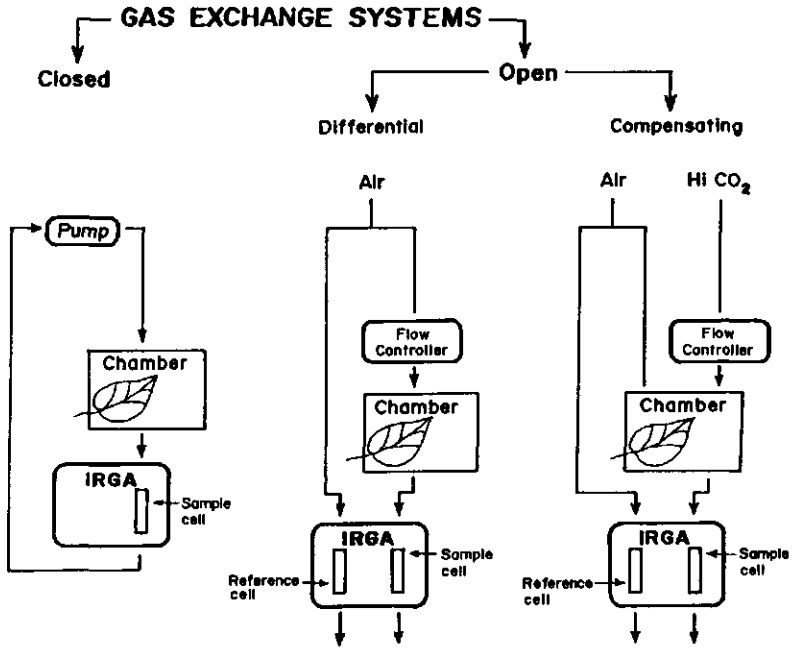

Figure 2.2. Three basic types of gas-exchange measurement systems (redrawn from Field et al., 1989).

The principle of photosynthesis measurements is the same for a single leaf, branch, whole plant and canopy. There are several photosynthesis systems commercially available.

Relationship between photosynthesis and production

Dingkuhn et al. (1990) measured the diurnal canopy CO_2 exchange rate of a rice crop at 69 days after seeding (DAS) when LAI was 4.28 and the seasonal maximum canopy CO_2 exchange rate (Figure 2.3). The daily averaged canopy CO_2 uptake rate for 10 hours was 27.6 µmol m^{-2} s^{-1} and the ratio of CO_2 respired at night to CO_2 fixed in the day time was 0.223. Based on seasonal measurements, the seasonal averaged maximum canopy CO_2

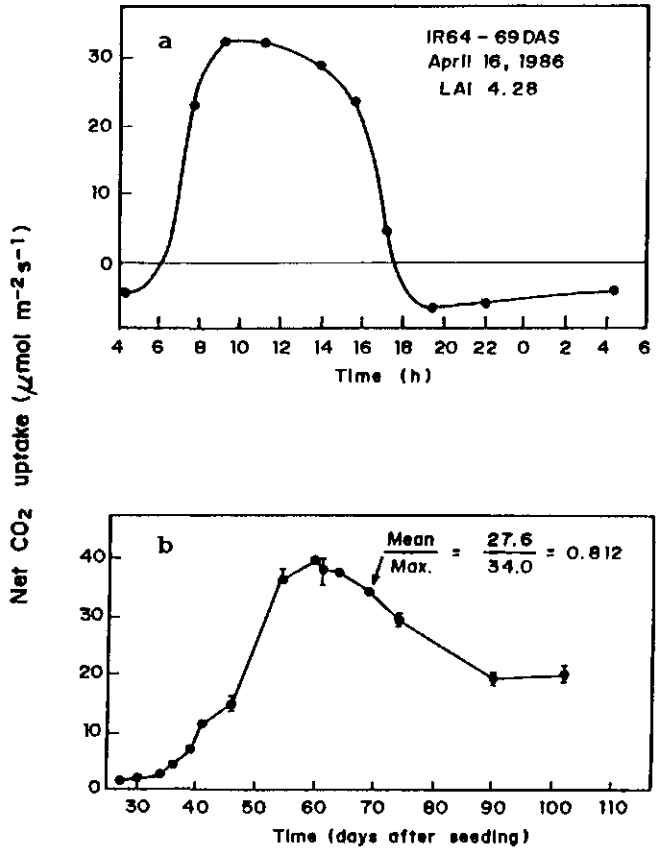

Figure 2.3. Diurnal change in canopy C exchange 69 days after seeding (a) and seasonal pattern of maximum canopy net C (b) in transplanted IR64 rice crop (redrawn from Dingkuhn et al., 1990).

uptake rate was 22.5 μmol m^{-2} s^{-1} for 75 days. At 69 DAS, the ratio of daily averaged canopy CO_2 uptake rate to maximum canopy CO_2 uptake rate was 0.812 (27.6/34.0). If we assume that this ratio was constant across the growing season, the seasonal averaged canopy CO_2 uptake rate was 18.3 μmol m^{-2} s^{-1} (22.5 x 0.812) for 75 days and 10 hours per day. Average carbon content of rice biomass is 41 %. Therefore,

Biomass production = 18.3 x 10-6 x 77.7 % x 44 x 12 / 44 x 75 x 10 x 60 x 60 /41 %
= 1124 g m^{-2} = 11.2 t ha^{-1}.

The above-ground biomass reported in this study was 11.8 t ha^{-1} which was very close to the calculated value. Root biomass may represent 20-3 % of total dry weight for the irrigated rice plants. The rice root system can take up CO_2, which is transported to the leaf tissue for fixation. The carbon assimilation rate determined by above ground gas exchange method does not include CO_2 uptaken by the root system. It is suggested that CO_2 uptaken by the root system may contribute up to 50 % of total CO_2 uptake and biomass production. Theoretically, higher rates of photosynthesis should lead to higher yield. Evidence suggests that genetic variation in single leaf photosynthetic rates exists within a number of crop species. Unfortunately, measured leaf photosynthetic rates and seed yield are poorly associated in previous studies (Evans, 1975). Plant breeders have not successfully use genotypic differences in leaf photosynthetic rates as selection criteria for higher yield (Gifford et al., 1984). The lack of a strong, positive relationship between production and leaf photosynthesis is due to instantaneous photosynthetic measurements conducted at a single moment of crop development under ideal laboratory conditions rather than seasonal measurements conducted under field conditions (Zelitch, 1982). In addition, single leaf measurements fail to account for canopy leaf area and architecture differences which influence light interception and whole canopy CO_2 assimilation. Positive relationships between photosynthetic rates at the canopy level and plant productivity have been reported for wheat, barley, sorghum, maize, soybeans, and cotton (Zelitch, 1982; Wells et al., 1986).

We tested 22 grain sorghum lines in the field under well-watered and water-limited conditions (Peng et al., 1991). Averaged leaf photosynthetic rates across growth stages from panicle initiation to head exertion and water treatments were highly correlated with biomass production (r^2=0.79) and grain yield (r^2=0.82). The strong, positive correlation reported in this study was attributed to: 1) many measurements were taken during the period of maximum growth rates under field conditions, 2) the highly significant differences in leaf photosynthetic rate, total biomass production, and grain yield for the materials tested, and 3) LI-6200 portable photosynthesis system which provided rapid and accurate determinations of leaf photosynthetic rates under field conditions.

Yield components

The grain yield can be divided into several components: panicle number per unit area, spikelet number per panicle, percentage of filled-spikelets, 1,000-grain weight. For a

given cultivar, 1,000-grain weight is a relatively constant quantity. Traditional rice varieties have heavier grains than modern varieties. For instance, the Indonesian local variety Cisadane's 1,000-grain weight is approximately 30 g while the 1,000-grain weight of IR64 is around 26 g. Panicle number per unit area and spikelets number per panicle account for most of the yield variation. Panicle number per unit area is always negatively correlated with spikelet number per panicle. In transplanted rice with lower planting density, panicle number per unit area is largely a function of tiller number per unit area (Yoshida, 1981).

Tiller Production

Tillers are branches that develop from the leaf axils at each unelongated node of the shoot during vegetative growth. The nth leaf on the main stem and the tiller from the axil of the (n-3)th leaf emerge at the same time. Tillers can be produced from all the leaf axils at unelongated nodes. When the 13th leaf on the main stem emerges, theoretically, one plant can produce 40 tillers: 9 primary, 21 secondary, and 10 tertiary (Figure 2.4). In reality, however, not all the tiller buds develop into tillers. Some may remain dormant. A tiller can survive only when it has three leaves, because it develops its independent root system at three-leaf stage. Surviving tillers do not necessarily develop into productive tillers. The proportion of tillers becoming non-productive tillers depends on planting space, incident radiation, nutrient supply, and other environmental and cultural conditions (Yoshida, 1981).

The tillering period includes active tillering stage, the end stage of productive tillering, and maximum tiller number stage (Figure 2.5). Panicle initiation may happen before, at, or after the maximum tiller number stage, depending on a variety's growth duration. Tillers developed at early growth stages normally have a better chance to produce panicles than those developed later.

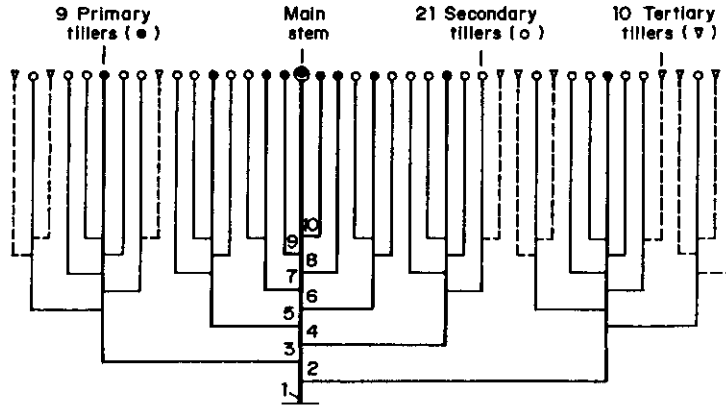

Figure 2.4. Tillering pattern of a rice plant (redrawn from Yoshida, 1981).

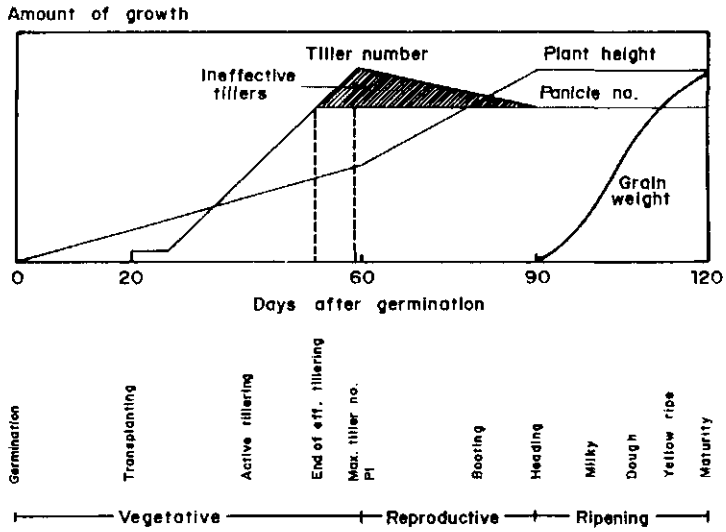

Figure 2.5. Life history of a 120-day variety grown in the tropics under transplanted conditions (redrawn from Yoshida, 1981).

Different varieties have different tillering capacities. Indica rice usually produces more tillers than japonica rice under the same conditions. Varieties with high tillering capacity can tolerate abnormal or suboptimal conditions better than low tillering varieties.

Compensation of stem borer damage and its mechanism

The effects of stem borer on a rice crop are very complex, and depend on growth stage, variety, management system, etc. Stem borer can damage rice plants by reducing the leaf area in the vegetative stage and panicle number per unit area in the reproductive stage. Leaf area reduction will cause decreases in canopy photosynthesis and consequently biomass production. On the other hand, a rice crop can compensate the stem borer damage (Rubia et al., 1989). Luo (1987) reported compensation of at least 32 % of yield loss caused by the infection of Asian rice borer. Hybrid rice had larger compensating capacity than conventional varieties.

A rice plant compensates stem borer damage by producing new tillers (Akinsola, 1984), and increasing the number of productive tillers and grain weight (Luo, 1987). Zebarth and Sheard (1991) reported that barley partially compensated yield loss (decreases in panicle number per m^2) caused by pests through increasing the number of grains per panicle (Figure 2.6). A strong negative relationship between panicle number per m^2 and the number of grains per panicle (Figure 2.7) was observed in rice (Matsushima, 1980). Therefore, rice may compensate stem borer damage by increasing the number of grains per panicle.

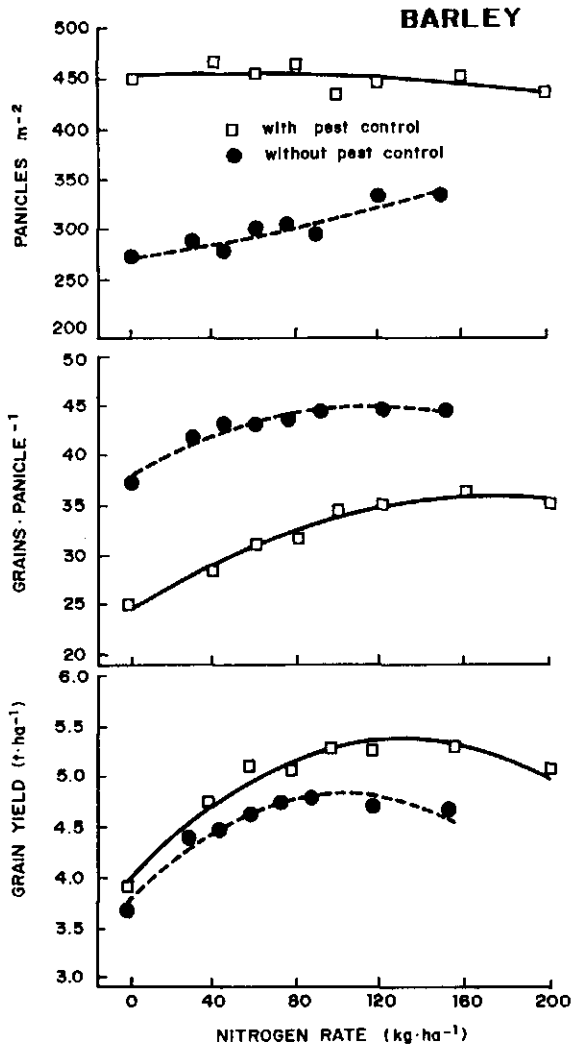

Figure 2.6.
Yield components of barley as a function of nitrogen rate and pest management system averaged across ten environments (redrawn from Zebarth and Sheard, 1991).

If stem borer infects young tillers which have no chance to become productive tillers, stem borer can serve as a tool to depress the non-productive tillers. The reduction of non-productive tillers can increase the supplies of N and other nutrients to the tillers which will produce panicles, improve the canopy environments, and increase light penetration in the canopy. The C and N in the dying shoots due to stem borer damage could be translocated to other parts of plants. In addition, plants may produce hormones or other substances during the infection of stem borer, which may stimulate plant growth. Luo (1987) reported that chlorophyll content and photosynthetic rate of remaining parts of the plant after rice borer damage increased compared with control (Figures 2.8 and 2.9).

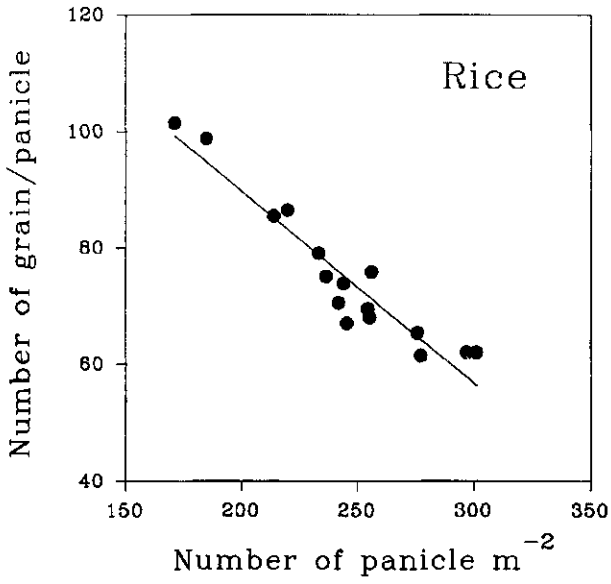

Figure 2.7.
Relationship between number of grain per panicle and number of panicle per m^2 (redrawn from Matsushima, 1980).

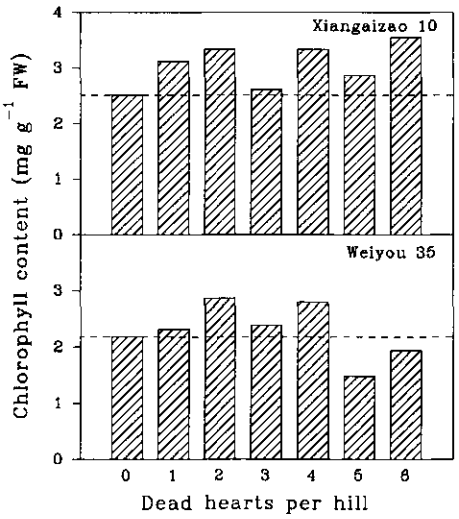

Figure 2.8.
Chlorophyll content of uppermost fully opened leaves of remained plants after stem borer damage during tillering stage (redrawn from Luo, 1987).

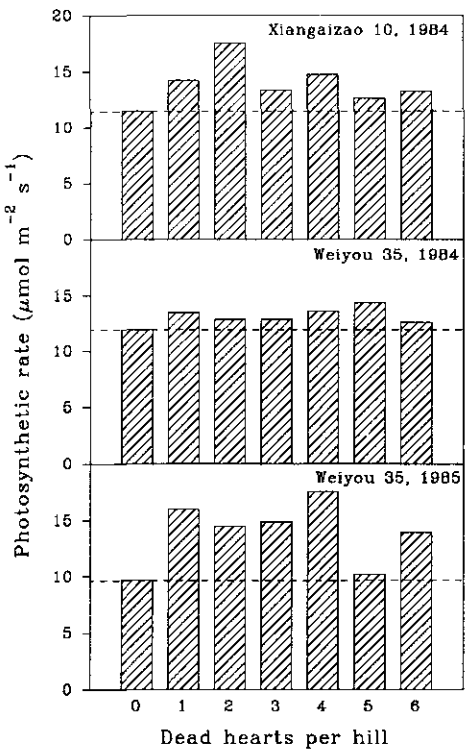

Figure 2.9.
Photosynthetic rates of uppermost fully opened leaves of remained plants after stem borer damage during tillering stage (redrawn from Luo, 1987).

Strategies to minimize stem borer damage

Strategies which can increase the tillering capacity and duration at the vegetative stage and increase the conversion of non-productive tillers into productive tillers at reproductive stage are effective to minimize stem borer damage. Most of currently used varieties have high tillering capacity, therefore, increasing the number of productive tillers is important in minimizing the stem borer damage.

Management

Nitrogen. Adequate N supply during the tillering stage can increase the number and duration of tiller production. Topdressing N at panicle initiation will increase the number of productive tillers.

Plant density. At low fertility soil, increase in plant density by increasing the seedling number per hill or decreasing transplanting space can reduce the relative stem borer damage.

Transplanting depth. Deep transplanting will delay tiller production and reduce the duration of tillering.

Breeding
Selecting varieties with higher tiller capacity. Hybrid rice has higher tillering capacity than conventional varieties. Indica has higher tillering capacity than japonica.

Compensation of damage by bacterial leaf blight and sheath blight and its mechanism

Little is known about the effects of bacterial leaf blight and sheath blight on crop growth processes. Since chlorosis of leaf blade and leaf sheath are among the first symptoms (Ou, 1985) disruption of leaf photosynthesis after colonization of the host plant is likely. Even such simple damage mechanism may give rise to a complex relation between injury and damage, since injury and damage are spatially and temporally separated. Timing of infection, distribution of symptoms over the canopy profile and crop nitrogen status may play important roles in the crop's response to injury.

Early infection and concomitant decrease in leaf photosynthesis will decrease leaf growth and accumulation of stem reserves. In contrast, infection around flowering does not affect development of the source of carbohydrates since all leaves are fully developed, but will decrease the flow of carbohydrates to the grains directly.

The distribution of infected leaves over the canopy profile affects the distribution of light in the crop. Dead leaves in the top of the profile affect photosynthesis of lower leaves due to shading. Decrease of crop photosynthesis may be amplified due to the existence of vertical leaf nitrogen gradients. Top leaves often have the highest nitrogen contents, and the highest rates of photosynthesis at light saturation.

Crop nitrogen content may affect damage in two opposite ways. On the one hand, high nitrogen content promotes infection and rapid expansion of the epidemic (Ou, 1985). On the other hand, high rates of leaf photosynhesis associated with high nitrogen contents provide a mechanism for compensation of loss of leaf area due to infection.

To unravel the relative importance of timing of infection, distribution of symptoms and crop nitrogen status a mechanistic crop growth model combined with damage mechanisms is needed. Research along this line recently yielded new insights into the causes of damage by leaf blast, Pyricularia oryzae in rice (Bastiaans, in press).

Strategies to minimize damage by bacterial leaf blight and sheath blight

From a crop ecological perspective maximizing green leaf area duration is an effective strategy to minimize damage by bacterial leaf blight and sheath blight. This can be achieved by cultivars with abundant leaves, by high nitrogen application rates and by moderate plant density to allow deeper penetration of light into the crop. Clearly, these measures have to be weighed against the risk of accelerating epidemics. For this purpose, more information is urgently needed on the potential of these strategies for compensating damage.

Conclusions

In this brief review we presented the major plant and crop physiological processes which result in crop growth, development, and production. Simple calculations were used to illustrate quantitative aspects. The effect of environmental factors on the processes was pointed out. To further increase food production, many, but not all, environmental factors are managed by crop husbandry and/or crop breeding. Efficient and effective management aims at improving those factors which have the larger effect on crop growth. Elucidation of such factors is an important area of application of crop growth models. In these models quantitative knowledge of physiological processes and their interaction with the environment is used to gain insight into crop growth and yield development in various environments and under various levels of infestation by pests, such as stem borers, bacterial leaf blight and sheath blight.

2.2 Modelling effects of insects and pathogens on growth and yield of field crops

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Introduction

Insects and pathogens constitute irregularly occurring causes of economically unacceptable yield losses. Estimates of yield loss in farmers' rice fields in south-east Asia vary between 6 % and 100 % of the attainable yield (review by Teng et al., 1990). Integrated pest management is generally accepted as a useful concept for sustainable crop protection. It aims at utilizing all available methods and techniques to control pests at densities below those causing economic damage. The level of pest density at which economic damage will ensue is called the damage threshold (Zadoks, 1985). Agronomic measures such as cultivar choice and crop rotation form the basis of integrated pest management, and are supplemented by biological control methods. Pesticides are used only when other methods have failed to maintain pests below the damage thresholds. Knowledge of future yield loss to be expected on the basis of the current level of infestation is essential for cost-benefit analysis of control measures, and constitutes a cornerstone of integrated pest management systems. Lack of such knowledge will prompt a farmer to spray pesticides prophylactically, and to regard the expenditure on pesticides as an insurance premium.

The relation between pest attack and yield loss has been analyzed primarily by statistical methods. Statistical methods are based on a description of the field situation but give no insight into the background of damage. Extrapolating the damage relations to other field situations is hazardous as the consequences of the interaction between pest and crop may vary considerably and could result in a different yield loss-pest density relation. The limitations of the descriptive approach can be overcome by developing damage relations based on insight in the plant physiological and crop physiological backgrounds of yield loss.

Damage is a result of interactions between a pest, a crop, and weather. All three components can be influenced by farm management (Figure 2.10). From a system analytic viewpoint, study of the population dynamics of the pest can be carried out independently of study of yield loss. Studies of pest population dynamics focus on the population at given weather and substrate (crop) dynamics, while in yield loss research

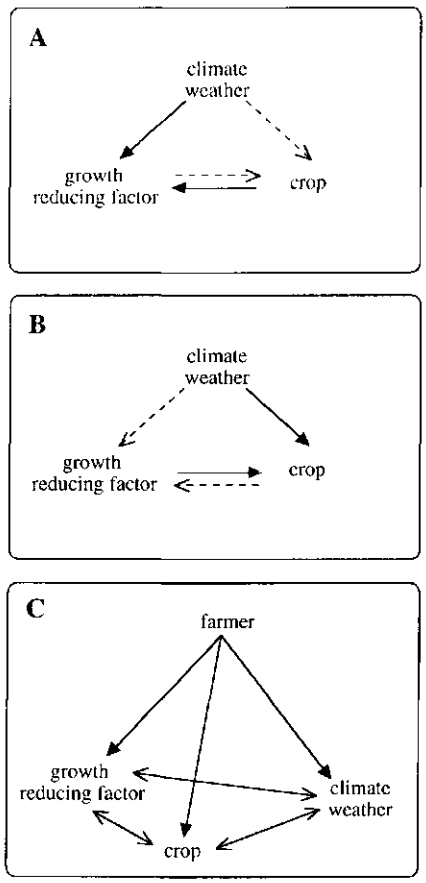

Figure 2.10.
The disease triangle with emphasis on (A) population dynamics of the growth reducing factor, (B) injury and damage, and (C) crop protection.

the system studied is the crop, growing under prevailing environmental conditions and at a given level of infestation.

In this Section a general approach to analyzing the causes of yield loss due to growth reducing factors is presented with some emphasis on insects. This framework is illustrated with an example from the Wageningen school of production ecology.

Factors affecting damage thresholds

To study the causes of yield loss due to insects and pathogens, but also due to other growth reducing factors, understanding of growth and development of the healthy crop is required (Peng, this volume). This physiological knowledge may be used to develop hypotheses on the factors which affect the relation between yield loss and pest density.

Dynamic crop growth simulation models provide a powerful tool for quantitative evaluation of the hypotheses.

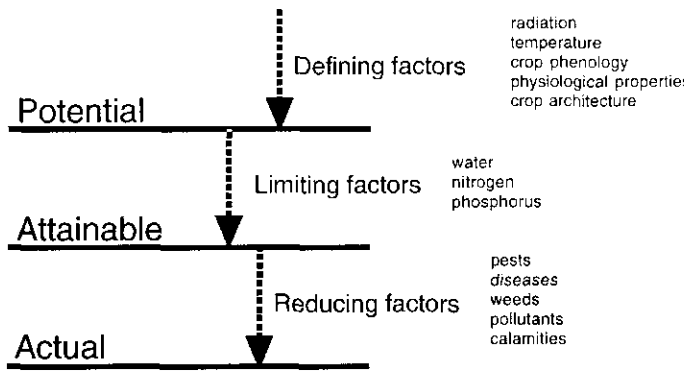

Figure 2.11. Levels of crop production.

Growth rates of crops vary between years and locations, depending on the amount of light (solar radiation, 400-700 nm) received by the crop. However, variation in crop growth rate and yield may also be caused by other factors. According to resource levels and the presence or absence of injurious factors, three yield levels can be defined: the potential yield level, the attainable level and the actual level (Figure 2.11, Zadoks and Schein, 1979).

Potential yields are attained when crops grow with an ample supply of water and nutrients, while harmful biotic and abiotic agents are absent. Such situations are rare and may occur only in protected cultivation. Under such conditions, yield depends on site-specific abiotic conditions and crop physiological characteristics. Together these factors constitute the growth and yield defining factors. Potential growth rates appear to be in the order of 15-35 g dry matter (DM) m^{-2} d^{-1}. Expressed per unit of light, by definition the only limiting resource under optimal conditions, the growth rate is approximately 3 µg (DM) J^{-1} (light).

Shortage of water, nutrients, or both, limits yield to the attainable level (Figure 2.11). In addition to uptake of CO_2, which is used in photosynthesis, transpiration of water takes place through the stomata. The rate of transpiration depends on radiation, vapour pressure deficit, and stomatal aperture. The transpiration coefficient, the ratio of transpiration and CO_2 assimilation, is about 150 to 300 g (water) g^{-1} (DM). Thus, to maintain a potential growth rate of 25 g dry matter (DM) m^{-2} d^{-1}, 4,000 to 8,000 g (water) m^{-2}, or 4 to 8 mm, must be available for transpiration each day. Nitrogen concentrations of approximately 6 % of the leaf dry matter are needed to maintain rates of CO_2 assimilation needed for potential crop growth rates. The amount of nitrogen needed to support potential growth of a crop with a leaf area index of 4 m^2 (leaf) m^{-2} (ground) and a specific leaf area of 20 m^2 (leaf) kg^{-1} (leaf DM) is 12 g m^{-2}. When less nitrogen is available in the leaf, the rate of photosynthesis is reduced. The figures presented are rules of thumb. Methods for

estimating water- or nutrient-limited growth rates are described in more detail by Van Keulen and Wolf (1986).

Pests, diseases, weeds, extreme weather conditions or pollutants reduce yield to the level which is actually realized in the field (Figure 2.11). The size of the yield reduction, i.e. yield loss or damage (Zadoks, 1985), depends on (1) the growth rate of the healthy crop, (2) the timing and the intensity of growth reduction, and (3) the plant processes affected by a growth reducing factor, i.e. damage mechanisms or injury components (Rossing et al., 1992).

The growth rate of the healthy crop must be known to be able to calculate the yield reduction caused by a particular growth reducing factor. Potential crop growth rates probably occur on less than 1 % of the total cropping area (Rabbinge, 1986). Therefore, damage caused by a growth reducing factor will usually be overestimated when it is calculated with reference to potential yield.

For insects, pathogens and other biotic growth reducing factors the timing and the intensity of growth reduction depends on their phenology and population dynamics.

An example of the effect of intensity and timing of attack is found in field experiments by Kropff et al. (1984). Maize biomass was lower at high densities of

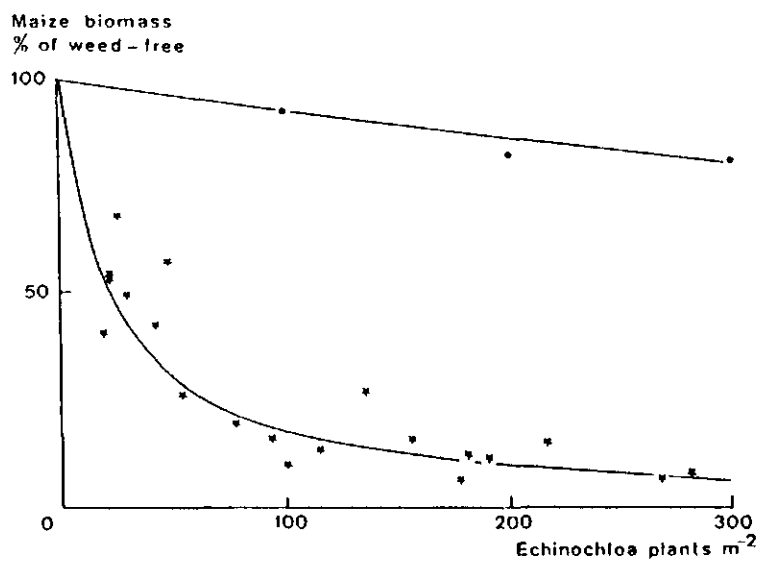

Figure 2.12. Final above-ground biomass of maize in 1982 (•) and 1983 (*), expressed as % of weed-free control, in dependence of initial density of *E. crus-galli* (Kropff et al., 1984).

Echinochloa crus-galli than at low densities. However, while in 1982, a density of 100 *E. crus-galli.* plants per m^2 in a maize field caused a yield loss of 8 %, the same weed density caused a yield reduction of 88 % in 1983 (Figure 2.12.). Analysis of these experiments with a simulation model for crop-weed interaction showed the difference between the two years to be explained completely by the difference in emergence of the weed, relative to emergence of the maize plants: in 1982 the crop emerged 5 days before the weed and did not have to compete for light with the weed. In 1983, however, crop emergence coincided with weed emergence, resulting in intense competition for light (Spitters, 1984). A statistical approach based on data of either year would not have been able to explain the events in the other year.

This example, which can be supplemented with many others, indicates that crop losses due to insects, pathogens and other growth reducing factors may be a complex function of a large number of variables. Experimental studies are unlikely to unravel the way in which these multifactorial systems function, especially if the variables covary with each other. However, explanatory simulation models of crop growth provide powerful vehicles for identifying the major mechanisms leading to yield loss.

Crop growth models as tools for development of damage thresholds

Crop growth at the potential production level can be modelled at different levels of physiological detail (Spitters, 1990). The set of models based on MACROS-L1D (Penning de Vries et al., 1989) and its successor ORYZA1 (Kropff et al., 1993), used in SARP represents a comprehensive approach to crop growth starting at the whole plant level (Figure 2.13). Light utilization by individual leaves is combined with the light profile within the crop to arrive at estimates of daily crop growth rates. Light utilization is described by the light response curve (Figure 2.14). In the model the vertical light profile is calculated using, basically, Beer's law for the penetration of three distinct light fluxes in the canopy: direct, diffuse and scattered light. At selected depths within the canopy and at selected times of the day, the rate of gross CO_2 assimilation is calculated using the response of individual leaves to light. The rate of gross CO_2 assimilation by the crop during one day is found by integration over the layers within the canopy and over the time within the day. The rate of daily dry matter production is found by subtracting the rate of maintenance respiration from the calculated gross assimilation rate and accounting for the costs of allocation of the assimilates to various organs, and conversion into structural biomass. Integration over the days in the growing season results in total dry matter production.

Analysis of the effect of a growth reducing factor on crop growth and production proceeds along the steps summarized in Figure 2.15. The effects of insect attack, the damage mechanisms, are expressed in terms of crop growth processes affected (Rabbinge and Rijsdijk, 1981). Boote et al. (1983) presented a phenomenological classification of

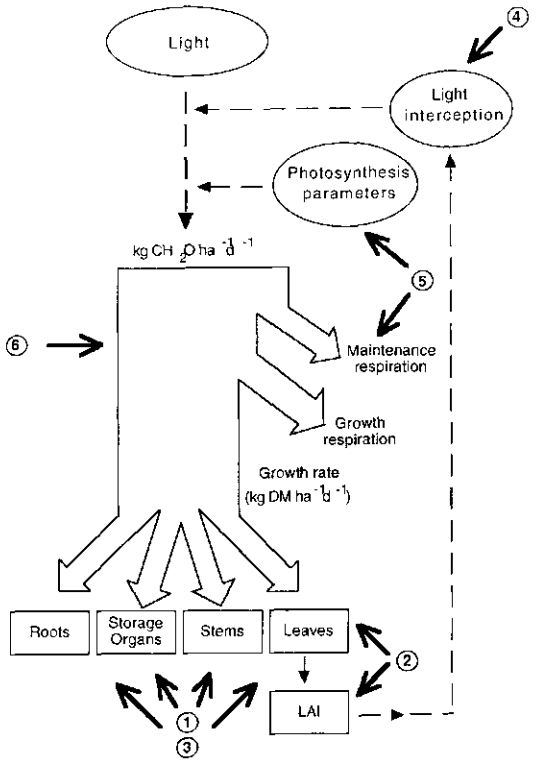

Figure 2.13.
Schematic representation of an explanatory approach to modelling crop growth and injury utilizing the light profile within the canopy, photosynthesis characteristics of individual leaves, respiration and dry matter partitioning factors (after Spitters, 1990). Arrows indicate potential components of injury: tissue consumption (1), leaf senescence acceleration (2), stand reduction (3), light theft (4), (net) photosynthetic rate reduction (5), and assimilate sapping (6).

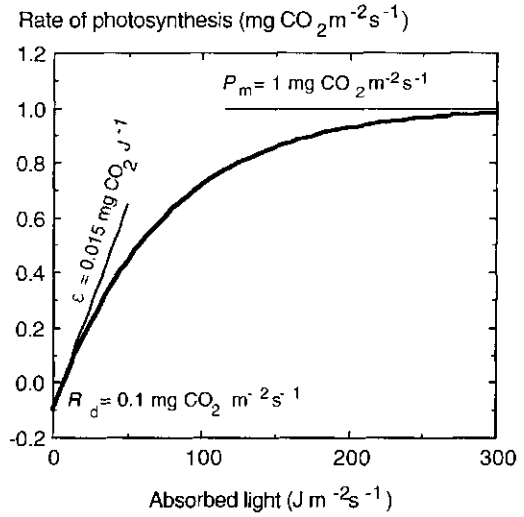

Figure 2.14.
Photosynthesis-light response curve, characterized by the parameters Pm,the maximum rate of photosynthesis, e, the initial light use efficiency, and Rd, the rate of dark respiration. The curve is described by a negative exponential equation.

of various damage components to total damage is shown in Figure 2.17. For the conditions used in the simulation, direct effects account for approximately 35 % of the total damage.

Application: damage at different attainable yield levels. The model was used to evaluate the damage caused by an aphid population under various crop growth conditions (Rossing, 1990b). For this purpose the model was initialized with crop data of a number of field experiments in which nitrogen input was varied. Temperature and radiation data were 33-year averages of Wageningen, the Netherlands. An exponentially growing aphid population was introduced with a peak density of 17 aphids tiller^{-1} at development stage late milky ripe. The results show that at low and moderate attainable yields aphid damage increases linearly with yield of the control. At high attainable yields (over 9000 kg ha^{-1}) damage exceeds the linear trend. High yield levels are attained only when green leaf area duration is large, resulting in more damage by honeydew. Later during the development of the crop the effects of honeydew are dominated by the direct effects, because honeydew effects take some time to develop. Then, aphid damage is independent of attainable yield.

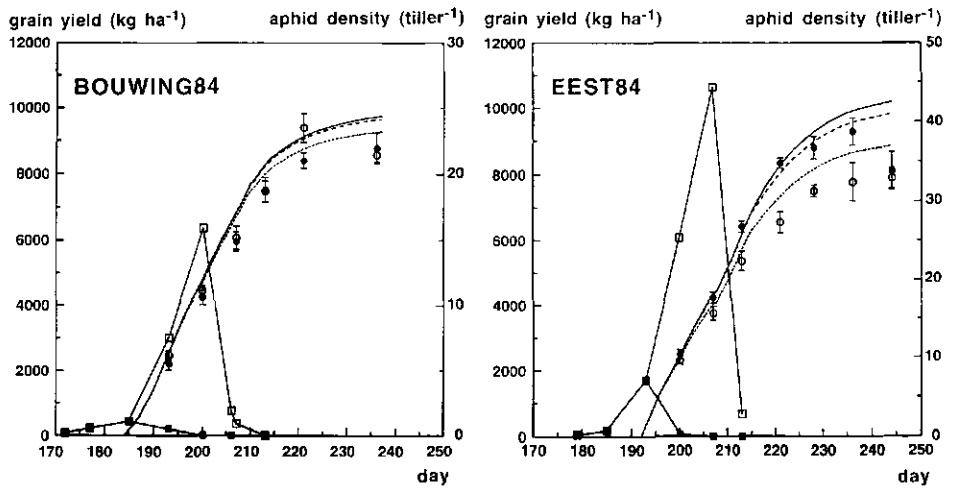

Figure 2.16. Actual and simulated grain yield for two infestations of *Sitobion avenae*. Vertical bars represent standard errors of the mean. Observed grain yield of the control (•) and the most severely infested treatment (o). Simulated grain yield without aphids (——), with an aphid infestation as observed in the control treatment (– – –) and in the most severely infested treatment (----), respectively. The size of the aphid infestations is shown for the control (—■—) ad the most severe infestation (—□—)

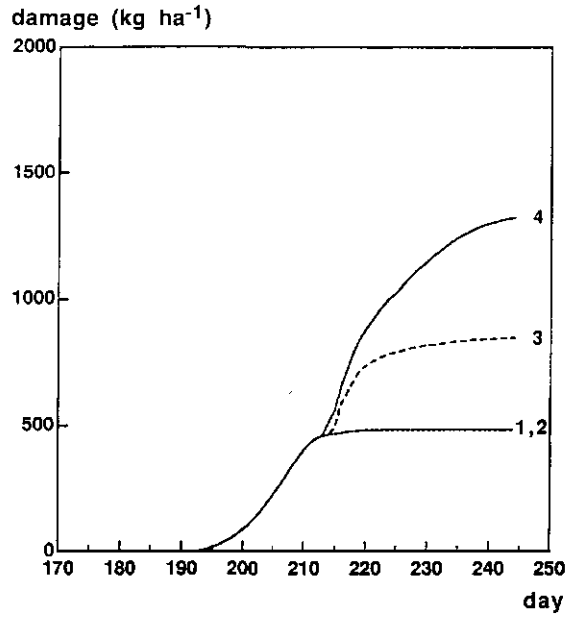

Figure 2.17. Simulated total damage by *S. avenae* (grain yield reduction, kg ha^{-1}) and the contribution of each damage mechanism. 1: carbohydrate uptake. 2: carbohydrate uptake and nitrogen uptake. 3: carbohydrate and nitrogen uptake + increased maintenance respiration. 4: carbohydrate and nitrogen uptake + increased maintenance respiration + decreased photosynthesis at light saturation.

Conclusion

The example in this Section illustrates the use and the usefulness of explanatory crop growth models in studies on damage by pests and diseases. Methodologically similar studies have been made on damage by other harmful agents, e.g. leaf blast (*Pyricularia oryzae*) in rice (Bastiaans, 1993), brown plant hopper (*Nilaparvata lugens*) in rice (Kenmore, 1980), powdery mildew (*Erysiphe graminis*) on winter wheat (Daamen and Jorritsma, 1990), barnyard grass (*Echinochloa crus-galli*) in maize (Spitters, 1989), and SO2 in faba bean (Kropff, 1989). The aim of this type of work is to obtain better insight into the effects of growth reducing factors on the physiology and production of crops in interplay with growth defining and growth limiting factors. Such insight is needed for rationalizing pesticide usage, such that productivity of crop can be maintained with a minimum of negative effects on the environment.

A major bottleneck for widespread application of this production ecological approach (Rabbinge, 1986) is the availability of suitable information at both the process and the systems levels. To quantify damage mechanisms information is needed of the effects of growth reducing factors on plant growth processes, such as photosynthesis, respiration, leaf area development, and tillering. To test the crop growth model in which relevant damage mechanisms are accounted for requires data of the consequences of growth reducing factors on the state of the crop, such as biomass of various crop organs, area of leaves, and crop development stage. In comparison with the traditional statistical approach the effort per field experiment is higher. However, as a result of the explanatory nature of the approach experiments of different locations can be used to develop the same model. Thus, the approach offers excellent perspectives for increasing efficiency when used in research in a network.

