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Analysis of damage mechanisms by pests and diseases and their effects on rice yield

A. Elings & E.G. Rubia (Editors)

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Preface

This volume of the SARP Research Proceedings contains results of the Pest and Disease Management Application Programme, which were presented at the Applications Workshop that was held at the International Rice Research Institute from 18 April to 6 May, 1994. In addition, reports written during the research visits that were paid by Dr. P.R. Reddy, Mr. Xu Zhihong and Ms. E.G. Rubia to the DLO-Research Institute for Agrobiology and Soil Fertility and the WAU - Department of Theoretical Production Ecology, during May - September, 1994, are included.

The activities of the Pest and Disease Management Application Programme are focused on stem borers, bacterial leaf blight and sheath blight. In a series of workshops, these pests and diseases were selected, and a joint research approach aimed at understanding damage was developed. This resulted in experimental protocols and two simulation models, viz. one for stem borers, and one for blight diseases (W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, SARP Research Proceedings - December 1993).

The joint research approach consists of 6 steps:

1. Identification of all possible effects of a reducing factor on plant growth and crop physiology.
2. Identification of the mechanisms which are hypothesized to be the most important ones for explaining damage.
3. Quantification of these mechanisms.
4. Introduction of these mechanisms into the crop growth model.
5. Quantitative comparison of model outcomes with results of field experiments, to evaluate to which extent damage is understood, and whether additional damage mechanisms need to be quantified and included in the model.
6. Model application.

The crop gowth models represent hypotheses with regards to pest-rice interactions, which have been tested in field experiments. The results of these joint validation experiments are presented in this book, with up-dated versions of the models (steps 4 and 5).

Dr. W.H. Settle introduces possibilities for model application, particularly in training. Section A is devoted to blight diseases. The FSE version of the BLIGHT model for bacterial leaf blight (BLB) and sheath blight (ShBl) is presented, and evaluated by various researchers. A revised experimental protocol for BLB and ShBl was agreed upon after evaluation of the original protocol. Section B contains reports on stem borers. As introduction, Dr. Settle elaborates on application possibilities for models, followed by the

presentation and evaluation of the FSE version of the SBORER model for stem borers, which incorporates a simplified tiller module. A quantitative analysis of tiller dynamics, is presented by Xu Zhihong et al. As an illustration of the differences between crop growth models and regression models, the latter technique is presented by Dr. Sindhusake. Much interest in analysis of the rice - brown plant hopper system is developing, and therefore, part of the workshop was devoted to exploration of this crop-pathosystem (research steps 1, 2 and 3). In section C, Dr. Sogawa reports the brainstorming session on this subject, and summarises with Dr. Watanabe their models. An overview of the effect of the weather system on BPH migration in China, completes the subject. In section D, a dynamic threshold for Malayan Black Bug is developed by application of a pest - crop combination model. Model listings and examples of required input files are presented in appendices. Ir. D.W.G. van Kraalingen and Drs. J.J.M. Riethoven have verified the technical quality of the models.

We would like to acknowledge the assistance of the SARP secretariat and support staff at IRRI, and IRRI management, in organization of the workshop and transcription of lectures; the contribution of participants and their managements; and the organizational and supervisory support by the SARP secretariat and staff at AB-DLO and WAU-TPE during the research visits and the production of this book.

Wageningen, Los Baños, A. Elings
December, 1994. E.G. Rubia

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Introduction

SARP's models as a training tool: comments from an IPM researcher and trainer

W.H. Settle

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Agricultural research and education

In my opinion, the fundamental goal of research is to educate; hence, as researchers we should clearly have in mind who our intended audience is. This is particularly critical for those of us involved in the so-called 'applied sciences'. Unfortunately, most research results coming out of universities and research organizations are in the form of published papers aimed at providing information for other scientists, that is, the already-educated elite. Too rarely does the researcher seriously question for whom the research is done, let alone actively pursue questions concerning methods for educating the target audience such that they might obtain knowledge of, and put into practice the results of the research. While the process of informing our peers of our findings, as well as educating the next generation of researchers is indeed an important part of science, it is not by itself sufficient. Therefore, I think it is good that this conference is questioning the end-use of simulation models.

The creation of information by, and transfer of information among scientists is the 'normal' model for science. However, if we look within our own experiences we might agree that 'information' is different from 'knowledge'. 'Information' has to do with the words, ideas, and facts in themselves, but 'knowledge' has more to do with a personal cognitive experience. I find 'information' in a journal article, but I obtain 'knowledge' through the process of exploration and experimentation that constitutes experience – for example, through the process of doing science.

Indeed, it is only the acquisition of sufficient knowledge by the hundreds of millions of people on earth who every day make decisions about agriculture and the environment that will contribute significantly to the future sustainability of life on this planet. 'Information', in the form of scientific papers, extension publications, radio programs, and computer models, can only play a supporting role at best.

If we obtain knowledge through experience, then an effective method for educating farmers should be through 'hands-on' exploration and experimentation. The FAO Regional IPM programme is based on just such 'experiential' learning methods. The philosophy of the programme is that IPM is not a technology created by scientists FOR farmers, but rather, a process of self-education done BY farmers, and assisted by highly trained extensionists using non-formal educational methods and – when applicable – the results of recent research. These results from research, however, are in all cases presented in the

form of simple experiments or group exercises done by farmers in their own fields. It is this process of 'learning-by-doing' in a collaborative environment that is the key to unlock the untapped strength and intelligence of Asian farmers.

Our experiences with the hundreds-of-thousands of rice farmers in Asia that have now undergone full-season training with the FAO IPM programme show that farmers are intensely motivated to delve into the details of the mechanisms that constitute the functioning of rice ecosystems. In so doing they become better able to question, explore, evaluate, discuss and decide – in short, farmers take on the operational attributes of scientists. The motivation comes not merely from the prospect of increased monetary savings through the reduction of unnecessary pesticide applications – but more from the excitement generated by the process of learning for themselves with the tools of science.

The old model of agricultural science and extension limits the process of discovery and exploration to the scientist in the lab or research station who creates a technological output for the farmer. Traditional agricultural researchers in rice are pursuing the next TECHNOLOGICAL revolution. However, the next revolution in agricultural production in Asian rice is already taking place, and furthermore it is not a technological revolution, but rather a sociological and educational revolution. Traditional agricultural research will either take note of and adapt to the potential held in this educational revolution, or it will be left behind.

SARP's models: for what purpose and for whom are they intended?

It is my belief – and the belief of most modellers – that computer simulation models are most properly used as a heuristic device, that is, as a tool for guiding further research by helping to generate hypotheses that are then tested in the field or lab. In this way SARP's models have already significantly contributed to the science of pest management by promoting field studies on the relationships among plants, insects, and diseases. Of particular value is the excellent work done on the relationships between stem borer damage and yield loss in rice. Additionally, SARP's models have great potential to contribute to the education of scientists, administrators and students.

The two key concepts that form the foundation of rice IPM training are 1) plant compensation, and 2) biological control of potential pests by natural enemies. Plant compensation is based on physiological processes, whereas biological control (in the broadest sense) is based on ecological processes. SARP's models, being limited to physiological mechanisms, have a great advantage in that physiological processes are far more deterministic, and hence more predictable and generalizable than highly stochastic ecological systems. The ability of rice plants to compensate for insect damage is possibly the most important and at the same time least understood principle in rice pest management today.

Clearly, Asian rice farmers are not going to be using computer models to explore plant compensation – nor do they need to. Farmers in IPM training do their own simulation models, using the actual rice plant. One of the key experiments in farmer field schools is one in which farmers manually de-foliate and de-tiller square meter blocks of rice, to

varying degrees and at varying times of the season. At the end of the season they harvest the plots and measure the differences. This same set of exercises is also part of the season-long training of IPM trainers. While not exploring the role of physiological mechanisms, these exercises provide a far more realistic and convincing demonstration of plant compensation.

For agricultural scientists, government administrators, and students, however, SARP's models could be very useful as a means of demonstrating the concept and probable mechanisms of plant compensation. For the national scientists, the models could be an excellent device to generate further research questions; for example, the effects of nutritional status, leaf and tiller age structure, water stress, and soil fertility on plant compensation.

As a tool in both undergraduate and graduate-level courses in agricultural universities, SARP's models (or perhaps more simplified versions) could be useful in giving students a more intuitive and dynamic understanding of plant physiological processes and how they interact with extrinsic factors such as insects and disease.

Economic thresholds (ETLs) have been a fundamental tool of the traditional IPM methods for several decades. An ETL is simply the cost of control divided by the product of the commodity cost and a damage coefficient. Plant compensation is just one of several factors that affects the damage coefficient, but is not taken into consideration when calculating ETLs. SARP's models might be useful as a tool to help educate scientists and administrators regarding the inadequacies of ETLs. ETLs, while an improvement on strict calendar applications, still promote a large degree of unnecessary pesticide use. Our experience has been that farmers are capable of complex decision making. In IPM training, farmers discuss the factors that should be included in considering economic losses. These include, but are not limited to: plant compensation, plant age, pest population dynamics, the nature of the pest damage, natural enemy populations, relative efficiency of various natural enemy species, natural enemy movement, water stress, soil fertility, costs of input, opportunity costs, uncertainty in the price of returns, plant variety, and social and environmental costs. Unfortunately, an ETL is an overly simplistic and inflexible tool that does not take into consideration most of the factors necessary for an intelligent decision as to whether or not to apply pesticides. An IPM-trained farmer, in contrast, is able to take the larger set of factors into consideration when deciding on a course of action.

Conclusions

In conclusion, it is my belief that the practice of science cannot be limited to scientists; that science, in the broadest most general sense, is a robust and powerful philosophical method that can transform the lives of traditional farmers by providing a tool to explore the factors and mechanisms of importance to their lives. SARP's models are highly sophisticated tools for educating educated people – scientists, administrators, and students. They have excellent potential for demonstrating the concept of plant compensation – one of the most important and least understood concepts in plant protection. The models

should be pursued to completion, and set in a 'user-friendly' format that can easily be operated by less-sophisticated computer users. They should then be distributed to national scientists, crop-protection agencies, and universities. To complete the program will require some investment in documentation and training for end users. It should be understood that the models are a tool for education and hypothesis generation, and not for forecasting and centralized decision making by crop protection agencies.

(Dr. Settle is an ecologist working on community dynamics of irrigated rice fields in Indonesia for the past three years. He had been asked to speak regarding the FAO IPM programme and the potential use of SARP's models as an educational tool.)

Section A

Bacterial leaf blight

and

sheath blight

Structure and development of BLIGHT, a model to simulate the effects of bacterial leaf blight and sheath blight on rice.

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Introduction

Bacterial leaf blight (BLB, causal organism *Xanthomonas campestris* pv. *oryzae*) is a foliar disease that can cause considerable yield reduction (Mew et al., 1993). Epidemic development is favoured by relatively high temperatures, strong winds, rainfall, and high air humidity (Ou, 1985). High nitrogen application may enhance pathogen development and lesion enlargement (Reddy et al., 1979a) if the variety-pathotype combination is compatible (Mew et al., 1979). Loss of green leaf area results in reduction of interception of photosynthetically active radiation, and bacterial presence in remaining green leaf tissue may result in reduced light use efficiency. These mechanisms interact with environmental conditions and farm management practices, such as incoming radiation and temperature, which vary within and among seasons, and nitrogen application, which may lead to increased CO_2 assimilation at increased levels of leaf nitrogen content (van Keulen & Seligman, 1987).

Yield loss studies (e.g. ten Have & Kaufman, 1972, Reddy et al., 1979a; Reddy et al., 1979b) have quantified the relations between nitrogen application rate, disease severity, season, and grain yield, which has resulted in qualitative understanding of host x pathogen x environment interactions, and disease management recommendations with regards to nitrogen management. However, the validity of such relations is limited, as they are strongly influenced by e.g. the moment of disease onset, disease spread, farm management practices, environmental conditions, and their interactions. A systems analytical approach requires definition of the system to be studied (de Wit, 1982), and monitoring of relevant characters of host, pathogen, and environment. Studies that attempt to understand crop growth and production at the field level, must therefore include crop characteristics, such as leaf nitrogen content and leaf area; environmental variables that influence crop growth at the production level it is grown at (Penning de Vries et al., 1989); and disease severity. As BLB development has not been sufficiently quantified, this process must be excluded. Detailed quantitative knowledge can be used to develop and test a crop growth simulation model that incorporates damage mechanisms, and that can be used, after validation, for scenario studies and generation of disease management recommendations.

A number of steps are distinguished in model building, which concentrate, in a logical order, on conceptualization, explanation, and instruction and management (Rabbinge et al., 1989), viz.: 1. formulation of objectives; 2. definition of the limits of the system; 3. conceptualization of the system; 4. quantification of processes; 5. model construction; 6 model verification, i.e. testing the intended behaviour of the model; 7. model validation, using independent experiments; 8. sensitivity analysis; 9. simplification and development of a summary model; 10. formulation of decision rules or forecasting models to be used in management.

The objective of building a model for the foliar diseases Bacterial Leaf Blight and Sheath Blight (ShBl) is to support the analysis of the effects of these diseases on rice growth, particularly in field experiments (step 1). The system to be analyzed is therefore limited to the rice crop growing under optimal supply of water and nutrients other than nitrogen, to which disease characteristics are introduced as forcing functions, just as weather characteristics (step 2). Nitrogen supply is accounted for by introducing leaf nitrogen content as forcing function. This chapter concentrates on steps 3, 4 and 6, and preliminary explores disease x crop interactions on the basis of the current state of affairs. The field experiment at the International Rice Research Institute (IRRI) during the 1993 dry season, which is used for model verification, is described in detail. The model listing (step 5) is presented in Appendix I. As a result of model building, knowledge gaps and new research goals may be identified, and after validation, the model can be used for exploring scenarios to assess the effect of disease development on grain yield reduction under various growing conditions.

Although BLIGHT is developed for BLB and ShBl, the model can also be applied to other diseases with similar damage mechanisms.

First simulation results of the effects of BLB and ShBl on rice growth and production were presented at SARP (Systems Analysis and Simulation for Rice Production) workshops in 1990 and 1991 (Narasimhan et al., 1991; Reddy et al., 1991; Singh & Das, 1991). L1DFDE, the standard model for foliar diseases, was SARP's first standard version of a model for blight diseases (Bastiaans, 1991), and was based on MACROS-L1D (Models of an Annual Crop Simulator, 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), version 1 of a new disease model, based upon ORYZA1, was developed (Elings, 1993a). Correction of some shortcomings and addition of a number of new crop processes resulted in model version 2 (Elings & Rubia, 1994). Main differences between versions 1 and 2 are:

- Some of the improvements and additions that are included in the latest version of ORYZA1 (Kropff et al., 1994), are incorporated, viz. loss of weight at transplanting, improved simulation of LAI, and crop death after a certain number of cold days.
- Simulation of leaf area index throughout the entire growing season, which enables exploration studies and sensitivity analyses, is now possible.

- If leaf area development is made model input, then the relevant input table is read starting at the date that first field observations are available. Before that moment, leaf area is simulated.
- In version 1, fractions total green leaf and stem area were assumed to be similar, which especially in the case of BLB caused an under-estimation of the amount of total green area, as this disease predominantly affects leaf area. Green stem area is now accounted for correctly.
- Intercepted photosynthetically active radiation and crop light use efficiency are calculated.
- Facilities for simple sensitivity analyses and exploration studies have been introduced.

BLIGHT was originally written in CSMP (Continuous System Modelling Program), however, version 2 is only available in FORTRAN77, and is compatible with the support software Fortran Simulation Environment (FSE) (van Kraalingen, 1991) and the SARP 'COME-ON' Shell (van Riethoven, 1994), which facilitate application of FORTRAN models, and offer a wide range of options with respect to data management and generating reruns. The Fortran Simulation Environment (FSE) is an environment for continuous simulation of crop growth. It consists of a main program (MAIN), a general model subroutine (MODELS), weather data and utilities to perform specific tasks. The WEATHER system (van Kraalingen et al., 1990) is used to read weather data, and utilities from the TTUTIL library (Rappoldt & van Kraalingen, 1990) are used for performing specific tasks, such as handling of input and output files, and integration of states. The model equations are defined in one or more subroutines. FSE distincts four main tasks (ITASKs) which control the order of calculations in the crop growth program, and which resemble the structure of crop growth models written in CSMP (ITASK 1 to 4, for initialization, rate calculations, state calculations, and terminal, respectively). Relevant subroutines are called under each of the tasks, to compute task-specific variables.

Model description

General structure

BLIGHT is a combination model with sections on crop growth and development, and sections which account for plant x disease interactions. The crop sections are, apart from some minor changes, very similar to ORYZA1 (see for a full explanation Kropff et al., 1994). The model structure is given in Figure 1. The BLIGHT subroutine is called by the general MODELS subroutine, and BLIGHT calls directly or indirectly subroutines with specific tasks. Most interaction processes between host and pathogen are placed in subroutines DIS1 (calculation of healthy, diseased and dead leaf area; fractions healthy, diseased and dead leaf area; stem area per canopy layer; disease severity; and green leaf area) and DIS2 (calculation of the photosynthesis characteristics). Two subroutines read input data, viz. RDDIS for most experimental input data, and RDLAI for data on leaf area. Subroutine SENS facilitates simple sensitivity analyses; subroutine AVERAG averages leaf

nitrogen contents and specific leaf weights of the three canopy layers to one value, to facilitate dynamic simulation of leaf area; and subroutine ABSORB calculates intercepted photosynthetically active radiation and light use efficiency. Subroutines TOTASS and ASSIM of ORYZA1 have been rewritten to subroutines TASSDS and ASSIMD (DS and D stand for diseased), respectively, and compute with subroutine ASTRO canopy photosynthesis for 3 canopy layers. Leaf area dynamics are computed by GRLAI, model termination after a certain number of cold days is handled by subroutine SUBCD, and subroutine SUBCBC performs the carbon balance check.

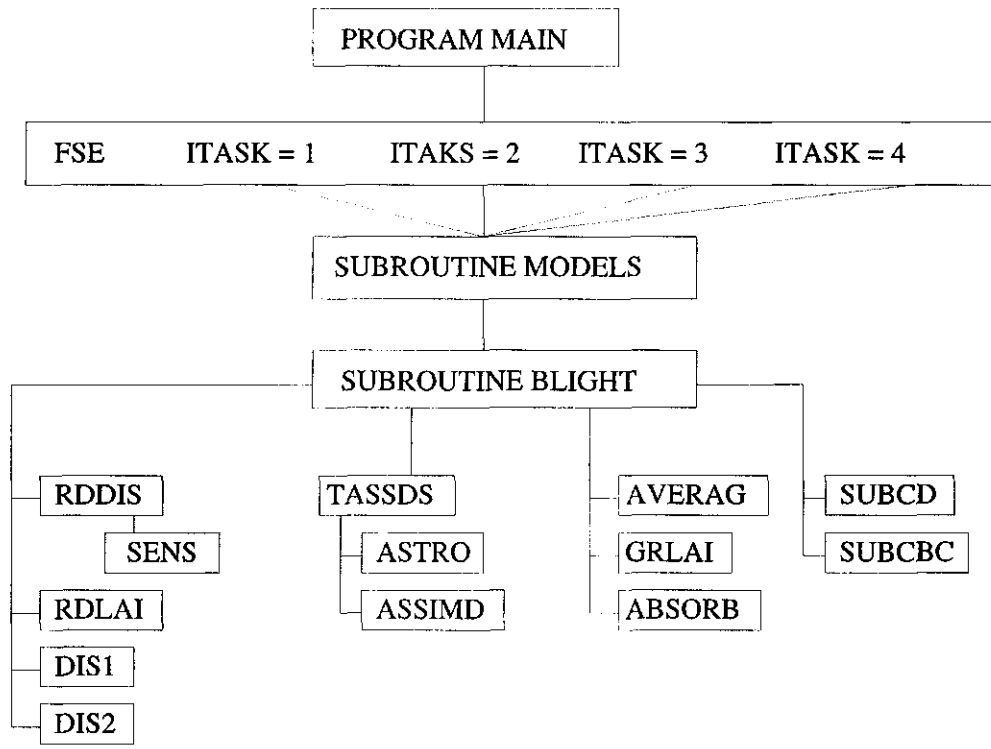

Figure 1. The BLIGHT model under the FSE simulation environment

The relational diagram of BLIGHT, which is given in Figure 2, is very similar to that of ORYZA1. Total daily rate of canopy CO_2 assimilation is calculated from the daily incoming radiation, temperature and leaf area index, by integrating instantaneous CO_2 assimilation. Photosynthesis characteristics of a single leaf depend upon leaf nitrogen concentration. After subtraction of maintenance and growth respiration requirements, the net daily growth rate is obtained. The dry matter produced is partitioned among the various plant organs. Phenological development is tracked as a function of ambient daily average temperature. When the canopy is not yet closed, leaf area increment is calculated from the daily average temperature, as carbohydrate production does not limit leaf expansion. After canopy closure, the increase in leaf area is obtained from the increase in leaf weight. Inte-

gration of daily growth rates of the organs and leaf area results in dry weight increment during the growing season. High and low temperatures result in spikelet sterility and sink limited grain filling (Kropff et al, 1994). Disease severity influences the characteristics of the photosynthesis light response curve.

For the analysis of experimental data, LAI is preferably made input, whereas for scenario studies, LAI is preferably simulated, as there is a large difference between analysis of experiments, in which damage mechanisms are studied, and scenario studies, in which the effects of variation in disease pressure on (green) leaf area and growth are studied. The latter require feed backs between growth and leaf area. For instance, an earlier onset of the epidemic will likely cause reduced growth, which results in a lower leaf area, which subsequently may cause even more reduced growth, etcetera. A fixed LAI in this case would probably lead to an over-estimation of crop growth. By setting parameter SWILAI (0 = reading input data, 1 = simulation) the desired model option is selected. If the switch is set to 0, then the LAI input data are read starting at the date that first field observations are available.