2.3 Case study: Growth and development of rice in response to artificial stem borer damage*

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Introduction

Stem borers (*Scirpophaga incertulas* Wlk., *Chilo suppresalis* Wlk., *Scirpophaga innotata* Wlk., *Sesamia inferens* Wlk., *Chilo polychrysus* Mey.) are among the most important pests of rice (*Oryza sativa* L.). In reports from some provinces of 11 countries, estimated rice yield losses attributed to stem borers ranged from 3 to 95 % (Frances, 1965; Isa et al., 1971; Barr et al., 1975; Ho, 1984b; Ahmed, 1984; Tantawi et al., 1985). Total crop losses were reported in 4 districts of Pakistan (Moiz and Rizvi, 1971), and in some fields of Bangladesh (Barr et al., 1975), and Formosa (Frances, 1965).

Insecticides may control stem borer infestation, but they are expensive and may pose health hazards to farmers and consumers. Furthermore, pesticides may be toxic to the natural enemies of stem borer and other pests so that their use may cause future resurgence of pest populations (Kenmore et al., 1984).

Active tillering in rice occurs from about 10 days after transplanting (DAT) to about panicle initiation (Yoshida, 1981). Typically, rice produces more tillers than are retained until harvest; after panicle initiation up to 50 % of tillers may be aborted.

Stem borers can attack rice from seedling stage to maturity (Frances, 1965; Calora and Reyes, 1971). Stem borer larvae feed on leaf sheaths. A few days after hatching they bore into internodes and feed on stems. Each larva may attack 3 or 4 tillers on 2 hills (Rothschild, 1971).

Economic thresholds aid in the proper timing of control measures. During the middle to late vegetative development phase, thresholds for rice stem borers are based on fractions or numbers of damaged tillers, called deadhearts, or on numbers of egg masses or moths present. The former proved unreliable because by the time deadhearts are observed, the pest has pupated and spraying is not effective as pupae do not feed (Bandong and Litsinger, 1986). Nevertheless, most farmers base their decision of when to

* Figures are shown at the end of this Section

spray on insect injury rather than on the presence of insects (Bandong and Litsinger, 1986) probably because moths and egg masses are less visible than deadhearts.
Stem borer injury during the reproductive phase results in panicles with unfilled spikelets, called whiteheads. The relationship between whiteheads and grain yield is well established (Wyatt, 1957; Pathak, 1968; Rai and Naidu, 1974; van Halteren, 1977; Rubia et al., 1989). On the other hand, the relationship between deadhearts and yield is not clear. Majar et al. (1985) found that 10 % deadhearts up to 60 DAT was not correlated with yield loss. Ho (1984a) reported that plants with 10 to 50 % deadhearts at 35 DAT recovered and produced grains. Van Halteren (1977) noted that the number of deadhearts is a poor indicator of yield loss. This lack of correlation between deadhearts and yield could be due to the ability of rice to compensate for damaged tillers. During the vegetative growth phase new tillers can be formed after infestation, but not all new tillers may bear panicles and not all panicles may be mature at harvest (Israel and Vedamoorthy, 1958; Ahmed, 1984; Akinsola, 1984).

Because the severity and timing of injury by naturally occurring insect infestation is difficult to regulate, artificial stem borer injury in rice has been used. Htun (1976) and El-Abdallah and Metwally (1984) simulated deadhearts by destroying the growing point of tillers with a needle. Htun found that at a particular level of detillering yield decreased as age of the crop at detillering increased. Similar findings were obtained by El-Abdallah and Metwally (1984) but they also found the heaviest grains after 10 % detillering imposed at 40 DAT and after 2 and 6 % detillering at 60 DAT. Another method of simulating stem borer damage is by clipping of tillers (Rubia et al., 1989). Five, 15, 30 and 60 % detillering did not affect the grain yield at 23 DAT, but at 43 and 77 DAT, there was a linear relationship between grain yield and injury level.

The effects of stem borer infestation, natural or artificial, on grain yield at different growth stages depend on the crop's ability to respond to or compensate for stem borer injury during its growth and development. Detailed analyses of growth and development of rice attacked by stem borer are, however, not available.

Therefore, the objectives of this study were: (1) to quantify the effects of different levels of artificial stem borer injury at different growth stages of lowland rice by means of growth analysis; 2) to determine the ability of rice to compensate for or recover from the injury; and 3) to provide data for studies of stem borer injury and damage using crop-pest modeling and simulation.

Materials and methods

Rice (*Oryza sativa* L.) var. IR64 was grown in a lowland site at the International Rice Research Institute, Los Baños, Laguna, Philippines from February to March 1987 (dry season) and October 1987 to January 1988 (wet season). Seeds were sown on a seedbed and protected with a nylon net to avoid early infestation of green leafhopper (*Nephotettix* spp.). At 20 days after seeding seedlings were uprooted from the seedbed and transplanted

in a well-puddled field. Planting density was 20 x 20 cm with 3 seedlings per hill. One day before transplanting N, P, and K were broadcast at 60:30:30 kg/ha and incorporated into the soil by harrowing. At 41 DAT for the dry season and at 35 DAT for the wet season additional 30 kg N ha^{-1} was broadcast. Insecticides were applied to control natural insect pests.

To impose artificial stem borer injury, 0.25 ml of 25 ppm paraquat was injected at the growing point of tillers (Table 2.1). The technique was based on a preliminary greenhouse experiment in which all injected tillers were observed dead within 7 days after injection. The procedure mimicks natural stem borer injury which resluts in decreased flows of nutrients and carbohydrates to panicles on attacked tillers. The herbicide-injected tillers remain in the crop, thsu reperesenting better a natural infestation than if tillers were cut and removed. Zero (control), 10, 30, or 60 % of the tillers were injected at 23 (early vegetative), 33 (near maximum tillering), and 43 (panicle initiation) DAT for dry season experiment and at 26 (vegetative) and 46 (after panicle initiation) DAT for wet season experiment. In dry season experiment, 0, 10, 30, or 60 % of the exerted panicles were injected at 69 DAT (flowering). Detillering during flowering was not carried out in the wet season experiment because of a strong typhoon on November 27, 1987 (50 DAT) which caused lodging of many plants. Another strong typhoon occurred at 67 DAT.
The experiments were arranged in a randomized complete block design with 4 replications in the dry season experiment and 3 in the wet season experiment. Destructive

Table 2.1a. Number of tillers per m^2 injected with paraquat at different growth stages. Mean of four replications. Dry season, 1987.

	Crop Age at Detillering (DAT)			
Injury (% tillers)	23	33	43	69*
10	29	56	61	18
30	81	172	160	56
60	184	324	350	137

*Injury was based on number of exerted panicles.

Table 2.1b. Number of tillers per m^2 injected with paraquat at different growth stages. Mean of three replications. Wet season, 1987.

	Crop Age at Detillering (DAT)	
Injury (% tillers)	26	46
10	44	52
30	136	143
60	280	308

plant sampling was done 12 times to measure dry matter accumulation and distribution, and leaf area. Sampling area was 0.32 m^2 (8 hills) for periodic biomass sampling. Plants were separated into leaf blade, leaf sheath plus culm, and panicle. Tillers and panicles were counted. Leaf blade area was measured with a Hayashi Denko (Model AAM-7) area meter. Plant parts were oven-dried at 80 °C for 2-3 days before measuring dry weight. At maturity panicle number, number of spikelets per panicle, percentage unfilled spikelets, and 100-grain weight were measured.

Leaf area index was computed as leaf blade area divided by ground area. Dry matter distribution among plant parts was calculated as the change in plant part dry weight divided by change in total shoot dry weight.

Analyses of variance were done on the data and means were separated on the basis of least significant differences.

Results

Leaf Area Index

Dry season. Leaf area index (LAI) increased until flowering (about 69 DAT), after which it declined as a result of senescence (Figure 2.18). The plants recovered fast from 10 and 30 % artificial stem borer injury during early vegetative growth (23 DAT) but not from 60 % detillering which reduced LAI at 70 DAT to 65 % of the LAI of the controls. Near maximum tillering (33 DAT) 10 % detillering had no significant effect on LAI but 30 and 60 % injury reduced LAI at 70 DAT to about 60 % and 45 % of the LAI of the controls, respectively. Results were similar for detillering at panicle initiation (43 DAT), except that 30 % injury reduced LAI at 70 DAT to 80 % of the LAI of the controls. Reduction of LAI 9 days after detillering was about 25 % for 10 and 30 % injury and 40 % for 60 % injury at 69 DAT.

Wet season. During vegetative growth (26 DAT) 10 % detillering did not significantly affect LAI except on 20 days after treatment (Figure 2.19). At 26 DAT, 30 and 60 % detillering significantly reduced LAI to 25 % of that of the control. All levels of injury after panicle initiation (46 DAT) reduced leaf area index.

Above-ground Dry Matter

Dry season. Trends in leaf blade dry weight followed those of leaf area index (Figure 2.20). Culm plus leaf sheath dry weights of control, 10, and 30 % detillered plants at 23 DAT increased until flowering and leveled off afterwards (Figure 2.21). Maximum shoot growth rate was about 25 g $m^{-2}d^{-1}$ which is typical for C3 crops growing under potential production conditions and high radiation intensities. The growth of culms plus leaf sheaths of plants detillered by 60 % at 23 DAT was slow but increased continuously resulting in similar weight as those plants with lower detillering rates. Culm plus leaf sheath dry weight of 10 % detillered plants at 33 DAT was significantly different from that of the control only at harvest. Culm plus leaf sheath at 30 and 60 % injury levels

increased with time but remained lower than that of controls. At 43 DAT, 30 and 60 % injury levels significantly decreased culm plus leaf sheath dry weight but 10 % detillering did not. After 86 DAT, there was sudden increase in culm plus leaf sheath dry weight of plants detillered by 60 % at 43 DAT because of formation of new tillers. Culm plus leaf sheath dry weight at all levels of detillering started to decrease nine days after treatment at 69 DAT.

As for other plant parts, 10 % and 30 % detillering at 23 DAT did not significantly affect panicle growth (Figure 2.22). For 60 % injury, panicle dry weight at harvest was reduced by 20 %. Panicle dry weight was not affected by 10 % detillering at 33 DAT but was affected by 30 and 60 % detillering. Panicle dry weight was reduced by all treatment levels at 43 and 69 DAT. Greatest reductions of panicle dry weight were observed in plants treated at 69 DAT.

Wet season. All levels of detillering at 26 and 46 DAT affected leaf blade dry weight (Figure 2.23). Leaf blade dry weights of plants detillered by 10, 30, and 60 % at 26 and 46 DAT decreased by up to 35, 50, and 85 % before 60 DAT. Similarly, detillering imposed at 26 and 46 DAT decreased culms plus leaf sheath (Figure 2.24) and panicle (Figure 2.25) dry weights. A strong typhoon at 67 DAT stopped growth after 70 DAT. Maximum shoot growth rate was about 17 g $m^{-2}d^{-1}$. Since water and nutrient supply were near optimum, the low growth rate was caused by low radiation levels.

Above-ground Dry Matter Distribution

Dry season. Distribution of dry matter among parts of the shoot is illustrated in (Figure 2.26). From 0 to 5 DAT there was no growth because of transplanting shock. Distribution of dry matter among leaf blades, culms plus leaf sheaths, and panicles was about the same for controls, plants detillered by 10 % at 23, 33, and 43 DAT, and for plants detillered by 30 % at 23 DAT. Plants detillered by 60 % at 23 DAT and more than 10 % at 33 and 43 DAT allocated dry matter to culms plus leaf sheaths at the expense of panicles after flowering. Culms plus leaf sheaths of these plants received 0.15 to 0.67 of the total dry matter after flowering whereas in the controls dry matter increase occurred only in the panicle.

Wet season. Early (26 DAT), strong (60 %) detillering caused leaf blade dry matter to increase at the expense of panicle dry matter (Figure 2.27). Detillering at 46 DAT increased allocation of dry matter to culms plus leaf sheaths at 10 % detillering. At 30 and 60 % detillering growth stopped after flowering (57 DAT).

Tiller Number

Dry season. All plants detillered at 23 DAT produced new tillers (Figure 2.28) At 23 DAT 60 % injury reduced tiller numbers by 40 % at maximum tillering. Because fewer tillers died from natural abortion after 60 % injury, tiller numbers between treatments were similar after flowering. Plants detillered at 33 DAT were still able to increase their tiller numbers. At 33 DAT, 60 % detillering had less effect on maximum tiller number than at 23 DAT but more tillers died from abortion at 33 DAT than at 23 DAT. When

detillering was carried out at 43 and 69 DAT no new tillers were produced after treatment. But new tillers were produced by plants detillered by 60 % at 43 DAT towards maturity. Fewer tillers died from natural abortion at 43 DAT such that tiller numbers at 10 and 30 % injury levels were about the same as in the controls.

Wet season. All plants detillered at 26 DAT produced new tillers (Figure 2.29). Ten percent detillering at 26 DAT did not significantly (p=0.05) affect the number of tillers. Tiller numbers of plants detillered by 30 and 60 % at 26 DAT remained significantly below those of controls. Plants treated at 46 DAT did not form new tillers.

Grain Yield and Yield Components

Dry season. Panicle number was reduced significantly by 60 % detillering at 43 DAT and by all detillering rates at 69 DAT (Table 2.2). Detillering at 69 DAT decreased the number of spikelets per panicle at 60 % injury and increased fraction of unfilled spikelets in all treatments (Tables 2.3 and 2.4). Detillering had no significant effect on 100-grain weight which was about 2.28 g.

Table 2.2. Panicles per m^2 at maturity for IR64 in response to artificial stemborer damage at different growth stages. Dry season, 1987.

	Crop Age at Detillering (DAT)			
Injury (% tillers)	23	33	43	69*
0 (Control)	402	402	402	402
10	364	418	377	263
30	410	350	336	188
60	359	402	190	132

LSD between detillering levels per initial crop age (p = 0.05): 74

Table 2.3. Spikelets per panicle at maturity for IR64 in response to artificial stemborer damage at different growth stages. Dry season, 1987.

	Crop Age at Detillering (DAT)			
Injury (% tillers)	23	33	43	69
0 (Control)	76	76	76	76
10	74	63	59	68
30	67	66	70	67
60	72	64	61	57

LSD between detillering levels per initial crop age (p = 0.05): 13

Table 2.4. Percentage unfilled spikelets at maturity for IR64 in response to artificial stemborer damage at different growth stages. Dry season, 1987.

	Crop Age at Detillering (DAT)			
Injury (% tillers)	23	33	43	69
0 (Control)	16	16	16	16
10	22	20	19	25
30	18	21	19	26
60	20	23	19	46

LSD between detillering levels per initial crop age ($p = 0.05$): 7

Table 2.5. Path coeffient analysis of effects of grain yield components on grain yield. Dry season, 1987. n = 52.

Variables	Direct Effect	Indirect Effect				Total Effect
		V1	V2	V3	V4	
Panicles/m^2 (V1)	0.506	---	0.054	0.101	0.023	0.684**
Spikelets/panicle (V2)	0.294	0.093	---	0.085	0.020	0.492**
Unfilled spikelets % (V3)	-0.210	-0.243	-0.119	---	-0.042	-0.614**
100-Grain weight (g) (V4)	0.115	0.102	0.051	0.077	---	0.345*

*, ** Significant at 5 and 1 % level, respectively.

Grain yield data (Figure 2.30) were presented by Rubia et al. (1989). To determine which yield component influenced most the grain yield a path coefficient analysis was performed (Table 2.5). The ratio of the direct effect to the total effect or correlation coefficient was highest for panicle number which means that panicle number mainly determined yield.

Wet season. Yield of control plants was only about 40 % of yield of control of the dry season experiment (Figure 2.31). Wet season grain yields, in general, were low because of low solar radiation and mechanical damage by typhoons. At 26 DAT, plants detillered by 60 % and all treatments at 46 DAT yielded less than controls.
Panicle number and spikelets per panicle of plants detillerd by 60 % at 26 DAT, and by 30 and 60 % at 46 DAT were less than those of controls (Tables 2.6 and 2.7). Detillering had no effect on percentage unfilled spikelets and grain weight (Tables 2.8 and 2.9).

Table 2.6. Panicles per m^2 at maturity for IR64 in response to artificial stemborer damage at 26 and 46 DT. Wet season, 1987.

	Crop Age at Detillering (DAT)	
Injury (% tillers)	26	46
0 (Control)	319	319
10	351	233
30	294	186
60	161	132

LSD between detillering levels per initial crop age ($p = 0.05$): 88

Table 2.7. Spikelets per panicle at maturity for IR64 in response to artificial stemborer damage at 26 and 46 DT. Wet season, 1987.

	Crop Age at Detillering (DAT)	
Injury (% tillers)	26	46
0 (Control)	76	76
10	69	60
30	64	47
60	46	51

LSD between detillering levels per initial crop age ($p = 0.05$): 19

Table 2.8. Unfilled spikelets at maturity for IR64 in response to artificial stemborer damage at 26 and 46 DT. Wet season, 1987.

	Crop Age at Detillering (DAT)	
Injury (% tillers)	26	46
0 (Control)	45	45
10	37	38
30	34	54
60	38	51

LSD between detillering levels per initial crop age ($p = 0.05$): 16

Table 2.9. One hundred-grain weight (g) at maturity for IR64 in response to artificial stemborer damage at 26 and 46 DT. Wet season, 1987.

Injury (% tillers)	Crop Age at Detillering (DAT)	
	26	46
0 (Control)	1.95	1.95
10	1.71	1.89
30	1.92	1.93
60	2.04	1.71

LSD between detillering levels per initial crop age ($p = 0.05$): 0.25

Discussion

The dry season experiment showed that leaf growth, tiller number, biomass, and yield fully recovered, that is, returned to levels equal to those of controls, from up to 30 % artificial stem borer detillering during early vegetative growth (23 DAT) and from 10 % detillering near maximum tillering (33 DAT). Plants only partially recovered after detillering by 60 % during early vegetative growth and by 30 and 60 % near maximum tillering. Plants detillered at panicle initiation (43 DAT) and flowering (69 DAT) failed to recover. IR64 grown during the wet season only partially recovered from 10 and 30 % detillering at 26 DAT because injury was imposed near maximum tillering.

Comparison between wet season grown plants detillered at 26 DAT and dry season grown plants detillered at 33 DAT indicates stem borer attack had greater effects on growth and yield of the former than the latter. To evaluate the extent to which differences in radiation levels between dry and wet seasons explain observed differences in growth and yield requires analysis with a crop growth model.

Compensation for injury was mainly through production of new tillers, not through increase in grain weight as reported by Ishikura (1964) and El-Abdallah and Metwally (1984) in rice, nor from increase in spikelets per panicle as observed by El-Alaoui et al. (1988) in barley (*Hordeum vulgare* L.). New tillers were formed in plants detillered by 60 % during early and late vegetative growth, but their yields were still reduced. Analysis of their yield components showed no significant effects on any of the components. This yield reduction could have resulted from distribution of dry matter to culms plus leaf sheaths even after flowering which was not true for control or other detillering levels during vegetative growth.

Detillering by injection of paraquat at the growing point of tillers resulted in slow death of tillers which probably nearly simulated actual formation of deadhearts or whiteheads. Yield loss was greater with paraquat injection than with clipping done in a parallel experiment (Rubia et al., 1989) probably because of contamination of non-target

panicles by paraquat, translocation of paraquat to uninjected tillers, or mechanical damage during paraquat injection.

The results suggest that during dry season up to 30 % detillering by stem borer during vegetative growth does not reduce yields and therefore, chemical control of stem borer should be avoided. By refraining from spraying natural enemies of stem borers and other pests are given a chance to increase in density, possibly resulting in natural pest control. During the reproductive phase, more than 10 % detillering results in yield loss as the compensatory ability of the crop has declined. In the wet season experiment, 10 % detillering at maximum tillering (46 DAT) significantly reduced yields, emphasizing the dependence of the economic threshold on environmental conditions. Comprehensive quantitative analysis of factors affecting the economic threshold requires a crop growth simulation model into which the effects of stem borer on physiological processes are introduced.

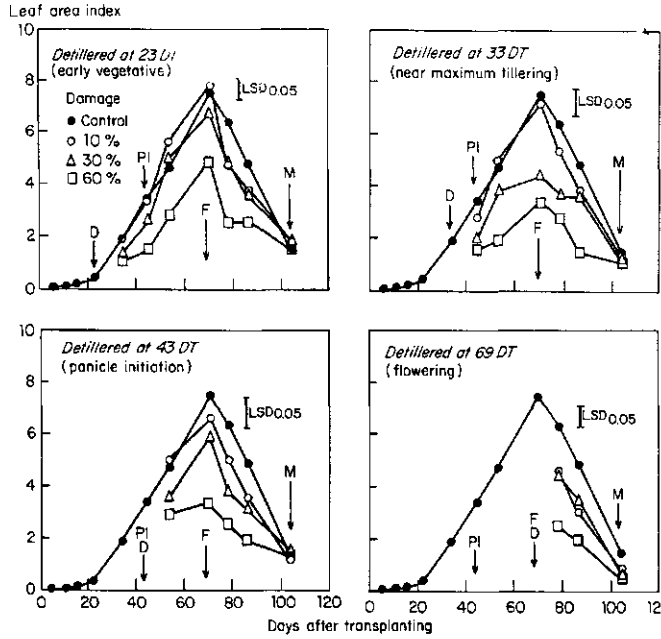

Figure 2.18. Leaf area index of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

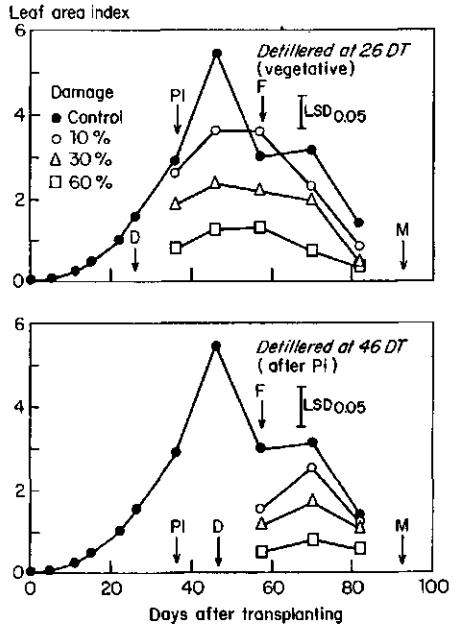

Figure 2.19.
Leaf area index of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

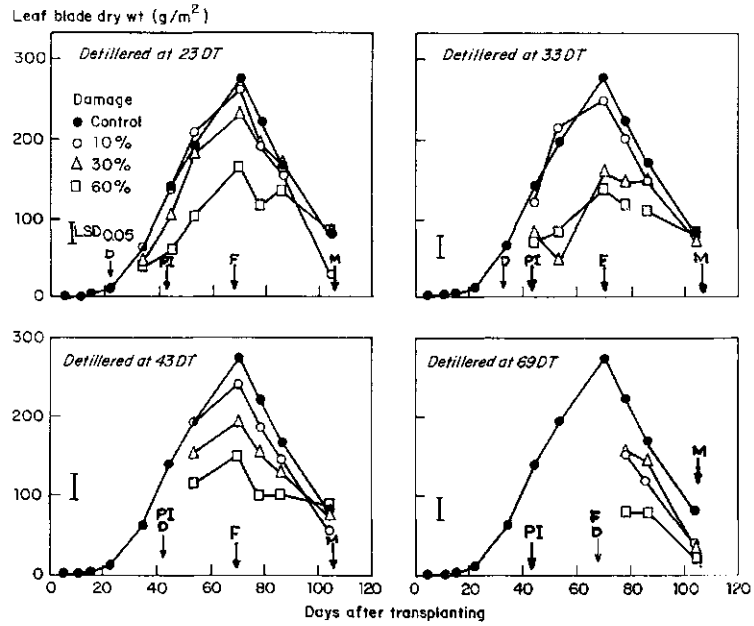

Figure 2.20. Leaf blade dry weight of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

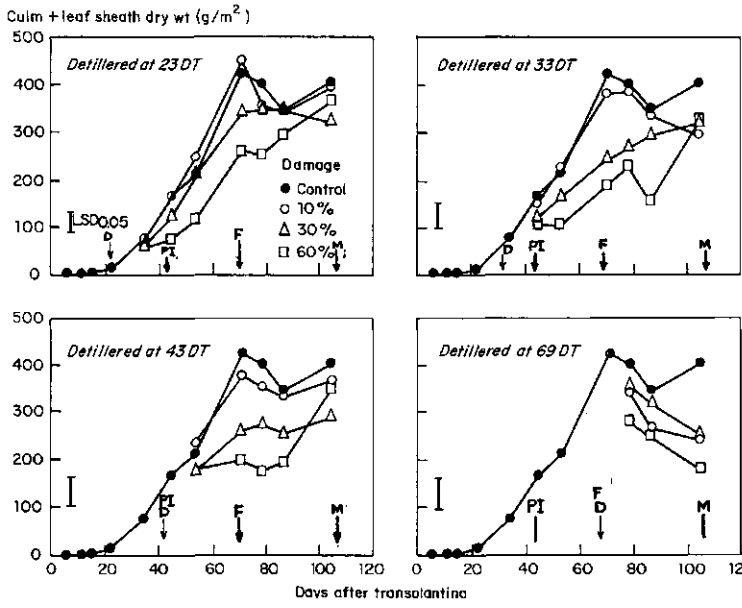

Figure 2.21. Culm plus leaf sheath dry weight of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

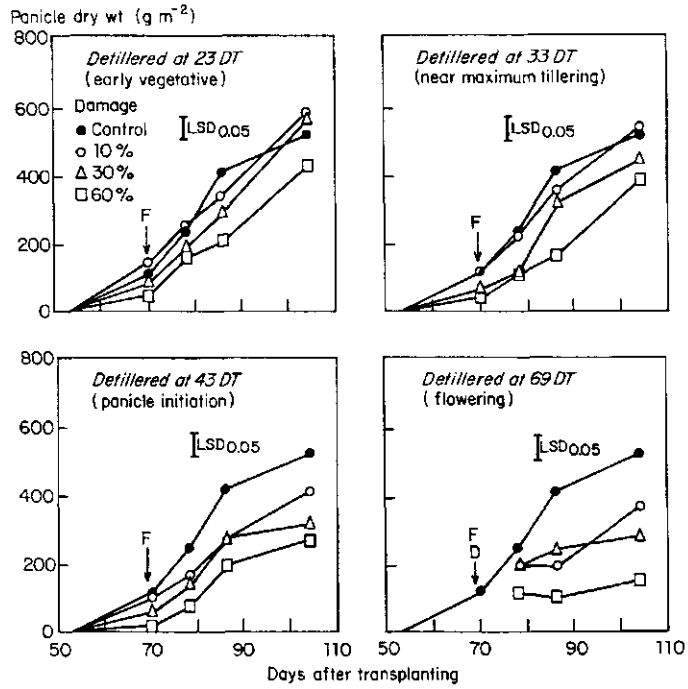

Figure 2.22. Panicle dry weight of IR64 as affected by stemborer damage at different times after transplanting. Dry season experiment, 1987. D = time of detillering, F = flowering.

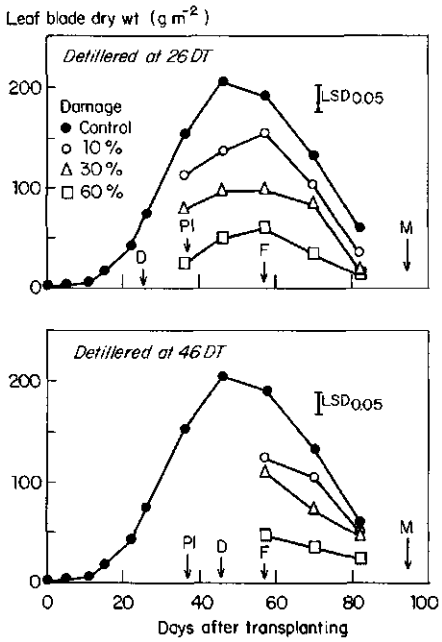

Figure 2.23.
Leaf blade dry weight of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

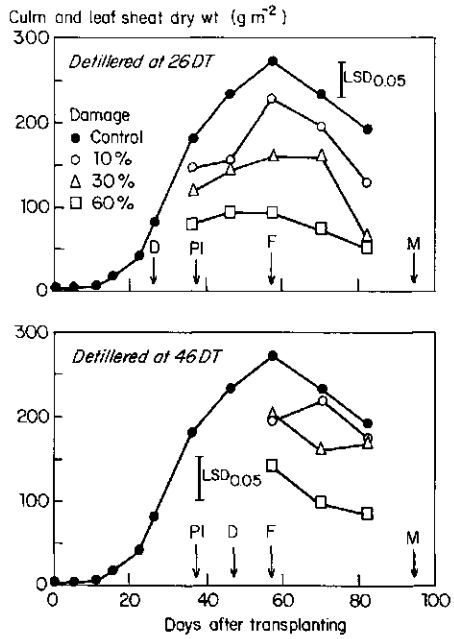

Figure 2.24.
Culm plus leaf sheath dry weight of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

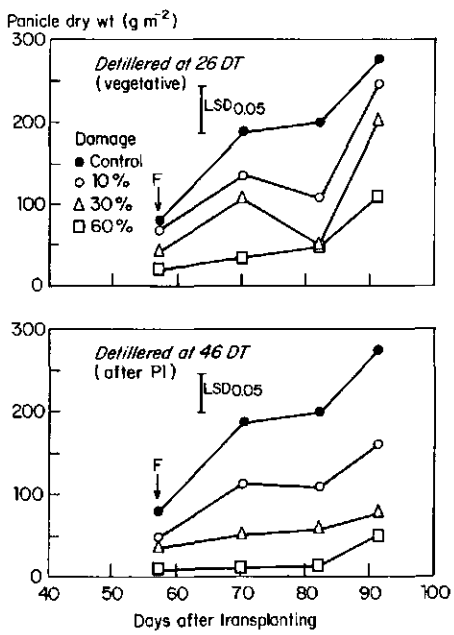

Figure 2.25.
Panicle dry weight of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987. PI = panicle initiation, F = flowering.

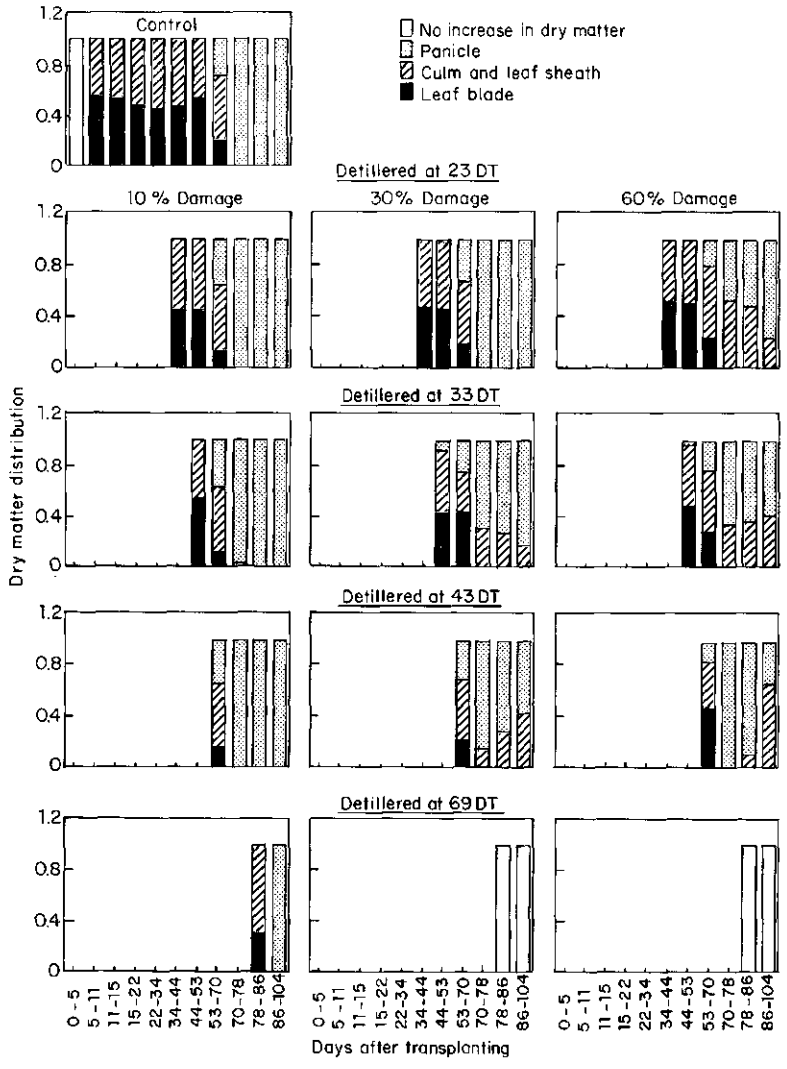

Figure 2.26. Dry matter distribution among plant parts of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987.

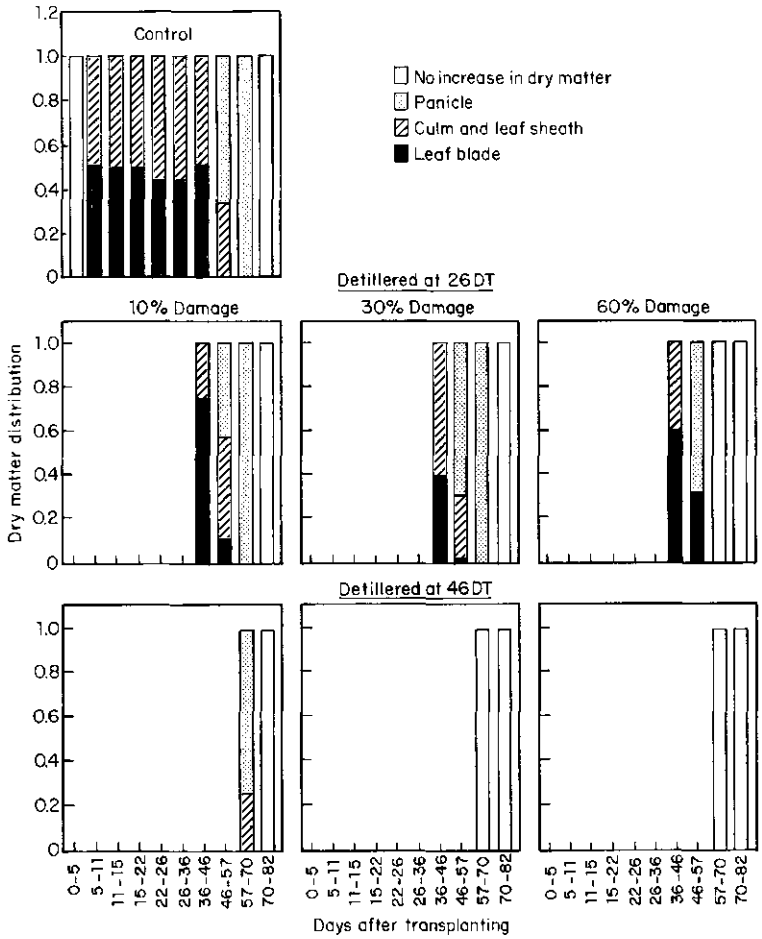

Figure 2.27. Dry matter distribution among plant parts of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987.

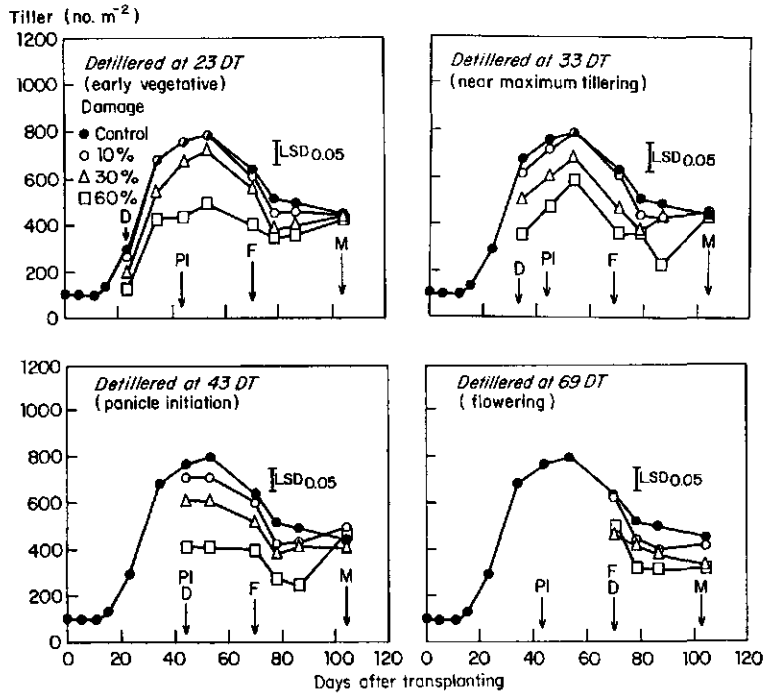

Figure 2.28. Number of tillers of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

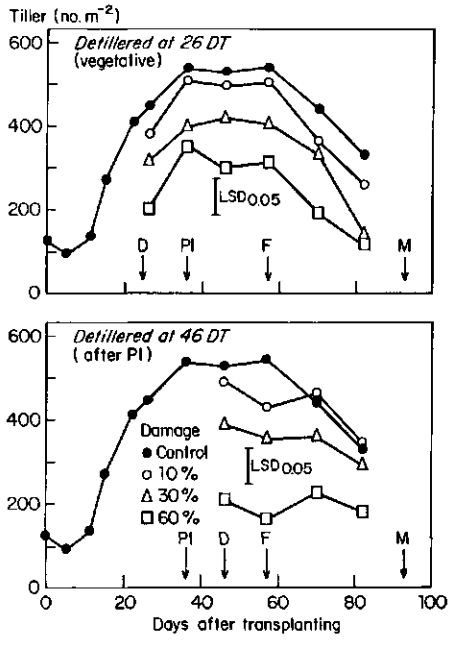

Figure 2.29.
Number of tillers of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987. D = time of detillering, PI = panicle initiation, F = flowering, M = maturity.

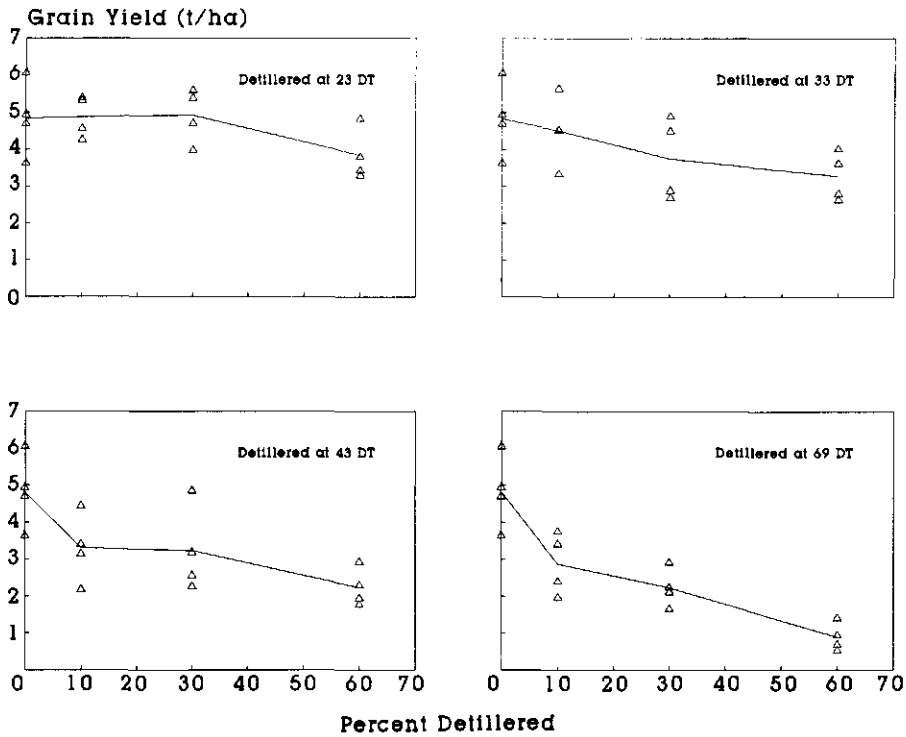

Figure 2.30. Grain yield of IR64 as affected by artificial stemborer damage at different times after transplanting. Dry season experiment, 1987 (Rubia et al., 1989).

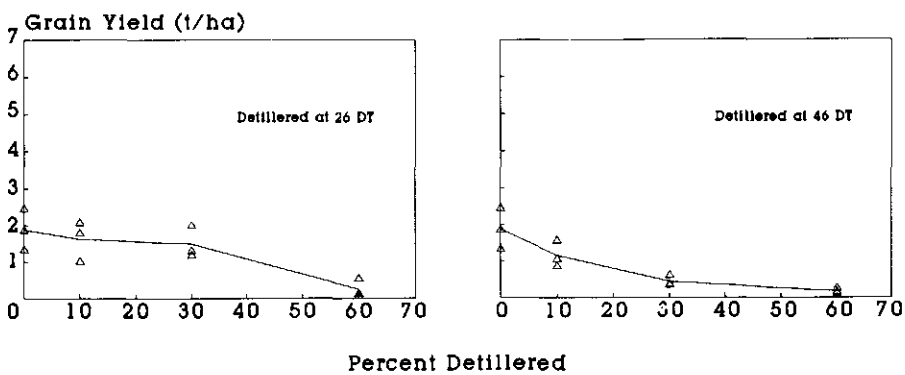

Figure 2.31. Grain yield of IR64 as affected by artificial stemborer damage at 26 and 46 DT. Wet season experiment, 1987.

3 State of the art of crop protection research in SARP

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3.1 Research on stem borer damage

In this Section the major entomological research activities of each of the teams are summarized. Detailed information on experiments and simulation is omitted.

Zhejiang Agricultural University, Mr. Xu Zhihong
In the province of Hangzhou two rice crops can be grown. Striped and pink stem borers constitute major pests. In 1988, a clipping experiment was carried out to establish damage by deadhearts and whiteheads. Results were presented during the 1989 SARP workshop on stem borer damage. The experiment was repeated in 1990 with two varieties, Bin-620 and GLA4. These experiments were analyzed using the L1D model into which tiller death due to stem borer was incorporated. In addition to experiments on damage by stem borer, research is done on the population dynamics of the pest. Recently attention had been focussed on survival of three species of stem borer in the early rice crop.

G.B. Pant University of Agriculture and Technology, Dr. P.K. Pathak
Rice in Pantnagar is grown once per year as a wet season crop. Currently the major pest in rice is yellow stem borer. In screening trials of Basmati rice infestations vary from 10 to 70 % whiteheads. There is an increase in stem borer incidence with the increase in area planted to the latest Basmati rice, Kasturi and Pusa Basmati. Experiments with clipping and artificial stem borer damage by herbicide injection were done with varieties IR36 and Pant Dhan 4. Observed results will be analyzed with a simulation model.

Khon Kaen University, Dr. Manochai Keerati-Kasikorn
Natural infestation of yellow stem borer at the Ubon Rice Research Centre was low during the wet seasons of 1986 to 1988, with infestation levels of approximately 6 % of the tillers. Control grain yields amounted to 3.3 ton ha^{-1}, except in 1987 when control yield was 1.9 ton ha^{-1}. In a detillering experiment conducted during the 1987 rainy

3.2 Research on bacterial leaf blight and sheath blight damage

The Central Rice Research Institute (CRRI), Cuttack, India, Dr. P.R. Reddy (BLB), Dr. U.D. Singh (ShBl)

A validation experiment for BLB was conducted in the wet season (June-September) of 1992 with the susceptible cultivar Annada. Different epidemics were obtained, e.g. disease severity of 24-70 % were reached in the top leaf layer during grain filling in the early inoculated treatments. However, differences in grain yield were small among treatments, which may be due to the fact that maximum severity during grain filling was similar for most treatments. The L1DFDE model over-estimated leaf and stem dry weight, but reproduced differences between treatments. On the whole, BLIGHT gave better simulation results.

In the 1992 experiments only very low disease severities were obtained, and therefore, in the 1993 experiments a high N level will be maintained to increase plant susceptibility.

In 1993, also validation experiments for ShBl will be started.

Tamil Nadu Agricultural University, The Tamil Nadu Rice Research Institute (TNAU-TNRRI), Aduthurai, India, Prof. Dr. V. Narasimhan (BLB)

Simulation studies on the basis of validation experiments for BLB, which were carried with cultivar IR50 in 1991, revealed that the effects of the disease could not be explained sufficiently by reduction of the photosynthesizing leaf area, and that functional relationships with photosynthesis and respiration had to be introduced.

Validation experiments were repeated in the wet season from November 1991 to February 1992. Inoculation at booting stage and at flowering stage caused 18 % and 9 % yield reduction, respectively. Radiation use efficiency was higher in the healthy crop than in the diseased crops. Simulated grain yields, obtained with L1DFDE, were 10-15 % under-estimated.

More validation experiments have been carried out in the 1992-93 season, and will be repeated in the 1993-94 season.

The G.P. Pant University of Agriculture and Technology (PUAT), Pantnagar, India, Dr. R.A. Singh (ShBl), Mr. B. Das (ShBl)

ShBl is a dominant disease in Uttar Pradesh, India. Investigations were undertaken with the objective to assess yield losses due to the disease at different crop development stages, in order to improve advises given to with respect to minimizing fungicide application.

Validation experiments for ShBl have been carried out with cultivar PD4 in 1991 and 1992. Data show that infection at maximum tillering stage has a stronger effect on the yield components that infection at panicle initiation stage. Tiller density reduces and chaffiness increases, whereas number of kernels per panicle and 1000-kernel weight were not influenced.Experimental results will be analyzed with the BLIGHT model.

Additional validation experiments will be carried out in the 1993 season.

4 Damage by stem borer, bacterial leaf blight and sheath blight in rice: conceptual models

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4.1 Aims and approaches

Entomologists and phytopathologists, like other experts, develop a conceptual model of the system they study, using experimental data and information obtained from literature. The conceptual model comprises hypotheses on crop-pest interactions. To test these hypotheses a fruitful approach is to develop a simulation model of system behavior, which constitutes the quantitative representation of the conceptual models. The simulation model is 'testable' i.e. its results can be compared to empirical data. Comparison with field data may lead to acceptance or rejection of the hypothesis or the conceptual model. Therefore, conceptual models of the rice crop with stem borer, bacterial leaf blight and sheath blight need to be established before embarking upon experiments and simulation. Brainstorming presents a useful tool towards this aim.

The brainstorming technique used during the stem borer workshop in Khon Kaen was adapted from the Goal Orientated Project Planning (GOPP) approach. Each participant expressed his/her idea by writing it on a card. The card was then pinned on a board for others to review. This approach can avoid language barriers and encourages participation. The cards were then rearranged and assigned into groupings through consensus of the group.

The brainstorming session was to elicit participants' opinions on the mechanisms of stem borer damage in rice under various external conditions, and the effect on yield. Three topics were raised:

I. What is the effect of deadhearts and whiteheads on yield components, compared to an uninfested control.

II. What is the effect of different levels of whiteheads at the end of the growing season on crop yield for high and low levels, respectively, of the following growing conditions: 1. nitrogen application; 2. radiation; 3. temperature; 4. planting density; 5. weed infestation; 6. water stress.

III. Describe yield response to different levels of whiteheads in terms of over-, under-, or exact compensation for high and low levels, respectively, of the growing conditions of topic II.

During the Cuttack workshop the brainstorm on damage mechanisms of bacterial leaf blight and sheath blight bore the character of an open exchange of opinion, centred around two questions, firstly, which are possible mechanisms by which bacterial leaf blight and sheath blight cause damage, and, secondly, which is the most important damage mechanism.

4.2 Results and discussion

Stemborer

For Topic I, discussions were on the timing of infestation in relation to effects on yield components. Participants agreed that a distinction between deadhearts and whiteheads for characterization of infestation during the vegetative phase and the reproductive phase, respectively, was oversimplified. Crop development was split up into the periods 'early vegetative', 'mid tillering', 'maximum tillering', 'panicle initiation', 'booting', 'flowering', and 'grain filling'. There was no consensus on the time of infestation which would result in whitehead formation. Both panicle initiation and booting were put forward as the first crop development stages at which infestation would result in whiteheads. For all yield components increases, decreases and neutral reactions to infestation in various phases of crop development were suggested (Figure 4.1). Infestation after booting appeared to cause more predictable effects than early infestation.

For topic II opinions differed especially on the interaction of plant density with end-of-season whitehead density (Figure 4.1). However, also for the other growing factors no consensus existed on the damage relation.

The brainstorm on topic III provoked discussions on the interpretation of 'compensation'. Participants agreed upon operationalizing compensation as yield of the infested crop relative to yield of an uninfested control. Overcompensation is equivalent to a yield ratio larger than 1, exact compensation to a ratio equal to 1 and undercompensation to a ratio smaller than 1. It was acknowledged that the level of infestation affects the compensatory reaction of the crop.

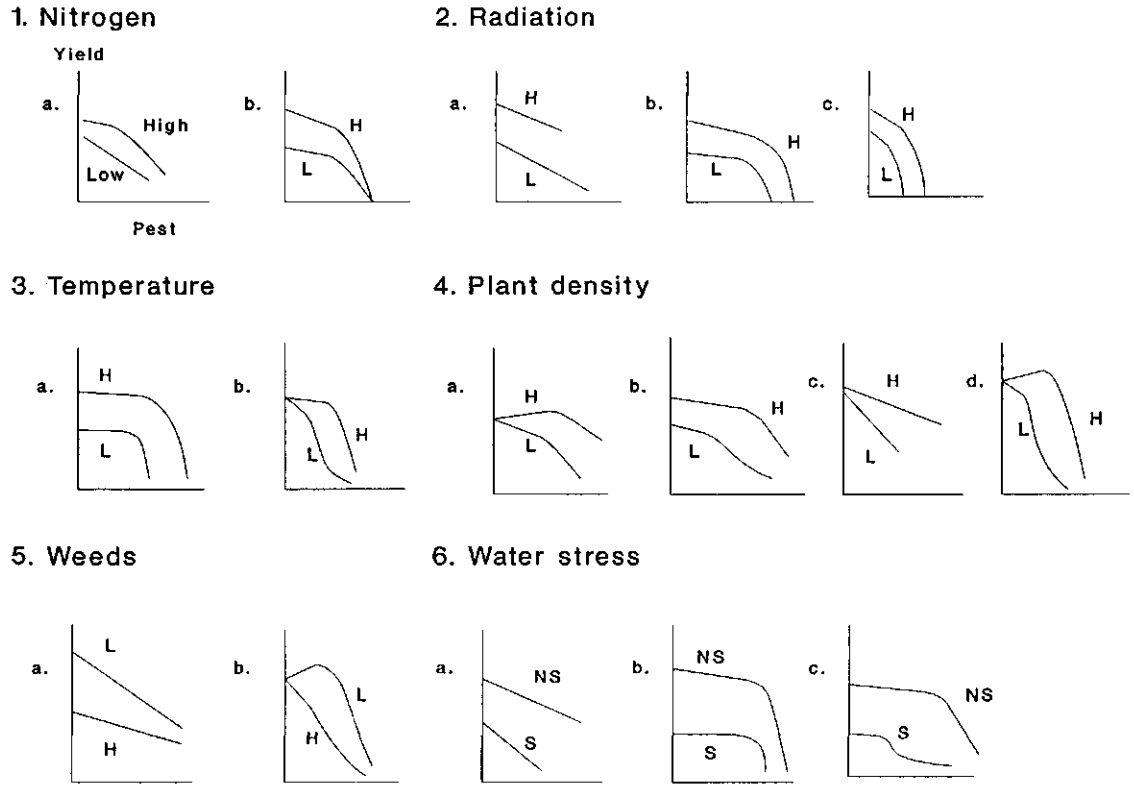

Figure 4.1. Overview of participants' opinions on stem borer - yield interactions at high and low levels of 6 growing conditions. H: high level; L: low level; NS: no water shortage; S: water shortage. More than one graph per growing condition indicates lack of agreement among participants.

Table 4.1. Effect of deadhearts and whiteheads on yield components at various crop stages [1].

Yield components	Deadhearts				Whiteheads		
	Early tillering	Mid tillering	Maximum tillering	Panicle Initiation	Booting	Flowering	Grain filling
Total panicles	I/N	I/N/	D/N/	D	D	D	D
% filled grains	N	N/?	N/D/	D	D/N	D	I/N
1000 grain wt	N	N	N/D	D/N	D/N	D	I/N
spikelet nr	D/N	D/N	I/N	D/N	N	N	N

[1] I = increase; D = decrease; N = no effect; P = plant dead; ? = no idea.

Table 4.2. Possible effects of different growing conditions at high/low levels on compensation[1].

Growing conditions and level		Compensation
1. Nitrogen	high	E/O
	low	U/E
2. Radiation	high	E/O
	low	U/E
3. Water stress	high	U/E
	low	U/E
4. Temperature	high	E/O
	low	E/U
5. Weed competition	high	U
	low	E/O
6. Plant density	high	E/O
	low	U/O

[1]U = undercompensation; E = equal; O = overcompensation.

Therefore, an infestation was assumed which resulted in 'average' intensity of whiteheads, implying late attack of the crop.

The results of the brainstorm (Table 4.1) show different opinions to exist for most growing conditions. Opposite views on the level of compensation existed on the effect of low planting density. The views on topic III were not always consistent with those on topic II.

Combining timing of infestation with growing conditions, a matrix was constructed of possible stem borer attack scenarios (Table 4.2). For the purpose of illustration, crop yield was expressed in terms of over-, under-, or exact compensation by the brainstorm

Table 4.3. Possible damage mechanisms of Bacterial Leaf Blight (BLB) and Sheath Blight (ShBl) for grain yield in rice (- = no importance, + = some importance, ++ = prime importance).

Damage mechanism	BLB	ShBl
Reduction of leaf blade area	+	++
Reduction of leaf sheath area	-	++
Disruption of translocation in sheaths	-	++
Reduction of leaf N content in diseased leaf tissue	+	-
Disruption of translocation to the panicle	-	+
Accelerated leaf senescence	+	+
Reduced tiller density	-	+
Reduced maximum photosynthesis	++	++
Increased respiration	+	+
Light stealing/shading	++	++

supervisor. The vast number of possible interactions between growing conditions, stem borer and crop made clear that a structure way of experimentally resolving the effect on yield was needed.

Bacterial leaf blight and sheath blight

Infection of seedlings with bacterial leaf blight results in destruction of whole plants, the so-called kresek phase of the disease. Teams stated that such early infections occur only in very susceptible cultivars which are not used in their mandate areas. Sheath blight infection seems to occur predominantly around maximum tillering, resulting in lesions on the sheaths, and in some cultivars on the leaf blades. During later crop development stages plants are less prone to infection by sheath blight and bacterial leaf blight.

Identification and prioritization of damage mechansisms is summarized in Table 4.3. Leaf area reduction, direct effects on leaf photosynthesis, and shading were hypothesized to represent major causes of damage by bacterial leaf blight. For sheath blight, green stem area reduction, accelerated senescence, disruption of translocation and possibly stand reduction were thought to be additionally important. Sheath blight was therefore identified as the more complex disease, in terms of damage mechanisms.

4.3 Conclusions

The brainstorm stimulated thinking about major factors influencing damage by insects and diseases in rice. For stem borer, timing of infestation was identified as very important. The distinction between early (deadhearts) and late (whiteheads) attack was considered insufficient for prediction of damage. Often the level of attack is expressed in terms of deadhearts and whiteheads, which represent the result of attack and give no information on the effects on crop growth in the course of the growing season.

Although the crop ecological effects of deadhearts are very different from those of whiteheads, no agreement existed among the participants on the relation between timing of attack and symptom development. This clearly represents a topic for further research. Also in other respects the conceptual models of stem borer damage differed considerably between expert participants. Generally, the qualitative categories distinguished in the brainstorm topics ('high' and 'low' nitrogen, etc.) and, most importantly, lack of knowledge on the system were considered the main causes.

Sheath blight was considered to affect crop growth by disruption of assimilate transport through the sheaths, in addition to the effects on leaf area and leaf functioning also identified for bacterial leaf blight. Whether such disruptions in a leaf sheath would affect apical transport of assimilates from lower leaves was not clear. The brainstorm clearly pointed to the relation between nitrogen input and epidemic severity. However, the effect of nitrogen on crop compensatory ability has received little attention.

5 Damage by stem borer in rice: a quantitative simulation model

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5.1 A model of sink-limited crop growth with one-day time step: L1DT

In this Chapter the conceptual model of stemborer damage in rice (Chapter 4) is translated into a quantitative simulation model. First, a model of crop growth and development of the healthy crop is presented (Section 5.1). Next, the major damage mechanisms are quantified and introduced into the crop growth model (Section 5.2). Finally, a sensitivity analysis is performed to assess the importance of various assumptions in the model for simulated yield and yield components (Section 5.3). The sensitivity analysis is presented in the form of exercises and answers.

Introduction

In *Simulation of ecophysiological processes of growth in several annual crops* (Penning de Vries et al., 1989) two modules to simulate potential crop growth are described: L1D and L1Q. Basic crop growth module L1D uses a time step of integration of one day while module L1Q uses a quarter day time step. By using the quarter day time step the course of temperature over the day can be taken into account. This is important in situations where day and night temperature differ greatly. A second difference between the two modules is that in module L1Q the dynamics of plant carbohydrate reserves are simulated in more detail. In L1Q translocation of reserves does not proceed according to a fixed rate, but depends on demand. Thus, simulated crop growth can be limited by both source size, as in L1D, and by sink size. An extra option of L1Q is the extention with module TIL, which simulates development of the sink by considering tillering and grain formation.
A drawback of module L1Q is the complexity of the model, which is mainly caused by the use of the quarter day time step. As a result frequent requests have been made by SARP participants to adapt model L1D in a way that would enable introduction of module

TIL. Module L1DT was developed for this purpose. The main adaptations to L1D are described in this Section.

Module TIL

In module TIL the formation rate of tillers, florets and grains is calculated. This module is based on concepts developed by Van Keulen and Seligman (1987). An explanation of this module can be found on page 94 in Penning de Vries et al. (1989). It should be noted that formation rates of tillers, florets and grains are assumed to depend on the daily net carbohydrate supply to the crop and that formation of each organ is restricted to a certain developmental period of the crop. The TIL-module thus requires the carbohydrate supply for crop growth (CAGCR) and the phenological development stage of the crop (DS) as inputs from the main module.
Sink size of the crop during grain filling is calculated as the number of grains multiplied by the maximum growth rate of an individual grain. The sink size determines the maximum growth rate for storage organs (GSOM), and is the output of the TIL-module to the main crop growth module.

Adaptations in module L1D related to the introduction of module TIL

After introduction of module TIL into the basic crop growth module, the growth rate of the storage organs (GSO) can be either source limited or sink limited. If the actual daily carbohydrate production exceeds the demand by the grains (GSOM), the carbohydrate surplus is stored in the stem. On the other hand, if the actual daily production is smaller than GSOM, the carbohydate supply to the grains will be supplemented by stem reserves. This demonstrates that use of module TIL requires flexible carbohydrate partitioning in the basic crop growth module during grain filling. Such flexible distribution of carbohydrates over reserves and kernels can be introduced into L1D by the following CSMP statements, which are explained below. A full listing of the model L1DT is given in Appendix A.2. New abbreviations are also described in Table 5.1.

```
0  CAGST   =  CAGSS*(1.-FSTR)*AFGEN(CASTT,DS)
1  CAGRSO  =  CAGSS-CAGLV-CAGST
2  CRGSOM  =  GSOM*CRGSO
3  CAGSR   =  INSW(CRGSOM-CAGRSO,(CAGRSO-CRGSOM)*0.947,...
                -AMIN1(WSR*0.1*1.111,(GRGSOM-CAGRSO)/0.947))
4  CAGSO   =  INSW(CRGSOM-CAGRSO,CRGSOM,CAGRSO-CAGSR*0.947)
5  GSR     =  CAGSR/1.111
6  RTSR    =  INSW(CRGSOM-CAGRSO,CAGSR/0.947,-CAGSR)*0.053*1.467
```

Table 5.1. New abbreviations used in L1DT in comparison with L1D.

Abbreviation	Explanation
CAGRSO	newly produced carbohydrates available for growth of stem reserves and storage organs (= carbohydrate supply) (kg CH_2O $ha^{-1}d^{-1}$).
CAGSR	carbohydrates available for growth of shielded reserves (kg CH_2O $ha^{-1}d^{-1}$); a negative value indicates that carbohydrates are removed.
CRGSOM	maximum growth rate of the storage organs expressed in carbohydrate equivalents (= carbohydrate demand) (kg CH_2O $ha^{-1}d^{-1}$).
NCLV	nitrogen content of leaves (g g^{-1}).
NCLVT	relation between DS and NCLV.
NGRM2	number of grains per m^2 (m^{-2}).
NGRPTI	number of grains per tiller (or panicle) (ha^{-1}).
NHILL	number of hills (ha^{-1}).
NTIM2	number of tillers per m^2 (m^{-2}).
NTIPH	number of tillers per hill (-).
PLMXN	correction factor to account for effect of leaf N-content on PLMX (-).
PLMXNT	relation between PLMXN and NCLV.
RTSR	rate of growth respiration due to transport of shielded reserves (kg CO_2 $ha^{-1}d^{-1}$).
WG1000	1000-grain weight at 14 % moisture (g).

line 0: CAGST refers to the carbohydrates available for the growth of the stem. In module L1D these comprise both structural material and stem reserves. In L1DT CAGST only includes carbohydrates available for the growth of structural stem material. For this purpose the original statement is extended with the multiplication factor (1.-FSTR), where FSTR represents the fraction remobilizable stem weight at flowering.

line 1: The amount of newly produced carbohydrates available for growth of stem reserves or storage organs (CAGRSO) is calculated as the amount of carbohydrates available for growth of the shoot (CAGSS) that remain after meeting the requirements for growth of leaves (CAGLV) and structural stem material (CAGST).

line 2: The demand of the grains is calculated as GSOM in module TIL, and expressed in g dry matter $ha^{-1}d^{-1}$. In order to be able to compare supply (CAGRSO) and

demand, the amount of carbohydrates required to meet demand (GSOM) are calculated: GSOM*CRGSO. CRGSOM is thus expressed in g CH2O $ha^{-1}d^{-1}$.

lines 3 and 4:These lines deal with the distribution of available carbohydrates over stem reserves (line 3) and grains (line 4). Both statements include an INSWitch function where in the first argument demand (CRGSOM) and supply (CAGRSO) are compared. If supply exceeds demand,CRGSOM-CAGRSO, the first argument of the INSW-function in line 3, is smaller than zero, and the function takes the value of the second argument. The requirements of the storage organs are met: CAGSO=CRGSOM (line 4). The surplus carbohydrates are incorporated as stem reserves: CAGSR=(CAGRSO-CRGSOM)*0.947 (line 3). Multiplication by 0.947 is needed to account for carbohydrates needed to cover the costs of transportation. The transportation costs are estimated at 5.3 % of the energy content of the transported carbohydrates (Penning de Vries et al., 1989; page 61).
If demand exceeds supply, CRGSOM-CAGRSO, the first argument of the INSW-function in line 3, is larger than zero, and the function takes the value of the third argument. Carbohydrate supply to the storage organs now is supplemented by stem reserves. The total amount needed from the stem reserves is CRGSOM-CAGRSO. Since some carbohydrates are required to cover the costs of transportation, the total withdrawal from stem reserves can be calculated as: (CRGSOM-GAGRSO)/0.947. However, there is a maximum to the amount of carbohydrates that can be withdrawn from stem reserves daily. This maximum is set to 10 %. Multiplication by 1.111 is needed to express the reserves (kg starch) in carbohydrate-equivalents. The multiplication factor represents the ratio between the molecular weights of glucose (C6H12O6=180) and starch (C6H10O5=162). To obtain the actual amount of carbohydrates withdrawn from the reserves, the minimum value of both arguments is selected with the AMIN-function. The negative sign indicates that carbohydrates are withdrawn, equivalent with a negative growth rate of the stem reserves. CAGSO comprisesthe newly produced assimilates (CAGRSO) and the contribution of stem reserves (-CAGSR*0.947; the factor 0.947 indicates that 5.3 weight-% is used to cover transportation costs).

line 5: Growth of shielded reserves (GSR) is calculated by dividing the carbohydrates available for the growth of stem reserves (CAGSR) by 1.111 (the ratio of molecular weights of starch and glucose, respectively). The multiplication factor 1/1.111 is comparable with CRGLV or CRGST (weight of carbohydrates required for the growth of leaves or stems, respectively). The main difference is that CRG.. values also account for costs of transportation. As discussed previously these costs are already taken care of in case of stem reserves.

line 6: The costs of transporting carbohydrates to or from stem reserves (RTSR) are calculated explicitely, since this value is required for the carbon balance. These costs are added to the growth respiration of the crop (RGCR). As mentioned previously the transportation costs are estimated to be 5.3 % of the energy content of the transported carbohydrates. An INSW-function is used to calculate the total

amount of carbohydrates used in the transport process. In case carbohydrates are added to the existing reserves, i.e. if CRGSOM-CAGRSO < 0, the amount of carbohydrates used can be calculated as CAGSR/0.947. In case carbohydrates are withdrawn from stem reserves, i.e. if CRGSOM-CAGRSO > 0, the amount used equals the amount of carbohydrates withdrawn (CAGSR). The minus sign is added to obtain a positive value. Multiplication by 1.467 (the ratio of molecular weights of carbohydrates (M=30) and CO_2 (M=44), respectively) is needed to convert carbohydrates into carbon dioxide-equivalents, since growth respiration is expressed in kg CO_2 $ha^{-1}d^{-1}$.

Adaptations of L1DT not related to the introduction of module TIL

N-dependent maximum leaf photosynthetic rate.

The maximum rate of carbon dioxide assimilation at high radiation levels (PLMX) depends upon the N concentration of the leaf. A consistent and lineair relationship between net photosynthesis at light saturation and leaf N content (g (N) m
(leaf)) of several Oryza species was found by Cook & Evans (1983). Penning de Vries et al. (1990) used these data to derive a relationship between PLMX (kg CO_2 ha^{-1} h^{-1}) and the fraction leaf N (g g^{-1}), for leaves with a specific leaf weight (SLW) of 300 kg ha^{-1}. To account for the effect of N on PLMX this relationship is introduced into the model:

```
0   PLMXN            =   AFGEN(PLMXNT,NCLV)
1   NCLV             =   AFGEN(NCLVT,DS)
2   PARAM PLMXP      =   45.
3   PLMX             =
    PLMXP*AFGEN(PLMTT,TPAD)*LIMIT(200.,600.,SLA)/300.*PLMXN
4   FUNCTION PLMXNT  =   0.,0., 0.005,0.01, 0.05,1., 0.07,1.3
5   FUNCTION NCLVT   =   0.,0.05,    0.2,0.05,    1.,0.04,    2.0,0.03,
                         2.1,0.03
```

line 0: PLMXN is a multiplication factor to correct PLMX for the N-content of leaves (NCLV; g (N) g^{-1} (leaf)).

line 1: The N-content of leaves is given as function of the phenological development stage. Similarly N-content may be related to Julian date.

line 2: PLMXP is the assimilation rate at light saturation for standard leaves (here: SLW=300 kg ha^{-1}; N-content= 0.05 g g^{-1}).

line 3: PLMX, the actual assimilation rate at light saturation is calculated by correcting PLMXP for temperature, SLW and N-content, respectively. The correction for temperature is identical to the one in module L1D. The same holds for the correction on specific leaf weight. SLC however has been replaced by 300., since

this is the SLW of standard leaves. Multiplication by PLMXN accounts for the effect of N-content on PLMX.

line 4: Function PLMXNT gives the relationship between NCLV and the correction factor for PLMX. For NCLV = 0.05 g g^{-1} (the N-content of standard leaves) the correction factor equals 1.

line 5: Function NCLVT gives the course of leaf N-content in dependence of phenological development stage. The values represent a crop in which N-content during grain filling is relatively high.

Additional output values

Extra output is generated to facilitate the comparison between field observations and model output:

```
0  NTIPH    =  NTI/NHILL
1  NTIM2    =  NTI/10000.
2  WG1000   =  (WGR*1.E6)*100./86.
3  NGRPTI   =  NGR/NTI
4  NGRM2    =  NGR/10000.
```

line 0: the number of tillers per hill (NTIPH) is calculated as the number of tillers (NTI; ha^{-1}) divided by the number of hills (NHILL; ha^{-1}).

line 1: the number of tillers per m^2 (NTIM2) is calculated as the number of tillers (NTI; ha^{-1}) divided by 10000 (m^2 ha^{-1}).

line 2: 1000 grain weight (WG1000; g) calculated from the individual grain weight (WGR; kg). Multiplication by 1.E6 represents the conversion of kg in g, and the conversion of individual grain weight to the weight of 1000 grains. Multiplication by (100./86.) is applied since 1000 grain weight is usually expressed on basis of 14 percent moisture. Note that the simulated 1000 grain weight is an average value, based on filled and unfilled grains. Experimentally determined 1000 grain weights usually refer to filled grains only.

line 3: the number of grains per tiller (NGRPTI) is calculated as the number of grains (NGR; ha^{-1}) divided by the number of tillers (NTI; ha^{-1}).

line 4: the number of grains per m^2 (NGRM2) is calculated as the number of grains (NGR; ha^{-1}) divided by 10000 (m^2 ha^{-1}).

5.2 A model of stem borer damage: L1DTSB

Introduction

Stem borers may infest the rice plant at any stage from seedling to maturity. Timing of infestion strongly affects the amount of yield loss. Infestation in the vegetative phase

results in dead tillers or deadhearts. Attack in the reproductive phase results in whiteheads. In this Section a model is described which simulates effects of stem borer on crop production. It consists of crop growth module L1DT (Section 5.1) extended with statements to simulate effects related to stem borer injury.

The model concept is based on general information about the stem borer-rice system. The model parameters are merely rough estimates. In its present form, the model should not be used for making predictions of yield reduction. Rather, the model is meant to structure thinking about the behaviour of an infested crop, specially with respect to the existence and functioning of compensation mechanisms. The increased understanding of the system obtained after analysis of the model results, will help to focus experimental research. In turn, experimental results will contribute to improvement of the model. Ultimately this interaction between experimentation and simulation should result in a sound understanding of yield reduction due to stem borer and a well tested damage model.

Model description

General structure

Infestation by stem borer is represented by a stem borer infestation rate, which is introduced as a forcing function. The stem borer infestation rate is a relative rate, expressing the fraction of newly infested tillers per day. Weights of the various organs of healthy tillers, leaf area and tiller number are reduced with a fraction identical to the infestation rate.

In the model only growth of healthy tillers is considered. Newly infested tillers are put into separate integrals representing weights, leaf area, and number of tillers, and their effect on the remaining tillers (through shading) is taken into account. Depending on the developmental stage of the crop newly infested tillers are classified as deadhearts or whiteheads. Deadhearts are assumed to remain in the canopy for a short period of time, after which they gradually disintegrate. Whiteheads are assumed to remain in the canopy till maturity. Just like healthy tillers they are subject to natural senescence. Whiteheads may contribute to kernel filling of healthy tillers. In the model this is introduced as an option.

Stem borer infestation rate

The stem borer infestation rate (SBINFR) is introduced as a forcing function, in dependence of either the phenological development stage (DS; line 1) or Julian date (DATE). It is a relative rate, expressing the fraction of healthy tillers that is infested per day:

```
1   SBINFR    =   AFGEN(SBINRT,DS)
```

Calculation of SBINFR from field observations is explained in Appendix A.4. Weight loss rates of the various plant organs are calculated using SBINFR (illustrated in line 2 for

leaf weight). Similarly the loss rate of tillers (line 3), florets and grains is calculated. Specific leaf weight (SLA and SSC) is used to derive the loss rate of leaf (line 4) and stem area:

```
2   LLVSB     =   WLV*SBINFR
3   LNTISB    =   NTI*SBINFR
4   LLASB     =   LLVSB/SLA
```

The loss rates are introduced into the integrals describing the weights of various crop organs, the leaf and stem areas, and the number of tillers. These integrals refer to healthy tillers only (line 5-7).

```
5   WLV       =   INTGRL(WLVI,GLV-LLV-LLVSB)
6   NTI       =   INTGRL(0.,GNFL-LNTISB)
7   ALVG      =   INTGRL(ALVI,GLA-LLA-LLASB)
```

New integrals are introduced to keep track of the weight of deadhearts (DH; line 9) and whiteheads (WH; line 10). Classification of newly infested tillers as deadhearts or whiteheads depends on the phenological development stage of the crop. Parameter DSWH (line 8) defines the development stage after which stem borer infestation leads to the formation of whiteheads. The value of 0.7 is just an estimate and should be determined through experimentation. In the model classification as deadheart of whitehead is arrived at with the help of an INSWitch function:

```
8   PARAM DSWH  =   0.7
9   WLVDH       =   INTGRL(0.,INSW(DS-DSWH,LLVSB,0.)-LLVDH)
10  WLVWH       =   INTGRL(0.,INSW(DS-DSWH,0.,LLVSB)-LLVWH)
```

As long as the phenological development stage (DS) is smaller than DSWH the first argument of the INSW-function is negative, and the function takes the value of the second argument. The newly infested tillers are then added to the integral which keeps track of the weight of deadhearts. The growth rate of whiteheads is zero. in this situation. In case DS is larger than DSWH the function takes the value of the third argument, and LLVSB is added to WLVWH. In this situation the growth rate of the deadhearts is zero.
Similar calculations are made for weights of the other crop components, the area of leaves and stems, and the number of tillers, florets and grains. Also in the following sections the procedure will only be illustrated for the weight of leaves.

Deadhearts
Deadhearts are assumed to remain in the canopy for a limited period of time. After their appearance an exponential decline of biomass, leaf area and number of deadhearts is assumed, characterized by a fixed average residence time (ARTDH; line 11). This

parameter ARTDH is used to calculate the rate of disappearance of deadhearts (illustrated for leaves in line 12; LLVDH). This loss rate is fed into the integral that keeps track of the weight of leaves of deadhearts (WLVDH;line 9).

```
11 PARAM ARTDH  =  14.
12 LLVDH        =  WLVDH/ARTDH
```

Whiteheads

Whiteheads are supposed to remain in the canopy until maturity. Due to natural senescence dry matter of green leaves and other organs decreases at a relative rate similar to that of healthy tillers (line 13 and 14). The loss rates are subtracted from the corresponding integrals (illustrated for leaf weight in line 10).

```
13 LLVWH    =  WLVWH*AFGEN(LLVT,DS)
14 LLAWH    =  LLVWH/SLA
```

Whitehead panicles which appear during late ripening contain already a certain fraction of filled grains. This implies that in such a situation not the entire weight of storage organs (WSO) of is lost. In the model this is not considered, since whiteheads appearing during late ripening are not a common phenomenon.

Shading effect of deadhearts and whiteheads

Deadhearts and whiteheads compete with healthy tillers for light and thus affect crop production. The effect of deadhearts and whiteheads on the production of healthy tillers is related to the relative fraction of leaf area that is occupied by the infested tillers. Growth of deadhearts and whiteheads is not considered in the model. Their share in the canopy is determined at the moment of infestation, and an increase in leaf area after infestation is considered absent. Although this assumption may be an over-simplification it seems appropriate for the simulation of competition for light. Deadhearts gradually disintegrate after infestation. Continuing carbon dioxide assimilation after infestation may enable the infested tillers to maintain themselves for some time. This is reflected in the average residence time of deadhearts in the model. Whiteheads appear only at later growth stages, when healthy leaf area growth is almost negligible. Ignoring growth of whiteheads in the model therefore hardly affects their competiveness. Competition for light is now modelled by:

```
15 ALV      =  ALVG+ALVDH+ALVWH
16 PCGC     =  FUPHOT(PLMX,PLEA,ALV,RDTM,DATE,LAT)
17 PCGW     =  (ALVG/ALV)*PCGC*PCEW
```

Total leaf area consists of leaf area of healthy tillers (ALVG), deadhearts (ALVDH) and whiteheads (ALVWH) (line 15). Gross photosynthesis is calculated with function

FUPHOT (line 16). Calculation is based on total leaf area. Actual photosynthesis of healthy tillers is calculated by multiplicatiing calculated photosynthesis per unit area by the fraction of healthy leaf area (ALVG/ALV; line 17), which implies that leaf area of deadhearts and whiteheads is distributed uniformly overthe vertical canopy profile.

Contribution of whiteheads to kernel filling
It is often suggested that whiteheads contribute to the kernel filling of neighbouring tillers. This option is introduced in the model. Production of assimilates by whiteheads is assumed to be identical to production of assimilates by healthy tillers, and can thus be calculated as (ALVWH/ALV)*PCGC. The fraction of newly produced assimilates translocated to neighbouring tillers can be adjusted through parameter FTLWH (line 18). A value of zero. indicates that translocation does not occur. A value of 1 causes all produced assimilates to flow to neighbouring tillers. This value is not realistic, since it implies that no assimilates are used for the maintenance of whiteheads. Experiments are required to obtain a realistic value. The translocated assimilates are added to the production of healthy tillers (line 19).

```
18  PARAM FTLWH  =  0.
19  PCGW         =  (ALVG/ALV+FTLWH*ALVWH/ALV)*PCGC*PCEW
```

A full listing of the model is given in Appendix A.3. New abbreviations are also explained in Table 5.2.

5.3 Exercises to L1DT and L1DTSB

Following construction and programming of the simulation model (Sections 5.1 and 5.2, respectively) a sensitivity analysis is performed. Aim of the sensitivity analysis is to asses the relative importance of various assumptions in the model for model output, i.e. yield. Components of the model to which model output is sensitive and which numerical values are not well known, should be investigated further in experiments. Thus, sensitivity analysis gives directions for empirical research.

In this Section the rationale, the method and the results of a number of sensitivity analyses are described as 'exercises' and 'solutions'. The first two exercises pertain to a healthy crop, simulated using module L1DT, the other exercises consider a crop which is attacked by stem borer and require module L1DTSB. Solutions to the exercises are given at the end of the Section.

Table 5.2. New abbreviations used in L1DTSB.

Abbreviation	Explanation
ALV(DH,G,WH)	leaf area of dead hearts (DH), healthy tillers (G) and white heads (WH) (ha ha^{-1})
ARTDH	average residence time of a dead heart (d)
CAGRSO	newly produced carbohydrates available for the growth of stem reserves and storage organs (kg (CH_2O) ha^{-1} d^{-1})
CRGSOM	maximum growth rate of the storage organs expressed in carbohydrate-equivalents (kg (CH_2O) ha^{-1} d^{-1})
CAGSR	carbohydrates available for growth of shielded reserves (kg (CH_2O) ha^{-1} d^{-1}); a negative value means that carbohydrates are removed
CWTDDW	carbon lost as a result of disappearance of dead hearts and senescence of white heads (kg (C) ha^{-1})
DSWH	phenological development stage after which stem borer infestation results in formation of white heads
FR(DH,WH)	fraction dead hearts (DH), white heads (WH)
FTLWH	fraction of newly produced carbohydrates translocated from white heads to healthy tillers
LALVDH	disappearance rate of leaf area from dead hearts (ha ha^{-1} d^{-1})
LALVWH	disappearance rate of leaf area from white heads (ha ha^{-1} d^{-1})
L(LA,SA)SB	rate of loss of leaf area (LA) and stem area (SA) due to stem borer infestation (ha ha^{-1} d^{-1})
L(LV,RT,SR,ST)DH	disappearance rate of leaves (LV), roots (RT), shielded reserves (SR) and stems (ST) from dead hearts (dry matter; kg ha^{-1} d^{-1})
LLVWH	disappearance rate of leaves from white heads (dry matter; kg ha^{-1} d^{-1})
L(LV,RT,SO,SR,ST)SB	rate of loss of leaves (LV), roots (RT), storage organs (SO), shielded reserves (SR) and stems (ST) due to stem borer infestation (dry matter; kg ha^{-1} d^{-1})
LN(GR,FL,TI)SB	rate of loss of grains (GR), florets (FL) and tillers (TI) due to stem borer infestation (number ha^{-1} d^{-1})
LNTIDH	disappearance rate of dead hearts (tillers ha^{-1} d^{-1})
NTI(DH,WH)	number of dead hearts (DH), and white heads (WH) (number ha^{-1})
NT(DH,WH)M2	number of dead hearts (DH) and white heads (WH) per m^2
NTTIM2	total number of tillers per m^2 (m^{-2})
SBINFR	stem borer infestation rate (tiller $tiller^{-1}$ day^{-1})
W(LV,RT,SR,ST)DH	weight leaves (LV), roots (RT), shielded reserves (SR) and stems (ST) of dead hearts (kg ha^{-1})
W(LV,RT,SO,SR,ST)WH	weight leaves (LV), roots (RT), storage organs (SO), shielded reserves (SR) and stems (ST) of white heads (kg ha^{-1})

Exercise 1. Sensitivity of yield components to the tiller initiation threshold CNTI

In the module L1DT tillers are formed between developmental stages 0.3 and 0.75. The formation rate of tillers depends on the difference between the potential number of tillers (NTIP) and the actual number of tillers (NTI). The potential number of tillers is calculated by dividing the actual daily rate of carbohydrate production (CAGCR) by the carbohydrates required to initiate and maintain one tiller (CNTI). A high-tillering variety is simulated by a low value for CNTI, whereas a low tillering variety is characterized by a high CNTI.

Replace the statement

```
CNTI          =   AFGEN(CNTIT,DS)
```

by

```
CNTI          =   MPFTI*AFGEN(CNTIT,DS)
PARAM MPFTI   =   1.0
```

and generate reruns by introducing the following lines between the END and STOP statements:

```
PARAM MPFTI   =   0.5
END
PARAM MPFTI   =   2.0
END
```

Study the yield components (i.e. NTIM2, NGRPTI, NGRM2, WG1000) of the various reruns at DS=2.0 (DATE=287.).

Exercise 2. Sensitivity of yield and yield components to sink-limitation

Module L1DT can also be used without the sub-module on tillering and grain formation. In that case the TILLER-module should be removed. This involves all statements starting with:

```
** TILLER-MODULE
```

and ending with

```
FUNCTION CNTIT   =   0.0,5.E-6, 0.3,5.E-6, 0.75,25.E-6,...
                     1.0,75.E-6, 2.1,75.E-6
```

in the programme listing (Table 5.1). The statement describing the maximum growth rate of the grains (GSOM) should be changed into:

```
GSOM             =   INSW(DS-0.95,0.,(WSO+100.)*GSORM)
```

This statement ensures that grain filling starts at DS=0.95, and that the rate of grain filling only gradually increases. GSORM is the maximum relative growth rate of storage organs, and is already specified as a parameter in the model.

Replace the TILLER-module by the single statement for carbohydrate demand. Remove the variables related to the TILLER-module from the PRINT-statement (i.e. NTIM2, NGRM2, NGRPTI, WG1000), and remove WGR=WGRMX as a condition in

the FINISH-statement. Make PRDEL=1., and study the increase in WSO. Compare the simulated rate of grain filling with the rate simulated with the original model.

Exercise 3. Sensitivity of yield to persistence of deadhearts in the crop

Parameter ARTDH represents the average residence time of deadhearts, and is set to 14 days. This value is merely a 'guesstimate'. A different value for this parameter probably affects simulated yield reduction. A higher value means that deadhearts remain in the canopy for a longer period of time and compete more intensely for light with healthy tillers. A smaller value has an opposite effect.

Run module L1DTSB for different values of ARTDH (7, 14, 21) and study the output.

Exercise 4. Sensitivity of yield to timing of a small, persistent infestation

Stem borer infestation in the vegetative phase affects crop production in a different way than does an infestation around flowering. An infestation in the vegetative phase is simulated with:

```
FUNCTION SBINRT =  0.2,0.01, 0.69,0.01, 0.7,0., 2.2,0.
```

Similarly an infestation around flowering is simulated with:

```
FUNCTION SBINRT =  0.2,0., 0.9,0., 0.91,0.01, ...
                   1.4,0.01, 1.41,0., 2.2,0.
```

Run module L1DTSB and generate reruns for both seasonal infestation profiles. Include the following statements to determine the total number of tillers that was infested and appeared as a deadheart:

```
TTDH            =  INTGRL(0.,INSW(DS-DSWH,LNTISB,0.))
TTDHM2          =  TTDH/10000.
```

Study the model outputs of the reruns.

Exercise 5. Sensitivity of yield to timing of a large, brief infestation

From the previous exercises it appears that stem borer infestations during the vegetative phase hardly affect rice production. The simulations were performed assuming a moderate stem borer infestation during a long period (SBINFR=0.01 from DS=0.2 until DS=0.69, see exercise 3). The effect of short lasting but severe infestations may be different. This will be tested with infestation rates of 20 tillers $m^{-2}d^{-1}$ for five consecutive days, which start on different days after transplanting.

For this purpose, remove the following statement from the model:

```
SBINFR          =  AFGEN(SBINRT,DS)
```

and replace it by:

```
NINFM2          =  AFGEN(NIM2T,DATE)
SBINFR          =  NINFM2/NTIM2
FUNCTION NIM2T  =  200.,0., 210.,0., 211.,20., ...
                   215.,20., 216.,0., 290.,0.
```

Run the model and make reruns with the infestation starting on day numbers 216, 221, 226, and 231, respectively. Study the output of the model.

Exercise 6. Sensitivity of yield to assimilate transport from whiteheads to healthy tillers

In exercise 3 it is concluded that compensation during late infestations is negligible. However, this would be different if whiteheads contribute to the production of healthy tillers. In the model this can be simulated by adjusting the value of the parameter FTLWH.

Introduce the infestation around flowering into the model as given in Exercise 3. Run the model and make reruns with FTLWH=0.35 and FTLWH=0.7. Study the model output.

Solution to exercise 1

Number of grains per unit area (NGRM2) and 1000-kernel weight (WG1000) are not affected by tillering capacity since the simulation of grain formation is independent of the simulation of tiller formation (Table 5.3). As expected, low values for CNTI generate a high number of tillers, and consequently a low number of grains per tiller.