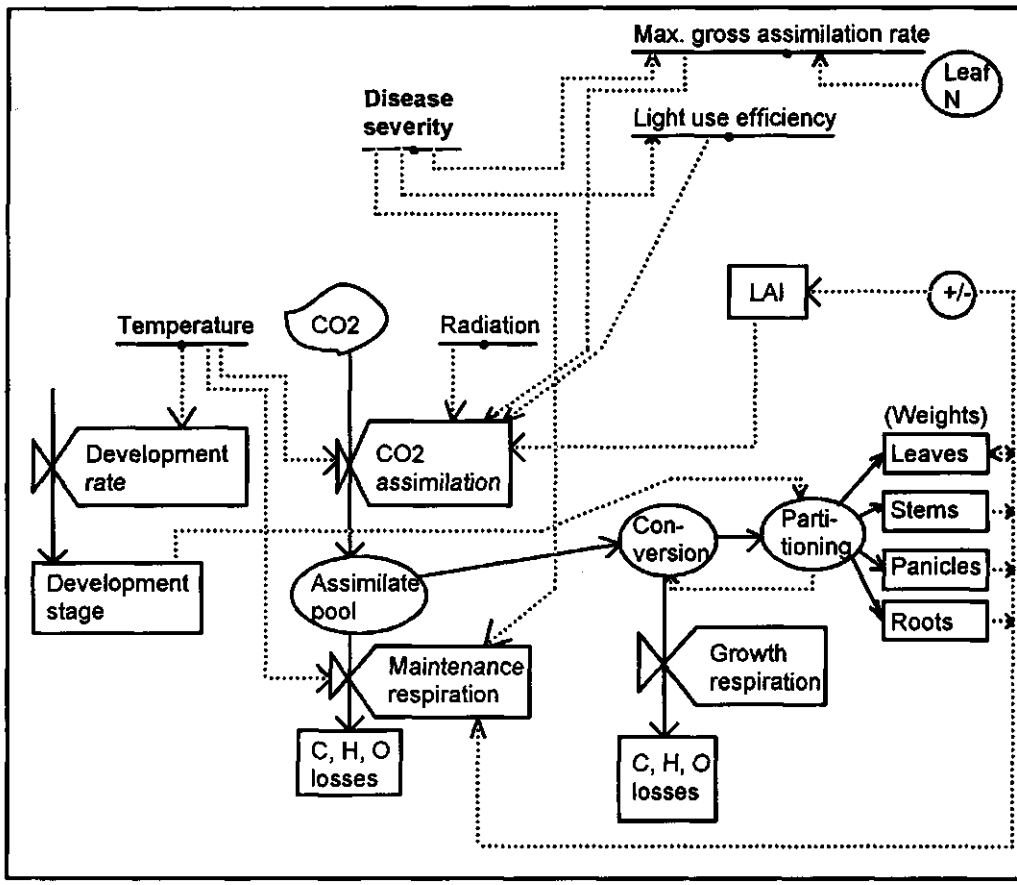

Figure 2. The relational diagram of the BLIGHT model

BLIGHT does not simulate disease development in time, but requires this as input, which is achieved through a detailed definition of the leaf and stem areas covered by the disease. Three types of leaf area are distinguished: healthy, diseased and dead leaf area. These are introduced in the model as fractions healthy and diseased leaf area, from which the fraction dead leaf area is calculated. Diseased leaf area and diseased stem area are characterized by their respective disease severities. The fraction healthy leaf area is entirely green (apart from leaf area that has died due to natural senescence); the fraction dead leaf area is entirely dead; and the fraction diseased leaf area is partly green, partly dead, as defined by disease severity.

Leaf and stem area, and canopy layers

In contrast to ORYZA1, in which a single canopy layer is considered, in BLIGHT the canopy is divided into three canopy layers which are characterized separately. If the standard experimental design (Elings, 1993b) is followed, then three canopy layers are distinguished: (1) 0-25 cm, (2) 25-40 cm, and (3) above 40 cm, measured from the root crown. This approach allows a more precise simulation and analysis of events compared to a single canopy layer approach, as diseases are mostly not evenly distributed over canopy depth. However, further increase in realism is obtained by striving after an even distribution of LAI over layers. As a result, depth of canopy layers becomes dynamic, which is preferable to fixed depths in centimetres, as the latter may result in an uneven distribution of light interception over the canopy layers, which would undo the advantages of the multi-layer approach. (See also the updated experimental protocol in this volume.)

BLIGHT calculates stem area per canopy layer. Stem area distribution over layers is assumed proportional to leaf area distribution over layers. 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 decreased. Also, the distribution of stem area over canopy depth is generally more uniform than the distribution of leaf area, however, this is difficult to simulate without additional information. Total green leaf plus stem area is calculated for every canopy layer on the basis of leaf area fractions, disease severity, and stem area. Total green leaf area, which is an important variable, as it largely determines the amount of intercepted radiation, is calculated for the entire canopy.

It may be required to simulate leaf area, for instance in case of exploration studies, which needs feed backs between reduced or increased growth (in kg ha^{-1}) and the leaf area (in ha ha^{-1}). This is done by subroutine GRLAI from ORYZA1, which takes into account the transplanting shock and sink-limited, temperature-dependent, exponential growth early in the season. However, the output of GRLAI is the area of one canopy layer, whereas the BLIGHT model works with three layers. The calculated leaf area is therefore sub-divided in three layers of equal depth. This approach differs from simulation with LAI as input, which starts early in the growing season with one canopy layer, and which adds the second and third canopy layer of different depths later in the season.

Leaf nitrogen contents and specific leaf weights (SLW, in kg ha^{-1}) have been observed and introduced to the model for three canopy layers. As the GRLAI subroutine needs one value for SLW that characterizes the entire canopy, the data on leaf nitrogen content and SLW for the three layers are averaged to canopy values, and used to calculate the canopy SLW in the AVERAG subroutine. The canopy SLW is supposed to be the average of the SLW's of healthy and diseased leaf area. This ignores the contribution of dead leaf area, which is characterized by a high SLW, however, as this datum is not model input, it is difficult to correct for.

Crop light use efficiency

Crop growth rate is approximately linearly related to absorbed photosynthetically active radiation (PAR_a) by green foliage (Monteith, 1977) under conditions of unlimited availability of moisture and nutrients, and absence of pests and diseases, which results in a constant amount of biomass produced per PAR_a (Biscoe and Gallagher, 1977), or crop light use efficiency (CLUE, Rossing et al., 1992). The effects of BLB and ShBl damage on crop growth can be analyzed in terms of cumulatively intercepted light (LI) and CLUE, thus distinguishing between effects on photosynthetic area and activity per unit photosynthetic area, respectively (Waggoner & Berger, 1987). Absorbed photosynthetically active radiation by total green area is calculated per canopy layer with Beer's law:

$$PAR_a = (1-r_c) \cdot PAR_0 \cdot (1-e^{-k \cdot LAI})$$

PAR_a	:	absorbed photosynthetically active radiation	($J\ m^{-2}\ s^{-1}$)
PAR_0	:	photosynthetically active radiation above the crop canopy	($J\ m^{-2}\ s^{-1}$)
r_c	:	reflection coefficient for a green crop surface averaged over a day	(-)
k	:	extinction coefficient	(-)

Subroutine ABSORB, which is called by the BLIGHT subroutine, uses a value of r_c of 0.08, and calculates absorbed and transmitted PAR per canopy layer. Overall crop reflection is attributed to the top layer only, since lower layers are partially shaded and reflect less light than the top layer. Total daily PAR_a is the sum of the PAR_a values of the various canopy layers. Crop light use efficiency is daily calculated as the slope of the relation between daily PAR_a (independent variable) and daily crop growth (dependent variable). As daily CLUE tends to be very variable, average CLUE over the last 10 days is calculated.

Damage mechanisms

Leaf photosynthesis

At the SARP Crop Protection workshop in 1993, Cuttack, it was hypothesized that the major damage mechanisms of BLB and ShBl were reduction of maximum photosynthesis rate and increased respiration (Rossing et al., 1993).

Leaf photosynthesis can be described by an asymptotic exponential, the photosynthesis light response curve (Goudriaan, 1982):

$A_{net} = (A_{max} - R_d) \bullet (1 - e^{-I_a \cdot \varepsilon/(A_{max}-R_d)})$, in which

A_{net}	:	net CO_2 assimilation rate for leaves	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}],
A_{max}	:	maximum rate of net CO_2 assimilation rate for leaves at high light intensities,	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}]
I_a	:	absorbed photosynthetic active radiation (PAR)	[J m^{-2} s^{-1}],
ε	:	initial light use efficiency	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}/(J m^{-2} s^{-1})],
R_d	:	dark respiration	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}].

Effects of the disease on crop growth processes comprise the effects on the characteristics of the light response curve (assimilation rate at high light intensities, initial light use efficiency, respiration in the dark), which are determined in subroutine DIS2. Subroutines TASSDS and ASSIMD compute canopy photosynthesis for 3 canopy layers. Leaf plus stem area of each layer is divided in three fractions, viz. healthy, diseased, and dead. 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 subsequently calculated as the weighted average of these three values.

Assumptions of this approach are that light interception characteristics are similar for all three types of leaf area, and that within each layer healthy, diseased and dead leaf area are homogeneously distributed (which is in reality often not the case). Stem area is assumed to consist of entirely healthy and entirely dead leaf area. This approach offers no provision for diseased stem area with specific photosynthesis characteristics. This is only of relevance if ShBl is simulated, and if BLB extends to the leaf sheath. It is assumed that maintenance respiration of the stem is not affected.

A Gaussian integration procedure is used in ORYZA1 to integrate rates of instantaneous leaf CO_2 assimilation over the canopy LAI, which results in instantaneous canopy CO_2 assimilation (FGROS). In the BLIGHT model, this integration procedure is applied to each of the three canopy layers, by introduction of an extra DO-loop, which results in a FGROSL for each canopy layer. Summation of the FGROSL values yields FGROS for the entire canopy. This FGROS is integrated over the day to daily total gross assimilation (DTGA). This calculation procedure is summarized in Figure 3.

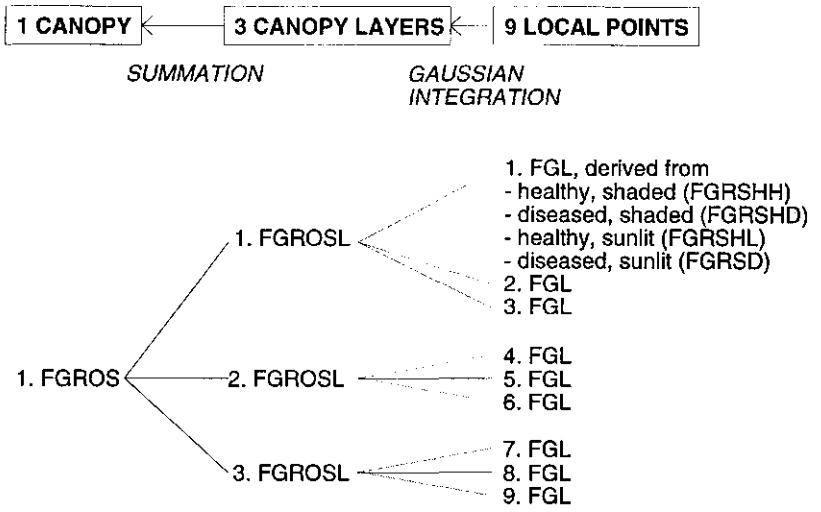

Figure 3. Schematic presentation of Gaussian integration procedure applied to three canopy layers, each characterized by healthy and diseased leaf area (to be read from right to left).