Table 5.3. Sensitivity of yield components to the tiller initiation threshold. MPFTI is the factor by which the standard threshold value is multiplied. NTIM2 is tiller density (m^{-2}), NGRPTI is grain density per tiller, NGRM2 is grain density (m^{-2}), and WG1000 is 1000-grain weight (g).

MPFTI	NTIM2	NGRPTI	NGRM2	WG1000
0.5	1768.1	13.867	24518	23.011
1.0	885.94	27.675	24518	23.011
2.0	444.58	55.113	24518	23.011

Solution to exercise 2

In the simplified model grain filling starts on day 257. During the first two days grain filling is limited by demand (GSOM) (Table 5.4).

Table 5.4. The role of sink-limitation in grain growth. GSOM is the maximum growth rate of the storage organs (kg ha^{-1} d^{-1}), GSO the actual growth rate of the storage organs (kg ha^{-1} d^{-1}), and WSO weight of the storage organs (kg ha^{-1}).

Day	GSOM	GSO	WSO
256	50.0	50.0	0.0
257	75.0	75.0	50.0
258	112.5	112.5	125.0
259	168.8	146.7	237.5

Starting on day 259 grain filling is not limited by demand, but by supply. In the original, more complex, model grain filling proceeds in almost identical fashion (not shown). This indicates that also in the original version of L1DT limitation of growth by sink size was unimportant.

Solution to exercise 3

The results (Table 5.5) indicate that yield and yield components are hardly sensitive to changes in ARTDH. This suggests that deadhearts affect crop production and yield components mainly directly, through loss of tillers, and not indirectly through shading.

Table 5.5. Sensitivity of yield and yield components to timing of infestation by stem borer. WSO is weight of the storage organs, NTIM2 tiller density, NGRPTI is grain density per tiller, WG1000 is 1000-grain weight, and TTDHM2 is cumulative number deadhearts.

Yield and yield components	Control	ARTDH=7	ARTDH=14	ARTDH=21
WSO (kg ha^{-1})	4852.1	4861.5	4845.8	4822.9
NTIM2 (m^{-2})	885.9	819.0	810.0	804.7
NGRPTI (-)	27.7	30.3	30.5	30.6
WG1000 (g)	23.0	22.8	22.8	22.8
TTDHM2 (m^{-2})	0.	125.7	125.3	125.1

Solution to exercise 4

The early infestation causes the fraction of deadhearts to increase to about 7.5 % on day 238. The total number of infested tillers is 125 (Table 5.6). At maturity most deadhearts have decayed. The number of healthy tillers at maturity is smaller than was simulated for the healthy crop. However, the difference is 75 instead of 125. This means that loss of tillers is partly compensated for by production of new tillers. A second compensation mechanism is a higher number of grains per tiller. The result of both compensation mechanisms is that grain yield is hardly affected.
The infestation around flowering reduces grain yield with about 17 %. This percentage equals the reduction in number of healthy tillers, and indicates that compensation in later growth stages is absent.

Table 5.6. Sensitivity of yield and yield components to timing of infestation by stem borer. Relative infestation rate is constant and low (0.01 d^{-1}). WSO is weight of the storage organs, NTIM2 tiller density, NGRPTI is grain density per tiller, WG1000 is 1000-grain weight, TTDHM2 is cumulative number deadhearts, and NTWHM2 is whitehead density.

Yield and yield components	Control	Early infestation	Late infestation
WSO (kg ha^{-1})	4852.1	4845.8	4052.2
NTIM2 (m^{-2})	885.9	810.0	739.2
NGRPTI (-)	27.7	30.5	27.8
WG1000 (g)	23.0	22.8	22.9
TTDHM2 (m^{-2})	0.	125.3	0.
NTWHM2 (m^{-2})	0.	0.	146.7

Solution to exercise 5

The simulation study demonstrates that grain yield is only slightly affected by the short, severe infestation because the crop is able to compensate for the formation of deadhearts (Table 5.7). A very early infestation decreases yield most. In an early development phase appearance of 100 deadhearts is equivalent with removal of more than half of the standing biomass, resulting in a clear decrease of tiller formation. However, the crop partly compensates for the loss of tillers by a larger number of grains per tiller.

Table 5.7. Sensitivity of yield and yield components to timing of infestation by stem borer. In contrast to Table 5.5 relative infestation rate is variable and high. WSO is weight of the storage organs, NTIM2 tiller density, NGRPTI is grain density per tiller, WG1000 is 1000-grain weight, and TTDHM2 is cumulative number deadhearts.

Yield and yield components	Start of infestation					
	control	day 211	day 216	day 221	day 226	day 231
WSO (kg ha^{-1})	4852.1	4811.0	4863.8	4857.2	4849.5	4839.4
NTIM2 (m^{-2})	885.9	619.2	811.2	835.1	839.2	836.1
NGRPTI (-)	27.7	40.6	30.7	29.6	29.4	29.4
WG1000 (g)	23.0	22.2	22.7	22.8	22.9	22.9
TTDHM2 (m^{-2})	0.	100.	100.	100.	100.	100.

Solution to exercise 6

The results are in agreement with our expectations. If whiteheads contribute to the production of healthy tillers the reduction due to stem borer infestation is smaller. This type of compensation manifests itself in an increased number of grains per tiller and an increased 1000 grain weight.

Table 5.8. Sensitivity of yield and yield components to assimilate transport from whiteheads to healthy tillers. FTLWH is fraction of newly produced carbohydrates translocated from white heads to healthy tillers, WSO is weight of the storage organs, NTIM2 tiller density, NGRPTI is grain density per tiller, WG1000 is 1000-grain weight.

Yield and yield components	Control	FTLWH=0.	FTLWH=0.35	FTLWH=0.7
WSO (kg ha^{-1})	4852.1	4052.2	4311.7	4570.9
NTIM2 (m^{-2})	885.9	739.2	739.2	739.2
NGRPTI (-)	27.7	27.9	28.8	29.7
WG1000 (g)	23.0	22.9	23.6	24.2

6 Damage by bacterial leaf blight and sheath blight in rice: a quantitative simulation model

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6.1 General structure of the model ORYZA1[1]

ORYZA1 is a model for irrigated lowland rice production. The model is based on Macros-L1D (Penning de Vries at el., 1989) and SUCROS87 (Spitters et al., 1989). A more detailed description of ORYZA1 is given by Kropff et al. (1993).

The general structure of the model is presented in Figure 6.1. Under favourable growth conditions, light, temperature and the varietal characteristics that determines phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day. The model follows the daily calculation scheme for the rates of dry matter production of the plant organs, the rate of leaf area development and the rate of phenological development (Figure 6.1). By integrating these rates over time, dry matter production of the crop is simulated throughout the growing season.

The total daily rate of canopy CO_2 assimilation is calculated from the daily incoming radiation, temperature and the leaf area index. The model contains a set of subroutines that calculate the daily rate by integrating instantaneous rates of leaf CO_2 assimilation. The calculation is based on an assumed sinusoidal time course of radiation over the day and the exponential light profile within the canopy. On the basis of the photosynthesis characteristics of single leaves, which depend upon the N concentration, the photosynthesis profile in the canopy is obtained. Integration over the leaf area index of the canopy and over the day gives the daily CO_2 assimilation rate. After subtraction of respiration requirements, the net daily growth rate in kg dry matter per ha per day is obtained. The dry matter produced is partitioned among the various plant organs.

Phenological development rate is tracked in the model as a function of ambient daily average temperature. When the canopy is not yet closed, leaf area increment is calculated from daily average temperature, because carbohydrate production does not limit leaf expansion. When the canopy closes, the increase in leaf area is obtained from the increase in leaf weight. Integration of daily growth rates of the organs and leaf area results in dry weight increment during the growing season.

---

[1] From: Kropff, Van Laar & Ten Berge (1993)

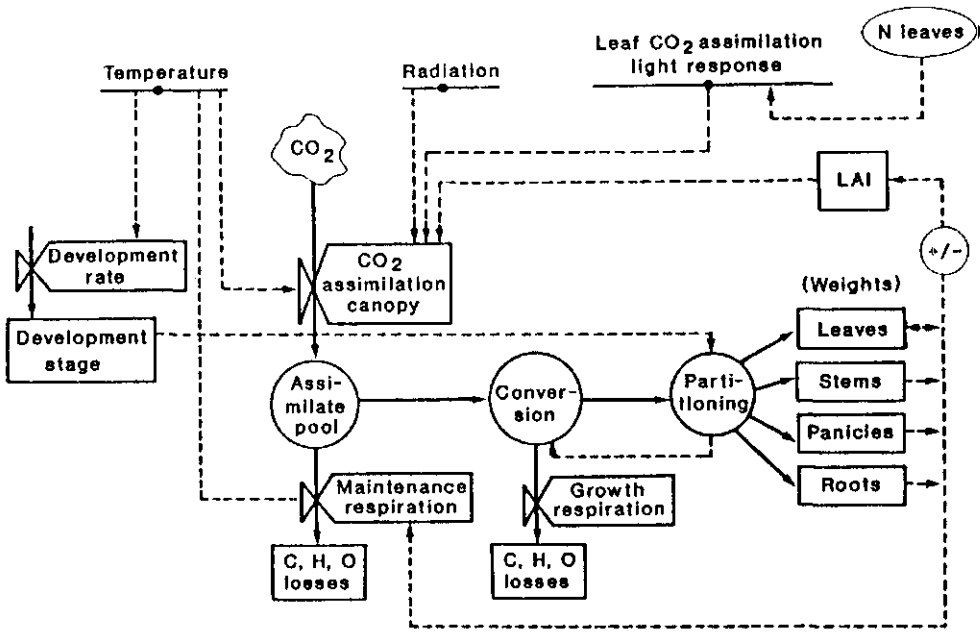

Figure 6.1. A schematic representation of the model ORYZA1. Boxes are state variables, valves are rate variables, circles are intermediate variables. Solid lines are flows of material, dotted lines are flows of information.

Input requirements of the model are: geographical latitude, daily weather data (radiation, minimum and maximum temperature), plant density, date of crop emergence and transplanting and parameter values that describe the morpho-physiological characteristics of the plant species. Time step of integration is one day.

6.2 BLIGHT, a simulation model for blight diseases on rice

Introduction

The combination model BLIGHT was developed to support the analysis of field experiments in which the effects of the foliar diseases Bacterial Leaf Blight (BLB) and Sheath Blight (ShBl) on plant growth are determined. As BLB and ShBl are focus diseases of the Crop Protection Theme of SARPIII, the model is called BLIGHT. However, its concepts, and a modified version, can be applied to other diseases as well. L1DFDE, the standard model for foliar diseases, was the first version of the model

(Bastiaans, 1991), and was an extension of model MACROS-L1D (Penning de Vries et al., 1989). With the introduction of ORYZA1, a new model for the production of rice under irrigated lowland conditions (Kropff et al., 1993; Section 6.1), also a new disease model based upon ORYZA1 was developed.

BLIGHT does not simulate disease development in time, but requires this as input. Also a number plant characteristics need to be determined experimentally and introduced into the model as forcing functions. The model can be applied to analysis of field experiments, to identify research goals, to construct and explore possible scenarios with respect to disease development and grain yield reduction, given the disease dynamics for specific environmental conditions, etcetera.

Three phases are distinguished in the process research on BLB and ShBl:

1. Collection of quantitative information on the influence of the diseases on basic plant growth processes;
2. Development of an extended crop growth model, in which these effects are introduced;
3. Validation of the model through field experiments.

Characteristics of the photosynthesis light response curve (initial light use efficiency, respiration in the dark, assimilation rate at high light intensity) are inputs into the ORYZA1 model. However, the influence of BLB and ShBl on these characteristics is not known as yet, and therefore have been estimated. Research is carried out at IRRI and CABO/TPE to acquire this information. The BLIGHT model will be validated on the basis of common experiments carried out by SARP teams (see Chapter 8), and other experimental data available.

BLIGHT in brief

Effects of the disease on crop growth processes comprise the effects on the characteristics of the light response curve. Effects on green leaf and stem area, dry matter partitioning, leaf nitrogen content, and relative senescence rate are described in the input data. Effects of the disease on crop development are disregarded.

Crop processes are similar to the ones of ORYZA1, which is documented by Kropff et al. (1993). A number of plant characteristics have to be introduced as forcing function, viz. total leaf area (LAI), nitrogen content per unit leaf area (NFLV) and specific leaf weight (SLW) of the leaf area. Nitrogen content per unit leaf area is strongly related to the rate of photosynthesis at light saturation (AMAX) (van Keulen & Seligman, 1987; Penning de Vries et al., 1990).

Three types of leaf area are distinguished: healthy, diseased and dead leaf area. These are introduced into the model as fractions healthy (FHLL) and diseased (FDSL) leaf area, from which fraction dead leaf area (FDDL) is calculated. Diseased leaf area and diseased stem area are described by their respective disease severities (SEVL and SEVS).

In contrast to ORYZA1, in which a single leaf layer is distinguished, in BLIGHT the canopy is subdivided into three leaf layers which are characterized separately. Leaf layer classes are: (1) 0-25 cm, (2) 25-40 cm, and (3) above 40 cm, measured from the stem base. This approach allows a more precise simulation and analysis of events, as diseases are mostly not evenly distributed over canopy depth.

Also daily gross canopy photosynthesis (DTGA) is calculated per leaf layer. Therefore, the subroutine ASSIM, which calculates photosynthesis for one layer (i.e. the entire canopy), is extended with an extra loop to calculate photosynthesis for three leaf layers, and is renamed to ASSIMD.

The effects on photosynthesis of diseased leaf area are introduced into the model as correction factors (between 0 and 1) on the initial light use efficiency (EFF) and the assimilation rate at light saturation (AMAX). Similarly, maintenance respiration of diseased leaf area is given a correction factor larger than 1. The values of the correction factors are related to disease severity. Photosynthesis rates of healthy and dead leaf area are assumed to be unaffected and zero, respectively.

Detailed explanation of BLIGHT

BLIGHT is a combination model with a crop growth and development section, and a section which accounts for the plant x disease interaction. The crop section is, apart from some minor changes, very similar to ORYZA1, and the disease section consists of two procedures and an input data set. The presented model version is written in CSMP, but in future, a FORTRAN version will be available running under the SARP-Shell (Riethoven, 1993).

Only differences with ORYZA1 are specified in this text. A full explanation of ORYZA1 is given by Kropff et al. (1993). Statements are explained in sequence of appearance in the listing. New acronyms are difined in Table 6.1.

Table 6.1. List of Acronyms not known to ORYZA1 and used in BLIGHT

Acronym	Explanation	Dimension
ADDL	Dead leaf area for a given leaf layer (intermediate variable)	ha ha^{-1}
ADSL	Diseased leaf area for a given leaf layer (intermediate variable)	ha ha^{-1}
AHLL	Healthy leaf area for a given leaf layer (intermediate variable)	ha ha^{-1}
AMAXD(1)	AMAX of diseased leaf area in layer 1	kg CO_2 ha^{-1} h^{-1}
AMAXDC(1)	Correction factor on AMAX for disease severity in layer 1	

AMAXDT	Function relating correction factor on PLMX	
AMAXH(1)	AMAX of healthy leaf area in layer 1 to disease severity	kg CO_2 ha^{-1} h^{-1}
ASEVL	Average disease severity of diseased leaf area	-
ASEV(1)	Average disease severity over stems and leaves in layer 1	-
EFFD(1)	EFF of diseased leaf area in layer 1	kg CO_2 ha^{-1} h^{-1}
EFFDC(1)	Correction factor on PLEI due to disease presence in layer 1	-
EFFDT	Function relating correction factor on PLEI due to disease presence to disease severity	
EFFH(1)	EFF of healthy leaf area in layer 1	kg CO_2 ha^{-1} h^{-1}
FDDLA	Total fraction dead stem+leaf area	-
FDDT(1)	Fraction dead stem+leaf area in layer 1	-
FDSL1	Function relating fraction diseased leaf area of layer 1 to time	
FDSL(1)	Fraction diseased leaf area of layer 1	-
FDSLA	Total fraction diseased stem+leaf area	-
FDSLW	Weight fraction of diseased leaf area	-
FDST(1)	Fraction diseased leaf+stem area in layer 1	-
FHLL1	Function relating fraction healthy leaf area of layer 1 to time	
FHLL(1)	Fraction healthy leaf area of layer 1	-
FHLLA	Total fraction healthy stem+leaf area	-
FHLLW	Weight fraction of healthy leaf area	-
FHLT(1)	Fraction healthy leaf+stem area in layer 1	-
IN	Number of leaf layers in canopy	-
LAIDD	Total dead leaf area	ha ha^{-1}
LAIDS	Total diseased leaf area	ha ha^{-1}
LAIHL	Total healthy leaf area	ha ha^{-1}
LAIL	Total leaf area	ha ha^{-1}
LAILL1	Function relating total leaf area of layer 1 to time	
LAILL(1)	Total leaf area of layer 1	ha ha^{-1}
LAITL(1)	Total leaf+stem area in layer 1	ha ha^{-1}
LAIX	Total leaf area (intermediate variable)	ha ha^{-1}
MAINDT	Function relating respiration to disease severity	
NCNTD1	Function relating N content of diseased leaf area in layer 1 to time	
NCNTD(1)	N content of diseased leaf area in layer 1	g N g^{-1} dm
NCNTH1	Function relating N content of healthy leaf area in layer 1 to time	
NCNTH(1)	N content of healthy leaf area in layer 1	g N g^{-1} dm

NFLVD(1)	Nitrogen fraction of diseased leaf area in layer 1	ha ha^{-1}
NFLVH(1)	Nitrogen fraction of healthy leaf area in layer 1	ha ha^{-1}
RMAIN	Ratio between respiration of diseased and healthy leaf area	-
RMLVD	Maintenance respiration of diseased leaf area	kg CO_2 ha^{-1} d^{-1}
RMLVH	Maintenance respiration of healthy leaf area	kg CO_2 ha^{-1} d^{-1}
SAIL(1)	Stem area in layer 1	ha ha^{-1}
SEVL1	Function relating disease severity of diseased leaf area in layer 1 to time	
SEVL(1)	Disease severity of diseased leaf area in lef layer 1	-
SEVS1	Function relating disease severity of diseased stem area in layer 1 to time	
SEVS(1)	Disease severity of diseased stem area in layer 1	-
SLWDS1	Function relating SLW of diseased leaf area in layer 1 to time	
SLWDS(1)	SLW of diseased leaf area in layer 1	kg ha^{-1}
SLWHL1	Function relating SLW of healthy leaf area in layer 1 to time	
SLWHL(1)	SLW of healthy leaf area in layer 1	kg ha^{-1}
TSEVL	Total leaf area occupied by disease (total severity)	kg ha^{-1}
TSEVS	Total stem area occupied by disease (total severity)	kg ha^{-1}
WLVDS	Weight of diseased leaf area	kg ha^{-1}
WLVHL	Weight of healthy leaf area	kg ha^{-1}

The crop section

The number of leaf layers is specified by the integer variable IN.

```
FIXED IN
```

The canopy is divided in three leaf layers. Array-variables specifying leaf characteristics must be given storage declarations. If more leaf layers are simulated, which is possible, the STORAGE declaration must be changed accordingly.

```
STORAGE  LAILL(3),LAITL(3),SAIL(3),...
         NCNTH(3),NCNTD(3),SLWHL(3),SLWDS(3),...
         FHLL(3),FDSL(3),FDDL(3),SEVL(3),SEVS(3),ASEV(3),...
         FHLT(3),FDST(3),FDDT(3),...
         AMAXDC(3),EFFDC(3),AMAXH(3),AMAXD(3),EFFH(3),EFFD(3),...
         NFLVH(3),NFLVD(3)
```

The switches for leaf area index (SWILAI) and leaf nitrogen (SWINLV) have been removed, as only observed values are used.

No changes in section on PHENOLOGICAL DEVELOPMENT.

In section on DAILY GROSS CANOPY CO_2 ASSIMILATION, simulation of the N profile has been removed (statements on NPROF and NFLV). Experimental data should provide the N contents of the 3 leaf layers. This information is processed in the disease procedures. Within leaf layers, N is assumed to be uniformly distributed.

AMAX and EFF are calculated separately for healthy and diseased leaf area in the disease procedure, which gives AMAXH, AMAXD, EFFH and EFFD. Only EFF is required as input.

The factor accounting for temperature effect on AMAX, REDFT, has been moved to the disease procedure.

The call to TOTASS has been extended, and renamed to TASSDS, total assimilation of diseased canopy. Stem area is accounted for in TASSDS.

```
            DAYL,DTGA,DS0 = ...
TASSDS(DOY,LAT,RDT,SCP,AMAXH,AMAXD,EFFH,EFFD,KDF,LAITL,...
            FHLT,FDST,IN)
```

Calculation of MAINTENANCE RESPIRATION is basically unchanged. However, maintenance respiration of healthy and diseased leaf area are calculated separately in the DIS procedure, and summed to total maintenance respiration (RMLV). It is assumed that in the gross, stem maintenance respiration does not change.

```
RMCR    =  RMLV + (WST*MAINST + WSO*MAINSO + WRT*MAINRT) * TEFF
           * MNDVS
```

No changes in the sections on DAILY DRY MATTER GROWTH RATES OF THE CROP and DRY MATTER PARTITIONING .

No changes in the section on GROWTH RATE OF PLANT ORGANS.
However, the following should be noted. If leaf senescence is accelerated as a result of disease presence, the fraction dead leaf area will increase more rapidly than in a healthy crop. Since total leaf area, and both the fractions healthy and diseased leaf area are given as input, implicitly the fraction dead leaf area is specified as well. The weight of dead leaf area must be subtracted from the weight of healthy and diseased leaf area (WLVG), since dead leaf area does not contribute to maintenance respiration. Weight of dead leaves is put into the integral WLVD. The loss of leaf weight (LLV) is calculated through multiplication of WLVG by a relative loss rate, which depends upon the development

stage of the crop (FUNCTION DRLVT). Adaptation of this function becomes necessary if the disease causes an accelerated leaf senescence.

```
LLV        =   WLVG*AFGEN(DRLVT,DVS)
```

No changes in section on DRY MATTER PRODUCTION.

In the calculation of LEAF AREA DEVELOPMENT, the procedure PROLAI has been extended with LAIX from the DIS procedure. The leaf area of separate leaf layers is calculated from observed leaf weights in procedure DIS. The switch SWILAI and accompanying statements have been removed, as only observed values are used.

```
PROCEDURE LAIL   =   PROLAI(DVS,WST,LAIX)
     SSGA        =   AFGEN (SSGATB, DVS)
     SAI         =   SSGA * WST
     LAIL        =   LAIX
     LAI         =   0.5 * SAI + LAIL
ENDPRO
```

No changes in sections on TIME AND ENVIRONMENTAL VARIABLES, CARBON BALANCE CHECK and RUN CONTROL. Make sure that the run control matches the actual experimental situation.

In section on OBSERVED VALUES, only observed values for green and dead leaf weight, stem weight, panicle weight and total dry matter weight have been maintained. Leaf area, nitrogen content and specific leaf weight are input values, which do not need to be compared with simulated values.
Values given in section on FUNCTIONS AND PARAMETERS FOR RICE should be maintained.

The disease section
All statements related to the disease are placed in two procedures. Procedure RDDIS reads the forcing functions that have been obtained from results of field experiments, and procedure DIS calculates the consequences of disease presence for photosynthesis characteristics; maintenance respiration; fractions healthy, diseased and dead leaf area; and average severity.

Procedure RDDIS reads forcing functions that define plant characteristics for three leaf layers (x = 1, 2 or 3). As BLB does normally not spread to the stem, the values for SEVS can be set to zero in that case.

```
PROCEDURE  LAILL,NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL, SEVS...=
RDDIS(IDATE)
      LAILL(x)   =  AFGEN(LAILL1,DOY)
      NCNTH(x)   =  AFGEN(NCNTH1,DOY)
      NCNTD(x)   =  AFGEN(NCNTD1,DOY)
      SLWHL(x)   =  AFGEN(SLWHL1,DOY)
      SLWDS(x)   =  AFGEN(SLWDS1,DOY)
      FHLL(x)    =  AFGEN(FHLL1,DOY)
      FDSL(x)    =  AFGEN(FDSL1,DOY)
      SEVL(x)    =  AFGEN(SEVL1,DOY)
      SEVS(x)    =  AFGEN(SEVS1,DOY)
ENDPROCEDURE
```

Procedure DIS calculates for three leaf layers the consequences of disease presence for photosynthesis characteristics; fractions healthy, diseased and dead leaf area; average severity; and maintenance respiration. A 2-step approach is followed: initial calculations are made in step 1, and consequences for photosynthesis are determined in in step 2

```
PROCEDURE LAIX,LAITL,SAIL,FHLLA,FDSLA,FDDLA,ASEVL,FHLLW,...
FDSLW,AMAXH,AMAXD,EFFH,EFFD,RMLV,ASEV...
          =  DIS(IN,LAILL,SAI,FHLL,FDSL,SLWHL,SLWDS,SEVL,SEVS,...
             NCNTH,NCNTD,REDFT,EFF,MAINLV,WLVG,TEFF,MNDVS)
```

In STEP 1, average disease levels are calculated per leaf layer. Variables are initially set to zero.

For each layer, the fraction dead leaf area is calculated from the fractions healthy and diseased leaf area and total leaf area , which are given as input. Actual healthy, diseased and dead leaf area are calculated as the products of their respective fractions and the total leaf area.

```
DO 10 I=1,IN
    FDDL(I)   =  1.-FHLL(I)-FDSL(I)
    AHLL      =  FHLL(I)*LAILL(I)
    ADSL      =  FDSL(I)*LAILL(I)
    ADDL      =  FDDL(I)*LAILL(I)
```

Total leaf area, and healthy, diseased and dead leaf area per layer are integrated to total canopy values.

```
    LAIX      =  LAIX + LAILL(I)
    LAIHL     =  LAIHL + AHLL
```

```
LAIDS     =  LAIDS + ADSL
LAIDD     =  LAIDD + ADDL
```

Stem area is calculated per layer. Its distribution over layers is assumed proportional to leaf area distribution. This causes some error, as for instance late in the season leaves in the bottom layer may have died, which does not necessarily imply that stem area also has reduced. Also, the depths of the leaf layers (0-25 cm, 25-40 cm, above 40 cm) have been chosen such that the leaf area index in all layers at flowering is approximately equal. Stem area obviously will be distributed differently at that moment.

```
SAIL(I)   =  SAI * LAILL(I)/(LAIX+NOT(LAIX))
```

Total stem+leaf area is calculated per layer according the approach followed in procedure PROLAI in ORYZA1. In this, and may other equations that are related to photosynthesis calculation, only 50 % of the green stem area is added to the LAI, because sheaths are less photosynthetically active than leaves.

```
LAITL(I)  =  LAILL(I) + 0.5 * SAIL(I)
```

The total leaf area occupied by lesions equals the sum of severity times diseased leaf area per leaf layer. For total stem area occupied by lesions a similar calculation is made.

```
TSEVL     =  TSEVL + SEVL(I)*ADSL
TSEVS     =  TSEVS + SEVS(I)*SAIL(I)
```

The average severity over stem and leaves is calculated per leaf layer

```
ASEV(I)   =  SEVL(I)*ADSL/(ADSL+0.5*SAIL(I)+...
             NOT(ADSL+0.5*SAIL(I)))+...
             SEVS(I)*0.5*SAIL(I)/(ADSL+0.5*SAIL(I)+...
             NOT(ADSL+0.5*SAIL(I)))
```

The total weight of healthy and diseased leaf areas equals the sum of healthy or diseased leaf area times specific leaf weight per leaf layer.

```
WLVHL     =  WLVHL + AHLL*SLWHL(I)
WLVDS     =  WLVDS + ADSL*SLWDS(I)
```

The fractions healthy, diseased and dead leaf+stem area per layer are calculated. All fractions take values between 0 and 1, and their sum must be equal to 1.

```
FHLT(I)   =  (FHLL(I) * LAILL(I) + INSW(-SEVS,0.,1.) * 0.5 * ...
             SAIL(I))/(LAITL(I) + NOT(LAITL(I)))
```

```
      FDST(I)   =   (FDSL(I) * LAILL(I) + INSW(-SEVS,1.,0.) * 0.5 * ...
                    SAIL(I))/(LAITL(I) + NOT(LAITL(I)))
      FDDT(I)   =   1. - FHLT(I) - FDST(I)
10    CONTINUE
```

The fractions healthy, diseased and dead leaf area are calculated.

```
      FHLLA     =   LAIHL/(LAIX+NOT(LAIX))
      FDSLA     =   LAIDS/(LAIX+NOT(LAIX))
      FDDLA     =   LAIDD/(LAIX+NOT(LAIX))
```

The average severity over all layers is calculated as total leaf area affected relative to total diseased leaf area.

```
      ASEVL     =   TSEVL/(LAIDS+NOT(LAIDS))
```

The total weight fractions of healthy and diseased leaf area of alive leaf area are calculated as their weights relative to total healthy+diseased leaf area. These fractions are used in the calculation of maintenance respiration.

```
      FHLLW     =   WLVHL/((WLVHL+WLVDS)+NOT(WLVHL+WLVDS))
      FDSLW     =   WLVDS/((WLVHL+WLVDS)+NOT(WLVHL+WLVDS))
```

In STEP 2, the effects of the disease on photosynthesis characteristics of diseased leaf+stem area are determined. Correction factors for maximum photosynthesis (AMAX) and initial light use efficiency (EFF) of diseased tissue, in relation to average disease severity over stem and leaf area, are determined per layer.

```
      DO 20 I = 1,IN
            AMAXDC(I)   =   AFGEN(AMAXDT,ASEV(I))
            EFFDC(I)    =   AFGEN(EFFDT,ASEV(I))
20    CONTINUE
```

If the standard experimental procedure (see Chapter 8) is followed, then nitrogen data are available in kg N per kg leaf. Multiplication with the specific leaf weight gives kg N per ha leaf, and multiplication with 0.1 gives g N per m^2 leaf area.

```
      DO 30 I = 1,IN
      NFLVH(I)  =   0.1 * SLWHL(I) * NCNTH(I)
      NFLVD(I)  =   0.1 * SLWDS(I) * NCNTD(I)
```

AMAX and EFF for healthy and diseased leaf area are calculated per layer.
The temperature correction (REDFT) is calculated in the crop section of the model.
Maximum photosynthesis of healthy leaf area is corrected for nitrogen content (NFLVH), and maximum photosynthesis of diseased leaf area is additionally corrected for disease severity (AMAXDC).
Initial light use efficiency of healthy leaves is not corrected, but initial light use efficiency of diseased leaves is multiplied with the correction factor for disease severity (EFFDC).

```
      AMAXH(I)  =  (-6.5 + 32.4 * NFLVH(I)) * REDFT
      AMAXD(I)  =  (-6.5 + 32.4 * NFLVD(I)) * REDFT * AMAXDC(I)
      EFFH(I)   =  EFF
      EFFD(I)   =  EFF*EFFDC(I)
30    CONTINUE
```

The effect of the disease on respiration is introduced as an effect on maintenance respiration, by defining the ratio between respiration of diseased and healthy leaves. Maintenance respirations for healthy and diseased leaf area are calculated separately. Maintenance respiration is proportional to dry weight, and therefore, the weight fractions rather than the area fractions of the healthy and diseased leaves should be used. The equations are otherwise similar to the ones in the crop section.

```
      RMAIN     =  AFGEN(MAINDT,ASEVL)
      RMLVH     =  FHLLW * WLVG * MAINLV * TEFF * MNDVS
      RMLVD     =  FDSLW * WLVG * MAINLV * TEFF * MNDVS * RMAIN
      RMLV      =  RMLVH + RMLVD
      ENDPROCEDURE
```

Inputs
The model has three input sections, characterizing crop, disease, and site. In the standard disease input, all variables unknown to ORYZA1, but incorporated in BLIGHT and necessary to simulate the disease are given. In principle, values are obtained in field experiments. Values given in the present listing are estimates or dummies!

```
      STANDARD DISEASE INPUT DATA.
```

AMAX, EFF and MAIN related to disease severity (SEVFD), as ratios between diseased and healthy leaf area (-). These values are estimates; research is going on to determine these relations.

```
      FUNCTION AMAXDT  =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
      FUNCTION EFFDT   =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
      FUNCTION MAINDT  =  0.,1., 0.05,1.5, 0.10,2.5,  0.5,5., 1.0,5.
```

Number of leaf layers (-).

```
PARAM IN =  3
```

Total leaf area (ha/ha) per layer.

```
FUNCTION LAILLx =  180.,0.02, 302.,1., 350.,1.
```

Nitrogen content of healthy and diseased leaf area (kg/kg), per layer.

```
FUNCTION NCNTHx =  180.,0.05, 302.,0.03, 350.,0.03
FUNCTION NCNTDx =  180.,0.05, 302.,0.03, 350.,0.03
```

Specific leaf weight of healthy and diseased leaf area (kg/ha), per layer.

```
FUNCTION SLWHLx =  180.,300., 302.,300., 350.,300.
FUNCTION SLWDSx =  180.,300., 302.,300., 350.,300.
```

Fraction healthy and diseased leaf area (-), per layer.

```
FUNCTION FHLLx  =  180.,1., 302.,0., 350.,0.
FUNCTION FDSLx  =  180.,0., 302.,0.5,  350.,1.
```

Disease severity of diseased leaf and stem area (-), per layer.

```
FUNCTION SEVLx  =  180.,0., 302., 0.05, 350.,0.05
FUNCTION SEVSx  =  180.,0., 302.,0., 350.,0.
```

Optional plant and weather input data files are given, for example:
Experimental data on IR72.
Weather data for Los Banos, Philippines, 1991.

```
END
STOP
```

Calculation of photosynthesis
Subroutines TOTASS and ASSIM of ORYZA1 have been rewritten to subroutines TASSDS and ASSIMD, which compute canopy photosynthesis for 3 layers; if more layers need to be simulated, then storage and dimension declarations need to be adapted. Leaf+stem area of each layer is divided in three fractions; healthy, diseased, and dead (dead stem area does not exist in the current version). Canopy photosynthesis is first calculated for a completely healthy canopy, then for a completely diseased canopy and

finally for a completely dead canopy. Actual canopy photosynthesis is calculated as the weighted average of these three values.

Implicit assumptions of this approach are:

- ight interception characteristics are the same for all three types of leaf area.
- within each layer healthy, diseased and dead leaf area are homogeneously distributed (which is in reality often not the case).

A detailed explanation of these subroutines is given in Kropff et al. (1993).

Subroutine ASSIM has been changed substatially to subroutine ASSIMDS (see Appendix A5 for listing). The output is still FGROS, but the set of input variables has been extended with AMAXH, AMAXD (replacing AMAX), EFFH, EFFD (replacing EFF), LAITL (replacing LAI), FHLT, FDST and IN. Subroutine TOTASS has been changed to subroutine TASSDS, which calls ASSIMDS instead of ASSIM, and which has therefore an similarly adapted declaration.

```
SUBROUTINE TASSDS (DOY,  LAT , DTR, SCP, AMAXH, AMAXD, EFFH,
&   EFFD, KDF,  LAITL, FHLT, FDST, IN,
&   DAYL, DTGA, DS0)

SUBROUTINE ASSIMD (SCP, AMAXH, AMAXD, EFFH, EFFD, KDF, LAITL,
&   SINB,PARDR, PARDF, FHLT, FDST, IN,
&   FGROS)
```

6.3 Exercises to BLIGHT

The exercises are meant to provide, after completion, a better understanding of the relative importance of the various components of the blight-rice pathosystem. They are developed with reference to the standard experimental design (see Chapter 8), the data sheets for processing the experimental results (see Appendix A.7) and the simulation models ORYZA1 and BLIGHT (see sections 6.1 and 6.2). A number of sub-goals can be defined:

- illustrate the processing of field data (exercises 1, 2, 3, 4)
- illustrate the way disease effects have been introduced into the model (exercises 5, 6, 7)
- indicate the importance of collecting field data on (at first glance) less plausible field variables, such as distribution of disease and N over three leaf layers (exercise 7 and 8)
- indicate the necessity of accurate process-parameters (exercise 9)
- indicate the effect of crop husbandry measures (exercise 10).

Solutions to the exercises are given at the end of the Section.

Exercise 1

Purpose: Practice the transformation of field data to model input.

Sheets that assist in the transformation of field observations to model input are presented in Appendix A.7. Transformations should be correct. For instance, it is crucial that the proper dimensions are obtained.

a. Sheet 1
In the experiment, the number of tillers is determined per sub-plot. The multiplication factor of 2.963, which is applied to the average of all observations to transform number of tillers per hill to number of tillers per m^2, is based upon a sub-plot size of 3 x 5 hills at a planting distance of 15 x 15 cm.
Suppose that planting distance is 15 x 30 cm, sub-plot size is 6 x 3 hills, and average tiller number per sub-plot is 1620. What is the tiller densitiy per hectare?

b. Sheet 5
Kernel density is determined as number of kernels per panicle and has to be transformed to kernel density per hectare. Suppose panicle density is 1620 per sub-plot (see example 1a). The average number of filled kernels per panicle is 20. What is the filled kernel density per hectare?

Exercise 2

Purpose: Practice the calculation of the relative loss rate of leaf dry weight (DRLV).

Disease presence may cause accelerated death of vegetative tissue. In the model, the loss of leaf dry weight is described by an AFGEN function that relates the relative loss rate of leaf dry weight (DRLVT) to the crop development stage (DVS). This function may have to be adapted if it does not correspond with the senescence rate in your own healthy treatments. The function may also have to be adapted to account for the effects of disease presence.

```
LLV = WLVG * AFGEN(DRLVT,DVS)
```

The following leaf weights were observed (Table 6.2):

Table 6.2. Observed development stages (DVS) and leaf weights (WLV) after anthesis.

Day	DVS (-)	WLV (kg ha^{-1})
90	1.5	4370
97	1.62	3970
103	1.75	3035
112	1.85	2160
118	1.91	1530
125	2	1120

Determine AFGEN(DRLVT,DS) for the available development stages.

Exercise 3

Purpose: Practice the calculation of the dry matter partitioning

The method to calculate dry matter partitioning is similar to the calculation of DRLV (exercise 2). The following field observations on the weight of above-ground plant material and root weight were made (Table 6.3):

Table 6.3. Observed development stages (DVS), total above-ground dry matter (WAG) and root weight (WRT) during the first 100 days of the growing season.

Date	DVS (-)	WAG (kg ha^{-1})	WRT (kg ha^{-1})
0	0	0	0
20	0.18	115	95
40	0.39	313	185
60	0.60	1254	437
80	0.82	4273	877
100	1.18	7546	980

Determine the dry matter partitioning between shoot and root before anthesis (DVS = 1.).

Exercise 4

Purpose: Determine disease severity.

Leaf disease severity is introduced in the BLIGHT model as the area of the visible lesion relative to total leaf area. Calculate average disease severity for the leaves from the following data, which represent a sample of 5 hills. Input date are given in Table 6.4.

Table 6.4. Total leaf area and lesion area observed for 5 hills.

Hill no.	Total leaf area (cm^2)	Lesion area (cm^2)
1	25	4.3
2	28	6.7
3	22	5
4	30	10.1
5	26	7.4

Exercise 5

Purpose: examine the effects of reduced maximum photosynthesis rate, reduced initital light use efficiency, and increased respiration rate.

Bacterial Leaf Blight and Sheath Blight probably influence the photosynthesis characteristics (the light response curve) of the rice plant. The size of the effect may depend upon disease severity. The consequences of changed photosynthesis characteristics can be explored by introducing correction factors to the relevant statements in ORYZA1.

Note: The crop and weather data used in all exercises are of IR72 grown in the wet season of 1991 at IRRI, at 110 kg N per hectare (data R. Torres, see Kropff et al., 1993).

Change the following statements in ORYZA1, by adding the bold printed characters:

```
AMAX        =  CORR1 * AMIN(60.,(-6.5+32.4*NFLV)*REDFT)
EFF         =  CORR2 * AFGEN(EFFTB,TAVD)
RMCR        =  CORR3 * (WLVG*MAINLV + WST*MAINST + WSO*MAINSO + ...
               WRT*MAINRT) * TEFF * MNDVS
PARAM CORR1 =  1., CORR2 = 1., CORR3 = 1.
```

By giving value 1 to all correction factors, the output remains unchanged.

Generate reruns by introducing the following lines between END and STOP:

```
PARAM CORR1 =  0.75, CORR2 = 1., CORR3 = 1.
END
PARAM CORR1 =  1., CORR2 = 0.75, CORR3 = 1.
END
PARAM CORR1 =  1., CORR2 = 1., CORR3 = 1.25
END
PARAM CORR1 =  0.75, CORR2 = 0.75, CORR3 = 1.25
END
```

These reruns mimic the effects of 25 % decreased maximum photosynthesis rate, 25 % decreased initial light use efficiency, 25 % increased respiration rate, and their combined effects, respectively.

Generate output, and try to find explanations for differences in maximum leaf area index (LAI_{max}), total above-ground dry matter production (WAG) and grain yield (WSO), between the default run and the reruns, and between reruns.

Exercise 6

Purpose: Introduction of disease dynamics.

The effects of disease presence on the photosynthesis characteristics depend upon the fraction diseased leaf area, and the disease severity of that leaf fraction, which are characteristics that change through time. These two disease characteristics are incorporated in the simulation model by some additional AFGEN-functions. This exercise concentrates on reduction of maximum photosynthesis rate (AMAX) and initial light use efficiency (EFF), and does not take in to account increase of maintenance respiration (RMAIN).

Introduce to ORYZA1 a section 'diseases', where all matters related to Bacterial Leaf Blight or Sheath Blight are placed. What would you consider a good place?
Here, you insert the following (imaginary data):

```
**********************
***DISEASE SECTION***
**********************

AMAXDC            =   AFGEN(AMAXDT,SEV)
EFFDC             =   AFGEN(EFFDT,SEV)
SEV               =   AFGEN(SEVDT,DOY)
FUNCTION AMAXDT   =   0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION EFFDT    =   0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION SEVDT    =   180.,0., 260.,0.5, 290.,0.433
FHLL              =   AFGEN(FHLLTB,DOY)
FDSL              =   AFGEN(FDSLTB,DOY)
FDDL              =   1.-FHLL-FDSL
FUNCTION FHLLTB   =   180.,1., 260.,0.4, 290.,0.267
FUNCTION FDSLTB   =   180.,0., 260.,0.567, 290.,0.467
```

These statements relate the correction factors for AMAX and EFF of diseased leaf area to disease severity, which, in turn, is based upon field observations. Subsequently, fractions healthy (FHLL) and diseased leaf area (FDSL) are read, and fraction dead leaf area (FDDL) is calculated.

Photosynthesis in ORYZA1 is calculated in subroutines which are called from the main program. Photosynthesis in the BLIGHT model is calculated twice; once for a completely healthy crop, and once for a completely diseased crop. The actual photosynthesis is subsequently calculated by multiplying the photosynthesis rates by the fractions healthy and diseased leaf area, respectively, and adding the outcomes. Dead leaf area does not photosynthesize. All this is done in the subroutines TASSDS and ASSIMD, but for the sake of the exercise, the unchanged subroutines of ORYZA1 are utilized and called two times, and averaging is done in the main program.

We make use of some FORTRAN by replacing the call to TOTASS with:

```
PROCEDURE DAYL,DS0,DTGAH,DTGAD = ...
TASS(DOY,LAT,RDT,SCP,AMAX,AMAXDC,EFF,EFFDC,KDF,LAI,FHLL,...
FDSL)

DAYL,DTGA,DS0    =  TOTASS(DOY,LAT,RDT,SCP,AMAX,EFF,KDF,LAI)
   DTGAH         =  DTGA

   AMAX          =  AMAXDC * AMAX
   EFF           =  EFFDC  * EFF
DAYL,DTGA,DS0    =  TOTASS(DOY,LAT,RDT,SCP,AMAX,EFF,KDF,LAI)
   DTGAD         =  DTGA

   DTGA          =  FHLL*DTGAH + FDSL*DTGAD
ENDPROCEDURE
```

Run the model. What are the results?

Perform a sensitivity test by changing one by one in 4 reruns the input functions with 25 % towards more disease or stronger effects, viz.:

```
FUNCTION AMAXDT  =  0.,1., 0.05,0.68, 0.1, 0.57, 0.5,0., 1.,0.
FUNCTION EFFDT   =  0.,1., 0.05,0.68, 0.1, 0.57, 0.5,0., 1.,0.
FUNCTION SEVDT   =  180.,0., 260.,0.625, 290.,0.541
FUNCTION FDSLTB  =  180.,0., 260.,0.709, 290.,0.584
```

Note that, when (0.,0.567) in FUNCTION FDSLTB is increased tot (0.,0.709, (0.,0.4) in FUNCTION FHLLTB nust be decreased to (0.,0.291), as the sum of FHLL and FOSL can exceed 1.0.

What are the simulation results?

Exercise 7

Purpose: Introduction of a disease profile in the model.

Besides variation of photosynthesis characteristics in time due to changing disease presence, photosynthesis characteristics also show variation over the canopy profile.

Photosynthesis in the upper leaf layers contributes most to assimilate production, whereas the contribution of lower leaf layers is relatively small, due to the low light intensity at the bottom of the canopy. Accuracy of calculations will increase if this diversification is taken into account by working with leaf layers rather than with just one canopy. For each leaf layer, the disease characteristics can be specified, photosynthesis can be calculated, and the interaction between disease severity and photosynthesis can be accouned for. Such a model is rather complex, and writing it is beyond the aims of these exercises. Therefore, the BLIGHT model is used for illustration of the difference between simulation with one uniform canopy and with three leaf layers.

Use the BLIGHT model with the following data (nitrogen contents are kept constant):

```
FUNCTION AMAXDT  =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION EFFDT   =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION MAIND   =  0.,1., 0.05,1.5, 0.1,2.5 , 0.5,5., 1.,5.

PARAM IN         =  3

FUNCTION LAILL1  =  180.,0.02, 212.,0.6, 217.,0.8,  222.,1.,...
                    227.,1.,   252.,1.5, 262.,1.25, 290.,0.5
FUNCTION LAILL2  =  180.,0.,   212.,0.,  217.,0.4,  222.,0.8,...
                    227.,1.,   252.,1.5, 262.,1.25, 290.,0.5
FUNCTION LAILL3  =  180.,0.,   212.,0.,  217.,0.,   222.,0.3,...
                    227.,1.,   252.,2.,  262.,1.9,  290.,1.3

FUNCTION NCNTH1  =  180.,0.04, 290.,0.04
FUNCTION NCNTH2  =  180.,0.04, 290.,0.04
FUNCTION NCNTH3  =  180.,0.04, 290.,0.04

FUNCTION NCNTD1  =  180.,0.04, 290.,0.04
FUNCTION NCNTD2  =  180.,0.04, 290.,0.04
FUNCTION NCNTD3  =  180.,0.04, 290.,0.04

FUNCTION SLWHL1  =  180.,300., 212.,440., 217.,375., ...
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION SLWHL2  =  180.,300., 212.,440., 217.,375., ...
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION SLWHL3  =  180.,300., 212.,440., 217.,375., ...
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION SLWDS1  =  180.,300., 212.,440., 217.,375., ...
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION SLWDS2  =  180.,300., 212.,440., 217.,375., ...
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION SLWDS3  =  180.,300., 212.,440., 217.,375., ...
```

```
                    227.,375., 252.,425., 262.,475., 290.,500
FUNCTION FHLL1   =  180.,1., 260.,0.4, 290.,0.3
FUNCTION FHLL2   =  180.,1., 260.,0.5, 290.,0.3
FUNCTION FHLL3   =  180.,1., 260.,0.3, 290.,0.2

FUNCTION FDSL1   =  180.,0., 260.,0.6, 290.,0.4
FUNCTION FDSL2   =  180.,0., 260.,0.5, 290.,0.4
FUNCTION FDSL3   =  180.,0., 260.,0.6, 290.,0.6

FUNCTION SEVL1   =  180.,0., 260., 0.5, 290.,0.3
FUNCTION SEVL2   =  180.,0., 260., 0.5, 290.,0.5
FUNCTION SEVL3   =  180.,0., 260., 0.5, 290.,0.5

FUNCTION SEVS1   =  180.,0., 290.,0.
FUNCTION SEVS2   =  180.,0., 290.,0.
FUNCTION SEVS3   =  180.,0., 290.,0.
```

These statements mimic three leaf layers which are differently characterized with respect to fractions healthy and diseased leaf area and disease severity. These date resemble the crop simulated in exercise 5. Simulation of a healthy crop by setting FHLLX to 1. and FDSL to 0. results in WAG = 1378 kg ha^{-1} and WSO = 7356 kg ha^{-1}. What are grain yield and total above ground weight for the diseased crop?

BLIGHT in its default version works with three leaf layers. If labour does not allow observations on three leaf layers, one may decide to observe on the entire canopy. The consequences of this can be illustrated by averaging disease severity (SEVL), and fractions healthy and diseased leaf area (FHLL, FDSL) over the three layers. Assume a healthy stem.

```
FUNCTION FHLLx   =  180.,1., 260.,0.4,   290.,0.267
FUNCTION FDSLx   =  180.,0., 260.,0.567, 290.,0.467
FUNCTION SEVLx   =  180.,0., 260.,0.5,   290.,0.433
```

(x = 1, 2, 3)

Run the model, and compare the simulation results with the ones of the first run. Explain differences.

Green stem area contributes to photosynthesis and assimilate production. Therefore, if stem area is affected by a disease, daily total dry matter production will decrease. Make use of the model used in the first part of this exercise, the one with a differentiated canopy. Introduce disease presence on the stem:

```
FUNCTION SEVS1   =  180.,0., 260.,0.2, 290.,0.5, 302.,0.5
FUNCTION SEVS2   =  180.,0., 260.,0.2, 290.,0.5, 302.,0.5
FUNCTION SEVS3   =  180.,0., 260.,0.2, 290.,0.5, 302.,0.5
```

How does the crop respond to this?

Exercise 8

Purpose: Illustration of the need to observe N contents for all leaf layers, and the effect of N contents on photosynthesis.

Exercise 8a.
As explained in the ORYZA1 manual, leaf nitrogen content is linearly related to maximum photosynthesis rate, which is expressed by the equation for AMAX. The upper leaves contribute most to assimilate production during grain filling, due to the lower light intensities in lower leaf layers. Therefore, an under-estimation of the leaf nitrogen content in the upper leaves will cause lower simulated grain yields.
Make use of the model of exercise 7.

a. Simulate growth for a crop with a leaf nitrogen content of 0.04 kg kg^{-1} for all leaf layers (the average), for healthy and diseased leaf area.
b. Set the leaf nitrogen content at 0.05, 0.04 and 0.03 kg kg^{-1} for the top, middle, and bottom layer, respectively, for healthy and diseased leaf area.

Compare daily total gross CO_2 assimilation (DTGA), crop growth rate (GCR), grain filling rate (GSO), final above ground dry matter (WAG) and final grain yield (WSO). Try to explain differences.

Exercise 8b.
Increased leaf N content has two effects: (1) increased CO_2 assimilation, and (2) increased disease growth. Only the former is simulated, the latter should be observed and made model input.

Use the model developed in exercise 8a, with different leaf nitrogen concentrations. Decrease and increase the leaf N content in all layers by 20%, and compare simulation results with each other and with the results of exercise 8a.

Exercise 9

Purpose: Illustrate the importance of accurate process parameters.

Research is being conducted to determine how maximum photosynthesis rate (AMAX), initial light use efficiency (EFF) and maintenance respiration (RMAIN) are related to disease severity. These relations are expected to be non-linear: an increase in severity of 10 % would imply reductions of more than 10 % for AMAX and EFF, and an increase of more than 10 % for RMAIN.

The current (still hypothetic) functions are:

```
FUNCTION AMAXDT  =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION EFFDT   =  0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION MAINDT  =  0.,1., 0.05,1.5, 0.1,2.5,  0.,5.,  1.,5.
```

Use the BLIGHT model of exercise 7 (all leaf layers with a leaf nitrogen content of 0.04 kg kg^{-1}).

a. Simulate crop growth with these default values for AMAX, EFF and RMAIN.
b. Simulate crop growth with 25 % decreased values for AMAXDT and EFFDT, 25 % increased values for MAINDT, and all functions changed 25%, respectively. For example:

```
FUNCTION AMAXDT =  0.,1., 0.05,0.675, 0.1,0.563 0.5,0., 1.,0.
```

What are the simulation results?

The current relations imply that there is no photosynthesis if disease severity exceeds 50 %. One can question whether this is realistic, and whether a leaf photosynthesizes at higher levels of severity. Make a second set of simulation studies with adapted AMAXDT functions (EFFDT and MAINDT are not adapted):

```
FUNCTION AMAXDT =  0.,1., 0.05,1.0, 0.25,1.0, 0.5,0.75, ...
                   0.75,0.5, 1.,0.
FUNCTION AMAXDT =  0.,1., 0.05,0.95, 0.1,0.9, 0.25,0.75, ...
                   0.5,0.5, 0.75,0.25, 1.,0.
FUNCTION AMAXDT =  0.,1., 0.05,0.8, 0.1,0.65, 0.25,0.5, ...
                   0.5,0.25, 0.75,0.1, 1.,0.
FUNCTION AMAXDT =  0.,1., 0.05,0.8, 0.1,0.65, 0.25,0.5, ...
                   0.5,0.25, 0.75,0., 1.,0.
```

What are the effects on total dry matter production and grain yield?

Exercise 10

Purpose: Study the variation in damage by the same epidemic due to changes in crop husbandry.

Exercise 10a. Nitrogen application

Higher soil nitrogen availability probably results in an increased leaf nitrogen content, and therefore in an increased assimilate production and grain yield. However, disease incidence and severity of both Bacterial Leaf Blight and Sheat Blight are also favoured by a high nitrogen content in plant organs. The consequence is that high nitrogen application rates enhance the disease incidence. These two nitrogen effects will work against each other.

Use the BLIGHT model of exercise 7. Make a default run, and two reruns:

1. with increased leaf nitrogen content (NCNTH and NCNTD), viz. with 0.05 instead of 0.04 kg kg^{-1} throughout the entire season.
2. then, additionally increase severity data for the leaf (SEVL) increased with 0.1 (maintain the pair 180.,0.).

Explain the differences.

Exercise 10b. Sowing date
If disease outbreak may be expected at a specific date of the year, changed sowing date may be a means to limit damage.

Use the BLIGHT model of exercise 7, and simulate crop growth for advanced and postponed sowing and transplanting dates: 2 weeks earlier, 1 week earlier, 1 week later, and 2 weeks later, respectively. Extend all input data to days 160 and 320, and give the variables at these dates the same values as at days 180 and 290, respectively. Explain differences in simulation results.
(In reality, the moment of disease outbreak may change accordingly).

Solution to exercise 1

a. sub-plot size is 90 x 90 cm = 0.81 m^2; tiller density is 1620 x 1/0.81 = 2000 tillers m^{-2} = 2 x 10^7 tillers ha^{-1}.
b. Panicle density is 2 x 10^7 panicles ha^{-1}; kernel density is 20 x 2 x 10^7 = 4 x 10^8 kernels ha^{-1}.

Solution to exercise 2

Table 6.5. Tabular calculation of the relative loss rate of leaf dry weight (DRLV) on the basis of observed development stage (DVS) and leaf dry weight (WLV).

	Day	ΔT (d)	DVS (-)	WLV (kg ha^{-1})	ΔWLV (kg ha^{-1})	DRLV (d^{-1})
Obs	90		1.5	4370		
Int	93.5	7	1.56	4170	400	0.0137
Obs	97		1.62	3970		
Int	100	6	1.685	3502.5	935	0.0445
Obs	103		1.75	3035		
Int	107.5	9	1.8	2597.5	875	0.0374
Obs	112		1.85	2160		
Int	115	6	1.88	1845	630	0.0569
Obs	118		1.91	1530		
Int	121.5	7	1.955	1325	410	0.0442
Obs	125		2	1120		

Obs = Observed, Int = Interpolated
ΔT = change in T, ΔWLV = change in WLV

For example, between days 90 and 97, WLV has decreases with 400 kg ha^{-1} (ΔWLV). This value must be related to WLV itself, as we have to determine the relative death rate. We use the average leaf weight over the time interval of 7 days, viz. 4170 kg ha^{-1}: 400/4170 = 0.0959 over 7 days, which makes 0.0959/7 = 0.0137 d^{-1}.
The model input will be:

```
AFGEN(DRLVT,DS) =  ..............., 1.56,0.0137, 1.685,0.0445,...
                   1.8,0.0375, 1.88,0.0569, 1.955,0.0442, 2.1,0.0442
```

Solution to exercise 3

Table 6.6. Tabular calculation of dry matter partitioning between total above-ground dry matter (WAG) and root dry weight (WRT), as a function of development stage (DVS).

	Day	DVS (-)	WAG (kg ha^{-1})	ΔWAG (kg ha^{-1})	WRT (kg ha^{-1})	ΔWRT (kg ha^{-1})	TOTAL (kg ha^{-1})	ΔTOTAL (kg ha^{-1})
Obs	0	0	0		0		0	
Int	10	0.09		115		95		210
Obs	20	0.18	115		95		210	
Int	30	0.285		198		90		288
Obs	40	0.39	313		185		498	
Int	50	0.495		941		252		1193
Obs	60	0.60	1254		437		1691	
Int	70	0.71		3019		440		3459
Obs	80	0.82	4273		877		5150	
Int	90	1.00		3273		103		3376
Obs	100	1.18	7546		980		8526	

For example, between days 20 and 40, 313-115 = 198 kg ha^{-1} is allocated to the shoot. This is 198/288 = 0.69 kg per kg total plant weight. Similarly, 90/288 = 0.31 kg kg^{-1} is allocated to the roots. The partitioning is given as fractions, and is dimensionless. After replacement of day number by development stage, the partitioning tables until anthesis are therefore:

```
FSHTB      =  0.0,0.5, 0.09,0.55, 0.285,0.69, 0.495,0.79,...
              0.71,0.87, 1.0,0.97
FRTTB      =  0.0,0.5, 0.09,0.45, 0.285,0.31, 0.495,0.21,...
              0.71,0.13, 1.0, 0.03
```

It is assumed that initial dry matter distribution between above and below ground biomass is equal.

Solution to exercise 4

Total leaf area is 131 cm^2.
Total lesion area is 33.5 cm^2.
Average disease severity is 33.5/131 = 0.256.

Solution to exercise 5

Table 6.7. The consequences of reduced maximum photosynthesis rate (AMAX), initial light use efficiency (EFF) and maintenance respiration (RMCR) for simulated grain yield (WSO), total above-ground dry weight (WAG) and maximum leaf area index (LAI_{max}) of a healthy crop.

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})	LAI_{max} (kg ha^{-1})
default healthy, ORYZA1	5923	12122	5.34
25 % reduced AMAX	5122 (-14 %)	10713 (-12 %)	4.91 (-8 %)
25 % reduced EFF	4503 (-24 %)	9165 (-24 %)	4.20 (-21 %)
25 % increased RMCR	5425 (-8 %)	11198 (-8 %)	5.05 (-5 %)
combined effects	3589 (-39 %)	7535 (-38 %)	3.72 (-30 %)

Reductions of maximum photosynthesis rate (AMAX) and intitial light use efficiency (EFF) reduce leaf area index, total above-ground dry matter production and grain yield. The effect of reduced EFF is stronger than the effect of reduced AMAX. Increase of maintenance respiration (RMCR) does not change the gross amount of assimilates produced, but reduces the net amount available for crop growth. The effect is smaller than the effect of similar changes in AMAX and EFF. The combined effect results in strongest reductions of crop growth and grain yield.

Solution to exercise 6

The section 'diseases' can for example be placed at the end of the main program, before the plant and weather data. It is good practice to structure the model, and to keep together all statements related to the disease and plant x disease interaction.

Total above-ground dry matter production and grain yields are considerably lower than in exercise 5, as now a severely diseased crop is simulated.

Reductions of AMAX and EFF result in reduced above ground dry matter production and grain yield (see also exercise 5). However, under the simulated conditions, the effects of increased disease severity and increased fraction diseased leaf area appear much stronger.

Table 6.8. The consequences of reduced maximum photosynthesis rate (AMAX) and initial light use efficiency (EFF), and increased disease severity (SEV) and fraction diseased leaf area (FDSL) for simulated grain yield (WSO) and total above-ground dry weight (WAG).

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})
Default diseased, ORYZA1	1685	5214
reduced AMAXDT	1664	5143
reduced EFFDT	1652	5056
increased SEVDT	1498	4671
increased FDSLTB	1298	2056

Solution to exercise 7

Table 6.9. The consequences of canopy stratification and of additional disease presence on the stem (SEVS) for simulated grain yield (WSO) and total above-ground dry weight (WAG).

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})
3 leaf layers	1885	5260
one canopy	2374	5913
+SEVS	1277	4307

WAG and WSO of a diseased crop are much lower compared to a healthy crop, due to the strong disease pressure. The fraction diseased leaf area and the disease severity in the top layer (layer 3) of the differentiated canopy is higher than in the canopy with a uniform disease distribution. This results in lower assimilate production, due to the dominant contribution to it by the top layer. Therefore, total dry matter production and grain yield decrease. As green stem area contributes to assimilate production, disease presence on the stem causes also decrease of total dry matter production and grain yield.

The 'one canopy' run resembles the default-diseased run of exercise 6. However, in exercise 7 dry matter production and grain yield are higher than assimilate production in exercise 6, mainly because in exercise 6 LAI is simulated.

Solution to exercise 8a

The higher N concentration in the upper leaf layer (run with different N contents) results in a higher daily assimilation, crop growth rate and grain filling rate. As an indication,

maximum daily assimilation, crop growth rate and grain filling rate achieved by the crop during the season are presented. Note that the latter two have the same value, as after flowering all dry matter is transported to the storage organs. Final simulated grain yield is highest for the crop with the differentiated leaf layers.

Table 6.10. The consequences of canopy stratification with respect to leaf nitrogen content for simulated grain yield (WSO) and total above-ground dry weight (WAG) of a diseased crop.

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})	$DTGA_{max}$ (kg ha^{-1} d^{-1})	GCR_{max} (kg ha^{-1} d^{-1})	GSO_{max} (kg ha^{-1} d^{-1})
similar N contents	1885	5260	384	146	91
different N contents	2015	5466	403	146	98

Solution to exercise 8b

Replace a leaf nitrogen content of 0.03 by 0.024 and 0.036 kg kg^{-1}, replace 0.04 by 0.032 and 0.048 kg kg^{-1} , and replace 0.05 by 0.04 and 0.06 kg kg^{-1}.

Table 6.11. The consequences of reduced and increased leaf nitrogen content for simulated grain yield (WSO), total above-ground dry weight (WAG), daily assimilation (DTGA), crop growth rate (GCR) and grain filling rate (GSO).

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})	$DTGA_{max}$ (kg ha^{-1} d^{-1})	GCR_{max} (kg ha^{-1} d^{-1})	GSO_{max} (kg ha^{-1} d^{-1})
-20 % leaf N	1882	5103	307	133	90
+20 % leaf N	2110	5725	428	155	104

As a consequence of the positive linear relation between leaf nitrogen content and maximum photosynthesis rate, daily assimilation (DTGA) is strongly nitrogen dependent. This has direct consequences for crop growth rate and grain filling rate, total dry matter production and grain yield, as is illustrated by the differences in rates, total above-ground dry matter production and grain yield. The limited effect of reduced leaf N content indicates that other factors are growth limiting under the simulated conditions.

Solution to exercise 9

The adapted input functions used in the first set of reruns, with 25 % changed input functions are:

```
FUNCTION AMAXDT  =  0.,1., 0.05,0.675, 0.1,0.0.563, 0.5,0., 1.,0.
FUNCTION EFFDT   =  0.,1., 0.05,0.675, 0.1,0.563, 0.5,0., 1.,0.
FUNCTION MAINDT  =  0.,1., 0.05,1.875, 0.1,3.125,  0.5,6.25, 1.,6.25
```

The different AMAXDT-functions of the second set of reruns can be grafically represented as:

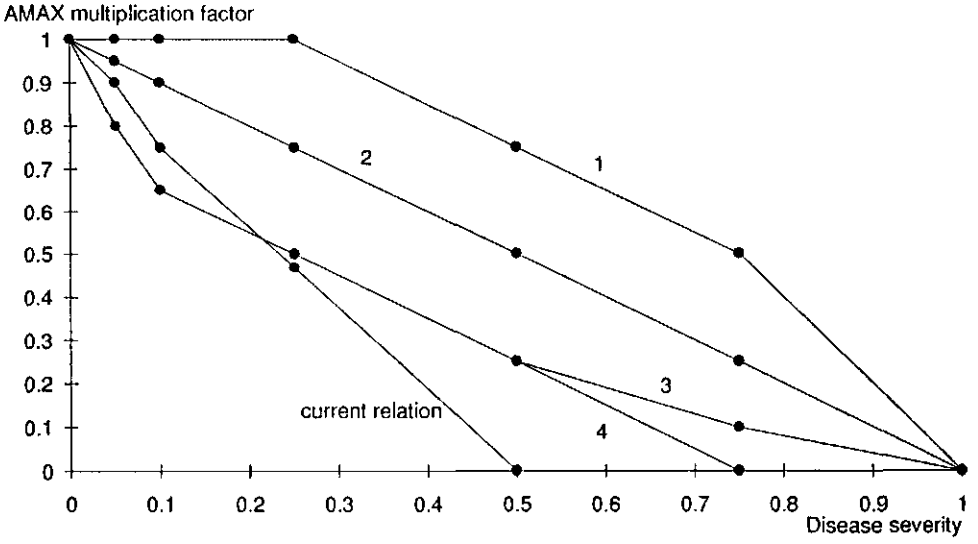

Figure 6.2. Five relationships between disease severity and the relative reduction of maximum photosynthesis rate (AMAX). The current relation is by default used in the BLIGHT model.

The first four reruns represent the result of stronger effects of disease presence on the photosynthesis characteristics. Total dry matter production and grain yield decrease in all cases. As a consequence of the large LAI, maintenance requirements are high, and changes in the maintenance requirements have a relatively strong effect on crop growth. The second set of reruns represent the effect of different effects of disease severity on maximum photosynthesis rate. The effects of changes in AMAX due to disease presence are in all cases low. This is the consequence of the fixed LAI. In reality, LAI will decrease when net assimilation decreases, causing further reduction of photosynthesis. However, this mechanism is excluded from the model.

Table 6.12. The consequences of reduced maximum photosynthesis rate (AMAX) and initial light use efficiency (EFF), of increased maintenance respiration (RMAIN), and of different relationships between disease severity and AMAX, for simulated grain yield (WSO) and total above-ground dry weight (WAG).

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})
Default	1885	5260
25 % decreased AMAX	1863	5191
25 % decreased EFF	1814	5055
25 % increased RMAIN	1671	4801
combined effects	1603	4582
AMAX function no. 1	1978	5480
AMAX function no. 2	1973	5448
AMAX function no. 3	1958	5382
AMAX function no. 4	1958	5382

Solution to exercise 10a

Table 6.13. The consequences of nitrogen application, through increased leaf nitrogen content and disease severity for simulated grain yield (WSO) and total above-ground dry weight (WAG).

Run	WSO (kg ha^{-1})	WAG (kg ha^{-1})
Default	1885	5260
Increased N	2015	5599
Increased N and severity	1641	4899

Increased leaf N content increased photosynthesis, which results in higher total dry matter production and grain yield. However, this is again reduced if disease severity increases as well due to increased leaf N.

Solution to exercise 10b

The moment of disease onset is the same in all situations. Therefore, the earlier the sowing, the longer the crop remains healthy. This results in increased total dry matter

production and grain yield with advanced sowing date. As in reality the moment of disease outbreak will change also, differences will be less pronounced.

Table 6.14. The consequences of sowing time for simulated grain yield (WSO) and total above-ground dry weight (WAG).

Run	Sowing	Transplanting	WSO	WAG
2 weeks earlier	168	180	2811	5813
1 week earlier	175	187	2359	5655
Default	182	194	1885	5260
1 week later	189	201	1519	4776
2 weeks later	196	208	1213	4191

Note: The ORYZA1 model daily calculates leaf area index (LAI) on the basis of leaf weight (WLV) and specific leaf weight (SLA). This mechanism operates in the simulations of exercises 5 and 6. However, the BLIGHT model, which is used in exercises 7, 8, 9 and 10, requires LAI as input. This has some consequences for sensitivity analyses. For example, a reduction in maximum photosynthesis rate (AMAX) in ORYZA1 leads to a reduction in leaf growth rate, WLV and LAI, which, in turn, further reduces the photosynthesis rate, etcetera. This circularity is in BLIGHT interrupted by the fixed LAI, which does not reduce, and causes limited effects of reduced AMAX on crop growth. Therefore, the results of exercises 7-10 have to be interpreted with care. BLIGHT has been developed for the support of analysis of field experiments, and fails when it is applied to further studies. For this, the model will have to be extended with a LAI-module which dynamically simulates the growth and leaf area of three leaf layers.

7 Damage by stem borer in rice: a joint experimental approach

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7.1 Introduction

To test the hypotheses represented in the L1DTSB model participants at the SARP Workshop in Khon Kaen on stem borer damage decided upon a joint experimental approach. In addition to experiments aimed at testing model validity, experiments were formulated to estimate values of model parameters. The experiments are described in this Chapter. Datasheets for recording and processing observations are summarized in appendix A. 6.

7.2 Dynamics of deadhearts and whiteheads

Introduction
The experiment is designed to verify various assumptions in L1DTSB and estimate various parameters used in the model. These assumptions are

- Deadhearts stay in the crop for a short period of time.
- Whiteheads remain in the canopy until maturity.
- Whiteheads senescence at a rate identical to the senescence rate of healthy tillers.

The parameters to be estimated are

- ARTDH, the average residence time of a deadheart.
- DSWH, the phenological development stage after which stem borer infestation results in formation of whiteheads.

General layout
Only a small area is required for this type of experiment. Rice plants are grown in a small plot comprising 40 x 40 hills, with normal plant spacing. Various stem borer infestation levels are generated in this plot by articial infestation (various number of egg-masses, various time of infestation). The number of tillers and their characteristics are monitored weekly. For each hill a separate data sheet is kept.

Weekly monitoring of tiller characteristics

Twenty hills are selected and marked with sticks. Selection of neighbouring hills should be avoided, since this may lead to mechanical damage during observation. The selected hills are monitored weekly, and of each hill a separate data sheet is kept. The phenological development stage of the crop is determined. Newly emerged tillers of a hill are marked with a label and registered after the appearance of the 4th leaf. Water resistant (e.g. waxed) paper or plastic tags should be used.

During the weekly observations four characteristics are recorded per tiller. First, the tiller is classified as healthy, deadheart, or whitehead. Second, the general appearance and, third, the height of the tiller are determined to characterize the competitive ability of the tiller. Height should be measured as the length from shoot base till the highest point of the tiller, while leaving the tiller in its natural appearance. Finally the panicle exertion state is scored. This is of special interest for whiteheads since little information exists on the degree to which they produce filled kernels. In Table 7.1 codes are defined that will be used for tiller classification. Examples of classifications entered in the datasheet are h\0\0.15\o, d\3\0.20\o, and w\1\0.80\b. In Appendix A. 6 a data sheet is presented that can be used to keep track of the development of a single hill.

Table 7.1 Codes agreed upon to classify tillers in the joint experiment on the dynamics of deadhearts and whiteheads.

Classification topic	Code	Description
1 Tiller type	h	healthy
	d	deadheart
	w	whitehead
2. General appearance (naturally senesced leaves are ignored)	0	no dead leaves
	1	one dead leaf
	2	two dead leaves
	3	more than two dead leaves
	4	tiller completely dead
3. Height	Height is recorded in m, using steps of 0.05 m (0.05, 0.10, 0.15, etc.)	
4. Panicle exertion	o	panicle not visible
	a	panicle exertion < 25%
	b	panicle exertion > 25%, but < 100 %
	c	panicle fully exerted

7.3 Experimental validation of the stem borer - rice model

Introduction

Stem borer infestation results in the formation of deadhearts or whiteheads, depending on the phenological development stage of the crop at the time of infestation. In this experiment the time course of dry matter production in healthy and infested plots is determined. Observations are made throughout the season. Some observations (LAI of healthy and dead leaf area, SLA, leaf N-content) are used later as inputs for the crop growth model. The observations on actual production (dry weight of various plant organs) will be used for comparison with model-outputs to investigate whether the model, fed with the observed inputs, can explain the differences in crop production.

Lay-out of the experiment

The experimental lay-out is a randomized complete block design (Figure 7.1). The number of replicates is set to five, the number of treatments to two (control and infested). An experiment either focuses on the effect of an early infestation (deadhearts) or on the effect of infestations after booting (whiteheads). Individual plot size is 20 x 25 rows, equivalent to 4 x 5 m, assuming a plant spacing of 20 x 20 cm. The distance between plots is 2 m, to avoid effects of neighbouring plots. The outer rows of a plot function as border rows.

Six areas of 6 x 2 hills (indicated as P in Figure 7.2 are reserved for periodic harvesting. These areas are separated by at least two rows, to avoid border effects. Four areas of 2 x 2 hills (indicated as M, Figure 7.2) are reserved for monitoring tiller dynamics and stem borer infestation throughout the growing season.

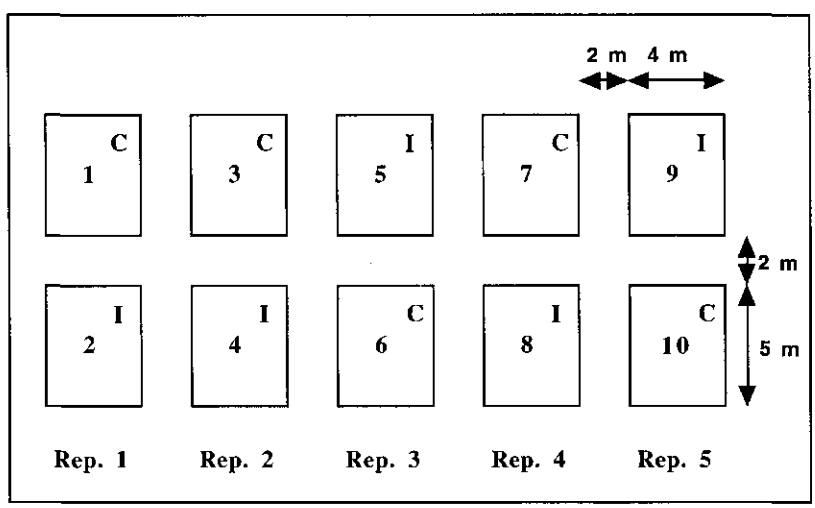

Figure 7.1. Layout of an experimental field with 10 plots, 5 replications (R1 to R5) and two treatments (control C, infested I).

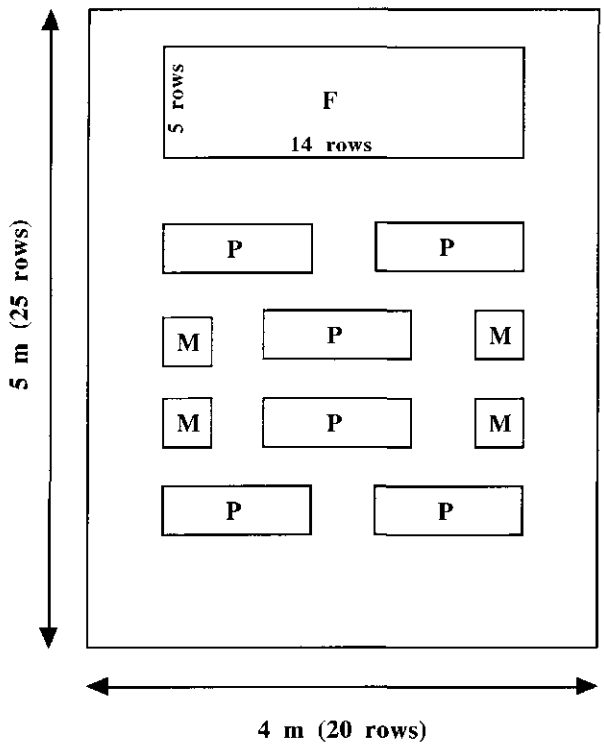

Figure 7.2. Layout subplots within one plot.

Artificial infestation

Deadhearts. Five days after transplanting egg-masses are put on one out of every four hills. The infestation pattern is indicated in Figure 7.3. This is considered to be the lowest infestation level which will give significant effects. If a higher infestation level is used, it should be noted that a group of four hills represents the experimental unit. The infestation level of these units should be similar throughout the entire plot.

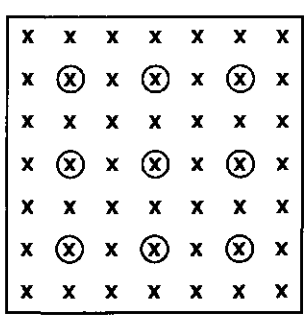

Figure 7.3.
Pattern of infestation with stemborer in each infested plot. A hill is indicated with x, an infested hill with ⊗.

After artificial infestation plots should be kept free of new infestations. Only in this way the effect of deadhearts can be studied. The control plots have to be protected without affecting the occurence of other insects or crop performance.

Whiteheads. At early booting egg-masses are put on a flag-leaf of one out of every four hills. The plots have to be kept free of stem borers during the vegetative phase in such a way that plants are not infested around booting.

For both the deadheart and the whitehead experiment a large number of egg masses is needed. Since for a single plot (18 x 20)/4 = 90 egg-masses are required, 5 x 90 = 450 egg-masses are needed for the entire experiment.

Monitoring of tillering (M-area)

The total number of tillers is counted weekly for every hill in the areas indicated with a M in Figure 7.2. This is done for all 2x2 hills in the four replicates. In addition, each tiller is classified as uninfested, deadheart or whitehead. Also, the phenological development stage of the crop is recorded.

Periodic harvesting (P-area)

Six periodic harvests are scheduled (Figure 7.2). Assuming it takes 90 days for a crop to develop from transplanting to maturity, the schedule looks as follows:

harvest	days after transplanting	development stage
1	15	tillering
2	30	
3	45	
4	60	heading/flowering
5	75	mid flowering
6	90	maturity

From each plot 12 hills in area P (Figure 7.2) are removed. The tillers are divided into uninfested tillers, deadhearts and whiteheads. This distinction is maintained throughout the further handling of the samples. The number of tillers in each category is recorded.
In the laboratory leaves, stems and leaf sheaths, and panicles are separated. The area of green, healthy leaves and the area of dead leaves is determined separately. In combination with the distinction between healthy tillers, deadhearts and whiteheads this results in the folowing categories for which leaf area is measured: uninfested-green, uninfested-dead, deadhearts-green, deadhearts-dead, whiteheads-green, whiteheads-dead. After measuring leaf area the leaves, stems and panicles are oven-dried at approximately 100 °C. After drying, the weights of the various organs are determined.

Specific leaf area is calculated by dividing leaf area and leaf dry weight. Leaf nitrogen content of green leaf area is determined (g (N) g^{-1} (dry matter)). Their quotient (N-content/SLA; g (N) m^{-2} (leaf)) yields the N-content on an area basis. Photosynthetic rate at light saturation is almost linearly related to leaf N-content per unit area. Proper simulation of dry matter production in both control and infested plots requires the course of N-content as a forcing function.

Representativeness of samples

At the start of the growing season plants are still small, and the number of samples is relatively easy to handle. However, later on in the season, sample processing will become a problem. Observations can then be carried out on sub-samples. The difficulty is to obtain representative sub-samples. The danger of selecting an unrepresentative sub-sample is very large, for instance by using large undamaged leaves for determination of leaf area, or selecting hills with a low number of tillers. Therefore some hints are given to avoid such mistakes.

Weighing leaf blade, stem and leaf sheath, and panicle in sub-samples

If not all tillers can be separated into leaf blade, stem and leaf sheath, and panicle, a fixed number of hills (say, 4) should be selected from which all tillers are separated into leaf, stem, and panicle. In this way the selection of systematically large or small tillers is avoided. Preferably, the selected hills should be neighbouring hills. The other 8 hills of the sample are cut into small pieces and dried in the oven. Thus, total dry weight is still based on 12 hills, and only the estimated distribution over leaf, sheath, and panicle is based on 4 hills.

Determination of leaf area on sub-samples

If it is not possible to determine leaf area of all the leaves of the selected 4 hills, sub-samples should be made. A random selection of tillers of the 4 hills is made. From the selected tillers all leaves should be used for determination of leaf area. After determination of leaf area, dry weight of these leaves is determined. SLA is calculated for the sub-sub-sample, while LAI is calculated using leaf dry weight of the sub-sample.

Summary

Summarizing, the data collected during periodic harvesting are:

1. Number of uninfested tillers, deadhearts and whiteheads.

And for uninfested tillers, deadhearts and whiteheads separately:

2. Leaf area index (total, green, dead).
3. SLA
4. N-content of green leaf area
5. Shoot dry weight
6. Distribution of dry weight over leaf, stem, and panicle.

At maturity, the following yield components are determined per tiller-type (uninfested, deadheart, whitehead):

- number of tillers
- number of panicle bearing tillers
- number of grains per panicle
- percentage of filled grains
- 1000 grain weight of filled grains.

8 Damage by bacterial leaf blight and sheath blight in rice: a joint experimental approach

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8.1 Introduction

Participants of the SARP workshop 'Simulation of Impact of Pests and Diseases on Rice' from 15 to 20 April 1991 at the Central Rice Research Institute (CRRI) in Cuttack, India, agreed that a standard field lay-out and a uniform observation method ought to be used in model validation experiments. Bastiaans developed the 'Standard Procedure for the Collection of Data' (1991) for foliar disease experiments, which has been applied since then. At the SARP workshop 'Mechanisms of Bacterial Leaf Blight damage and their Effects on Yield' from 3 to 5 March 1993 at CRRI, Cuttack, this procedure was evaluated, and after ample discussion on encountered problems, desired experimental results and resources, a new Standard Procedure was agreed upon.

The Standard Model for Foliar Diseases (L1DFDE), which was based upon MACROS-L1D (Penning de Vries et al., 1989) has been replaced by BLIGHT (see Section 6.2). As SARPIII focuses on Bacterial Leaf Blight (BLB) and Sheath Blight (ShBl), the new Standard Procedure is especially designed for these two diseases. However, its basic concepts are equally valid for validation experiments for other diseases. In this context, it is good to bear in mind that the current version of BLIGHT is especially written for the both blight diseases.

BLIGHT, just as L1DFDE, distinguishes three leaf layers, and per leaf layer three types of leaf area: healthy, diseased and dead, which implies that a total of 9 leaf categories have to be observed (layer 1 - healthy, layer 1 - diseased, layer 1 - dead, layer 2 - healthy, etcetera). The simulation model calculates photosynthesis per leaf layer and leaf area category, and processes the outcomes to one canopy value. In this process, healthy leaf area is considered unaffected, dead leaf area is supposed to intercept radiation, but not to photosynthesize and respire, and photosynthesis of diseased leaf area is described by input functions that relate maximum photosynthesis rate at high light intensity, initial light use efficiency and respiration to disease severity. Research is being conducted to quantify these relations.

The Standard Procedure describes validation experiments for the BLIGHT model, which are conducted to determine the agreement between actual and simulated yield

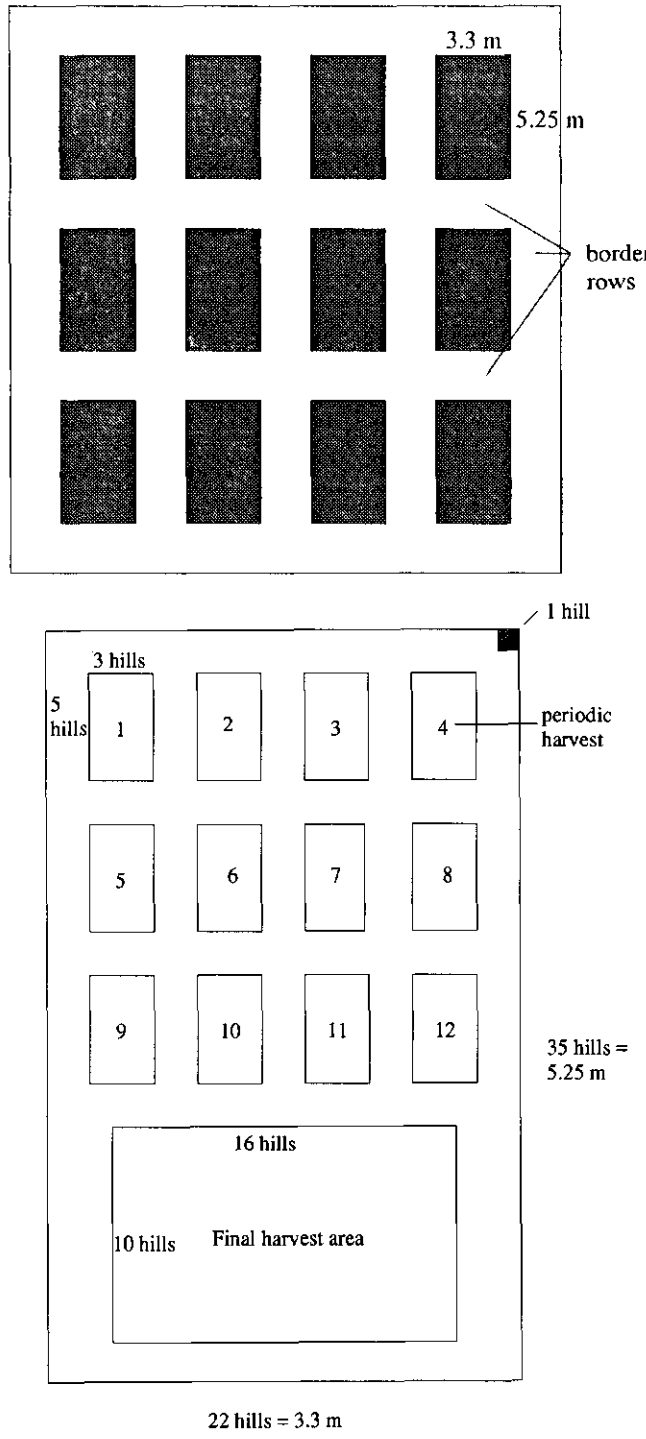

Figure 8.1a. (Upper) Experimental field lay-out with 12 sub-plots.