Assimilation is calculated at 9 depths in the canopy, viz. at 3 depths per canopy layer. This increase is the main reason for the longer duration of a simulation run with BLIGHT, in comparison with a run with ORYZA1.

Leaf nitrogen content is strongly related to the rate of photosynthesis at light saturation (van Keulen & Seligman, 1987; Penning de Vries et al., 1990). As the three canopy layers are characterized by separately for N content, no N gradient in the canopy is simulated.

Bacterial leaf blight

Preliminary research on the effects of BLB presence on the characteristics of the photosynthesis light response curve of rice leaves, under controlled conditions (Louwerse & van Oorschot, 1969) at AB-DLO in 1993, has indicated that in a 10 cm-long segment of a leaf blade that is infected by BLB, the relative reductions in A_{max} and ε are linearly related to the increase of the fraction diseased area, or disease severity, of that segment (Figure 4). The relative reduction at low severities appears to be supra-proportional, however, between 0.4 and 0.5 disease severity, relative A_{max} and ε increase. Pending additional research, 1:1 relations between disease severity and relative reduction in A_{max} and ε have been introduced in the BLIGHT model.

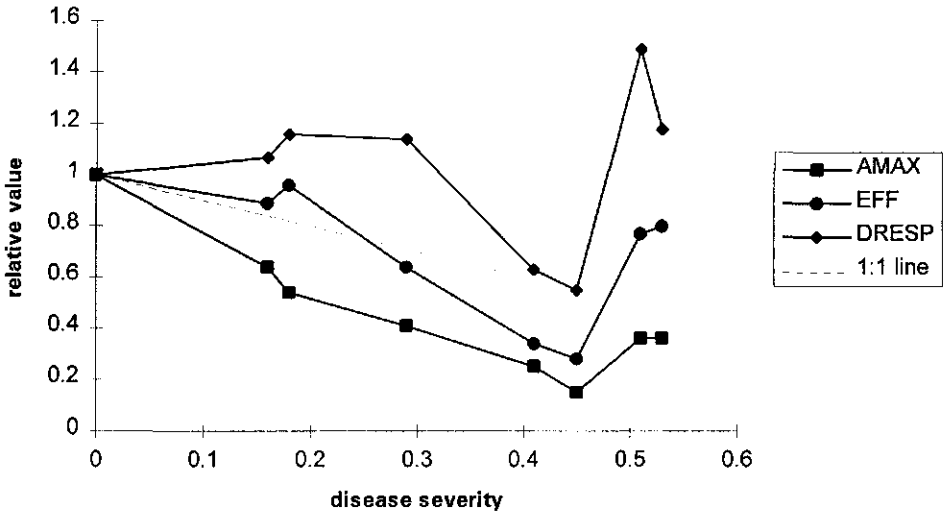

Figure 4. The effects of BLB severity on the characteristics of the photosynthesis light response curve

As the effects of BLB infection on R_d were difficult to establish (Figure 4), a similar 1:1 linear relation was assumed between disease severity and R_d reduction. This ignores a possible increase in R_d at low severities. In the model, this relation was applied to the maintenance respiration of diseased leaf area.

Sheath blight

The effects of Sheath Blight infection on the three characteristics of the photosynthesis light response curve of leaf blades have also been studied in the same experiment. The relative changes in A_{max}, ε and R_d in case of infection only on the leaf blade, and not on the leaf sheath, are difficult to relate to disease severity (Figure 5). At low severities, relative R_d increases, however, otherwise, the relative values of the three photosynthesis characteristics decrease proportionally or sub-proportionally with the increase in disease severity.

In case of sheath blight infection only at the leaf sheath, and not at the leaf blade, relative A_{max} of the leaf blade was 0.97 (s.d. = 0.21), relative ε was 1.05 (s.d. = 0.12); and relative R_d was 1.15 (s.d. = 0.17). The infections on the leaf sheath were quite severe, and characterized by a high degree of degradation of a substantial part of the leaf sheath tissue. Also transpiration rates were not significantly affected by the infection, which indicates that, although the mesophyll is degraded, water transport is not affected and/or that water transport is not sufficiently affected to have an effect on photosynthesis.

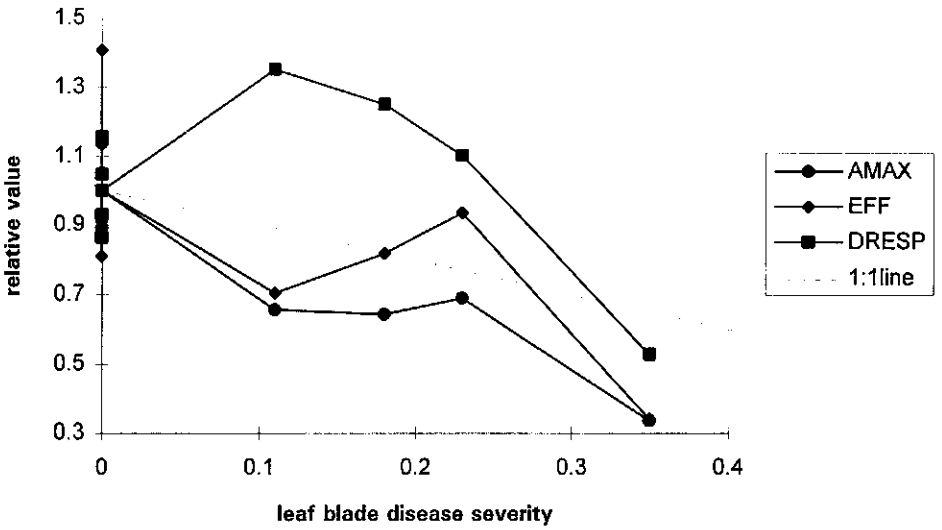

Figure 5. The effects of ShBl severity, for the leaf blade, on the characteristics of the photosynthesis light response curve

These limited data indicate that, for a 10 cm-long segment of a leaf blade that is infected by ShBl, the relative reductions in A_{max} and ε are linearly related to the increase of the fraction diseased area, or disease severity, of that segment, and that relative R_d increases at low disease severities. The data also indicate that infection of the leaf sheath does not significantly influence A_{max} and ε, and may cause limited increase of R_d, of the leaf blade. Some time after infection of the leaf sheath, the leaf blade dies. This process, however, is described in the model by increase of the fraction dead leaf area which is characterized by absence of photosynthesis

Other damage mechanisms

Besides the effects of BLB and ShBl on the characteristics of the photosynthesis light response curve, no other damage mechanisms are described in the model. Effects of the disease on green leaf and stem area, dry matter partitioning, leaf nitrogen content, and relative senescence rate are described in the input data.

Field experiment

Materials and Methods

The rice-BLB system was evaluated during the dry season of 1992-93 under irrigated lowland conditions at the International Rice Research Institute (IRRI), Los Baños, Philippines. Variety IR64 was sown on 27 December 1992, and transplanted on 18 January 1993 (23 DAS) at a rate of 3-5 plants per hill in 12 plots of 7 × 4.5 m. Hill spacing was 20 × 20 cm. Plants reached anthesis and physiological maturity on 24 March (92 DAS) and 16 April 1993 (111 DAS), respectively, and the crop was harvested on 29 April (124 DAS).

Basal NPK fertilizer was applied at a rate of 50-40-40 kg ha^{-1} at transplanting, and additional N fertilizer was applied as 45% ammonium sulphate at rates of 60, 60 and 50 kg ha^{-1} on 15 February (51 DAS), 10 March (78 DAS), and 26 March (94 DAS), respectively.

Four plots were maintained healthy, 4 plots were inoculated early, and 4 plots were inoculated late with BLB race 2, which is endemic to the Philippines and to which IR64 is moderately susceptible (Khush et al., 1989). Leaf blades were inoculated with the disease by the clipping method (Kauffman et al., 1973). Two of the early inoculated plots were inoculated at 61 and 78 DAS ('early, double'), and the two other early inoculated plots were inoculated at 61, 78 and 85 DAS ('early, triple'), in an effort to create distinct disease epidemics. The late treatments were inoculated at 85 and 92 DAS ('late').

Plant height and tiller density were determined, and sub-plots of 5 × 3 hills were periodically harvested, at weekly intervals, from 22 February (58 DAS) until final harvest (124 DAS) of a larger plot of 10 × 16 hills. Dry weights of stem plus leaf sheaths, leaf blades, and panicles were determined. Leaf blades were separated into three layers, and each canopy layer was separated into healthy, dead, and diseased leaf blades. Leaf area of all 9 leaf classes, and nitrogen content of healthy leaf blades and of the green leaf area of diseased leaf blades were determined. Leaf areas were converted to fractions healthy, diseased and dead leaf area per layer. Disease severity was defined as lesion area relative to total leaf area of the diseased leaf class. Green leaf area per layer was calculated as:

$$GLAI = LAI \cdot (1. - FDDLA - FDSLA \cdot SEV)$$

GLAI	:	green leaf area	(ha ha^{-1})
LAI	:	total leaf area	(ha ha^{-1})
FDDLA	:	fraction dead leaf area	(-)
FDSLA	:	fraction diseased leaf area	(-)
SEV	:	disease severity	(-)

Plant organ dry weights and thousand kernel weight were determined at final harvest. Kernel density was calculated on the basis of panicle weight and thousand kernel weight, assuming that 10% of the panicle weight is formed by chaff and peduncle. Further experimental details are given by Elings (1993b).

Results

Completely dead leaf blades were only found in the bottom layer. Fractions dead leaf area were similar among treatments. Triple inoculation of the early treatment resulted in some increase of the fractions diseased leaf area in the bottom and middle layers, and a substantial increase of this fraction in the top layer. Late inoculation caused later start of the epidemic, however, the fractions diseased leaf area at the end of the season were comparable with both early inoculated treatments. Disease severity, which also showed limited variation among treatments, varied at the end of the season between 0.6 and 1. Disease severity in the bottom layer was higher than in the middle and top layers.

Total crop growth rate of the early triple inoculated treatment reduced after 86 DAS, which is just after the moment of third inoculation. Total above-ground dry matter production up to 100 DAS differed little among the other three treatments (Figure 6). Growth of the early double and late inoculated treatments exceeded that of the healthy treatment after 100 DAS, however, total above-ground dry matter production at harvest of the four treatments did not differ significantly (Table 1). Plant organ weights at harvest were also similar (Table 1).

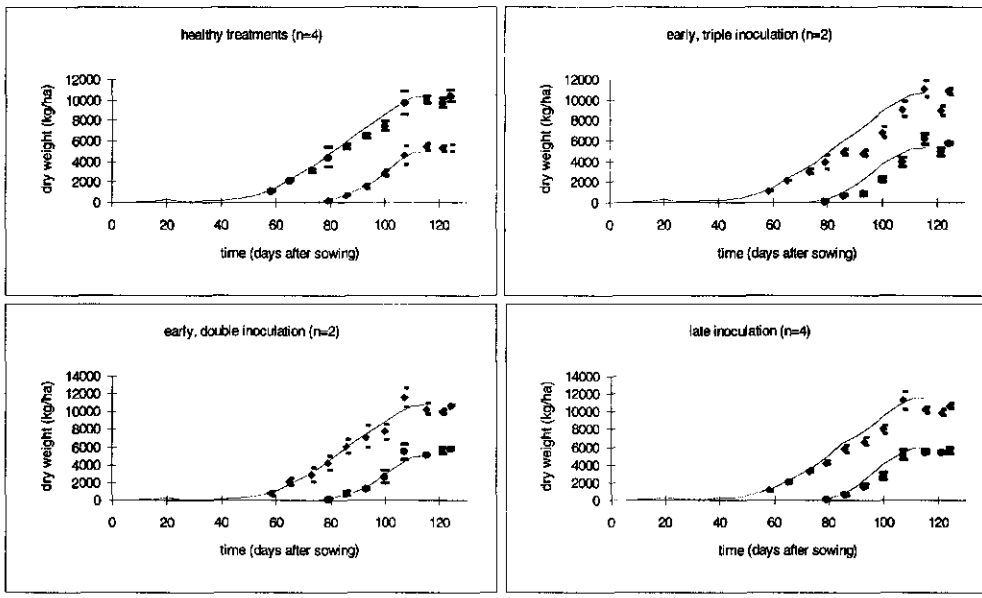

Figure 6. Simulated and observed total above-ground dry matter production and grain weight for the healthy (a), early triple inoculted (b), early double inoculated (c) and late inoculated (d) treatment.

Table 1. Average total above-ground dry matter production and plant organ weights at final harvest per treatment.

Treatment	Total above-ground dry matter production (kg ha^{-1})	Dry weight (kg ha^{-1})			thousand kernel weight (g)	kernel density ($\cdot 10^8$ ha^{-1})
		leaves	stems	panicles		
healthy	10223	1440	3403	5380	25.9	1.87
early, triple	10816	1594	3434	5788	25.5	2.05
early, double	10809	1568	3563	5679	25.4	2.02
late	10520	1434	3456	5630	25.5	1.99

Differences in total leaf area; fractions healthy, diseased and dead leaf area; and disease severity resulted in small differences in green area among treatments (Figure 7). The cumulative GLAI per treatment (the areas under the curves) better indicate treatment differences. These healthy area durations (HAD, Waggoner & Berger, 1987) were 147 ha ha^{-1} d for the healthy treatment, and 171, 149 and 167 ha ha^{-1} d for the late inoculated, early triple inoculated, and early double inoculated treatment, respectively. There is no reason to assume that the lower HAD of the healthy treatment is due to another factor than differences in growing conditions between treatments.

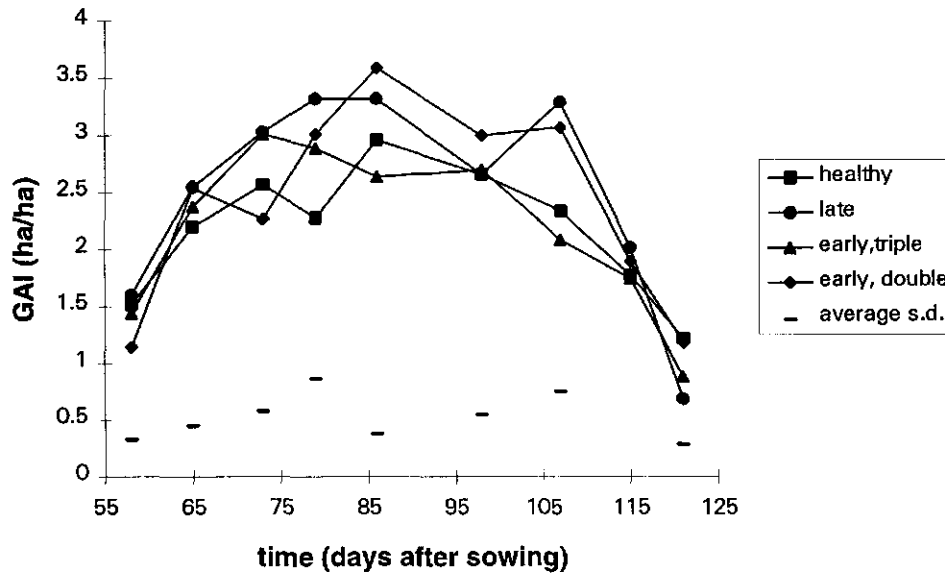

Figure 7. Average green area index, and average standard deviation of the healthy and inoculated treatments.

A more accurate approach is to relate observed above-ground dry matter to cumulative intercepted photosynthetic active radiation by green foliage (Figure 8), as this accounts for the distribution of the disease over canopy depth. Only crop light use efficiency of the early, triple inoculated treatment is significantly reduced during part of the growing season, which may be an effect of the repeated inoculations. Crop light use efficiency of the other two inoculated treatments, which were inoculated less than three times, is similar or larger than that of the healthy treatment. However, on the average, there appears not to be an effect of BLB infection on crop light use efficiency.

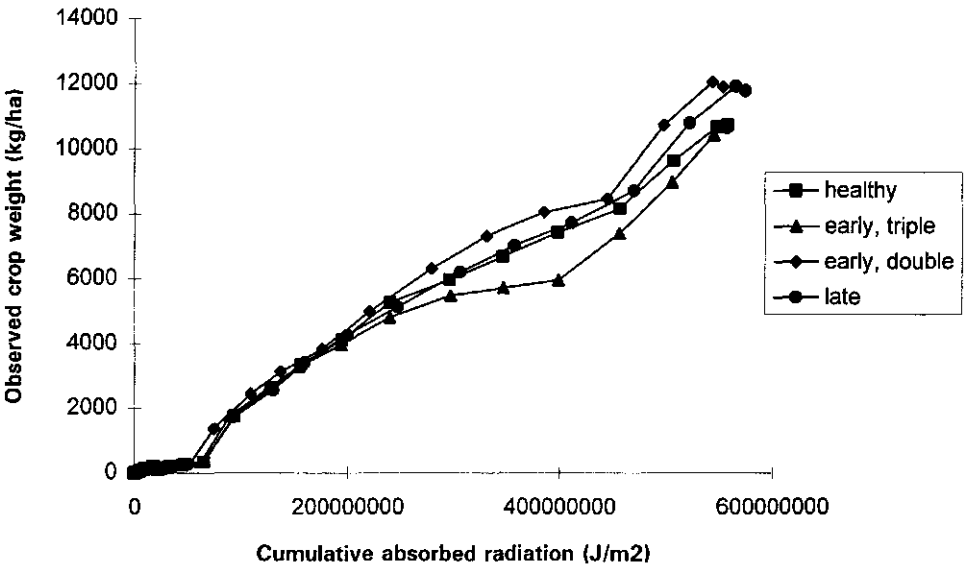

Figure 8. Observed crop weight (kg ha^{-1}) as a function of absorbed radiation (J m^{-2}) for the healthy and inoculated treatments

The three canopy layers absorbed after flowering similar amounts of daily total PAR_a (Figure 9). Therefore, the division of canopy layers as proposed in the common experimental set-up, appears to be suitable for modern short rice varieties during the grain filling phase. Research resources generally do not allow a division in canopy layers before flowering (see also the revised experimental protocol in this volume).

In summary, the various treatments were characterized by similar reductions in green leaf area, however, due to different causes, viz. natural senescence and BLB infection. Different effects on crop photosynthesis by these two causes were not suggested by the results.

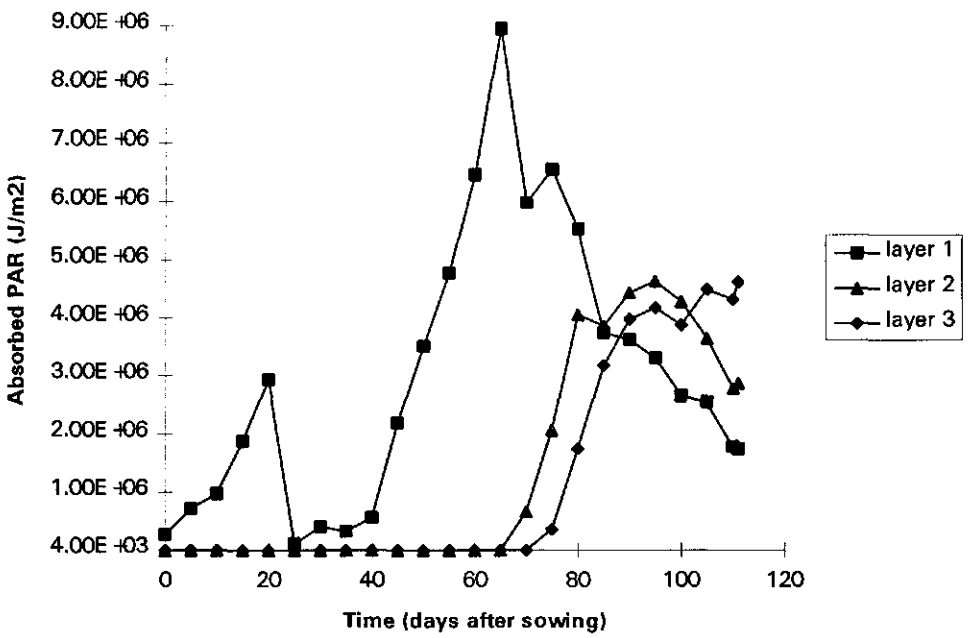

Figure 9. Intercepted PAR_a for the three canopy layers.

Model verification

Materials and methods

The BLIGHT model was calibrated for the above described experiment. Partitioning tables were built on the basis of observed plant organ weights; relative leaf death rate was determined on the basis of observed dead leaf weight (which included leaf material that had died due to BLB infestation, and due to other causes, as the model does not make a distinction between these two); and development rates before and after flowering were calculated on the basis of observed crop development stages. Relative growth rate of leaf area during exponential growth was calibrated such that simulated leaf area before first day of observation and observed leaf area after that day showed a smooth transition.

Results

Total dry matter production for all treatments was over-estimated with about 15%. There is no prior reason to assume more than normal experimental error in the data sets, and therefore, some un-identified environmental condition may have caused sub-potential growth. If the over-estimation of simulation results is attributed to model performance, calculation of crop photosynthesis remains as major source of error, as all other driving variables are model input (leaf area, leaf nitrogen content, specific leaf weight). The data that were compiled by van Keulen & Seligman (1987), and on the basis of which maxi-

mum photosynthesis rate is calculated, suggest variation in maximum photosynthesis rate of rice at a given nitrogen fraction (g m^{-2}). Also ORYZA1 validations (e.g. Kropff et al., 1994) show differences between observed and simulated total dry matter production. In addition to this uncertainty, the effects of BLB on the characteristics of the photosynthesis light response curve have only preliminary been researched, and may be quantified differently after further research. Also, it is possible that the damage mechanisms that are incorporated in the BLIGHT model (i.e. the effects on the characteristics of the photosynthesis light response curve) do not account for all effect of the disease on crop growth.

The model offers no additional tools for calibration, if all driving variables for growth are model input. Good similarity between observed and simulated total above-ground production and grain yield was obtained by simply multiplying the maximum photosynthesis rate by 0.85 (Figure 6). Grain weight was over-estimated at the beginning of grain filling, however, final grain yield was well simulated.