Figure 8.1b. (Lower) Lay-out of one sub-plot, based upon a hill distance of 15 x 15 cm.

reduction due to disease presence. The experimental results can be recorded on and processed with data sheets that are especially designed to support the transformation of field recordings to input for the simulation models described in Chapter 6 (Appendix A. 7).

8.2 Upgraded standard procedure for data collection

Field, fertilizer and variety requirements

The field consists of 12 plots of 5.25 x 3.3 m, preferably in a 4 x 3 lay-out (Figure 8.1a). The distance between plots should be sufficient to prevent disease spread to neighbouring plots, e.g. 2 to 4 m. Hill distance is 15 x 15 cm, which results in 35 x 22 hills per plot. Two seedlings are planted per hill.

A plot consists of 12 sub-plots (3 x 5 hills) for periodic harvest, and one larger plot (10 x 16 hills) for final harvest (Figure 8.1b). The outer rows of a plot and the 2 rows between sub-plots function as border rows. Some border rows around the entire field is advisable as well. Probably not all 12 sub-plots will be harvested, but some extra plots may be useful in case of calamities. High N application rates are recommended, as this stimulates disease development. A possible scenario is: 50 kg ha^{-1} basal, 60 kg ha^{-1} at start of tillering, 60 kg ha^{-1} at maximum tillering, and 50 kg ha^{-1} at anthesis. More N at anthesis is not effective.

IR64, which is susceptible to both BLB and ShBl, is used in the common validation experiments of the Crop Protection theme. Also in other themes, IR64 is the common variety. Seeds are sent from IRRI for this purpose, and multiplied by the teams. Each scientist is encouraged to add local varieties to the experiment, if resources permit.

Treatments

The creation of similar epidemics in different replications is not anticipated any longer. Experience learns that such is very difficult, and that therefore averaging over replications is not possible. Replications are abandoned, and use will be made of the fact that epidemics develop mostly differently, even if inoculation methods have been similar. A large number of distinct epidemics will allow better parameterization and validation of the model.

The onsets of epidemics should preferably correspond with the onsets under normal local farming conditions.

Bacterial Leaf Blight
Epidemics are started at three different crop development stages (Table 8.1), and are

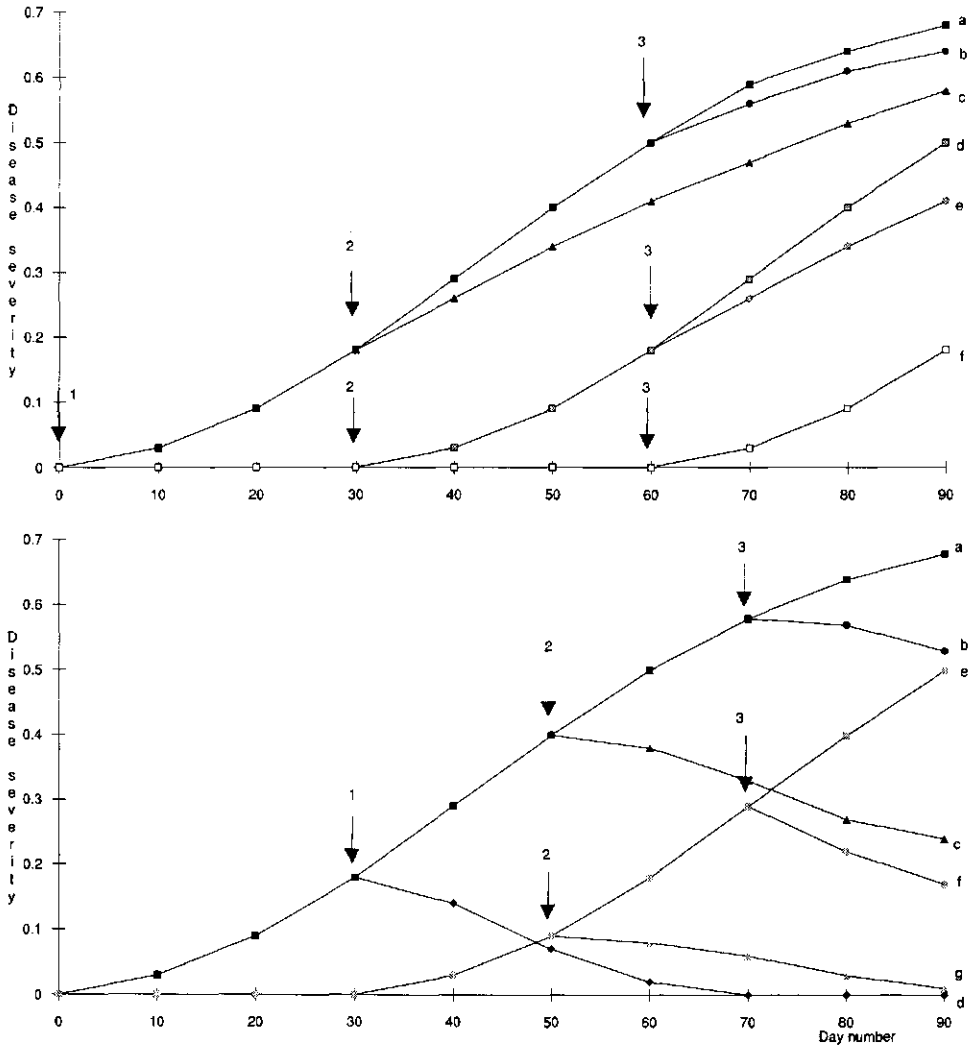

Figure 8.2a. (Upper) Anticipated Bacterial Leaf Blight epidemics in model validation experiments. Different combinations of inoculations result in 6 distinct epidemics (a, b, c, d, e and f). For example, inoculation of a plot at days 0, 30 and 60 results in epidemic a; inoculation of a plot only at day 30 results in epidemic e. 1 = inoculation at early tillering (day 0), 2 = inoculation at late tillering (day 30), 3 = inoculation at flag leaf appearance (day 60).

Figure 8.2b. (Lower) Anticipated Sheath Blight epidemics in model validation experiments. Different combinations of inoculations and sprayings result in 7 distinct epidemics (a, b, c, d, e, f and g). For example, inoculation of a plot at day 0 without spraying results in epidemic a; inoculation of a plot at day 30 and spraying at day 70 results in epidemic f. Day 0: first inoculation, day 30: second inoculation, 1 = spraying at day 30, 2 = spraying at day 50, 3 = spraying at day 70.

maintained by repeated inoculation (Figure 8.2a). Differences in epidemics are created through a different number of repeated inoculations. In the case of onset at early tillering, the highest epidemic is created by three consecutive inoculations at moments 1, 2 and 3; the second highest epidemic by inoculations at moments 1 and 2; and the lowest epidemic by a single inoculation at moment 1. In the case of onset at late tillering only two epidemics can be created, whereas inoculation at flag leaf appearance can result in only one single epidemic. Additionally, 4 plots are not inoculated; these healthy treatments may show some low natural infection rates, which should also be monitored.

The field lay-out includes 12 plots, as these conveniently fit into an approximately square field. Since the experiments require only 10 plots, 2 plots could be used for seed multiplication.

Table 8.1. Number and timing of BLB and ShBl epidemics.

	Epidemic onset at				
	Healthy	Early tillering	Maximum tillering	Late tillering	Flag leaf appearance
BLB	4 plots	3 epidemics		2 epidemics	1 epidemic
ShBl	4 plots		4 epidemics		3 epidemics

Sheath Blight

Epidemics are started at two different crop development stages (Table 8.1), and are interrupted by repeated spraying of a fungicide (Figure 8.2b). Differences in epidemics are created through a different number of sprayings. In the case of onset at tillering, the lowest epidemic is created through three consecutive sprayings at moments 1, 2 and 3; the highest epidemic through not spraying al all. In case of late inoculation, 3 different epidemics can be created. Additionally, 4 plots are not inoculated; these healthy treatments may show some low natural infection rates, which should also be monitored.

The field lay-out includes 12 plots, as these conveniently fit into an approximately square field. Since the experiment requires only 11 plots, 1 plot could be used for seed multiplication.

Randomization

The experimental design is a non-replicated trial, in which only the healthy treatment appears 4 times. You can therefore randomize in one go the 4 healthy, the 6 or 7 treatments and the 2 or 1 multiplication fields over the 12 available plots. A simple way to do this is randomizing the letters A, B, C, D, E, F, G, H, I, J, K and L. They may for instance appear in the sequence K, B, E, C, D, I, G, F, J, H, A and L. These letters you

assign to plot number 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12, respectively. Combination of this with the treatments results in:

Plot number	1	2	3	4	5	6	7	8	9	10	11	12
Letter	K	B	E	C	I	G	F	D	J	H	A	L
Treatment - BLB	SM	H	1a	H	2b	1c	1b	H	3a	2a	H	SM
Treatment - ShB1	2c	H	1a	H	2a	1c	1b	H	2b	1d	H	SM

H = healthy; SM = seed multiplication; 1a, 1b, etcetera = various treatments, see captions of Figure 8.2.

Leaf layers

Lesions are normally not evenly distributed over canopy depth. Simulation has to take this into account, as for instance lesions in the top of the canopy cause more reduction of dry matter production than lesions low in the canopy. Separation of the canopy in leaf layers strongly increased the amount of work involved in data collection, and therefore only three leaf layers are distinguished: 0-25 cm, 25-40 cm and more than 40 cm from the soil surface. Throughout the growing season, the bottom leaf layer (0-25 cm) is numbered 1, the middle layer (25-40 cm) is numbered 2, and the top layer (>40 cm) is numbered 3. Early in the season, layers 2 and 3 have not developed yet, and late in the season, layer 1 may have disappeared.

This division of leaf layers is based upon an anticipated equal amount of leaf area over the three layers at anthesis. Leaf area density is mostly high in the small middle leaf layer.

For the classification of the various layers, the position of the leaf collar (the transition of the leaf blade to the leaf sheath) is used as a reference. As leaves do not take a horizontal position, this classification will not exactly correspond with the actual leaf area and weight distribution over canopy depth. Its advantage, however, is that taking observations is much easier.

Severity assessment

Per leaf layer, leaves are separated in entirely healthy, entirely dead, and diseased (i.e. partly dead) leaves. This will yield three leaf area fractions per leaf layer: healthy, diseased and dead.

It may be possible that otherwise healthy leaves die due to other causes. This 'natural' senescence can best be observed separately, by determining the green and dead leaf area fractions of the healthy leaves. This information will be used to relate in the model the relative senescence rate to development stage.

Disease severity is the affected leaf area relative to the total leaf area of the diseased leaf area fraction. It is therefore better to determine severity on an area basis than on a length basis, as has been done previously. The best tool is the use of a leaf area meter, and it is strongly advised to use such a machine, if available. However, accurate determination of the lesion area with a leaf area meter is still labourious, and moreover, the equipment may not always be available. If one has to decide that a leaf area meter can not be used, than the relative lesion area can be assessed visually.

Many scales are non-proportional, as they discriminate better at the lower and upper ends than in the middle of the scale. For simulation purposes it is best to use a proportional scale, which discriminates equally well at all places of the scale. This is achieved by a step-wise approach: the observer assesses by halving several times the estimate. First it is decided whether severity is between 0 and 50 %, or between 50 and 100 %. If for example the first is true, then it is decided whether severity is between 0 and 25 % or between 25 and 50 %. Four assessment steps are made in this manner, which leads to final determination of the disease severity (Figure 8.3). In a preliminary research by CABO/IRRI, a correlation coefficient (r^2) of 0.88 was found between visually assessed severity and actual severity as determined with a leaf area meter.

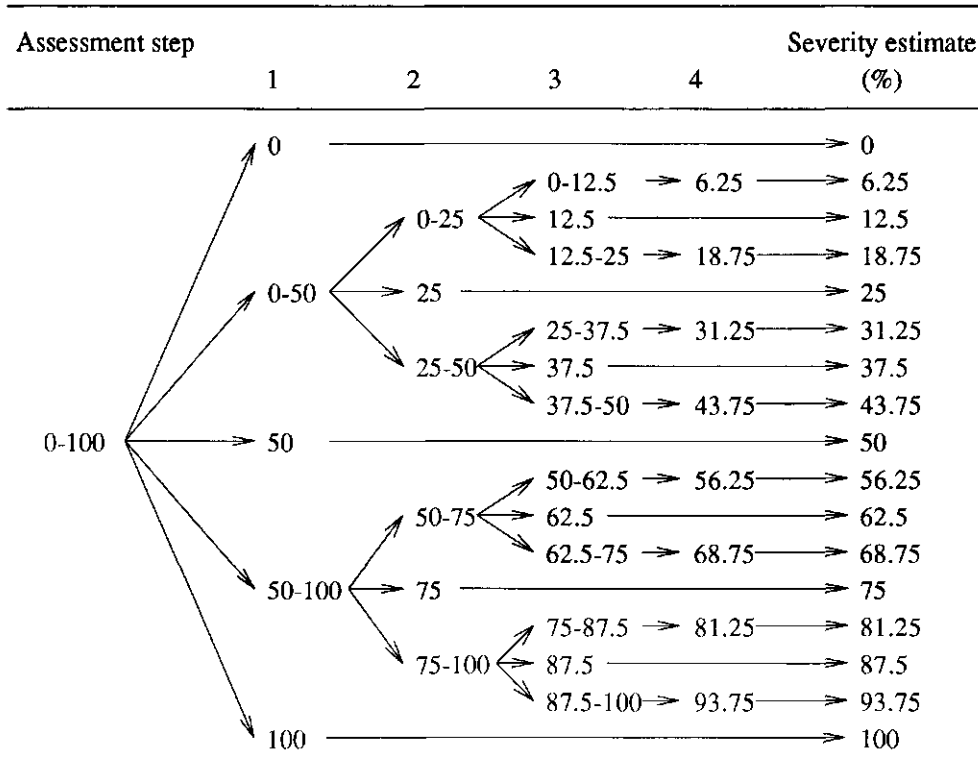

Figure 8.3. Severity assessment steps for foliar diseases.

Bacterial Leaf Blight

Disease severity is assessed with a leaf area meter or visually. The total leaf blade area is considered. A diseased leaf is separated only in healthy and affected leaf area.

Sheath Blight

Leaf blade. Disease severity is assessed with a leaf area meter or visually. The total leaf blade area is considered. In addition to severity, the location of the lesion is recorded: at the base, in the middle, or at the tip of the leaf blade.

Leaf sheath or stem. The lesion length relative to the total stem length in the relevant leaf layer is determined. Additionally, the 'width' of the lesion is determined relative to the circumference of the stem at that place. These values are transformed to a severity estimate for the stem on an area basis. (Example: if the length of a lesion in layer 2 is 5 cm, then its relative length is 5/25=0.2; if its relative 'width' is 0.25, then disease severity for layer 2 is 0.2*0.25=0.05).

For a mature plant, stem length in layers 1 (the bottom layer) and 2 is 0.25 and 0.15 cm, respectively, but stem length in layer 3 has to be measured. Early in the growing season, the top of the stem may not yet have reached 25 or 40 cm height, and therefore, stem length in the highest present leaf layer must be measured. In all cases, the stem ends at the collar of the upper leaf. The above plant material belongs to the panicle. Do neither confuse stem length with plant height, as plant height includes erect leaves early in the season, and panicles late in the season.

Minimum sample size and observation frequency

It is important that a sufficient number of hills, plants or tillers is observed in order to limit the effects of any heterogeneity. Early in the growing season, there is only one leaf layer, plants have not yet been infected with a disease, and the amount of labour required to obtain all data is limited. However, as more tillers and additional leaf layers appear, and diseased and dead leaf classes have to be measured, the availability of labour may be limiting. Although it is recommended that as much as possible plant material is measured, at some point sub-sampling will be required. The moment in the growing season when this is started will depend upon local time and labour constraints. It is important that the sub-sampling is representative, by harvesting a fixed set of hills, or randomly selecting tillers. It is advised to increase the sample size if plant growth or disease development within a plot is heterogeneous.

A number of minimum sample sizes has been agreed upon:

- early in the growing season, when plants have only one leaf layer and are not yet infected with a disease, all 15 hills of the sub-plot are harvested;
- later on in the season, when tiller density or number of leaf layers increases, or after inoculation, 4 bordering hills in the centre of the sub-plot;

- even later, when the disease is spread over all leaf layers, 50% of the tillers of the 4 bordering hills in the centre of the sub-plot are harvested.

Each plot consists of 12 sub-plots for periodic harvest. Although the model can handle any pattern of time interval, from practical point of view, it may be best to harvest with a fixed time interval. The length of that interval will very much depend upon your local resources; for example, you could harvest every 14 days. This could be changed to 7 days if epidemics increase rapidly. A good starting point for data collection is the moment when plants have just recovered from transplanting (about 14 DAT), or just before first disease inoculation.

Variables to be monitored

Both model input and output data are collected periodically, and at final harvest.

General observations
Non-destructive observations, of which especially the crop development stage is of great importance, as it is used to calculate the crop development rate.

1. Phenological crop development stage (-). Dates of sowing, emergence, anthesis and physiological maturity are recorded. The latter two are defined as the date on which 90 % of the hills show a minimum of one flowering panicle, and the date on which 90 % of the panicles is yellow, respectively. In view of standardization among SARP teams, it is very important that these two definitions are adhered to. This data set may be extended with additional development stages, e.g. start of, maximum, and end of tillering, and panicle initiation. Although not true development stages, also dates of transplanting and harvest should be recorded.

2. Tiller density (m^{-2}). Various techniques may be followed. A sound method is to select one row of 15 - 20 hills which are not periodically harvested, and determine periodically tiller number per hill. The average value is then processed to tillers per m^2.

3. Plant height (m). Plant height is measured from the crown to the top of the canopy, without altering the plant habitus (in other words: do not pull the plant upright).

Model input data, periodic harvests
Destructive observations, taken periodically on sub-plots.

4. Healthy, diseased and dead leaf area, per leaf layer (m^2). Plants are separated in leaf layers, and per leaf layer three different types of (complete) leaves are distinguished: healthy leaves, which are not affected by the disease; diseased leaves, which are partially affected; and dead leaves, which are for 100 % affected. Leaf area is measured, preferably

by feeding the entire leaves through a leaf area meter. The sum of all leaf classes (maximum 9) per unit of ground area is the crop's leaf area index (LAI).

5. Disease severity for diseased leaf area, per leaf layer (-). There will be 1 to 3 categories of diseased leaf area (one per leaf layer), for which disease severity is determined by measuring lesion area (cm^2). Disease severity is defined as lesion area relative to total diseased leaf area. This results in a fraction between 0 and 1.

6. Leaf N content for healthy and diseased leaf area (kg kg^{-1}). Maximum photosynthesis rate is linearly related to leaf nitrogen content, and is as such incorporated in the simulation model. Therefore, it is essential to determine leaf nitrogen content for the photosynthesizing leaf categories, viz. the healthy and diseased leaf area fractions. For the diseased leaf area, N content should only be determined for the green, unaffected leaf area, as the dead leaf area does not contribute to photosynthesis. N content is determined after drying and determining the dry matter weight.

Model output data, periodic harvests
Destructive observations, taken periodically on sub-plots.

7. Plant organ dry weights (kg ha^{-1}). Leaves, stems and sheaths, and panicles are distinguished as plant organs. Roots are ignored. After leaf area determination, material of all 9 leaf categories is dried, and their weights are determined. The sum of all dry weight is total shoot dry weight. The specific leaf area can be calculated from leaf area and weight.

Model output data, final harvest

8. Final grain and straw yield (kg ha^{-1})

9. Panicle density (ha^{-1})

10. Number of filled kernels per panicle (-) and percentage unfilled kernels (%)

11. 1000 kernel weight (g)

9 Participants' workplans

9.1 Stem borer

- At IRRI effects of distribution of assimilates from whiteheads to neighbouring tillers will be investigated using ^{14}C studies.
- Information on dynamics of deadhearts and whiteheads will be collected by the teams and at IRRI. The following schedule was agreed upon:

Team	Varieties	Start of experiment
KKU	RD27, IR64	Dec. 1992 (DS)
CRRI	Jaya	June 1992 (WS)
	Jaya, IR64	Dec. 1992 (DS)
TNRRI	ADT39, IR64	Dec. 1992 (WS)
ZAU	XS620	June 1992 (late rice)
	IR64	May 1993 (mid rice)
PUAT	IR36, PD4	June 1992 (WS)
	IR64	June 1993 (WS)
IRRI	Binato, IR64	Febr. 1993 (DS)

- Validation experiments will be conducted, focusing on deadhearts or whiteheads (timing of infestation) as represented in the following overview:

Team	Deadhearts	Whiteheads	Start of experiment
KKU	X		Dec. 1992 (DS)
CRRI		X	June 1992 (WS)
	X		Dec. 1992 (DS)
TNRRI	X		Dec. 1992 (WS)
ZAU	X		May 1993 (mid rice)
PUAT		X	June 1993 (WS)
IRRI	X		Jan. 1993 (DS)

9.2 Bacterial leaf blight and sheath blight

- Collection of quantitative information on the influence of the diseases on basic plant growth processes, such as photosynthesis and respiration, will by carried out at IRRI and CABO/TPE.
- Development of combination models will be done by CABO in collaboration with TPE.
- Validation experiments and application studies in which local situations can be explored will be carried out at CRRI, PUAT, TNAU-TNRRI and IRRI. The following experiments have been agreed upon for the near future:

	BLB	ShBl
CRRI	June - Oct '93	June - Oct '93
PUAT		June - Oct '93
TNRRI	Sep '93 - Jan '94	
IRRI	Jan - April '93	Jan - April '94

10 Perspective

Traditionally, entomologists and phytopathologists throughout the world focus on the population dynamics of a pest and how it is affected by the crop, but have little expertise of the effects of the pest on the crop. As a result, few relevant research data on damage mechanisms are available. By aiming at the development of conceptual and quantitative understanding of damage mechanisms and their consequences for yield the Crop Protection theme of SARPIII has put itself very ambitious goals.

Discussions during the workshops resulted in distinction of three perspectives for research in the SARP Crop Protection theme. The *current* research perspective involves identification and prioritization of damage mechanisms, carrying out experiments according to the standard format for model validation, and transfer from the generation of L1D-based crop growth models to the ORYZA generation of models. The transfer to ORYZA1 has been made in the BLIGHT model and is underway for stem borer.

The *short-term* research perspective is to have mechanistic models of damage by the various pests which have been tested using data of the joint experiments using cultivar IR64. This phase should be concluded with a workshop in 1994 during which data are presented, analyzed and compared with model output.

Finally, the *long-term* research perspective describes research aimed at creating tools for tactical and strategic decision support which are considered useful by the participating National Agricultural Research Centres. Tactical decision tools comprise, for example, critical periods, or 'windows', during which the crop is especially prone to damage, damage thresholds for chemical control of stem borer and sheath blight, and iso-loss lines for bacterial leaf blight which cannot be controlled chemically. Strategic decision tools show the relation between cultural practices such as cultivar choice, nitrogen fertilizer application and planting distance, and damage. Such tools enable on the one hand retrospective analysis of causes of yields lower than the potential level ('yield gap analysis'), and on the other hand prospective evaluation of the positive and negative contributions of various cultural choices to economic and ecological objectives of rice cultivation.

By-products of these research perspectives are tools for research itself. Currently (May 1993) a user-friendly simulation environment, standard data reports on common experiments and a data base with all SARP research data are under development. These tools allow increase of research efficiency and provide a framework for the long-term research perspective. Understanding of damage mechanisms may lead to new approaches in other pest-crop systems.

To realize the long-term research perspective cross-links to other themes in SARP and to national and supranational organizations focusing on applying Integrated Pest Management (IPM) are indispensable. Within SARP, the tactical and strategic decision tools for Crop Protection strongly resemble those for water and nitrogen management in

the theme Crop and Soil Management. A promising field of application is Integrated Pest Management , which is currently implemented by various national networks, and by international networks, such as the Inter-Country Programme for Integrated Pest Control in Rice in South and Southeast Asia. The tactical and strategic decision tools will form the basis of such collaboration.

The ideas formulated by NARS and SARP staff during the workshops reported in this volume represent a starting point for discussions on strategic decision support tools that can usefully be derived from mechanistic knowledge of pest-crop interactions. These discussions should result in a clear research agenda from 1994 until the end of the SARPIII project in 1995.

11 References

Akinsola, E.A., 1984. Effect of rice stem borer infestation on yield and yield components. Insect Sci. Applic. 5(2):91-94.

Ahmed, M., 1984. A sample study of stemborer infestation of rice crop and its expected effects on yield of rice at Gujjo (Sind) 1981. Pakistan J. Sci. Ind. Res. 27:33-37.

Austin, R.B., 1981. A combined genetic and chemical approach to increasing and stabilizing wheat yields. In A.F. Hawkins and Jeffcoat (ed.), Opportunities for manipulation of cereal productivity. Monograph 7. British Plant Growth Regulator Group, Oxford.

Bandong, J.P. and J.A. Litsinger, 1986. Development and implementation of rice insect pest management in the Upper Pampanga River Integrated Irrigation System (UPRIIS) Service area, Central Luzon, Philippines, Saturday Seminar, April 19, 1986. International Rice Research Institute, Los Baños, Laguna, Philippines. 50 pp.

Barr, B.A., C.S. Koehler and R.F. Smith, 1975. Rice: Field losses to insects, diseases, weeds and other pests. In Case studies in crop growth simulation. April 1986 - Jan. 1987.

Bastiaans, L., 1991. Quantification of crop growth and yield reduction in rice due to foliar diseases, using simulation and systems analysis; description of an approach.

Bastiaans, L., 1991. Standard Procedure for the Collection of Data. Internal SARP publication.

Bastiaans, L., 1993. PhD thesis Wageningen Agricultural University. In press.

Bastiaans, L. and M.J. Kropff, 1991. Understanding and quantifying damage by air pollution and leaf blast. In: Systems simulation at IRRI. Eds. F.W.T. Penning de Vries et al. IRRI Research Paper Series Number 151. p.21-26.

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

Calora, F.B. and S.L. Reyes, 1971. The ecology og rice stemborers in the Philippines. Proceedings in International Symposium on Rice Insects in Tokyo, Japan from July 19-24, 1971, sponsored jointly by the Tropical Agricultural Research Center Ministry of Agriculture and Forestry and the FAO/IAEA Coordination Meeting of Research Contractors on Rice Insects.

Cock, J.H., and S. Yoshida, 1972. Accumulation of 14C-labelled carbohydrate before flowering and the subsequent redistribution and respiration in the rice plant. Proc. Crop Sci. Soc. Jpn. 41:226-234.

Cook, M.G. and L.T. Evans, 1983. Nutrient responses of seedlings of wild and cultivated Oryza species. Field Crops Research 6: 205-218.

Coombs, J. 1984. Prospects of improving photosynthesis for increased crop productivity. p. 85-94. In C. Sybesma (ed.) Advances in photosynthesis research, Vol. IV. The Hague: Martinus Nijhoff/Dr W Junk Publishers.

Daamen, R.A. and I.T.M. Jorritsma, 1990b. Effects of powdery mildew and weather on winter wheat yield. 2. Effects of mildew epidemics. Netherlands Journal of Plant Pathology 96:35-46.

Dingkuhn, M., H.F. Schnier, S.K. De Datta, E. Wijanco and K. Dörffling, 1990. Diurnal and developmental changes in canopy gas exchange in relation to growth in transplanted and direct-seeded flooded rice. Aust. J. Plant Physiol. 17:119-134.

El-Abdallah, F. and S.M.I. Metwally, 1984. Effect of the simulated damage caused by *Chilo agamemnon* Bles. on the rice grain yield. J. Agric. Res. Tanta Univ. 10:1438-1443.

El-Alaoui, A.C., S.R. Simmons, and R.K. Crookston, 1988. Effects of tiller removal on spring barley. Crop Sci. 28:305-307.

Elmore, C.D. 1980. The paradox of no correlation between leaf photosynthetic rates and crop yields. p. 155-167. In J.D. Hesketh and J.W. Jones (ed.) Predicting photosynthesis for ecosystem models. Vol. II. CRC Press, Boca Raton, FL.

Evans, L.T. 1975. The physiological basis of crop yield. p. 327-335. In L.T. Evans (ed.) Crop physiology. Cambridge University Press, Cambridge, UK.

Field, C.B., J.T. Ball and J.A. Berry, 1989. Photosynthesis: principles and field techniques. p. 209-254. In R.W. Pearcy et al. (ed.) Plant physiological ecology: field methods and instrumentation. Chapman and Hall, London.

Frances, A.M., 1965. The rice stemborers. Saturday Seminar. April 24, 1965. International Rice Research Institute, Los Baños, Laguna, Philippines, 21 pp.

Gifford, R.M., J.H. Thorne, W.D. Hitz, and R.T. Giaquinta. 1984. Crop productivity and photoassimilate partitioning. Science 225:801-808.

Ho, D.T., 1984a. Rice stemborers. Ann. Rep. Int. Cent. Insect Physiol. Ecol.

Ho, D.T., 1984b. Stemborer incidence in rice ecosystems in Kenya, East Africa, In An overview of upland rice research proc of the 1982 Bouake, Ivory Coast Upland Rice Workshop. Int. Rice Res. Inst. pp. 566. Los Baños, Laguna, Philippines.

Htun, T., 1976. Population dynamics of the yellow rice stemborer, Tryporyza incertulas (Walker), and its damage to the rice plant. M.Sc. Thesis Univ. of the Philippines at Los Baños. 92 pp.

Isa, A., W.H. Awadallah and A.M. El-Tantawy, 1971. Losses in rice yield due to the attack of the rice stemborer Chilo agamemnon Bles. U.A.R. Agric. Res. Rev. 49:(1)1-5.

Ishikura, H., 1964. Assessment of rice pest caused by the rice stemborer. pp. 251-275. In The major insect pests of rice plant. Int. Rice Res. Inst., Los Baños, Laguna, Philippines.

Israel, P. and C. Vedamoorthy, 1958. Insect incidence and branching of rice. Curr. Sci. 17:309-310.

Kenmore, P., 1980. Ecology and pest outbreaks of a tropical insect pest of the Green Revolution: The rice brown planthopper Nilaparvata lugens (Stal). Ph.D. dissertation, Division of Biological Pest Control, University of California, Berkeley. 226pp.

Kenmore, P. E., F. O. Cariño, C. A. Perez, V. A. Dyck and A. P. Gutierrez, 1984. Population regulation of the rice brown planthopper (*Nilaparvata lugens* Stal) within rice fields in the Philippines. J. Plant Protection Tropics 1:19-37.

Kropff, M., 1989. Quantification of SO_2 effects on physiological processes, plant growth and crop production. Ph.D. thesis, Wageningen Agricultural University. 201pp.

Kropff, M.J., H.H. van Laar and H.F.M. ten Berge, 1993. ORYZA1. A basic model for irrigated lowland rice production. SARP. IRRI, Los Banos, TPE, Wageningen, DLO-CABO, Wageningen. 89pp.

Kropff, M.J., F.J.H. Vossen, C.J.T. Spitters and W. de Groot, 1984. Competition between a maize crop and a natural population of *Echinochloa crus-galli*. Netherlands Journal of Agricultural Science, 32, 324-327.

Luo, S., 1987. Studies on the compensation of rice to the larval damage caused by the Asian rice borer. Scientia Agriculture Sinica 20(2):67-72.

Majar, M.M., I.M. Bhatti and A.R. Dhuyo, 1985. Stemborer infestations and yield-loss relationship in rice and cost-benefits of control. In Rice Research Inst., Dokri. Research Publications, 1983 to 1985. Sind. 1986. p. 133-150.

Mar, S., 1964. Translocation between main stems and tillers of rice. Plant Physiology Communications 4:15-19.

Matsushima, S., 1980. Rice cultivation for the million. Japan Scientific Societies Press, Tokyo.

McCree, K.J., 1974. An equation for the rate of dark respiration of white clove and grain sorghum as function of dry weight, photosynthetic rate, and temperature. Crop Sci. 14:509-514.

Moiz, S.A. and N.A. Rizvi, 1971. Ecological studies on Tryporyza incertulas (Walker) in Southern Part of West Pakistan. pp. 1-11. In International Symposium on Rice Insects in Tokyo, Japan. Tropical Agricultural Research Center, Ministry of Agriculture and Forestry and the FAO/IAEA Coordination Meeting of Research Contractors on Rice Insects.

Monteith, J.L., 1969. Light interception and radiative exchange in crop stands. In J.D. Eastin (ed.) Physiological aspects of crop yield. American Society of Agronomy, Madison, Wisconsin.

Pathak, M.D., 1968. Ecology of common insect pest of rice. Ann. Rev. Entomol. 13:257-294.

Peng, S., D.R. Krieg and F.S. Girma, 1991. Leaf photosynthetic rate is correlated with biomass and grain production in grain sorghum lines. Photosynthesis Research 28:1-7.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge and A. Bakema, 1989. Simulation of ecophysiological processes of growth of seveal annual crops. Simulation Monographs, Pudoc, Wageningen, The Netherlands. 217 pp.

Penning de Vries, F.W.T., H. van Keulen and J.C. Alagos, 1990. Nitrogen redistribution and potential production in rice. In: Sinha, S.K. (Ed.), Proceedings of the international Congress of Plant Physiology. New Delhi, India, p. 513-520.

Rabbinge, R., 1986. The bridge function of production ecology. Netherlands Journal of Agricultural Science 34, 239-251.

Rabbinge, R. and G. Coster, 1984. Some effects of cereal aphids on growth and yield of winter wheat. In: P. Barley and D. Swinger (Eds.): Proceedings of the Fourth Australian Applied Entomological Research. 24-28 sept. 1984.

Rabbinge, R., E.M. Drees, M. van der Graaf, F.C.M. Verberne and A. Wesselo, 1981. Damage effects of cereal aphids in wheat. Netherlands Journal of Plant Pathology 87:217-232.

Rabbinge, R. and F.H. Rijsdijk, 1981. Disease and crop physiology: a modeller's point of view. In: Effects of disease on the physiology of the growing plant (ed. P.G. Ayres). Cambridge University Press, Cambridge. pp. 201-220.

Rabbinge, R., S.A. Ward and H.H. van Laar, (Eds), 1989. Simulation and systems management in crop protection. Pudoc, Wageningen.

Rai, P.S. and B.S. Naidu, 1974. Estimation of loss in grain yield caused by rice stemborer, Tryporyza incertulas (Walker). Curr. Res. 3:129.

Riethoven, J.J.M., 1993. The SARP-Shell, a crop growth simulation environment. Simulation and Systems Analysis for Rice Production (SARP), CABO-DLO, TPE-WAU, IRRI. 41 pages.

Rossing, W.A.H., M. van Oijen, W. van der Werf, L. Bastiaans and R. Rabbinge, 1992. Modelling effects of foliar pests and pathogens on light interception, photosynthesis, growth rate and yield of field crops. In: P.G. Ayres (Ed), Pests and pathogens: plant responses to foliar attack. BIOS, Oxford. p. 161-180.

Rossing, W.A.H., 1991a. Simulation of damage in winter wheat caused by the grain aphid Sitobion avenae. 2. Construction and evaluation of a simulation model. Netherlands Journal of Plant Pathology 97: 25-54.

Rossing, W.A.H., 1991b. Simulation of damage in winter wheat caused by the grain aphid Sitobion avenae. 3. Calculation of damage at various attainable yield levels. Netherlands Journal of Plant Pathology 97: 87-103.

Rossing, W.A.H. and L.A.J.M. van de Wiel, 1990. Simulation of damage in winter wheat caused by the grain aphid Sitobion avenae. 1. Quantification of the effects of honeydew on gas exchange of leaves and aphid populations of different size on crop growth. Netherlands Journal of Plant Pathology 96: 343-364.

Rothschild, G.H.L., 1971. The biology and ecology of rice stemborers in Sarawak (Malaysian Borneo). J. Appl. Ecol. 8:287-322.

Rubia, E.G., B.M. Shepard, E.B. Yambao, K.T. Ingram, G.S. Arida, and F. Penning de Vries. 1989. Stem borer damage and grain yield of flooded rice. Journal of Plant Protection in the Tropics 6(3):205-211.

Saka, H., and H. Chisaka. 1985. Photosynthesis measurement by oxygen electrode as a simple bioassay method. JARQ 18(4):252-259.

Spitters, C.J.T., 1984. A simple simulation model fo crop-weed competition. COLUMA (Comité Francais de Lutte Contre les Mauvais Herbers)-EWRS (European Weed Research Society), Paris. p. 13-27.

Spitters, C.J.T., 1989. Weeds: Population dynamics, germination and competition. In: Rabbinge, R., S.A. Ward and H.H. vanLaar, (eds). Simulation and systems management in crop protection. Pudoc, Wageningen. p. 182-216.

Spitters, C.J.T, 1990. Crop growth models: their usefulness and limitations. Acta Hort. 267, 349-368.

Spitters, C.J.T., H. van Keulen and D.W.G. van Kraalingen, 1989. A. simple and universal

Tantawi, A.M., F. El-Abdallah, and A.M. Soliman, 1985. Losses in rice yield due to rice stemborer, Chilo agmemnon Bles. Proc. 6th Arab Pesticide Conf. Tanta Univ. 1:183-189.

Teng, P.S., C.Q. Torres, F.L. Nuque and S.B. Calvero, 1990. Current knowledge on crop losses in tropical rice. In Crop loss assessment in rice. IRRI. p.39-53.

Thorne, G.N., and D.W. Wood. 1987. The fate of carbon in dying tillers of winter wheat. J. Agric. Sci., Camb. 108:515-522.

van Halteren, P., 1977. Yield losses and economic injury levels of rice pests in South Sulawesi, Indonesia. Int. Rice Res. News 2:6.

Keulen, H. van and N.G. Seligman, 1987. Simulation of Water Use, Nitrogen Nutrition and Growth of a Spring Wheat Crop. Simulation Monographs, Centre for Agricultural Publishing and Documentation (PUDOC), Wageningen, 310 pages.

van Keulen, H. and J. Wolf, (eds), 1986. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen.

Vereijken, P.H., 1979. Feeding and multiplication of three aphid species and their effect on yield of winter wheat. Agric. Res. Rep. 888. 58pp.

Wells, R., W.R. Meredith Jr., and J.R. Williford, 1986. Canopy photosynthesis and its relationship to plant productivity in near-isogenic cotton lines differing in leaf morphology. Plant Physiol. 82:635-640.

Wyatt, I.J., 1957. Field investigations of padi stemborers, 1955-1956. Federation of Malaya Dept. Agric. Bull. No. 102. 42 pp.

Yoshida, S., 1981. Fundamentals of Rice Crop Science. The International Rice Research Institute. Los Baños, Philippines.

Zadoks, J.C., 1985. On the conceptual basis of crop loss assessment: the threshold theory. Annual Review of Phytopathology, 23, 455-73.

Zadoks, J.C., T.T. Chang and C.F. Conzak, 1974. A decimal code for the growth stages of cereals. Eucarpia Bulletin 7:42-52.

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

Zebarth, B.J., and R.W. Sheard. 1991. Response of barley yield and yield components to nitrogen rate under low and high input management systems. Can. J. Plant Sci. 71:71-80.

Zelitch, I., 1982. The close relationship between net photosynthesis and crop yield. BioScience 32:796-802.

Appendix A.1 Workshop programs and participants

Workshop on Mechanisms of stem borer damage and their effects on yield, Khon Kaen University, Khon Kaen, Thailand, 3-5 August 1992.

Programme

Monday August 3		
0830	Welcome address	N. Tongsopit President KKU
0845	Introduction of participants and presentation of workshop objectives	W.A.H. Rossing
0930	Photo session	
1015	Review on stem borer research, an insight	E.G. Rubia
1035	Stem borer research in CHina Short presentations from the participants	Xu Zhihong
1055	PUAT team	P.K. Pathak
1110	KKU team	M. Keerati-Kasikorn
1125	TNRRI team	N. Raju
1140	IRRI team	L. Fabellar
1155	CRRI team	R.C. Dani
1210	MARDI team	Md. Norowi Hamid
1225	Lunch	
1330	Yield components and grain yield	E.G. Rubia
1400	Physiological processes of crop growth	S. Peng
1500	Coffee break	
1530	Plant growth and response of crops to insect injury	W.A.H. Rossing
1600	Effect of artificial stem borer damage on crop growth and grain yield	L. Yambao
1900	Welcome dinner	
Tuesday August 4		
0800	Brainstorming session	K.L. Heong

1200	Lunch	
1330	Summarizing important points from morning session	K.L. Heong
1400	The crop growth model and incorporation of stem borer damage within the model	E. Rubia / L. Bastiaans
1500	Coffee break	
1530	Field trip	M. Keerati-Kasikorn
1700	Adjourn	
Wednesday August 5		
0800	Discussion of the first version of model L1DTSB, a model for simulation of damage due to stem borer	L. Bastiaans
1000	Coffee break	
1030	Presentation of a proposal for joint experiments on damage due to stem borer	L. Bastiaans
1200	Lunch	
1330	Work plans morning session	L. Bastiaans/W.A.H. Rossing
1500	Coffee break	
1530	Presentation of proposed experimental plans per team	E.G. Rubia
1630	Conclusions	W.A.H. Rossing
1700	Closing remarks	

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Workshop on Mechanisms of bacterial leaf blight damage and their effects on yield, The Central Rice Research Institute, Cuttack, Orissa 753 006, India, 3-5 March 1993.