Sensitivity analyses

The consequences of variation in BLB disease pressure for total dry matter production and final grain yield can be explored with the BLIGHT model by varying the fractions diseased leaf area and disease severity. The combined effect of variation in these and other characters, e.g. increase in leaf nitrogen content, and increase in disease severity, can be studied additionally. This can be combined with variation in weather conditions, sowing date, onset of the epidemic, farm management practices, etcetera.

On the basis of the calibrated model, the consequences of variation in leaf nitrogen content, disease pressure, and onset of epidemic were studied. The effects of variation in leaf nitrogen content and fraction diseased leaf area on final grain yield are presented in Figure 10. Increase and decrease in leaf nitrogen content of 0.02 g N g^{-1} leaf, has large effects on final grain yield. Increased disease pressure (by increasing fraction diseased leaf area and disease severity by 0.2) at a reduced leaf nitrogen level causes further reduction of final grain yield, however, reduced disease pressure at reduced leaf nitrogen level does lead to only marginally higher grain yield. Similar variation in disease pressure at increased leaf nitrogen level results in limited variation in final grain yield. Therefore, the effect of increased disease pressure increases with reducing leaf nitrogen content, and variation in disease pressure has less effect on crop growth than variation in leaf nitrogen content.

The effects of variation in leaf nitrogen content and onset of the epidemic on final grain yield are presented in Figure 11. A one week earlier onset of the disease has at all nitrogen levels a considerable effect on final grain yield, which can be related directly to accumulated intercepted radiation.

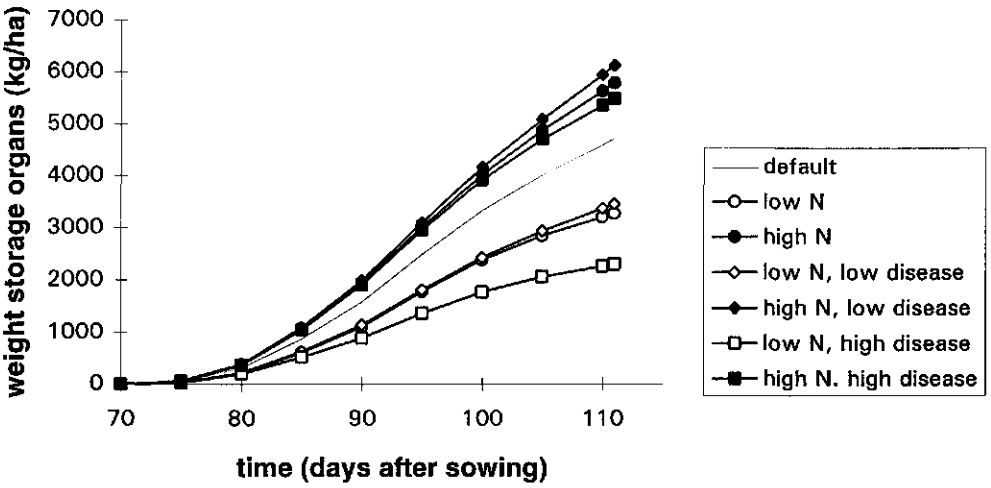

Figure 10. The effects of variation in leaf nitrogen content and fraction diseased leaf area on final grain yield.

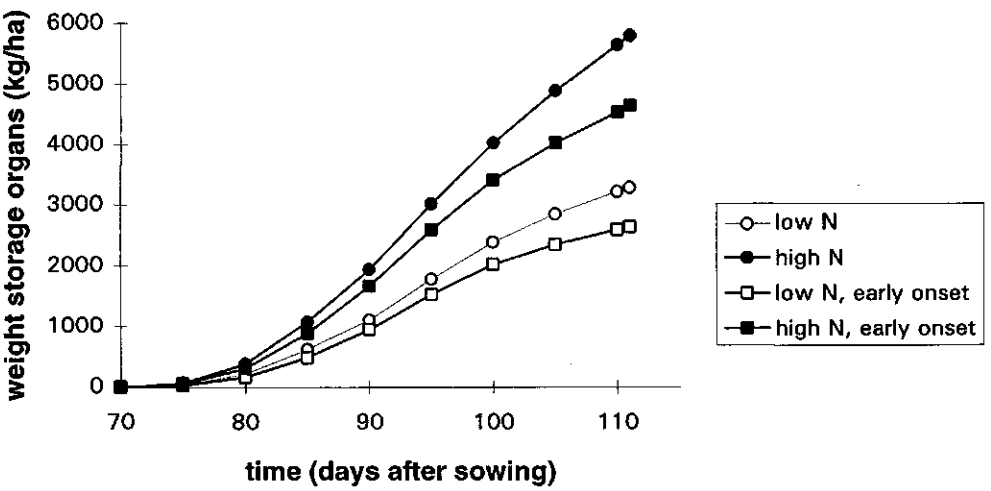

Figure 11. The effects of variation in leaf nitrogen content and onset of the epidemic on final grain yield.

Conclusions

The BLIGHT model is a tool to analyze in detail the effects of bacterial leaf blight and sheath blight on growth and production of a rice crop. Available field data, however, describe a relatively narrow range of epidemics, which did not lead to significant yield reductions due to bacterial leaf blight. Also, production was over-estimated by 15%. Additional photosynthesis research will provide more information with regards to the damage mechanisms, and data sets from additional field experiments will be used to validate the model.

References

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.

Biscoe, P.V. & J.N. Gallagher, 1977. Weather, dry matter production and yield. In: J.J. Landsber & C.V. Cutting (Eds.), Environmental Effects on Crop Physiology, Academic Press, London, pp. 75-100.

Elings, A., 1993a. Damage by Bacterial Leaf Blight and Sheath Blight in Rice: a Quantitative Simulation Model. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 79-109.

Elings, A., 1993b. Damage by Bacterial Leaf Blight and Sheath Blight in Rice: a Joint Experimental Approach. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 119-128.

Elings, A. & E.G. Rubia, 1994. Models for the Crop - Pathosystems Rice - Bacterial Leaf Blight, Sheath Blight and Stem Borer. SARP, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños, 102 pages.

Goudriaan, J., 1982. Potential Production Processes. In: Simulation of Plant Growth and Crop Production, Eds. F.W.T. Penning de Vries & H.H. van Laar, Simulation Monographs, Centre for Agricultural Publishing and Documentation, Wageningen, p. 98-113.

Have, H. ten & H.E. Kaufmann, 1972. Effect of nitrogen and spacing on bacterial leaf blight of rice. Indian Farming 21: 8-13.

Kauffman, H.R., A.P.K. Reddy, S.P.Y. Hsieh & S.D. Merca, 1973. An improved technique for evaluating resistance of rice varieties to *Xanthomonas oryzae*. Plant Dis. Rep. 57: 537-541.

Keulen, H. van & 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.

Kropff, M.J., H.H. van Laar & H.F.M. ten Berge, 1993. ORYZA1, a basic model for irrigated lowland rice production. Simulation and Systems Analysis for Rice Production (SARP), IRRI, TPE-WAU, CABO-DLO, 89 pages.

Kropff, M.J., H.H. van Laar, R.B. Matthews & H.F.M. ten Berge, 1994. ORYZA1, an ecophysiological model for irrigated rice production. Simulation and Systems Analysis for Rice Production (SARP), IRRI, TPE-WAU, CABO-DLO, 100 pages.

Kraalingen, D.W.G. van, W. Stol, P.W.J. Uithol & M.G.M. Verbeek, 1990. User manual of CABO/TPE Weather System. CABO/TPE internal communication, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 27 pages.

Kraalingen, D.W.G. van, 1991. The FSE System for Crop Simulation. CABO- TT Simulation Report no. 21, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 77 pages.

Khush, G.S, D.J. Mackill & G.S. Sidhu, 1989. Breeding for resistance to bacterial blight. In: S.J. Banta, E. Cervantes & T.W. Mew (Eds.), Bacterial Blight of Rice, Proceedings of the International Workshop on Bacterial Blight of Rice, International Rice Research Institute, Manila, Philippines, 1989, pp. 207-217.

Louwerse, W. & J.L.P. van Oorschot, 1969. An assembly for routine measurements of photosynthesis, respiration and transpiration of intact plants under controlled conditions. Photosynthetica 3: 305-315.

Mew, T.W., C.M. Vera Cruz & R.C. Reyes, 1979. Effect of nitrogen on lesion development in rice resistant to bacterial blight. Int. Rice Res. Newsl. 4: 12-13.

Mew, T.W., A.M. Alvarez, J.E. Leach & J. Swings, 1993. Focus on bacterial blight of rice. Plant Disease 77: 5-12.

Montheith, J.L., 1977. Climate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. London, Ser. B, 281: 277-294.

Narasimhan, V, S. Mohandass, A. Abdul kareem & S. Palanisamy, 1991. Simulation of the effect of bacterial leaf blight infection at different growth stages on rice yield. In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production (SARP), Selected Papers at Workshops on Crop Simulation of a Network of National and International Agricultural Research Centres of several Asian Countries and The Netherlands, PUDOC, Wageningen, pp. 332-339.

Ou, S.H., 1985. Rice Diseases. CMI, Kew, 2nd edition. 380 pages.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of Ecophysiological Processes of Growth in Several Annual Crops, Simulation Monographs 29, Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, 271 pages.

Penning de Vries, F.W.T., H. van Keulen & J.C. Alegos, 1988. Nitrogen redistribution and potential production in rice. In: S.K. Sinha (Ed.), Proceedings of the International Congress of Plant Physiology, New Delhi, India, February 15-20, 1988, Society for Plant Physiology and Biochemistry, New Delhi, pp. 513-520.

Rabbinge, R., S.A. Ward & H.H. van Laar (Eds.), 1989. Simulation and Systems Management in Crop Protection. Simulation Monographs 32, Pudoc, Wageningen. 420 pages.

Rappoldt, C. & D.W.G. van Kraalingen, 1990. Reference manual for the FORTRAN utility library TTUTIL with applications. CABO- TT Simulation Report no. 20, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 122 pages.

Reddy, A.P.K., J.C. Katyal, D.I. Rouse & D.R. MacKenzie, 1979a. Relationship between nitrogen fertilization, bacterial leaf blight severity, and yield of rice. Phytopathology 69: 970-973.

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

Reddy, P.R., S.K. Nayak & L. Bastiaans, 1991. Simulation of the effect of bacterial blight disease on grop growth and yield of rice. In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production (SARP), Selected Papers at Workshops on Crop Simulation of a Network of National and International Agricultural Research Centres of several Asian Countries and The Netherlands, PUDOC, Wageningen, pp. 340-347.

Riethoven, J.J.M., 1993. The SARP-Shell, a crop growth simulation environment. Simulation and Systems Analysis for Rice Production (SARP), revision 2, version 1.0. CABO-DLO, TPE-WAU, IRRI.

Rossing, W.A.H., M. van Oijen, W. van der Werf, L. Bastiaans & R. Rabbinge, 1992. Modelling the 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 Scientific Publishers, Oxford, pp. 161-180.

Rossing, W.A.H., E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), 1993. Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield,), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. 137 pages.

Singh, R.A. & B. Das, 1991. Simulation of yield loss due to sheath blight in rice crops. In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production (SARP), Selected Papers at Workshops on Crop Simulation of a Network of National and International Agricultural Research Centres of several Asian Countries and The Netherlands, PUDOC, Wageningen, pp. 348-352.