Programme

Monday March 3		
0830	Welcome address	B. Venkateswarlu Director CRRI
0845	Report to the president	W.A.H. Rossing
0900	Introduction of participants and presentation of workshop objectives	A. Elings
0915	Words of thanks	P.R. Reddy
1000	Presentation research CRRI team	P.R. Reddy
1045	Presentation research PUAT team	R.A. Singh
1130	Presentation research TNAU team	V. Narasimhan
1215	Lunch	
1330	Physiological processes of crop growth and their relationship to BLB damage	W.A.H. Rossing
1430	Plant growth and response to disease damage	P.S. Teng
1515	Coffee break	
1545	BLB damage in rice: experiments and results	P.R. Reddy
1630	Excursion to field experiments	P.R. Reddy
1900	Welcome dinner	
Tuesday March 4		
0800	Brainstorming session	P.S. Teng
1200	Lunch	
1330	The ORYZA1 model	A. Elings
1400	Incorporation of blight in ORYZA1: the BLIGHT model	A. Elings
1500	Coffee break	
1530	Exercises and discussion of experimental results	A. Elings
1700	Adjourn	

Wednesday March 5

0800	Exercises and discussion of experimental results, continuation	A. Elings
1000	Coffee break	
1030	Identification of problems: proposals for, and discussion on joint experimentation	A. Elings/W.A.H. Rossing
1200	Lunch	
1330	Discussion of exp's: cont'd	A. Elings/W.A.H. Rossing
1430	Setting of time table	A. Elings/W.A.H. Rossing
1500	Coffee break	
1530	Summary and conclusions	A. Elings
1600	Closing	W.A.H. Rossing

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Appendix A.2 Listing of model L1DT

Major differences with model L1D are in bold print. New abbreviations are summarized at the end of this appendix.

```
TITLE L1DT (L1D adapted for introduction of module TIL)
****
** In this model a flexible distribution of assimilates over
** stem reserves and storage organs is introduced.
** If the actual carbohydrate production exceeds demand,
** carbohydrates are stored as stem reserves. If the actual
** production is not able to meet demand, carbohydrate supply
** to the grains is completed by stem reserves.
** This flexible distribution of assimilates both enables and
** requires the introduction of module TIL
**
** Author: Lammert Bastiaans
** Version: 1; Date: may 1992
*****

FIXED IDATE,I,NL
STORAGE RDTMT(365),TPHT(365),TPLT(365),RAINT(365),...
   HUAAT(365),WDST(365),TKL(11),TYL(11)
INITIAL
   WRTI  =WLVI
   WSRI  =0.
   ALVI  =WLVI/(SLC*AFGEN(SLT,DSI))
   CPEW  =1.
   DREW  =1.
   PCEW  =1.
   PARAM NHILL=250000., NTILHI=3.
*  spacing 0.20*0.20; 3 tillers/hill
   NTII  =NHILL*NTILHI

DYNAMIC
**WEIGHTS OF CROP COMPONENTS
**Explanation in sections 3.2, 2.2, 3.4
   WLV   =INTGRL(WLVI,GLV-LLV)
   WST   =INTGRL(WSTI,GST)
   WSR   =INTGRL(WSRI,GSR)
   WSO   =INTGRL(WSOI,GSO)
   WEPSO =WSO*FEPSO
   WRT   =INTGRL(WRTI,GRT-LRT)
   WSS   =WLV+WST+WSO+WSR
   WCR   =WSS+WRT
   WLVD  =INTGRL(0.,LLV)
   WRTD  =INTGRL(0.,LRT)

**GROWTH RATES AND LOSS RATES
**Explanation in sections 2.4, 3.2, 2.2
   GLV   =CAGLV/CRGLV
   GST   =CAGST/CRGST
```

```
      GRT   =CAGRT/CRGRT
      GSR   =CAGSR/1.111
      GSO   =CAGSO/CRGSO

      LLV   =WLV*AFGEN(LLVT,DS)
      LRT   =WRT*AFGEN(LRTT,DS)

**CARBOHYDRATE AVAILABLE FOR GROWTH, EXPORT
**Explanation in sections 3.2, 2.4, 2.3, 2.2
      CAGCR =PCGW*0.682-RMCR*0.682
      CAGSS =CAGCR*AFGEN(CASST,DS)*CPEW
      CAGRT =CAGCR-CAGSS
      CAGLV =CAGSS*AFGEN(CALVT,DS)
      CAGST =CAGSS*(1.-FSTR)*AFGEN(CASTT,DS)
      CAGRSO=CAGSS-CAGLV-CAGST
      CRGSOM=GSOM*CRGSO
      CAGSR =INSW(CRGSOM-CAGRSO,(CAGRSO-CRGSOM)*0.947,...
             -AMIN1((CRGSOM-CAGRSO)/0.947,WSR*0.1*1.111))
      CAGSO =INSW(CRGSOM-CAGRSO,CRGSOM,CAGRSO-CAGSR*0.947)

      CELV  =PCGW-(RMLV+RMST+0.5*RMMA)
      CELVN =INTGRL(0.,INSW(CELV,1.,-CELVN/DELT))

**PHOTOSYNTHESIS, GROSS AND NET
**Explanation in sections 2.1, 3.3, 3.4
      PCGW  =PCGC*PCEW
      PCGC  =FUPHOT(PLMX,PLEA,ALV,RDTM,DATE,LAT)
      PLMX  =PLMXP*AFGEN(PLMTT,TPAD)*LIMIT(200.,600.,SLA)/300....
             *PLMXN
      PLEA  =PLEI*AFGEN(PLETT,TPAD)
      PCGT  =INTGRL(0.,PCGW)
      RCRT  =INTGRL(0.,RMCR+RGCR)
      PCNT  =INTGRL(0.,PCGW-(RMCR+RGCR))
*     PLMX depends on nitrogen-content of the leaves
      PLMXN =AFGEN(PLMXNT,NCLV)
      NCLV  =AFGEN(NCLVT,DS)
      FUNCTION PLMXNT=0.,0., 0.005,0.01, 0.05,1., 0.07,1.3
      FUNCTION NCLVT=0.,0.05, 0.2,0.05, 1.0,0.04, 2.1,0.03

**RESPIRATION
**Explanation in sections 2.4, 2.3
      RMCT  =INTGRL(0.,RMCR)
      RMCR  =RMLV+RMST+RMSO+RMRT+RMMA
      RMLV  =WLV*RMCLV*TPEM*0.75
      RMST  =WST*0.010*TPEM+WSR*0.0
      RMRT  =WRT*0.015*TPEM
      RMSO  =AMIN1(1000.,WSO)*0.015*TPEM
      TPEM  =Q10**((TPAV-TPR)/10.)

      RMMA  =0.20*PCGW*0.5

      RGCR  =RGLV+RGST+RGSO+RGRT+RTSR
      RGLV  =GLV*CPGLV
      RGST  =GST*CPGST
      RGSO  =GSO*CPGSO
      RGRT  =GRT*CPGRT
```

```
   RTSR  =INSW(CRGSOM-CAGRSO,CAGSR/0.947,-CAGSR)*0.053*1.467
*  respiration due to transport of reserves (loss=5.3 %)

**CARBON BALANCE CHECK
**Explanation in section 3.4
   CKCRD =FUCCHK(CKCIN,CKCFL,TIME)
   CKCIN =(WLV-WLVI)*FCLV+(WST-WSTI)*FCST+...
          (WSO-WSOI)*FCSO+(WRT-WRTI)*FCRT+(WSR-WSRI)*0.444
   CKCFL =PCNT*0.2727-(WLVD*FCLV+WRTD*FCRT)

**LEAF AREA
**Explanation in section 3.3
   ALV   =INTGRL(ALVI,GLA-LLA+GSA)
   GLA   =GLV/SLN
   LLA   =LLV/SLA
   GSA   =0.5*GST/SSC
   SLN   =SLC*AFGEN(SLT,DS)
   SLA   =WLV/(ALV-0.5*WST/SSC)

**PHENOLOGICAL DEVELOPMENT OF THE CROP
**Explanation in section 3.1
   DS    =INTGRL(DSI,INSW(DS-1.,DRV,DRR))
   DRV   =DRCV*DRED*DREW*AFGEN(DRVTT,TPAV)
   DRED  =AFGEN(DRDT,DLP)
   DRR   =DRCR*AFGEN(DRRTT,TPAV)

** TILLER-MODULE
*  tillers
   NTI   =INTGRL(NTII,(GNTI-LNTI))
   GNTI  =DSTF*AMAX1(0.,(NTIP-NTI)/TCFT)
   LNTI  =DSTD*AMAX1(0.,(NTI-NTIP)/TCDT)
   NTIP  =CAGCR/CNTI
   DSTF  =NOR(DST1-DS,DS-DST2)
   DSTD  =NOR(DST1-DS,DS-(DST2+0.15))
   CNTI  =AFGEN(CNTIT,DS)
   NTIPH =NTI/NHILL
   NTIM2 =NTI/10000.

*  florets
   NFL   =INTGRL(0.,GNFL)
   GNFL  =DSFL*AMIN1(NFLMX-NFL,NFLP-NFL)/TCFF
   NFLP  =CAGCR/CNFL
   CNFL  =0.7*GGRMN
   NFLMX =NFLMXT*NTI
   DSFL  =NOR(DSF1-DS,DS-DSF2)

*  grains
   NGR   =INTGRL(0.,GNGR)
   GNGR  =DSGR*AMAX1(0.,AMIN1(NGRP-NGR,NGRMX-NGR)/TCFG)
   NGRP  =CAGCR/GGRMN
   NGRMX =NFL
   DSGR  =NOR(DSG1-DS,DS-DSG2)
   GGRMN =WGRMX/GFP
   GFP   =1./(1.33*DRR)
   GGRMX =GGRMN*2.
```

```
   WGR    =WSO/(AMAX1(NGR,1000.))
   WG1000=(WGR*1.E6)*100./86.
   NGRPTI=NGR/NTI
   NGRM2 =NGR/10000.
   GSOM   =NGR*GGRMX*AFGEN(GGRT,TPAV)

   PARAM DST1  =0.3, DSF1  =0.7, DSG1  =0.95
   PARAM DST2  =0.75,DSF2  =0.95,DSG2  =1.15
   PARAM TCFT  =15., TCFF  =7.,  TCFG  =3.,  TCDT  =10.
   PARAM NFLMXT =100., WGRMX =23.5E-6
   FUNCTION GGRT  =10.,0.0, 15.,0.0, 18.,0.75, ...
                   23.,1.0, 27.,0.9, 40.,0.0
   FUNCTION CNTIT =0.0,5.E-6,  0.3,5.E-6,  0.75,25.E-6, ...
                   1.0,75.E-6, 2.1,75.E-6

**WEATHER DATA AND TIME
**Explanation in chapter 6 and section 3.4
   RDTM  =RDTMT(IDATE)*RDUCF
   RDTC,DLA,DLP=SUASTR(DATE,LAT)
   TPAV  =(TPLT(IDATE)+TPHT(IDATE))/2.
   TPAD  =(TPHT(IDATE)+TPAV)/2.

   DATE  =AMOD(DATEB+TIME+364.,365.)+1.
   IDATE =DATE

**RUN CONTROL AND OUTPUT
METHOD RECT
TIMER DELT=1.,TIME=0.,FINTIM=1000.,PRDEL=5.,OUTDEL=10.
FINISH  DS    =2., CELVN =3., WGR =WGRMX

PRINT DATE,DS, WLV,WLVD,WST,WSR,WSO,WRT,ALV,...
      NTIM2,NGRM2,NGRPTI,WG1000
   WLVT  =WLV+WLVD
   WLVST =WLVT+WST+WSR
   WLVSO =WLVST+WSO
   HI    =WSO/WSS
   RSH   =RMLV+RMST+RMSO+RMMA+RGLV+RGST+RGSO+RLSR
   WSTR  =WST+WSR


TITLE OSIR50.DAT: ORYZA SATIVA, RICE, CV IR50

**PHOTOSYNTHESIS AND RESPIRATION
PARAM PLMXP=45., PLEI=0.50
FUNCTION PLMTT=-11.,0.00, 0.0,0.0, 10.,0.0, 25.,1.00,...
                30.,1.00, 42.,0.0, 45.,0.0
FUNCTION PLMHT= 0.0,1.00, 1.0,1.0, 2.0,0.99, 3.0,0.86,...
                4.0,0.71
FUNCTION PLETT=-11.,1.00, 0.0,1.0, 15.,1.0, 25.,0.90,...
                35.,0.60, 45.,0.2, 50.,0.01

PARAM CRGLV=1.326, CRGST=1.326, CRGSO=1.462, CRGRT=1.326
PARAM CPGLV=0.408, CPGST=0.365, CPGSO=0.357, CPGRT=0.365
PARAM FCLV =0.419, FCST =0.431, FCSO =0.487, FCRT =0.431
PARAM RMCLV=0.02,  TPR  =25.,     Q10=2.
```

```
**BIOMASS PARTITIONING AND AGING
FUNCTION CALVT = 0.0,0.51, 0.5,0.51, 0.6,0.47, 0.7,0.32,...
                 0.8,0.26, 1.0,0.00, 1.1,0.00, 2.5,0.00
FUNCTION CASTT = 0.0,0.49, 0.5,0.49, 0.6,0.53, 0.7,0.68,...
                 0.8,0.74, 1.0,1.00, 1.1,0.27, 1.2,0.00,...
                 2.1,0.0
FUNCTION CASST = 0.0,0.86, 0.5,0.86, 0.6,0.86, 0.7,0.95,...
                 0.8,0.94, 1.0,0.89, 1.1,1.00, 2.5,1.00

PARAM FSTR=0.25, FEPSO=0.8, GSORM=0.50

FUNCTION LLVT =0.0,0.0, 1.0,0.0, 1.3,0.007, 1.8,0.012,...
               2.5,0.012
FUNCTION LRTT =0.0,0.0, 1.0,0.0, 1.3,0.011, 1.8,0.010,...
               2.5,0.010

**PHENOLOGICAL DEVELOPMENT
PARAM DRCV=0.0129, DRCR=0.033
FUNCTION DRVTT=-11.,0.10, 10.,0.10, 19.,0.80, 25.,1.00,...
                27.,1.10, 32.,1.20, 40.,1.00, 45.,1.0
FUNCTION DRRTT=-11.,0.54, 10.,0.54, 19.,0.83, 25.,1.00,...
                28.,1.10, 30.,1.21, 40.,1.21, 45.,1.21
FUNCTION DRDT =0.0,1.0, 24.,1.
FUNCTION DRWT =0.0,1.0, 1.,1.

PARAM SLC=370., SSC=1000., WDLV=0.015
FUNCTION SLT  =0.0,0.82, 0.6,1.00, 2.1,1.00
FUNCTION PLHTT=0.0,0.00, 1.0,1.00, 2.1,1.

**WATER RELATIONS AND ROOT GROWTH
PARAM WSSC  =0.5, WFSC =1., FIEC=0.65
PARAM ZRTMC =0.70, GZRTC =0.03

**INITIALIZATION
PARAM DATEB=203.
PARAM WLVI=6.8, WSTI=6.8, WSOI=0.
PARAM  DSI=0.200, ZRTI=0.2

PARAM RDUCF =  1.E6
PARAM ELV   = 21.0
PARAM LAT   = 14.17
PARAM ZREF  =  2.0

TITLE Los Banos (IRRI) 1988
* radiation Los Banos 1988, day 190-305
TABLE RDTMT(190-305)=...
   22.0, 16.9, 17.8, 15.7, 16.2, 15.8, 22.0, 15.7,...
   19.6, 12.2,.........

* minimum temperature (day 190-305)
TABLE TPLT(190-305)=...
   24.0, 24.5, 24.0, 24.2, 23.1, 23.0, 23.5, 24.5,...
   24.3, 24.3,.............

* maximum temperature (day 190-305)
TABLE TPHT(190-305)=...
```

```
    33.1, 32.5, 31.8, 31.4, 30.8, 30.7, 32.9, 32.1,...
    32.5, 31.6,.................

END
STOP
ENDJOB
```

New abbreviations used in L1DT as compared to L1D.

Abbreviation	Explanation
CAGRSO	newly produced carbohydrates available for growth of stem reserves and storage organs (= carbohydrate supply) (kg CH_2O $ha^{-1}d^{-1}$).
CAGSR	carbohydrates available for growth of shielded reserves (kg CH_2O $ha^{-1}d^{-1}$); a negative value indicates that carbohydrates are removed.
CRGSOM	maximum growth rate of the storage organs expressed in carbohydrate equivalents (= carbohydrate demand) (kg CH_2O $ha^{-1}d^{-1}$).
NCLV	nitrogen content of leaves (g g^{-1}).
NCLVT	relation between DS and NCLV.
NGRM2	number of grains per m^2 (m^{-2}).
NGRPTI	number of grains per tiller (or panicle) (ha^{-1}).
NHILL	number of hills (ha^{-1}).
NTIM2	number of tillers per m^2 (m^{-2}).
NTIPH	number of tillers per hill (-).
PLMXN	correction factor to account for effect of leaf N-content on PLMX (-).
PLMXNT	relation between PLMXN and NCLV.
RTSR	rate of growth respiration due to transport of shielded reserves (kg CO_2 $ha^{-1}d^{-1}$).
WG1000	1000-grain weight at 14 % moisture (g).

Appendix A.3 Listing of model L1DTSB.

Major differences with model L1DT are printed bold. New abbreviations are summarized at the end of this appendix.

```
TITLE L1DTSB (L1DT extended with damage due to stem borer)
****
** In this model the effect of an infestation with stem borer
** on dry matter production of a rice crop is simulated.
** Stem borer infestation rate (/day) is introduced as a
** forcing function. Depending on the developmental growth
** stage either deadhearts or whiteheads are produced.
** Deadhearts only remain in the canopy for a short period.
** Whiteheads on the other hand remain in the canopy till
** maturity, and thus provide shade to neighbouring tillers.
** Contribution of whiteheads to grain filling of healthy
** tillers is introduced as an option.
**
** Author: Lammert Bastiaans
** Version: 1       Date: May 1992
****

FIXED IDATE,I,NL
STORAGE RDTMT(365),TPHT(365),TPLT(365),RAINT(365),...
   HUAAT(365),WDST(365),TKL(11),TYL(11)
INITIAL
   WRTI  =WLVI
   WSRI  =0.
   ALVI  =WLVI/(SLC*AFGEN(SLT,DSI))
   CPEW  =1.
   DREW  =1.
   PCEW  =1.
   PARAM NHILL=250000., NTILHI=3.
*  spacing 0.20*0.20; 3 tillers/hill
   NTII  =NHILL*NTILHI

DYNAMIC
**WEIGHTS OF CROP COMPONENTS
**Explanation in sections 3.2, 2.2, 3.4
   WLV   =INTGRL(WLVI,GLV-LLV-LLVSB)
   WST   =INTGRL(WSTI,GST-LSTSB)
   WSR   =INTGRL(WSRI,GSR-LSRSB)
   WSO   =INTGRL(WSOI,GSO-LSOSB)
   WEPSO =WSO*FEPSO
   WRT   =INTGRL(WRTI,GRT-LRT-LRTSB)
   WSS   =WLV+WST+WSO+WSR
   WCR   =WSS+WRT
   WLVD  =INTGRL(0.,LLV)
   WRTD  =INTGRL(0.,LRT)

**GROWTH RATES AND LOSS RATES
**Explanation in sections 2.4, 3.2, 2.2
```

```
      GLV    =CAGLV/CRGLV
      GST    =CAGST/CRGST
      GRT    =CAGRT/CRGRT
      GSR    =CAGSR/1.111
      GSO    =CAGSO/CRGSO

      LLV    =WLV*AFGEN(LLVT,DS)
      LRT    =WRT*AFGEN(LRTT,DS)

   **CARBOHYDRATE AVAILABLE FOR GROWTH, EXPORT
   **Explanation in sections 3.2, 2.4, 2.3, 2.2
      CAGCR =PCGW*0.682-RMCR*0.682
      CAGSS =CAGCR*AFGEN(CASST,DS)*CPEW
      CAGRT =CAGCR-CAGSS
      CAGLV =CAGSS*AFGEN(CALVT,DS)
      CAGST =CAGSS*(1.-FSTR)*AFGEN(CASTT,DS)
      CAGRSO=CAGSS-CAGLV-CAGST
      CRGSOM=GSOM*CRGSO
      CAGSR =INSW(CRGSOM-CAGRSO,(CAGRSO-CRGSOM)*0.947,...
             -AMIN1((CRGSOM-CAGRSO)/0.947,WSR*0.1*1.111))
      CAGSO =INSW(CAGSOM-CAGRSO,CRGSOM,CAGRSO-CAGSR*0.947)

      CELV   =PCGW-(RMLV+RMST+0.5*RMMA)
      CELVN =INTGRL(0.,INSW(CELV,1.,-CELVN/DELT))

   **PHOTOSYNTHESIS, GROSS AND NET
   **Explanation in sections 2.1, 3.3, 3.4
      PCGW   =(ALVG/ALV+FTLWH*ALVWH/ALV)*PCGC*PCEW
   *  only green leaf area contributes to crop production and
   *  translocation from white heads is accounted for
      PCGC   =FUPHOT(PLMX,PLEA,ALV,RDTM,DATE,LAT)
      PLMX   =PLMXP*AFGEN(PLMTT,TPAD)*LIMIT(200.,600.,SLA)/300.*...
              PLMXN
      PLEA   =PLEI*AFGEN(PLETT,TPAD)
      PCGT   =INTGRL(0.,PCGW)
      RCRT   =INTGRL(0.,RMCR+RGCR)
      PCNT   =INTGRL(0.,PCGW-(RMCR+RGCR))
   *  PLMX depends on nitrogen-content of the leaves
      PLMXN =AFGEN(PLMXNT,NCLV)
      NCLV   =AFGEN(NCLVT,DS)
      FUNCTION PLMXNT=0.,0., 0.005,0.01, 0.05,1., 0.07,1.3
      FUNCTION NCLVT =0.,0.05, 0.2,0.05, 1.,0.04, 2.1,0.03

   **RESPIRATION
   **Explanation in sections 2.4, 2.3
      RMCT   =INTGRL(0.,RMCR)
      RMCR   =RMLV+RMST+RMSO+RMRT+RMMA
      RMLV   =WLV*RMCLV*TPEM*0.75
      RMST   =WST*0.010*TPEM+WSR*0.0
      RMRT   =WRT*0.015*TPEM
      RMSO   =AMIN1(1000.,WSO)*0.015*TPEM
      TPEM   =Q10**((TPAV-TPR)/10.)

      RMMA   =0.20*PCGW*0.5

      RGCR   =RGLV+RGST+RGSO+RGRT+RTSR
```

```
   RGLV  =GLV*CPGLV
   RGST  =GST*CPGST
   RGSO  =GSO*CPGSO
   RGRT  =GRT*CPGRT

   RTSR  =INSW(CRGSOM-CAGRSO,CAGSR/0.947,-CAGSR)*0.053*1.467
*  respiration due to transport of reserves (loss=5.3 %)

**CARBON BALANCE CHECK
**Explanation in section 3.4
   CKCRD =FUCCHK(CKCIN,CKCFL,TIME)
   CKCIN =(WLV-WLVI)*FCLV+(WST-WSTI)*FCST+...
          (WSO-WSOI)*FCSO+(WRT-WRTI)*FCRT+(WSR-WSRI)*0.444
   CKCFL =PCNT*0.2727-((WLVD+WLVDH+WLVWH)*FCLV+(WRTD+WRTDH+WRTWH)...
          *FCRT+(WSTDH+WSTWH)*FCST+(WSRDH+WSRWH)*0.444+...
          WSOWH*FCSO+CWTDDW)

**LEAF AREA
**Explanation in section 3.3
   ALV   =ALVG+ALVDH+ALVWH
*  total leaf area; green leaf area + leaf area of dead hearts
*  and white heads
   ALVG  =INTGRL(ALVI,GLA-LLA-LLASB+GSA-LSASB)
   GLA   =GLV/SLN
   LLA   =LLV/SLA
   GSA   =0.5*GST/SSC
   SLN   =SLC*AFGEN(SLT,DS)
   SLA   =WLV/(ALVG-0.5*WST/SSC)

**PHENOLOGICAL DEVELOPMENT OF THE CROP
**Explanation in section 3.1
   DS    =INTGRL(DSI,INSW(DS-1.,DRV,DRR))
   DRV   =DRCV*DRED*DREW*AFGEN(DRVTT,TPAV)
   DRED  =AFGEN(DRDT,DLP)
   DRR   =DRCR*AFGEN(DRRTT,TPAV)

**TILLER-MODULE
*  tillers
   NTI   =INTGRL(NTII,(GNTI-LNTI-LNTISB))
   GNTI  =DSTF*AMAX1(0.,(NTIP-NTI)/TCFT)
   LNTI  =DSTD*AMAX1(0.,(NTI-NTIP)/TCDT)
   NTIP  =CAGCR/CNTI
   DSTF  =NOR(DST1-DS,DS-DST2)
   DSTD  =NOR(DST1-DS,DS-(DST2+0.15))
   CNTI  =AFGEN(CNTIT,DS)
   NTIPH =NTI/NHILL
   NTIM2 =NTI/10000.

*  florets
   NFL   =INTGRL(0.,GNFL-LNFLSB)
   GNFL  =DSFL*AMIN1(NFLMX-NFL,NFLP-NFL)/TCFF
   NFLP  =CAGCR/CNFL
   CNFL  =0.7*GGRMN
   NFLMX =NFLMXT*NTI
   DSFL  =NOR(DSF1-DS,DS-DSF2)
```

```
*  grains
   NGR    =INTGRL(0.,GNGR-LNGRSB)
   GNGR   =DSGR*AMAX1(0.,AMIN1(NGRP-NGR,NGRMX-NGR)/TCFG)
   NGRP   =CAGCR/GGRMN
   NGRMX  =NFL
   DSGR   =NOR(DSG1-DS,DS-DSG2)
   GGRMN  =WGRMX/GFP
   GFP    =1./(1.33*DRR)
   GGRMX  =GGRMN*2.
   WGR    =WSO/(AMAX1(NGR,1000.))
   WG1000=(WGR*1.E6)*100./86.
   NGRPTI=NGR/NTI
   NGRM2  =NGR/10000.
   GSOM   =NGR*GGRMX*AFGEN(GGRT,TPAV)

   PARAM DST1  =0.3, DSF1  =0.7, DSG1  =0.95
   PARAM DST2  =0.75,DSF2  =0.95,DSG2  =1.15
   PARAM TCFT  =15., TCFF  =7.,  TCFG  =3.,  TCDT  =10.
   PARAM NFLMXT =100., WGRMX =23.5E-6
   FUNCTION GGRT  =10.,0.0, 15.,0.0, 18.,0.75, ...
                   23.,1.0, 27.,0.9, 40.,0.0
   FUNCTION CNTIT =0.0,5.E-6,  0.3,5.E-6,  0.75,25.E-6, ...
                   1.0,75.E-6, 2.1,75.E-6

**INTRODUCTION OF Stem borer EFFECTS
**Stem borer infestation level
   SBINFR=AFGEN(SBINRT,DS)
**Weights of deadhearts and whiteheads
*** deadhearts
   WLVDH =INTGRL(0.,INSW(DS-DSWH,LLVSB,0.)-LLVDH)
   WSTDH =INTGRL(0.,INSW(DS-DSWH,LSTSB,0.)-LSTDH)
   WSRDH =INTGRL(0.,INSW(DS-DSWH,LSRSB,0.)-LSRDH)
   WRTDH =INTGRL(0.,INSW(DS-DSWH,LRTSB,0.)-LRTDH)
   ALVDH =INTGRL(0.,INSW(DS-DSWH,LLASB+LSASB,0.)-LALVDH)
   NTIDH =INTGRL(0.,INSW(DS-DSWH,LNTISB,0.)-LNTIDH)
*** whiteheads
   WLVWH =INTGRL(0.,INSW(DS-DSWH,0.,LLVSB)-LLVWH)
   WSTWH =INTGRL(0.,INSW(DS-DSWH,0.,LSTSB))
   WSRWH =INTGRL(0.,INSW(DS-DSWH,0.,LSRSB))
   WSOWH =INTGRL(0.,INSW(DS-DSWH,0.,LSOSB))
   WRTWH =INTGRL(0.,INSW(DS-DSWH,0.,LRTSB))
   ALVWH =INTGRL(0.,INSW(DS-DSWH,0.,LLASB+LSASB)-LLAWH)
   NTIWH =INTGRL(0.,INSW(DS-DSWH,0.,LNTISB))

**Loss rates of healthy and infested tillers
*** loss rates due to stem borer infestation
   LLVSB =WLV*SBINFR
   LSTSB =WST*SBINFR
   LSRSB =WSR*SBINFR
   LSOSB =WSO*SBINFR
   LRTSB =WRT*SBINFR
   LLASB =LLVSB/SLA
   LSASB =0.5*LSTSB/SSC
   LNTISB=NTI*SBINFR
   LNFLSB=NFL*SBINFR
   LNGRSB=NGR*SBINFR
```

```
*** disappearance rate of deadhearts
   LLVDH =WLVDH/ARTDH
   LSTDH =WSTDH/ARTDH
   LSRDH =WSRDH/ARTDH
   LRTDH =WRTDH/ARTDH
   LALVDH=ALVDH/ARTDH
   LNTIDH=NTIDH/ARTDH
*** disappearance rate of white heads
*   assumption: only natural senesence of leaves
   LLVWH =WLVWH*AFGEN(LLVT,DS)
   LLAWH =LLVWH/SLA
*** for carbon balance check;
*   C lost through disappearance of deadhearts and whiteheads
   CWTDDW=INTGRL(0.,(LLVDH+LLVWH)*FCLV+LSTDH*FCST+...
         LSRDH*0.444+LRTDH*FCRT)

**Output
   NTDHM2=NTIDH/10000.
   NTWHM2=NTIWH/10000.
   NTTIM2=NTIM2+NTDHM2+NTWHM2
   FRDH  =NTDHM2/NTTIM2
   FRWH  =NTWHM2/NTTIM2
**Functions and parameters
   PARAM DSWH=0.7
*  development stage after which whiteheads appear
   PARAM ARTDH=14.
*  average residence time of deadhearts
   PARAM FTLWH=0.
*  fraction newly produced assimilates translocated from whiteheads
*  to healthy tillers
   FUNCTION SBINRT=0.2,0., 2.2,0.
*  stem borer infestation rate in time

**Changes in other sections of the model:
* -Loss rates due to stem borer infestation are introduced in
*  sections: WEIGHT OF CROP COMPONENTS, LEAF AREA, and
*  TILLER-MODULE.
* -Various types of leaf area are introduced (section: LEAF AREA)
*  and this affects the calculation of gross photosynthesis
*  (section: PHOTOSYNTHESIS, GROSS AND NETT)

**WEATHER DATA AND TIME
**Explanation in chapter 6 and section 3.4
   RDTM  =RDTMT(IDATE)*RDUCF
   RDTC,DLA,DLP=SUASTR(DATE,LAT)
   TPAV  =(TPLT(IDATE)+TPHT(IDATE))/2.
   TPAD  =(TPHT(IDATE)+TPAV)/2.

   DATE  =AMOD(DATEB+TIME+364.,365.)+1.
   IDATE =DATE

**RUN CONTROL AND OUTPUT
METHOD RECT
TIMER DELT=1.,TIME=0.,FINTIM=1000.,PRDEL=5.,OUTDEL=10.
FINISH  DS    =2., CELVN =3., WGR =WGRMX
```

```
PRINT DATE,DS, WLV,WLVD,WST,WSR,WSO,WRT,ALV,...
      NTTIM2,FRDH,FRWH,NTIM2,NGRPTI,WG1000
   WLVT  =WLV+WLVD
   WLVST =WLVT+WST+WSR
   WLVSO =WLVST+WSO
   HI    =WSO/WSS
   RSH   =RMLV+RMST+RMSO+RMMA+RGLV+RGST+RGSO+RLSR
   WSTR  =WST+WSR


TITLE OSIR50.DAT: ORYZA SATIVA, RICE, CV IR50

**PHOTOSYNTHESIS AND RESPIRATION
PARAM PLMXP=45., PLEI=0.50
FUNCTION PLMTT=-11.,0.00, 0.0,0.0, 10.,0.0, 25.,1.00,...
               30.,1.00, 42.,0.0, 45.,0.0
FUNCTION PLMHT= 0.0,1.00, 1.0,1.0, 2.0,0.99, 3.0,0.86,...
               4.0,0.71
FUNCTION PLETT=-11.,1.00, 0.0,1.0, 15.,1.0, 25.,0.90,...
               35.,0.60, 45.,0.2, 50.,0.01

PARAM CRGLV=1.326, CRGST=1.326, CRGSO=1.462, CRGRT=1.326
PARAM CPGLV=0.408, CPGST=0.365, CPGSO=0.357, CPGRT=0.365
PARAM FCLV =0.419, FCST =0.431, FCSO =0.487, FCRT =0.431
PARAM RMCLV=0.02,  TPR  =25.,     Q10=2.

**BIOMASS PARTITIONING AND AGING
FUNCTION CALVT = 0.0,0.51, 0.5,0.51, 0.6,0.47, 0.7,0.32,...
                 0.8,0.26, 1.0,0.00, 1.1,0.00, 2.5,0.00
FUNCTION CASTT = 0.0,0.49, 0.5,0.49, 0.6,0.53, 0.7,0.68,...
                 0.8,0.74, 1.0,1.00, 1.1,0.27, 1.2,0.00,...
                 2.1,0.0
FUNCTION CASST = 0.0,0.86, 0.5,0.86, 0.6,0.86, 0.7,0.95,...
                 0.8,0.94, 1.0,0.89, 1.1,1.00, 2.5,1.00

PARAM FSTR=0.25, FEPSO=0.8, GSORM=0.50

FUNCTION LLVT =0.0,0.0, 1.0,0.0, 1.3,0.007, 1.8,0.012,...
               2.5,0.012
FUNCTION LRTT =0.0,0.0, 1.0,0.0, 1.3,0.011, 1.8,0.010,...
               2.5,0.010

**PHENOLOGICAL DEVELOPMENT
PARAM DRCV=0.0129, DRCR=0.033
FUNCTION DRVTT=-11.,0.10, 10.,0.10, 19.,0.80, 25.,1.00,...
               27.,1.10, 32.,1.20, 40.,1.00, 45.,1.0
FUNCTION DRRTT=-11.,0.54, 10.,0.54, 19.,0.83, 25.,1.00,...
               28.,1.10, 30.,1.21, 40.,1.21, 45.,1.21
FUNCTION DRDT =0.0,1.0, 24.,1.
FUNCTION DRWT =0.0,1.0, 1.,1.

PARAM SLC=370., SSC=1000., WDLV=0.015
FUNCTION SLT  =0.0,0.82, 0.6,1.00, 2.1,1.00
FUNCTION PLHTT=0.0,0.00, 1.0,1.00, 2.1,1.

**WATER RELATIONS AND ROOT GROWTH
```

```
PARAM WSSC  =0.5, WFSC =1., FIEC=0.65
PARAM ZRTMC =0.70, GZRTC =0.03

**INITIALIZATION
PARAM DATEB=203.
PARAM WLVI=6.8, WSTI=6.8, WSOI=0.
PARAM  DSI=0.200, ZRTI=0.2

PARAM RDUCF =  1.E6
PARAM ELV   = 21.0
PARAM LAT   = 14.17
PARAM ZREF  =  2.0

TITLE Los Banos (IRRI) 1988
* radiation Los Banos 1988, day 190-305
TABLE RDTMT(190-305)=...
   22.0, 16.9, 17.8, 15.7, 16.2, 15.8, 22.0, 15.7,...
   19.6, 12.2,..............

* minimum temperature (day 190-305)
TABLE TPLT(190-305)=...
   24.0, 24.5, 24.0, 24.2, 23.1, 23.0, 23.5, 24.5,...
   24.3, 24.3,...........

* maximum temperature (day 190-305)
TABLE TPHT(190-305)=...
   33.1, 32.5, 31.8, 31.4, 30.8, 30.7, 32.9, 32.1,...
   32.5, 31.6,.........

END
STOP
ENDJOB
```

New abbreviations used in L1DTSB.

Abbreviation	Explanation
ALV(DH,G,WH)	leaf area of dead hearts (DH), healthy tillers (G) and white heads (WH) (ha ha^{-1})
ARTDH	average residence time of a dead heart (d)
CAGRSO	newly produced carbohydrates available for the growth of stem reserves and storage organs (kg (CH_2O) ha^{-1} d^{-1})
CRGSOM	maximum growth rate of the storage organs expressed in carbohydrate-equivalents (kg (CH_2O) ha^{-1} d^{-1})
CAGSR	carbohydrates available for growth of shielded reserves (kg (CH_2O) ha^{-1} d^{-1}); a negative value means that carbohydrates are removed
CWTDDW	carbon lost as a result of disappearance of dead hearts and senescence of white heads (kg (C) ha^{-1})

DSWH	phenological development stage after which stem borer infestation results in formation of white heads
FR(DH,WH)	fraction dead hearts (DH), white heads (WH)
FTLWH	fraction of newly produced carbohydrates translocated from white heads to healthy tillers
LALVDH	disappearance rate of leaf area from dead hearts (ha ha^{-1} d^{-1})
LALVWH	disappearance rate of leaf area from white heads (ha ha^{-1} d^{-1})
L(LA,SA)SB	rate of loss of leaf area (LA) and stem area (SA) due to stem borer infestation (ha ha^{-1} d^{-1})
L(LV,RT,SR,ST)DH	disappearance rate of leaves (LV), roots (RT), shielded reserves (SR) and stems (ST) from dead hearts (dry matter; kg ha^{-1} d^{-1})
LLVWH	disappearance rate of leaves from white heads (dry matter; kg ha^{-1} d^{-1})
L(LV,RT,SO,SR,ST)SB	rate of loss of leaves (LV), roots (RT), storage organs (SO), shielded reserves (SR) and stems (ST) due to stem borer infestation (dry matter; kg ha^{-1} d^{-1})
LN(GR,FL,TI)SB	rate of loss of grains (GR), florets (FL) and tillers (TI) due to stem borer infestation (number ha^{-1} d^{-1})
LNTIDH	disappearance rate of dead hearts (tillers ha^{-1} d^{-1})
NTI(DH,WH)	number of dead hearts (DH), and white heads (WH) (number ha^{-1})
NT(DH,WH)M2	number of dead hearts (DH) and white heads (WH) per m^2
NTTIM2	total number of tillers per m^2 (m^{-2})
SBINFR	stem borer infestation rate (tiller $tiller^{-1}$ day^{-1})
W(LV,RT,SR,ST)DH	weight leaves (LV), roots (RT), shielded reserves (SR) and stems (ST) of dead hearts (kg ha^{-1})
W(LV,RT,SO,SR,ST)WH	weight leaves (LV), roots (RT), storage organs (SO), shielded reserves (SR) and stems (ST) of white heads (kg ha^{-1})

Appendix A.4 Calculation of SBINFR from field observations

Stem borer infestation in the field is determined by counting the number of healthy and infested tillers of a fixed number of hills. These countings are performed with regular intervals of for instance one week. Based on these weekly observations the SBINFR can be calculated, as is illustrated with the following example:

Just before maximum tillering the following observations were made:

Date	300	307	314	321
No. tillers (m^{-2})				
- total	500	585	625	657
- healthy	500	500	440	545
- deadhearts	0	85	185	112
Fraction deadhearts	0.0	0.15	0.27	0.17

The average residence time of deadhearts (ARTDH) is 14 days (an assumption that needs to be checked). The SBINFR between day 300 and 307 can now be calculated with the following procedure, consisting of three steps:

Step 1. Calculation of the number of deadhearts lost (NLDH).

An exponential decline characterized by an ARTDH of 14 days corresponds to a relative disappearance rate of deadhearts (RDRDH) of 1/14=0.07 (tiller tiller-1 day-1). This means that every day a fraction of 0.07 of the existing deadhearts disappear. The best estimate for the average number of existing deadhearts (NTIDHav) in the time span between day 300 and 307 is:

$$NTIDH_{av} = (NTIDH_{300}+NTIDH_{307})/2 = (0+85)/2 = 42.5$$

The number of deadhearts lost can then be estimated as:

$$NLDH = NTIDH_{av} * RDRDH * time = 42.5 * 0.07 * 7 = 21$$

Step 2. Calculation of the number of newly infested tillers (NNDH).

The newly infested tillers comprise the observed number of deadhearts on day 307 minus the number of deadhearts present on day 300. This number has to be increased by the deadhearts that disappeared (NLDH):

$NNDH = NTIDH_{307}-NTIDH_{300}+NLDH = 85 - 0 + 21 = 106$

Step 3. Calculation of the stem borer infestation rate (STINFR).

The infestation rate refers to healthy tillers. The average number of healthy tillers can be estimated as:

$NTI_{av} = (NTI_{300}+NTI_{307})/2 = (500+500)/2 = 500$

Since the number of disappeared deadhearts equals:

$NNDH = NTI_{av} * STINFR * time$

the stem borer infestation rate can be calculated as:

$STINFR = NNDH / (NTI_{av} * time) = 106/(500*7)=0.03$

Similarly STINFR between day 307 and 314, and between 314 and 321 can be calculated (0.05 and 0.00, respectively).

Appendix A.5 Listing of model BLIGHT

```
*-----------------------------------------------------------------------*
*                              BLIGHT                                   *
*                                                                       *
*             A Model for the Potential Production of Rice              *
*                  infected with a Foliar Disease,                      *
*                particularly Bacterial Leaf Blight                     *
*                        and Sheath Blight.                             *
*                                                                       *
*                             June 1993                                 *
*                             Version 2                                 *
*                                                                       *
* Based upon L1DFDE, version 2, January 1993 (L. Bastiaans)             *
* and        ORYZA1, version 1.0, February 1993 (M.J. Kropff,           *
*                    H.H. van Laar & H.F.M. ten Berge)                  *
*                                                                       *
* Author: A. Elings                                                     *
* Date  : 4 June 1993.                                                  *
*                                                                       *
*************************************************************************

FIXED     SWILAI, SWINLV, IDATE, IDOYTR, IN
STORAGE   RDTT(366),TMAXT(366),TMINT(366),...
          LAILL(3),LAITL(3),SAIL(3),...
          NCNTH(3),NCNTD(3),SLWHL(3),SLWDS(3),...
          FHLL(3),FDSL(3),FDDL(3),SEVL(3),SEVS(3),ASEV(3),...
          FHLT(3),FDST(3),FDDT(3),...
          AMAXDC(3),EFFDC(3),AMAXH(3),AMAXD(3),EFFH(3),EFFD(3),...
          NFLVH(3),NFLVD(3)

*********************************
*** 1.    Initial Conditions  ***
*********************************

INITIAL
* SWILAI and SWINLV are deactivated. This version of the model works
* only with observed leaf area and leaf nitrogen content.
*PARAM SWILAI = 0
*PARAM SWINLV = 0

DYNAMIC

*************************************
*** 2.    Phenological Development ***
*************************************

DVS    = INTGRL (0., DVR)

PROCEDURE DVR, TSHCKD = PRODVR (DVS, DVRV, HU, TS, DVRR)

          IF (DVS.LT.1.) THEN
```

```
            DVR = DVRV * HU
            IF (IDATE.EQ.IDOYTR) TSTR = TS
            TSHCKD = SHCKD * TSTR
            IF (IDATE.GT.IDOYTR .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.
         ELSE
            DVR = DVRR * HU
         ENDIF
ENDPRO

*****************************************
*** 3.    Daily Dry Matter Production ***
*****************************************

************************************************
*** 3.1   Daily Gross Canopy CO2 Assimilation ***
************************************************

* The disease model works with 3 layers. Field observations should
* provide their N contents, which are processed in the DIS procedure and
* the photosynthesis subroutines. Within layers, no N profile is
* assumed, but N is assumed to be uniformily distributed.
* Statements on NPROF and NFLV are removed from this place.
*
* AMAX and EFF are calculated separately for healthy and diseased leaf
* area in the DIS procedure, which gives AMAXH, AMAXD, EFFG and EFFD.
* Only EFF is required as input. The call for TOTASS has been extended
* and named TASSDS, total assimilation for diseased foliage.
*
* Stem area is accounted for.

KDF        = AFGEN(KDFTB,DVS)
PARAM SCP  = 0.2
REDFT      = AFGEN (REDFTT,TAVD)
EFF        = AFGEN (EFFTB, TAVD)

       DAYL,DTGA,DS0 = ...
TASSDS(DOY,LAT,RDT,SCP,AMAXH,AMAXD,EFFH,EFFD,KDF,LAITL,...
       FHLT,FDST,IN)

************************************
*** 3.2   Maintenance Respiration ***
************************************

* The maintenance respiration of leaves (RMLV) is calculated in the
* DIS procedure.

MNDVS  = WLVG/(WLVG+WLVD + NOT(WLVG+WLVD))
RMCR   = RMLV + (WST*MAINST + WSO *MAINSO + WRT*MAINRT) * TEFF * MNDVS
TEFF   = Q10**((TAV-TREF)/10.)
PARAM Q10 = 2., TREF = 25.

******************************************************
*** 3.3   Daily Dry Matter Growth Rates of the Crop ***
******************************************************

CRGCR  = FSH*(CRGLV*FLV  + CRGST *FST*(1.-FSTR) + CRGSTR*FSTR*FST + ...
```

```
          CRGSO*FSO) + CRGRT *FRT
GCR     = ((DTGA*30./44.) - RMCR + (LSTR*LRSTR*FCSTR*30./12.))/CRGCR

************************************
*** 3.4   Dry Matter Partitioning ***
************************************

FSH     = AFGEN (FSHTB, DVS)
FRT     = AFGEN (FRTTB, DVS)
FLV     = AFGEN (FLVTB, DVS)
FST     = AFGEN (FSTTB, DVS)
FSO     = AFGEN (FSOTB, DVS)
FAG     = FLV + FST + FSO

****************************************
*** 3.5   Growth Rates of Plant Organs ***
****************************************

GRT     = GCR * FRT
GLV     = GCR * FSH * FLV
GST     = GCR * FSH * FST * (1.-FSTR)
GSTR    = GCR * FSH * FST * FSTR
GSO     = GCR * FSH * FSO

LLV     = WLVG * AFGEN (DRLVT, DVS)
LSTR    = INSW(DVS-1., 0., WSTR / TCLSTR)

************************************
*** 3.6   Dry Matter Production ***
************************************

WLVG    = INTGRL (WLVGI, GLV - LLV)
WLVD    = INTGRL (0.,           LLV)
WSTS    = INTGRL (WSTI,         GST)
WSTR    = INTGRL (0.,  GSTR - LSTR)
WSO     = INTGRL (0.,           GSO)
WRT     = INTGRL (WRTI ,        GRT)
WST     = WSTS + WSTR
WAG     = WLVG + WST + WSO + WLVD
WCR     = WAG  + WRT
WRR     = WSO  * 0.90/0.86

************************************
*** 4.    Leaf Area Development ***
************************************

* The procedure PROLAI has been extended with LAIX from the DIS
* procedure.
* The leaf area of each layer is calculated from observed values
* in procedure DIS. The switch SWILAI has been removed: only
* observed values.
* Stem area is calculated per layer in DIS procedure.

PROCEDURE LAI,LAIL = PROLAI(DVS,WST,LAIX)

          SSGA  = AFGEN (SSGATB, DVS)
```

```
          SAI    = SSGA * WST
          LAIL   = LAIX
          LAI    = 0.5 * SAI + LAIL
ENDPRO

*********************************************
*** 5.    Time and Environmental Variables ***
*********************************************

DOY     = AMOD (DOYS+TIME, 365.)
IDATE   = DOY
TAV     = (TMINT(IDATE) + TMAXT(IDATE))/2.
TAVD    = (TMAXT(IDATE) + TAV)/2.
HU      = AMIN1(30.-TBD ,(AMAX1 (0., TAV-TBD)))
HULV    = AMIN1(26.-TBLV,(AMAX1 (0., TAV-TBLV)))
TS      = INTGRL (0., HU  )
TSLV    = INTGRL (0., HULV)
RDT     = RDTT (IDATE) * 1.E6

*********************************
*** 6.    Carbon Balance Check ***
*********************************

CKCRD   = CBCHK(CKCIN,CKCFL,TIME)

CKCIN   = (WLVG+WLVD-WLVGI)*FCLV + (WSTS-WSTI)*FCST + WSTR*FCSTR + ...
          (WRT-WRTI)*FCRT + WSO*FCSO
CKCFL   = PCNT * (12./44.)
PCNT    = INTGRL(0., ((DTGA*30./44. - RMCR)*44./30.) - RGCR)
RGCR    = GRT*CO2RT + GLV*CO2LV + GST*CO2ST + GSO*CO2SO + GSTR*CO2STR ...
          + (1.-LRSTR)*LSTR*FCSTR*44./12.
CO2RT   = 44./12. * (CRGRT *12./30. -  FCRT)
CO2LV   = 44./12. * (CRGLV *12./30. -  FCLV)
CO2ST   = 44./12. * (CRGST *12./30. -  FCST)
CO2STR  = 44./12. * (CRGSTR*12./30. - FCSTR)
CO2SO   = 44./12. * (CRGSO *12./30. -  FCSO)
CKCDIF  = ABS((CKCIN-CKCFL)/(NOT(CKCIN)+CKCIN))

*************************
*** 7.    Run Control ***
*************************

PARAM DOYS        = 182., IDOYTR = 194
FINISH DVS        = 2.
TIMER TIME        = 0., FINTIM = 350., DELT = 1., PRDEL = 5.
METHOD RECT

PRINT     DOY,DVS,TS,TSLV,LAI,LAIL,...
          WLVG,XWLVG,WLVD,XWLVD,WST,XWST,WSO,XWPA,WAG,XWTDM,...
          TSHCKD,FAG,CKCDIF,CKCIN,CKCFL,DTGA
PREPARE   DOY,DVS,LAI,LAIL,WLVG,WLVD,WST,WSTS,WSTR,WSO,WAG,DTGA,RDT,...
          TAV,SAI

*****************************
*** 8.    Observed Values ***
*****************************
```

```
XWLVG  = AFGEN(XWLVGT, DOY)
XWLVD  = AFGEN(XWLVDT, DOY)
XWST   = AFGEN(XWSTTB, DOY)
XWPA   = AFGEN(XWPATB, DOY)
XWTDM  = AFGEN(XWTDMT, DOY)

*********************************************
*** 9.    Functions and Parameters for Rice ***
*********************************************

PARAM CRGLV      = 1.326, CRGST  = 1.326
PARAM CRGSO      = 1.462, CRGRT  = 1.326
PARAM CRGSTR     = 1.111
PARAM MAINLV     = 0.02,  MAINST = 0.015
PARAM MAINSO     = 0.003, MAINRT = 0.01
PARAM FCSTR      = 0.444
PARAM FCLV       = 0.419, FCST   = 0.431
PARAM FCRT       = 0.431, FCSO   = 0.487
PARAM TBD        = 8.,    TBLV   = 8.
PARAM FSTR       = 0.20
PARAM LRSTR      = 0.947, TCLSTR = 10.
FUNCTION EFFTB   = 10.,0.54, 40.,0.36
FUNCTION SSGATB  = 0.,0.0003, 0.9,0.0003, 2.1,0.

*******************************
**---------------------------**
** FOLIAR DISEASE PROCEDURES **
**---------------------------**
*******************************

** Reading input functions from field observations.

   PROCEDURE LAILL,NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL,SEVS...
             = RDDIS(IDATE)

** LAILL = Total leaf area (ha/ha).
** NCNTH = Nitrogen content of healthy leaf area (kg/kg).
** NCNTD = Nitrogen content of diseased leaf area (kg/kg).
** SLWHL = Specific leaf weight of healthy leaf area (kg/ha).
** SLWDS = Specific leaf weight of diseased leaf area (kg/ha).
** FHLL  = Fraction healthy leaf area (-).
** FDSL  = Fraction diseased leaf area (-).
** SEVL  = Disease severity of diseased leaf area (-)
** SEVS  = Disease severity of stem area (-).

   LAILL(1) = AFGEN(LAILL1,DOY)
   LAILL(2) = AFGEN(LAILL2,DOY)
   LAILL(3) = AFGEN(LAILL3,DOY)
   NCNTH(1) = AFGEN(NCNTH1,DOY)
   NCNTH(2) = AFGEN(NCNTH2,DOY)
   NCNTH(3) = AFGEN(NCNTH3,DOY)
   NCNTD(1) = AFGEN(NCNTD1,DOY)
   NCNTD(2) = AFGEN(NCNTD2,DOY)
   NCNTD(3) = AFGEN(NCNTD3,DOY)
   SLWHL(1) = AFGEN(SLWHL1,DOY)
```

```
   SLWHL(2) = AFGEN(SLWHL2,DOY)
   SLWHL(3) = AFGEN(SLWHL3,DOY)
   SLWDS(1) = AFGEN(SLWDS1,DOY)
   SLWDS(2) = AFGEN(SLWDS2,DOY)
   SLWDS(3) = AFGEN(SLWDS3,DOY)
   FHLL(1)  = AFGEN(FHLL1,DOY)
   FHLL(2)  = AFGEN(FHLL2,DOY)
   FHLL(3)  = AFGEN(FHLL3,DOY)
   FDSL(1)  = AFGEN(FDSL1,DOY)
   FDSL(2)  = AFGEN(FDSL2,DOY)
   FDSL(3)  = AFGEN(FDSL3,DOY)
   SEVL(1)  = AFGEN(SEVL1,DOY)
   SEVL(2)  = AFGEN(SEVL2,DOY)
   SEVL(3)  = AFGEN(SEVL3,DOY)
   SEVS(1)  = AFGEN(SEVS1,DOY)
   SEVS(2)  = AFGEN(SEVS2,DOY)
   SEVS(3)  = AFGEN(SEVS3,DOY)
ENDPROCEDURE

** Interaction between disease and rice plant.
** Calcultations for three layers.

   PROCEDURE LAIX,LAITL,SAIL,FHLLA,FDSLA,FDDLA,ASEVL,FHLLW,FDSLW,...
             AMAXH,AMAXD,EFFH,EFFD,RMLV,ASEV...
         = DIS(IN,LAILL,SAI,FHLL,FDSL,SLWHL,SLWDS,SEVL,SEVS,...
               NCNTH,NCNTD,REDFT,EFF,MAINLV,WLVG,TEFF,MNDVS)

** STEP 1: Calculation of the average disease level.
     LAIX  = 0.
     LAIHL = 0.
     LAIDS = 0.
     LAIDD = 0.
     TSEVL = 0.
     TSEVS = 0.
     ASEVL = 0.
     WLVHL = 0.
     WLVDS = 0.

     DO 10 I=1,IN

**           Fraction dead leaf area (-).
             FDDL(I) = 1.-FHLL(I)-FDSL(I)

**           Total healthy, diseased and dead leaf area per layer
**           (ha/ha); (fraction x total area of layer).
             AHLL = FHLL(I)*LAILL(I)
             ADSL = FDSL(I)*LAILL(I)
             ADDL = FDDL(I)*LAILL(I)

**           Total leaf area (ha/ha)
             LAIX = LAIX + LAILL(I)

**           Total healthy, diseased and dead leaf area (ha/ha).
             LAIHL = LAIHL + AHLL
             LAIDS = LAIDS + ADSL
             LAIDD = LAIDD + ADDL
```

```
**          Stem area index per layer (ha/ha).
**          Is assumed proportional to leaf area distribution.
            SAIL(I) = SAI * LAILL(I)/(LAIX+NOT(LAIX))

**          Total area index per layer (leaves + stems) (ha/ha).
            LAITL(I) = LAILL(I) + 0.5 * SAIL(I)

**          Total leaf and stem area occupied by lesions (ha/ha);
**          (severity x diseased leaf area).
            TSEVL = TSEVL + SEVL(I)*ADSL
            TSEVS = TSEVS + SEVS(I)*SAIL(I)

**          Average severity over stem and leaves, per layer (-).
            ASEV(I) = SEVL(I)*ADSL/(ADSL+0.5*SAIL(I)+...
                      NOT(ADSL+0.5*SAIL(I)))+...
                      SEVS(I)*0.5*SAIL(I)/(ADSL+0.5*SAIL(I)+...
                      NOT(ADSL+0.5*SAIL(I)))

**          Weight of healthy and diseased leaf area (kg/ha);
**          (area x specific leaf weight).
            WLVHL = WLVHL + AHLL*SLWHL(I)
            WLVDS = WLVDS + ADSL*SLWDS(I)

**          Fractions healthy, diseased and dead total area,
**          per layer (-).
            FHLT(I) = (FHLL(I) * LAILL(I) + INSW(-SEVS,0.,1.) * 0.5 * ...
                      SAIL(I))/(LAITL(I) + NOT(LAITL(I)))
            FDST(I) = (FDSL(I) * LAILL(I) + INSW(-SEVS,1.,0.) * 0.5 * ...
                      SAIL(I))/(LAITL(I) + NOT(LAITL(I)))
            FDDT(I) = 1. - FHLT(I) - FDST(I)

10    CONTINUE

** Fractions healthy, diseased and dead leaf area (-);
** (leaf area/total leaf area).
      FHLLA = LAIHL/(LAIX+NOT(LAIX))
      FDSLA = LAIDS/(LAIX+NOT(LAIX))
      FDDLA = LAIDD/(LAIX+NOT(LAIX))

** Average severity (-);
** (total leaf area affected/total diseased leaf area).
      ASEVL = TSEVL/(LAIDS+NOT(LAIDS))

** Weight fraction of healthy and diseased leaf area of alive leaf
** area (-) (weight/weight of healthy+diseased leaf area).
      FHLLW = WLVHL/((WLVHL+WLVDS)+NOT(WLVHL+WLVDS))
      FDSLW = WLVDS/((WLVHL+WLVDS)+NOT(WLVHL+WLVDS))

** STEP 2: Effect of disease on photosynthesis characteristics of
**          diseased leaf area.

      DO 20 I = 1,IN
**          Reading from input files correction factors for maximum
**          photosynthesis and initial light use efficiency of diseased
**          leaves.
```

```
            AMAXDC(I) = AFGEN(AMAXDT,ASEV(I))
            EFFDC(I)  = AFGEN(EFFDT,ASEV(I))

20    CONTINUE

      DO 30 I = 1,IN

**          Field observations are, if the standard procedure is
**          followed, available as kg N/kg leaf. Multiplication with the
**          specific leaf weight gives kg N/ha leaf; and multiplication
**          by 0.1 gives g N/m2 leaf.
            NFLVH(I) = 0.1 * SLWHL(I) * NCNTH(I)
            NFLVD(I) = 0.1 * SLWDS(I) * NCNTD(I)

**          AMAX of healthy and diseased leaf area in layers (kg/ha/d),
**          corrected for nitrogen and temperature and disease severity.
**          Stem green area is supposed to be characterized by AMAXH.
            AMAXH(I) = (-6.5 + 32.4 * NFLVH(I)) * REDFT
            AMAXD(I) = (-6.5 + 32.4 * NFLVD(I)) * REDFT * AMAXDC(I)

**          EFF of healthy and diseased leaf area in layers (kg/ha/d).
            EFFH(I) = EFF
            EFFD(I) = EFF*EFFDC(I)

30    CONTINUE

**    Ratio between respiration of diseased and healthy leaf area (-).
      RMAIN = AFGEN(MAINDT,ASEVL)

**    Maintenance respiration of healthy and diseased leaf area, and
**    total leaf area (kg/ha/d).
      RMLVH = FHLLW * WLVG * MAINLV * TEFF * MNDVS
      RMLVD = FDSLW * WLVG * MAINLV * TEFF * MNDVS * RMAIN
      RMLV  = RMLVH + RMLVD

      ENDPROCEDURE

*********************************
*-------------------------------
TITLE STANDARD DISEASE INPUT DATA
*-------------------------------
*********************************

** AMAX, EFF and MAIN related to disease severity, as ratios between
** diseased and healthy leaf area (-).
FUNCTION AMAXDT = 0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION EFFDT  = 0.,1., 0.05,0.9, 0.1,0.75, 0.5,0., 1.,0.
FUNCTION MAINDT = 0.,1., 0.05,1.5, 0.1,2.5 , 0.5,5., 1.,5.

** Number of layers.
PARAM IN = 3

** Crop data from field experiments, for three layers.
** Total leaf area (ha/ha).
FUNCTION LAILL1 = 180.,0.02, 302.,1., 350.,1.
FUNCTION LAILL2 = 180.,0.,   302.,1., 350.,1.
```

```
FUNCTION LAILL3 = 180.,0.,   302.,1., 350.,1.

** Nitrogen content of healthy leaf area (kg/kg).
FUNCTION NCNTH1 = 180.,0.05, 302.,0.03, 350.,0.03
FUNCTION NCNTH2 = 180.,0.05, 302.,0.03, 350.,0.03
FUNCTION NCNTH3 = 180.,0.05, 302.,0.03, 350.,0.03

** Nitrogen content of diseased leaf area (kg/kg).
FUNCTION NCNTD1 = 180.,0.05, 302.,0.03, 350.,0.03
FUNCTION NCNTD2 = 180.,0.05, 302.,0.03, 350.,0.03
FUNCTION NCNTD3 = 180.,0.05, 302.,0.03, 350.,0.03

** Specific leaf weight of healthy leaf area (kg/ha).
FUNCTION SLWHL1 = 180.,300., 302.,300., 350.,300.
FUNCTION SLWHL2 = 180.,300., 302.,300., 350.,300.
FUNCTION SLWHL3 = 180.,300., 302.,300., 350.,300.

** Specific leaf weight of diseased leaf area (kg/ha).
FUNCTION SLWDS1 = 180.,300., 302.,300., 350.,300.
FUNCTION SLWDS2 = 180.,300., 302.,300., 350.,300.
FUNCTION SLWDS3 = 180.,300., 302.,300., 350.,300.

** Disease data from field experiments, for three layers.
** Fraction healthy leaf area (-).
FUNCTION FHLL1 = 180.,1., 302.,0., 350.,0.
FUNCTION FHLL2 = 180.,1., 302.,0., 350.,0.
FUNCTION FHLL3 = 180.,1., 302.,0., 350.,0.

** Fraction diseased leaf area (-).
FUNCTION FDSL1 = 180.,0., 302.,0.5,  350.,1.
FUNCTION FDSL2 = 180.,0., 302.,0.75, 350.,1.
FUNCTION FDSL3 = 180.,0., 302.,1.,   350.,1.

** Disease severity of diseased leaf area (-).
FUNCTION SEVL1 = 180.,0., 302., 0.05, 350.,0.05
FUNCTION SEVL2 = 180.,0., 302., 0.05, 350.,0.05
FUNCTION SEVL3 = 180.,0., 302., 0.05, 350.,0.05

** Disease severity of stem area (-).
** In the case of bacterial leaf blight, stem is not infected, and
** stem disease severity is 0. In the case of sheath blight, disease
** severity is equal to affected stem area/total stem area.
FUNCTION SEVS1 = 180.,0., 350.,1.0
FUNCTION SEVS2 = 180.,0., 350.,0.5
FUNCTION SEVS3 = 180.,0., 350.,0.1

*---------------------------------------------------------------------
* Experimental initial conditions, parameters and functions from:
* R. Torres, 1991; Oryza sativa cv.IR72, IRRI WS 1991 at 110 kg N
*---------------------------------------------------------------------

.....
.....

*--------------------*
```

```
* WEATHER INPUT DATA *
*--------------------*

* Weather data, Los Banos, Philippines, 1991

.....
.....

END
STOP
```

```
*-----------------------------------------------------------------------*
*  FUNCTION CBCHK                                                       *
```

Similar to function in ORYZA1

```
*-----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                     *
```

Similar to function in ORYZA1

```
*-----------------------------------------------------------------------*
*  SUBROUTINE TASSDS                                                    *
*  Purpose: This subroutine calculates daily total gross                *
*           assimilation (DTGA) by performing a Gaussian integration    *
*           over time. At three different times of the day,             *
*           radiation is computed and used to determine assimilation    *
*           whereafter integration takes place.                         *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  DOY     R4  Daynumber (January 1 = 1)                   -      I     *
*  LAT     R4  Latitude of the site                     degrees   I     *
*  DTR     R4  Daily total of global radiation          J/m2/d    I     *
*IS CALLED RDT IN MAIN PROGRAM!
*  SCP     R4  Scattering coefficient of leaves for visible             *
*              radiation (PAR)                             -      I     *
*  AMAX    R4  Assimilation rate at light saturation    kg CO2/   I     *
*                                                       ha leaf/h       *
*  EFF     R4  Initial light use efficiency             kg CO2/J/ I     *
*                                                       ha/h m2 s       *
*  KDF     R4  Extinction coefficient for diffuse light                 I     *
*  LAI     R4  Leaf area index                           ha/ha    I     *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)     h      O     *
*  DTGA    R4  Daily total gross Assimilation          kg CO2/ha/d O     *
*  DS0     R4  Daily extraterrestrial radiation         J m-2 s-1 O     *
*                                                                       *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIMD                     *
*  FILE usage : none                                                    *
*                                                                       *
*  WARNING: THIS VERSION OF TOTASS HAS BEEN WRITTEN FOR FOLIAR          *
*           DISEASES!!                                                  *
```

```
*                                                                      *
*----------------------------------------------------------------------*

      SUBROUTINE TASSDS (DOY,  LAT , DTR, SCP, AMAXH, AMAXD, EFFH,
     &                   EFFD, KDF,  LAITL, FHLT, FDST, IN,
     &                   DAYL, DTGA, DS0)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, IGAUSS, IN
      DIMENSION FHLT(3),FDST(3)
      DIMENSION AMAXH(3),AMAXD(3),EFFH(3),EFFD(3)

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

      PI    = 3.141592654

      CALL ASTRO(DOY,LAT,SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE)

*-----assimilation set to zero and three different times of the day
*     (HOUR)
      DTGA = 0.

      DO 10 I1=1,IGAUSS

*--------at the specified HOUR, radiation is computed and used to
*        compute assimilation
         HOUR = 12.0+DAYL*0.5*XGAUSS(I1)

*--------sine of solar elevation
         SINB  = AMAX1 (0., SINLD+COSLD*COS (2.*PI*(HOUR+12.)/24.))

*--------diffuse light fraction (FRDF) from atmospheric
*        transmission (ATMTR)
         PAR   = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
         ATMTR = PAR/(0.5*SC*SINB)

         IF (ATMTR.LE.0.22) THEN
            FRDF = 1.
         ELSE IF (ATMTR.GT.0.22 .AND. ATMTR.LE.0.35) THEN
            FRDF = 1.-6.4*(ATMTR-0.22)**2
         ELSE
            FRDF = 1.47-1.66*ATMTR
         END IF

         FRDF = AMAX1 (FRDF, 0.15+0.85*(1.-EXP (-0.1/SINB)))

*--------diffuse PAR (PARDF) and direct PAR (PARDR)
         PARDF = PAR * FRDF
         PARDR = PAR - PARDF

         CALL ASSIMD (SCP,AMAXH,AMAXD,EFFH,EFFD,KDF,LAITL,SINB,PARDR,
     &                PARDF,FHLT,FDST,IN,
     &                FGROS)
```

```
*--------integration of assimilation rate to a daily total (DTGA)
         DTGA = DTGA+FGROS*WGAUSS(I1)

10     CONTINUE

       DTGA = DTGA * DAYL

       RETURN
       END


*-----------------------------------------------------------------------*
*  SUBROUTINE ASSIMD                                                    *
*  Purpose: This subroutine performs a Gaussian integration for three   *
*           layers, over the canopy depth of each leaf layer by         *
*           selecting three different LAI's and computing assimilation  *
*           at these LAI levels. The assimilation of the layers         *
*           is integrated to total gross canopy photosynthesis FGROS.   *
*           Healthy, diseased and dead leaf area is taken into account.*
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- -------                                    -----  -----  *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                              -       I   *
*  AMAX    R4  Assimilation rate at light saturation     kg CO2/    I   *
*                                                       ha leaf/h       *
*  EFF     R4  Initial light use efficiency              kg CO2/J/  I   *
*                                                       ha/h m2 s       *
*  KDF     R4  Extinction coefficient for diffuse light                I   *
*  LAI     R4  Leaf area index                            ha/ha     I   *
*  SINB    R4  Sine of solar height                         -       I   *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2    I   *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2    I   *
*  FGROS   R4  Instantaneous assimilation rate of         kg CO2/   O   *
*              whole canopy                             ha soil/h       *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*                                                                       *
*  WARNING: THIS VERSION OF ASSIM HAS BEEN WRITTEN FOR FOLIAR           *
*           DISEASES!!                                                  *
*                                                                       *
*-----------------------------------------------------------------------*

      SUBROUTINE ASSIMD (SCP, AMAXH, AMAXD, EFFH, EFFD, KDF, LAITL,
     &                   SINB,PARDR, PARDF, FHLT, FDST, IN,
     &                   FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, I3, IGAUSS, IN
      DIMENSION LAITL(3),LAIA(3),FHLT(3),FDST(3)
      DIMENSION AMAXH(3),AMAXD(3),EFFH(3),EFFD(3)

*-----Gauss weights for three point Gauss
      DATA IGAUSS /3/
```

```
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)

*-----extinction coefficient for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/SINB) * CLUSTF
      KDRT   = KBL * SQV

*-----selection of depth of canopy, canopy assimilation is set to zero
      FGROS = 0.

*-----Leaf area above selected layers is calculated.
      LAIA(1) = LAITL(2) + LAITL(3)
      LAIA(2) = LAITL(3)
      LAIA(3) = 0.

*-----Calculation per layer.
      DO 30 I3 =1,IN

      FGROSL = 0.

      DO 10 I1=1,IGAUSS
*--------Leaf area index above selected height in canopy
         LAIC = LAITL(I3) * XGAUSS(I1) + LAIA(I3)

*--------absorbed fluxes per unit leaf area: diffuse flux, total direct
*        flux, direct component of direct flux.
         VISDF = (1.-REFH)*PARDF*KDF  *EXP (-KDF  *LAIC)
         VIST  = (1.-REFS)*PARDR*KDRT *EXP (-KDRT *LAIC)
         VISD  = (1.-SCP) *PARDR*KBL  *EXP (-KBL  *LAIC)

*--------absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation
*        of shaded leaves
         VISSHD = VISDF + VIST - VISD

*--------Healthy leaf area, shaded.
         IF (AMAXH(I3).GT.0.) THEN
            FGRSHH  = AMAXH(I3) * (1.-EXP(-VISSHD*EFFH(3)/AMAXH(I3)))
         ELSE
            FGRSHH = 0.
         END IF

*--------Diseased leaf area, shaded.
         IF (AMAXD(I3).GT.0.) THEN
            FGRSHD  = AMAXD(I3) * (1.-EXP(-VISSHD*EFFD(I3)/AMAXD(I3)))
         ELSE
            FGRSHD = 0.
         END IF

*--------Total leaf area, shaded.
         FGRSH = FHLT(I3) * FGRSHH + FDST(I3) * FGRSHD
```

```
*--------direct flux absorbed by leaves perpendicular on direct beam and
*         assimilation of sunlit leaf area
          VISPP  = (1.-SCP) * PARDR / SINB
          FGRSUN = 0.
          DO 20 I2=1,IGAUSS
             VISSUN = VISSHD + VISPP * XGAUSS(I2)

*-----------Healthy leaf area, sunlit.
             IF (AMAXH(I3).GT.0.) THEN
                FGRSHL = AMAXH(I3) * (1.-EXP(-VISSUN*EFFH(I3)/AMAXH(I3)))
             ELSE
                FGRSHL = 0.
             END IF

*-----------Diseased leaf area, sunlit.
             IF (AMAXD(I3).GT.0.) THEN
                FGRSD = AMAXD(I3) * (1.-EXP(-VISSUN*EFFD(I3)/AMAXD(I3)))
             ELSE
                FGRSD = 0.
             END IF

*-----------Total leaf area, sunlit.
             FGRS = FHLT(I3) * FGRSHL + FDST(I3) * FGRSD

             FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
20        CONTINUE

*--------fraction sunlit leaf area (FSLLA) and local assimilation
*         rate (FGL)
          FSLLA = CLUSTF * EXP(-KBL*LAIC)
          FGL   = FSLLA  * FGRSUN + (1.-FSLLA) * FGRSH

*--------integration of local assimilation rate to canopy
*         assimilation (FGROS)
          FGROSL = FGROSL + FGL * WGAUSS(I1)

10     CONTINUE

       FGROSL = FGROSL * LAITL(I3)
       FGROS  = FGROS + FGROSL

30     CONTINUE

       RETURN
       END

ENDJOB
```

Appendix A.6 Data sheets for joint stem borer experiments

DATA SHEETS FOR PERIODIC HARVESTS (P-AREA)

LAI AND LEAF CHARACTERISTICS

Variety:	
Date of transplanting:	DAS:
Date of harvest:	DAT:

Number of tillers: per m2
SLA: m2/g
N-content: g/g

HEALTHY PLOTS							INFESTED PLOTS						
	Uninfested tillers							*Uninfested tillers*					
	Number	Green			Dead			Number	Green			Dead	
		LAI	SLA	N-content	LAI	SLA			LAI	SLA	N-content	LAI	SLA
Plot 1							Plot 2						
3							4						
6							5						
8							7						
9							10						
aver.							aver.						
	Deadhearts							*Deadhearts*					
Plot 1							Plot 2						
3							4						
6							5						
8							7						
9							10						
aver.							aver.						
	Whiteheads							*Whiteheads*					
Plot 1							Plot 2						
3							4						
6							5						
8							7						
9							10						
aver.							aver.						

DATA SHEETS FOR PERIODIC HARVESTS (P-AREA)

DRY WEIGHT (kg/ha)

Variety:	
Date of transplanting:	DAS:
Date of harvest:	DAT:

HEALTHY PLOTS							INFESTED PLOTS						
	Uninfested tillers							*Uninfested tillers*					
	WLV			WST	WSO	WTOT		WLV			WST	WSO	WTOT
	green	dead	total					green	dead	total			
Plot 1							Plot 2						
3							4						
6							5						
8							7						
9							10						
aver.							aver.						
	Deadhearts							*Deadhearts*					
Plot 1					x		Plot 2					x	
3					x		4					x	
6					x		5					x	
8					x		7					x	
9					x		10					x	
aver.					x		aver.					x	
	Whiteheads							*Whiteheads*					
Plot 1							Plot 2						
3							4						
6							5						
8							7						
9							10						
aver.							aver.						

DATA SHEETS FOR TILLER DYNAMICS IN A VALIDATION EXPERIMENT (M-AREA)

Variety:
Date of transplanting
Date of harvest:

Weekly observations
Number of tillers per m2.

Date	DAS	DAT	Uninfested tillers	Deadhearts	Whiteheads	Total

DATA SHEET TO TRACK TILLER DYNAMICS OF A SINGLE HILL

Variety:	Date:
Date of transplanting:	DAS:
Hill number:	DAT:

Tiller	Observation														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															
16															
17															
18															
19															
20															
21															
22															
23															
24															
25															

Appendix A.7 Data sheets for joint experiments on foliar diseases

The standard experimental design that is described in Chapter 8 was developed at the March 1993 workshop in Cuttack on foliar diseases to ensure that obtained data will be sufficient for model validation and hypothesis testing, and to facilitate easy data exchange.

Data sheets which are compatible with the Standard Procedure have been developed. The first set of sheets allows data processing, the second set of sheets forms the basis for the SARPIII data base for foliar disease experiments.

The first set, for data processing, consists of 5 sheets, of which some are meant to be filled out in the field or laboratory, whereas others can be used to summarize the basic observations. The summary sheets provide you with the required input data for the model, and data for verification of model output.

At the top of each sheet, general information on the experiment has to be specified, along with details on the observed treatment, plot, and sub-plot. As periodic harvests are destructive, each sub-plot is encountered only once.

Sheet 4 is designed for use for more than one plant character. Please indicate always clearly which plant character, in which dimensions has been observed.

Two procedures of sub-sampling are described in the Standard Procedure.

Procedure 1: Total dry weight is determined on the basis of all 15 hills, whereas dry matter distribution, leaf area, leaf nitrogen content and disease severity are determined on the basis of 4 hills.

Procedure 2: Total dry weight is determined on the basis of all 15 hills, whereas dry matter distribution, leaf area, leaf nitrogen content and disease severity are determined on the basis of randomly selected tillers from these 4 hills. Remember to separate in any case the three categories healthy, diseased and dead leaf area. The data sheets can be used for either method.

In case you have used a different experimental design than the one described in the Standard Procedure, be careful with calculations as indicated on the sheets. The multiplication factors are based upon a sub-plot size of 3 x 5 hills with hill distance of 0.15 x 0.15 m, which equals 0.3375 m^2.

Development stage, tiller density and plant height.

These non-destructive field observations are recorded on sheet 1, and summarized on sheet 2. If you observe tiller density on a different set of tillers (for example, each observation on the same set), then change the multiplication factor to obtain tiller density (m^{-2}) accordingly.

Dry weights.
Record basic data on sheet 3 (column A), and process grand total to kg ha^{-1} (column G). Determine also the fractions on the basis of original observations (column A), and give these in column H. By multiplying the various fractions with the grand total in kg ha^{-1}, the weight of all plant organs in kg ha^{-1} is obtained (column I). Data are summarized on sheet 4.

Leaf area.
Record observations on sheet 3 in cm^2 (column B). Specific leaf area (columns C and D) and specific leaf weight (columns E and F) are calculated from dry weight and leaf area (see instructions at the bottom of sheet 3). Leaf area index (column J) is subsequently calculated by multiplying specific leaf area and dry weight (columns D and I). Summarize on sheet 4.

Disease severity.
Fill out on sheet 3 for diseased leaf area and stem area (for Sheath Blight), and summarize on Sheets 4.

Leaf nitrogen content.
Observations on leaf nitrogen content are recorded on sheet 3. Summarize on sheet 4.

Yield components.
Final harvest data are recorded on Sheet 5, organized per treatment. Process data to proper dimensions, dependent upon your own experminental methods.

Input of the BLIGHT model

Completed data sheets form the basis for the data set that has to be incorporated in the BLIGHT model. Please prepare your data in ready-to-use data sets, which are compatible with the model.

Relevant input requirements are:

`AFGEN(LAILLx,DOY)`	Obtain from sheet 4. Total leaf area for three layers (x = 1, 2, 3).
`AFGEN(NCNTHx,DOY)` `AFGEN(NCNTDx,DOY)`	Obtain from sheet 4. Leaf nitrogen content of healthy and diseased leaf area, for three layers.
`AFGEN(SLWHLx,DOY)` `AFGEN(SLWDSx,DOY)`	Obtain from sheet 4. Specific leaf weight of healthy and diseased leaf area, for three layers.

AFGEN(FHLLx,DOY)	Can be obtained from sheet 3 or 4.
AFGEN(FDSLx,DOY)	Determine per layer the fractions healthy/total and diseased/total leaf weight.
AFGEN(SEVLx,DOY)	Obtain from sheet 4.
AFGEN(SEVSx,DOY)	Disease severity for leaves and stem, for 3 layers.
AFGEN(DRLVT,DVS)	Relation of relative loss rate of leaf dry weight to development stage. May be modified to increase rate of leaf senescence as a consequence of disease presence. see for further explanation and calculation exercise 2 of section 6.3
AFGEN(FSHTB,DVS)	See exercise 3 of section 6.3.
AFGEN(FRTTB,DVS)	Dry matter partitioning.
AFGEN(FLVTB,DVS)	
AFGEN(FSTTB,DVS)	
AFGEN(FSOTB,DVS)	

SARP data base for foliar disease experiments

Participants of the Cuttack workshop agreed upon the development of a SARP data base for foliar disease experiments. The rationale behind this was that the various research teams are working on one large joint experiment rather than several isolated ones. Consequently, research data have to be combined, and interpreted as one set at some stage. After experimental data have been analyzed and used for model validation, the model can be further developed and utilized in application studies.

The presented data sheets are suitable for raw data, which will be processed by the Theme Coordinator Crop Protection, who will also be responsible for development and maintenance of the data base.

Researcher:	Variety:
Observer:	Date of sowing:
Station:	Date of transplanting:
Season:	
Date:	Treatment
	Plot number
	Sub-plot number

NON-DESTRUCTIVE FIELD OBSERVATIONS.

Hill number	Development stage (-)	Number of tillers (-)	Plant height (m)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
Total			
Average		xx	
Multiply with	xx	1/0.3375 or 2.963	xx
		..... = Tiller density (/m2)	
Multiply with	xx	10000	xx
		..... = Tiller density (/ha)	

Transfer data to sheet 2.

Researcher: Observer: Station: Season: Date:	Variety: Date of sowing: Date of transplanting:

Transfer from sheet 1.

SUMMARY NON-DESTRUCTIVE FIELD OBSERVATIONS.

Date (dd-mm)	Treatment ...		
	Development stage (-)	Tiller density (/ha)	Plant height (m)

Researcher:	Variety:
Observer:	Date of sowing:
Station:	Date of transplanting:
Season:	
Date:	Treatment:
	Plot number:
	Sub-plot number:

DRY WEIGHT OBSERVATIONS.
LEAF AREA OBSERVATIONS.
LEAF NITROGEN OBSERVATIONS.

	A	B	C	D	E	F	G
	Dry weight (g)	Leaf area (cm2)	Specific leaf area (cm2/g)	(ha/kg)	Specific leaf weight (g/cm2)	(kg/ha)	Dry weight (kg/ha)
Layer 1							
Healthy							xx
Diseased							xx
Dead							xx
Total			xx	xx	xx	xx	xx
Layer 2							
Healthy							xx
Diseased							xx
Dead							xx
Total			xx	xx	xx	xx	xx
Layer 3							
Healthy							xx
Diseased							xx
Dead							xx
Total			xx	xx	xx	xx	xx
Total leaves			xx	xx	xx	xx	xx
Stems & sheaths		xx	xx	xx	xx	xx	xx
Panicles		xx	xx	xx	xx	xx	xx
Rest		xx	xx	xx	xx	xx	xx
Grand total		xx	xx	xx	xx	xx	

C = B/A
D = C/100.000 ; 100.000 = 1000 (cm2/kg) * 1/10.000 (m2/kg) * 1/10.000 (kg/ha)
E = A/B
F = E * 100.000
G = A * 29.63 ; 29.63 = 1/0.3375 (g/m2) * 10.000 (g/ha) * 1/1000 (kg/ha)
H : calculate from A
I : calculate from G and H
J = D * I

Transfer data to sheet 4.

	H	I	J	K	L
	Fraction dry weight	Dry weight (kg/ha)	Leaf area (ha/ha)	Nitrogen content (kg/kg)	Disease severity
Layer 1					
Healthy					xx
Diseased					
Dead				xx	xx
Total				xx	xx
Layer 2					
Healthy					xx
Diseased					
Dead				xx	xx
Total				xx	xx
Layer 3					
Healthy					xx
Diseased					
Dead				xx	xx
Total				xx	xx
Total leaves				xx	xx
Stems & sheaths			xx	xx	1:.....2: ..... 3: .....
Panicles			xx	xx	xx
Rest	xx	xx	xx	xx	xx
Grand total	1		xx	xx	xx

Give disease severity for stem for 3 layers

Researcher:	Variety:	Treatment:
Observer:	Date of sowing:	Plot number:
Station:	Date of transplanting:	Sub-plot number:
Season:		
Date:		

			Transfer data from sheet
SUMMARY	**DRY WEIGHT**	Dry weight (kg/ha)	3
	LEAF AREA	Leaf area (ha/ha)	3
	SPECIFIC LEAF AREA	SLA (ha/kg)	3
	SPECIFIC LEAF WEIGHT	SLW (ha/kg)	3
	LEAF NITROGEN CONTENT	Nitrogen content (kg/kg)	3
	DISEASE SEVERITY	Disease severity (-)	3

Fill out only relevant columns.

Date	Character (dimension)																		
(dd-mm)	Layer 1				Layer 2				Layer 3				Total	Stems & sheaths				Panicles	Grand
	Heal.	Dis.	Dead	Total	Heal.	Dis.	Dead	Total	Heal.	Dis.	Dead	Total	leaves	Total	1	2	3		total

Researcher: Observer: Station Season: Date:	Variety: Date of sowing: Date of transplanting:

FINAL HARVEST OBSERVATIONS.

Treatment	Pancile density (/hill, /m2)	No. filled kernels (/panicle)	Unfilled kernels (%)	1000-kernel weight (g)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

Process data to proper dimensions, dependent upon your own experimental methods.

SARPIII DATA BASE FOR FOLIAR DISEASE EXPERIMENTS

UNPROCESSED FIELD DATA.
NON-DESTRUCTIVE OBSERVATIONS.

Researcher: Station: Season:	Variety: Date of sowing: Date of transplanting:

Treatment: Plot number:

No. plants/m2 in seedbed: No. plants/hill:	Hill distance: No. hills/m2

Date (dd-mm)	Development stage (-)	Number of tillers per hill	Plant height (m)

Date of flowering: (90% of hills with at leas 1 flowering panicle)

SARPIII DATA BASE FOR FOLIAR DISEASE EXPERIMENTS

UNPROCESSED FIELD DATA.
DESTRUCTIVE OBSERVATIONS.

Researcher:	Variety:	Treatment:
Station:	Date of sowing:	Plot number:
Season:	Date of transplanting:	

Epidemic number:

Number					1				2			
Plant organ	Date:				Date:							
	Dry weight	Leaf area	Nitrogen content	Severity	Dry weight	Leaf area	Nitrogen content	Severity				
Layer 1												
Healthy												
Diseased												
Dead												
Layer 2												
Healthy												
Diseased												
Dead												
Layer 3												
Healthy												
Diseased												
Dead												
Stem												
Total												
Layer 1												
Layer 2												
Layer 3												
Panicles												
Rest												
Total												

Dry weight is measured in
Leaf area is measured in:
Nitrogen content is measured in:

SARPIII DATA BASE FOR FOLIAR DISEASE EXPERIMENTS

UNPROCESSED FIELD DATA.
FINAL HARVEST OBSERVATIONS.

Researcher:	Variety:
Station:	Date of sowing:
Season:	Date of transplanting:
	Date of harvest:

Plot number	Treatment	Panicle density	Number of filled kernles per panicle	% unfilled kernels	1000-kernel weight
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

Panicle density is measured in:	(per hill, per m2)
1000-kernel weight is measure in:	(g, kg)