Waggoner, P.E. & R.D. Berger, 1987. Defoliation, disease and growth. Phytopathology 77: 393-398.

Wit, C.T. de, 1982. Simulation of living systems. In: (Eds.) F.W.T. Penning de Vries & H.H. van Laar, Simulation of Plant Growth and Crop Production, Centre for Agricultural Publishing and Documentation, Wageningen, pp. 3-8.

Yield reduction due to different severity levels of bacterial leaf blight disease of rice

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Introduction

The bacterial leaf blight (BLB) disease of rice, caused by *Xanthomonas oryzae* pv. *oryzae*, is one of the major foliar diseases that limits increase in rice production. Disease severity, crop development stage at which the initial infection occurs, and rate of subsequent disease spread, determine yield loss. Increased crop nitrogen content has a positive effect on infection and spread of the disease (Mohanty, 1981). A susceptible cultivar grown at high levels of nitrogen has more chances of early initial infection and fast spread of the disease. Estimated yield loss ranges in India from 6-60% (Srivastava et al., 1966) and 2-74% (Reddy, 1974). Exconde et al. (1973) reported average yield losses of 22.5% and 7.2% in the wet and dry season, respectively, in the Philippines. However, clear quantitative information on the amount of yield loss due to BLB infection at various production levels is lacking. Systems analysis can be used to increase the quantitative understanding of the effect of the disease on crop, by using a simulation model to integrate the effects of various damage mechanisms on crop growth and yield. To quantitatively analyze the effects of bacterial leaf blight on rice growth and production, a field experiment was conducted.

Materials and Methods

Field experiment

A field experiment was conducted during the wet season (June to September) of 1993 at the Central Rice Research Institute, Cuttack, India. Cultivar IR64 was sown on May 29, and 30 day-old seedlings were transplanted on June 28 to a well puddled field with 10 plots. Single plots measured 5.25 ×3.3 m, and were separated by an open space of 2 m. One plant per hill was planted, hill distance was 15 × 15 cm , and plant density was 444,000 plants per hectare. Nitrogen fertilizer was applied on June 28 (30 DAS), July 19 (51 DAS), August 8 (71 DAS) and August 28 (91 DAS) as urea in four split doses, at the rate of 120 kg total N ha^{-1}. Treatments were allocated to plots on the basis of a randomized block design. Four plots were not inoculated, and different epidemics of bacterial blight were created in 6 plots. These epidemics were initiated at three different crop devel-

opment stages, viz., at early tillering (70 DAS) in 3 plots, at late tillering (85 DAS) in 2 plots and at flag leaf appearance (95 DAS) in 1 plot. One plot inoculated at early tillering was inoculated repeatedly (4 times) to maintain the disease spread throughout the crop growth period, and two plots were inoculated only twice to allow natural spread of the disease. The clipping method was used to inoculate the rice plants with BLB pathogen (Kauffman et al., 1973).

Crop and disease characteristics were observed periodically on 5 plants in 3 adjacent rows, starting at 20 days after transplanting, on days 190, 205, 219, 235, 245, 256, 265 and 272. Observed crop characteristics included leaf area and dry weights of leaves, stems and panicles. The crop canopy was separated into three leaf layers, dependent on crop height. The canopy was initially considered as a single layer, and was later split in two and three layers. In each layer, healthy, diseased and dead leaves were separated. Diseased leaf area is formed by leaves that are partially covered by lesions. Disease severity of the diseased leaves was determined visually as the fraction diseased leaf area relative to total leaf area (see Elings, 1993). Leaf nitrogen content was determined at flowering and 10 days after flowering. Anthesis and physiological maturity were reached on August 30 and September 30, respectively, and the crop was harvested on October 1.

Simulation model

The effects of bacterial leaf blight on crop growth and production were simulated with the BLIGHT model (Elings & Rubia, 1994), which was based upon the ORYZA_1 model (Kropff et al., 1993). The BLIGHT model incorporates damage mechanisms of diseased leaf area due to bacterial blight or sheath blight of rice and simulates crop growth under certain disease conditions during one season. Effects of the disease on crop growth processes comprise the effects on the characteristics of the light response curve, viz. CO_2 assimilation rate at light saturation, initial light use efficiency, and respiration in the dark, which were assumed to decrease proportionally with increasing disease severity. Effects of the disease on crop development are disregarded, however, effects on green leaf and stem area, dry matter partitioning, leaf nitrogen content, and relative senescence rate are described in the input data file.

The model was calibrated for all treatments, with the observed healthy, diseased and dead leaf areas as input. Crop development rates for the vegetative and reproductive phases of IR64 were calculated on the basis of observed phenology, and introduced in the model. Specific leaf weight was calculated from leaf area index (LAI) and dry weight of leaves. Dry matter partitioning to leaves, stems and shoots was based upon field observations. The fractions carbohydrates allocated to the stems, that is stored as reserves, were calculated from the differences between maximum stem weight and stem weight at harvest, and varied between 0.16 to 0.32 in different treatments. Relative growth rate of leaf area during exponential growth was set at 0.0059 for simulations.

Results

Effects of bacterial leaf blight on crop growth and production

Total leaf area initially increased in all treatments, and maximum LAI, which was reached just before flowering, ranged from 4.91 to 6.3. After flowering, LAI of the various treatments decreased to 1.48 to 2.67 at crop maturity (Table 1).

Table 1. Total leaf area index (ha ha^{-1}), diseased leaf area index (ha ha^{-1}), and disease severity in six inoculated plots at different crop development stages. Tot. = Total; Dis. = Diseased; Fr.dis. = Fraction diseased

Treatment	Leaf area	Development stage							
		0.39	0.57	0.74	0.93	1.13	1.46	1.74	1.97
		Day of the year							
		190	205	219	235	245	256	265	273
Early tillering inoculation									
1.	Tot. LAI	0.11	1.07	2.39	6.13	4.10	3.18	3.40	2.67
	Dis. LAI	0	0	0.17	1.40	1.38	1.86	1.33	1.55
	Fr.dis. LAI	0	0	0.07	0.23	0.34	0.58	0.39	0.58
	Severity	0	0	0.037	0.13	0.23	0.36	0.51	0.38
2.	Tot. LAI	0.18	0.97	2.55	4.37	3.76	3.24	2.46	1.62
	Dis. LAI	0	0	0.12	0.86	1.85	1.32	1.18	0.62
	Fr.dis. LAI	0	0	0.05	0.20	0.49	0.41	0.48	0.38
	Severity	0	0	0.019	0.10	0.38	0.44	0.75	0.47
3.	Tot. LAI	0.18	1.30	2.81	4.81	4.27	3.55	2.46	1.87
	Dis. LAI	0	0	0.15	1.21	1.61	1.37	1.23	0.92
	Fr.dis. LAI	0	0	0.05	0.25	0.38	0.39	0.50	0.49
	Severity	0	0	0.039	0.11	0.23	0.25	0.54	0.44

(Table 1 continued on next page)

Treatment	Leaf area	Development stage							
		0.39	0.57	0.74	0.93	1.13	1.46	1.74	1.97
		Day of the year							
		190	205	219	235	245	256	265	273
Late tillering inoculation									
1.	Tot. LAI	0.24	1.06	3.70	4.03	4.58	2.65	1.54	1.60
	Dis. LAI	0	0	0	0.35	1.65	1.71	0.96	1.08
	Fr.dis. LAI	0	0	0	0.09	0.36	0.65	0.62	0.68
	Severity	0	0	0	0.092	0.23	0.41	0.29	0.46
2.	Tot. LAI	0.14	1.18	3.59	3.74	4.36	3.03	2.29	1.98
	Dis. LAI	0	0	0	0.15	1.77	2.02	1.62	1.37
	Fr.dis. LAI	0	0	0	0.04	0.41	0.67	0.71	0.69
	Severity	0	0	0	0.058	0.28	0.36	0.36	0.39
Flag leaf inoculation									
1.	Tot. LAI	0.15	1.27	3.35	4.15	3.26	2.30	1.61	1.48
	Dis. LAI	0	0	0	0	0.67	0.75	1.20	1.19
	Fr.dis. LAI	0	0	0	0	0.21	0.33	0.75	0.80
	Severity	0	0	0	0	0.23	0.34	0.41	0.45

The overall diseased leaf area in the plots inoculated at early tillering ranged at 10 days after inoculation (70 DAS) from 0.12 to 0.17 LAI. Afterwards, the diseased leaf area and disease severity gradually increased (Table 1). The diseased leaf area in the plots inoculated at late tillering ranged at 10 days after inoculation (85 DAS) from 0.15 to 0.35 LAI. In the plot inoculated at flag leaf appearance, at 10 days after inoculation (95 DAS), diseased leaf area index was 0.67. Disease progress was fast and severity in different inoculated treatments ranged between 38 and 47 per cent at crop maturity. With the decrease in the total LAI after flowering, there was an increase in fraction diseased leaf area in different inoculated treatments. In the early tillering inoculated treatments, the increase in fraction diseased leaf area varied between 0.39 and 0.58, and in the two late tillering inoculated plots it varied between 0.36 to 0.71. Similarly, the fraction diseased leaf area increased from 0.21 to 0.80 in the flag leaf inoculated plot (Table 1).

The fraction diseased leaf area and disease severity of the bottom and middle leaf layers increased continuously from inoculation to crop maturity in the plots inoculated at early tillering. The fraction diseased leaf area of the top layer increased in one of the plots,

whereas it decreased in the two other plots after dough stage (DVS 1.15). The decrease was due to slow natural spread of the disease from the available inoculum in the lower leaf layers. The fraction diseased leaf area and disease severity in the two plots inoculated at late tillering increased from moment of inoculation to crop maturity. Disease spread in the plot inoculated at flag leaf appearance was limited to the middle and top leaf layers.

Average total dry matter production of the healthy plots was 11246 kg ha^{-1}. Total dry matter production of the three plots inoculated at early tillering stage was 9750, 9378 and 9724 kg ha^{-1}. In the two late tillering inoculations, it was 10017 and 8898 kg ha^{-1} while 9919 kg ha^{-1} was obtained in the single plot inoculated at the stage of flag leaf appearance (Table 2).

Table 2. Final dry weights of storage organs,stem and total dry matter of observed and simulated in healthy and inoculated treatments (kg ha^{-1}).

	Storage organs		Stems		Total dry matter	
Treatment	Observed	Simulated	Observed	Simulated	Observed	Simulated
Healthy	7215	6795	2952	2656	11246	11963
Early tillering inoculation						
1.	5550	5637	2797	2556	9750	10868
2.	5728	5613	2664	2597	9378	10497
3.	5905	5760	2753	2649	9724	10805
Late tillering inoculation						
1.	6100	5434	2797	2423	10017	10333
2.	5558	5269	2504	2369	8898	10149
Flag leaf inoculation						
1.	6038	6136	3064	2592	9919	11107

Stem dry weight gradually increased up to flowering, after which it decreased in both inoculated and healthy plots. Average stem weight at harvest was 2952 kg ha^{-1} in healthy plots. Stem weight at harvest ranged from 2664 to 2797 kg ha^{-1} in the three early tillering inoculated plots. Final stem weight was 2797 and 2504 kg ha^{-1} in the two late tillering inoculated plots, and 3064 kg ha^{-1} in the plot inoculated at flag leaf appearance (Table 2). However, maximum stem dry weight during the growing season, was 3634 kg ha^{-1} in healthy plots. Maximum stem weight ranged from 3685 to 4040 kg ha^{-1} in the three early

tillering inoculated treatments, was 4129 and 3703 kg ha^{-1} in two late tillering inoculated plots, and was 3641 kg ha-1 in the flag leaf inoculated plot.

Average final grain yield was 7215 kg ha^{-1} in healthy plots. Grain yields obtained in the three early tillering inoculated plots were 5550, 5728 and 5905 kg ha^{-1}. In the two late tillering inoculated plots, grain yields were 6100 and 5558 kg ha^{-1}, and in the flag leaf stage inoculation plot 6038 kg ha^{-1} (Table 2). Grain yield reduction in various diseased treatments ranged from 1115 to 1665 kg ha^{-1}.

Simulation

Average simulated total dry matter production of the healthy treatment was 11963 kg ha^{-1}. Simulated reductions in total dry matter production due to BLB presence ranged from 1095 to 1466 kg ha^{-1} in the three early tillering inoculated plots, were 1630 and 1814 kg ha^{-1} in the late tillering inoculations, and was 856 kg ha^{-1} for the flag leaf stage inoculated plot (Table 3).

Table 3. Observed and simulated reductions in total dry matter, grain yield and stem dry weight of different inoculated plots over healthy treatment (kg ha^{-1}).

Treatment	Total dry matter		Grain yield		Stem weight	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Early tillering inoculation						
1.	1496	1095	1665	1158	155	100
2.	1868	1466	1487	1182	288	59
3.	1522	1158	1310	1035	199	7
Late tillering inoculation						
1.	1229	1630	1115	1360	155	233
2.	2348	1814	1657	1526	448	287
Flag leaf inoculation						
1.	1327	856	1177	659	-	64

Average simulated stem dry weight of healthy plots was 2656 kg ha^{-1}. In the diseased treatments, simulated reductions were lowest , viz. 7 to 100 kg ha^{-1} in the three early tillering inoculations, and 64 kg ha^{-1} in the flag leaf stage inoculation. Reductions were higher in the two late tillering inoculated plots, viz. 233 and 287 kg ha^{-1} (Table 3). Average maximum simulated stem weight in healthy plots was 3500 kg ha^{-1}. Maximum stem weights ranged from 3019 to 3073 kg ha^{-1} in the three early tillering inoculated, were 2949 and 2880 kg ha^{-1} in the two late tillering inoculated plots, and 3095 kg ha^{-1} in the flag leaf inoculated plot.

Average simulated grain yield of healthy treatments was 6795 kg ha^{-1}. The simulated difference in grain yield between healthy and diseased treatments was highest in the two plots inoculated at late tillering stage, viz. 1360 and 1526 kg ha^{-1}. This was followed by the reductions ranging between 1035 and 1182 kg ha^{-1} in the three early tillering inoculated treatments. Lowest reduction of 659 kg ha^{-1} was simulated for the plot inoculated at flag leaf stage of the crop (Table 3).

There were differences in observed and simulated grain yields in healthy and different inoculated treatments. The model under-estimated grain yield by 420 kg ha^{-1} for the uninoculated healthy plots. The model slightly over-estimated grain yield by 87 kg ha^{-1} for the early tillering inoculated treatments, in which the disease was continuously progressing up to crop maturity, and under-estimated grain yield by 115 and 145 kg ha^{-1} for the plots in which the disease progress in the top and middle layers was reduced. Grain yield was under-estimated by 666 and 289 kg ha^{-1} for the two late tillering inoculated plots, and over-estimated by 98 kg ha^{-1} for the flag leaf stage inoculated plot.

Simulated and observed values were, in general, close for healthy and different inoculated treatments with respect to total dry matter, grain yield and stem dry weight. Total dry matter production was slightly over-estimated throughout the crop growth period for uninoculated healthy plots (Figure 1). For the early and late tillering inoculated treatments, trends in simulated and observed weights were similar for a great part of crop growing season, with an over-estimation at maturity (Figures 2 & 3). Similarly, there was an over-estimation after flowering in the case of the flag leaf inoculated plot (Figure 4).

The differences between observed and simulated weights of storage organs in healthy treatments were small, however, there was a slight under-estimation in the final grain yield (Figure. 1). For the early tillering and flag leaf inoculated treatments, after flowering, simulated values closely followed observed values (Figures 2 & 4). However, simulation under-estimated grain yield for the late tillering inoculated plot (Figure 3).

Stem dry weight was over-estimated until flowering and under-estimated later until maturity for the healthy treatments (Figure 1). The trends in observed and simulated stem weights were similar until flowering, after which simulated values were under-estimated for the early and late tillering inoculated plots (Figure 2 & 3). Simulated values were under-estimated until flowering, and followed the same trend as observed values in the plot inoculated at flag leaf appearance (Figure 4).

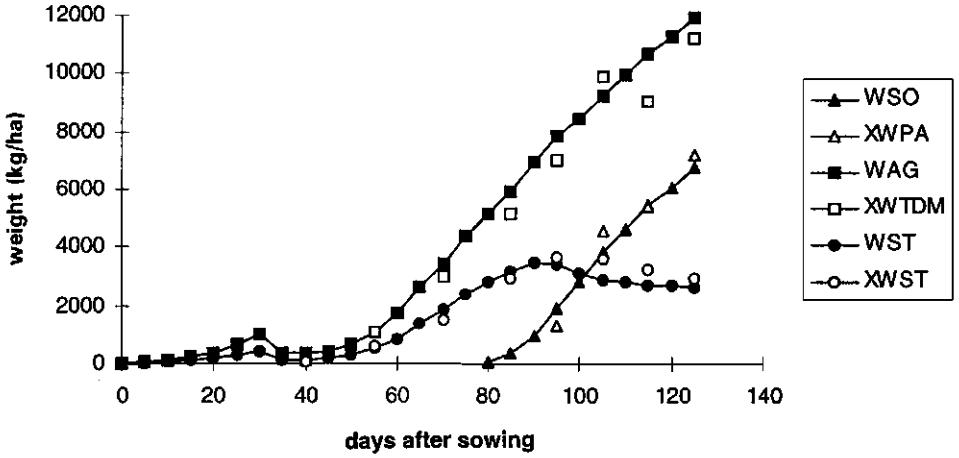


Figure 1. Simulated and observed weights of storage organs (WSO and XWPA), total dry matter (WAG and XWTDM) and stem (WST and XWST) of cultivar IR64, un-inoculated healthy treatment.

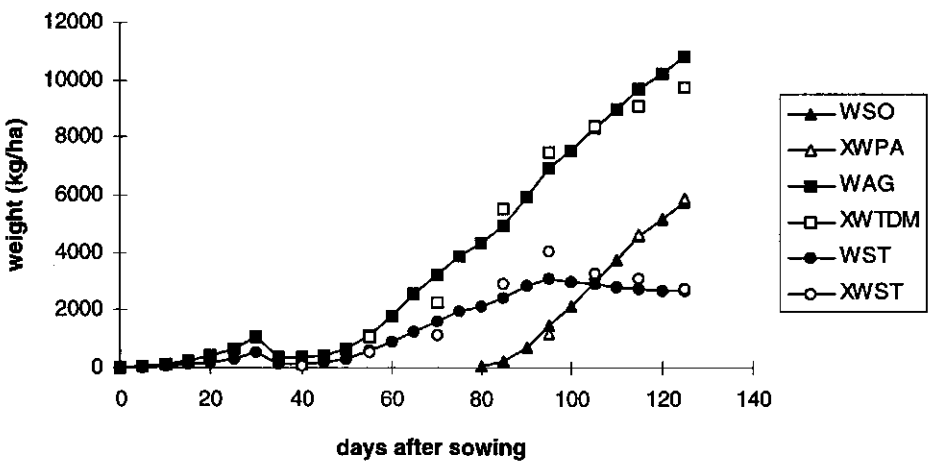


Figure 2. Simulated and observed weights of storage organs (WSO and XWPA), total dry matter (WAG and XWTDM) and stem (WST and XWST) of cultivar IR64, early tillering inoculated treatment.

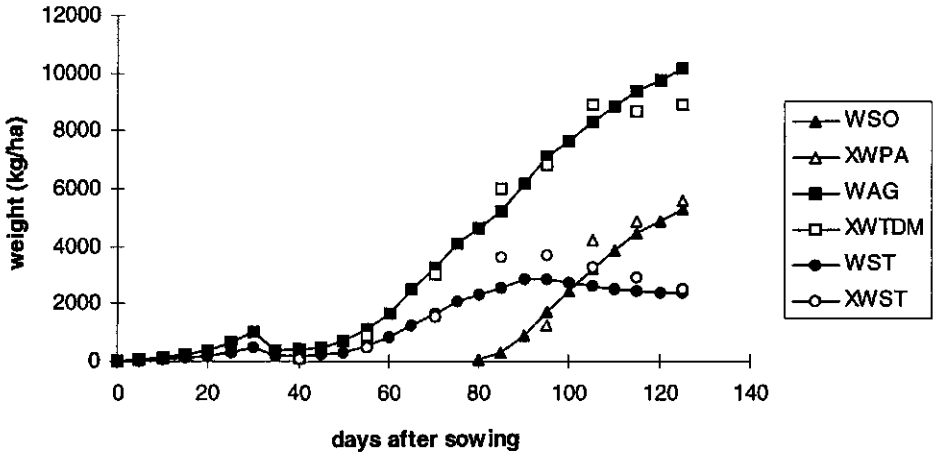


Figure 3. Simulated and observed weights of storage organs (WSO and XWPA), total dry matter (WAG and XWTDM) and stem (WST and XWST) of cultivar IR64, late tillering inoculated treatment.

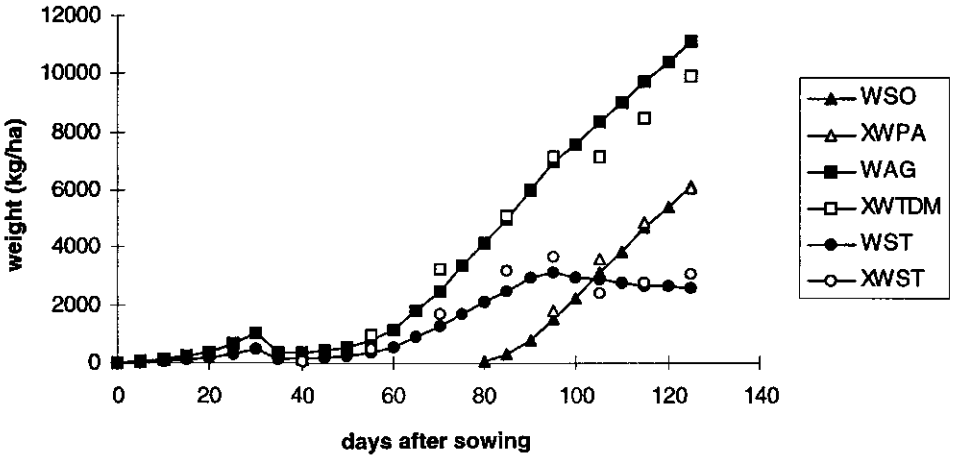
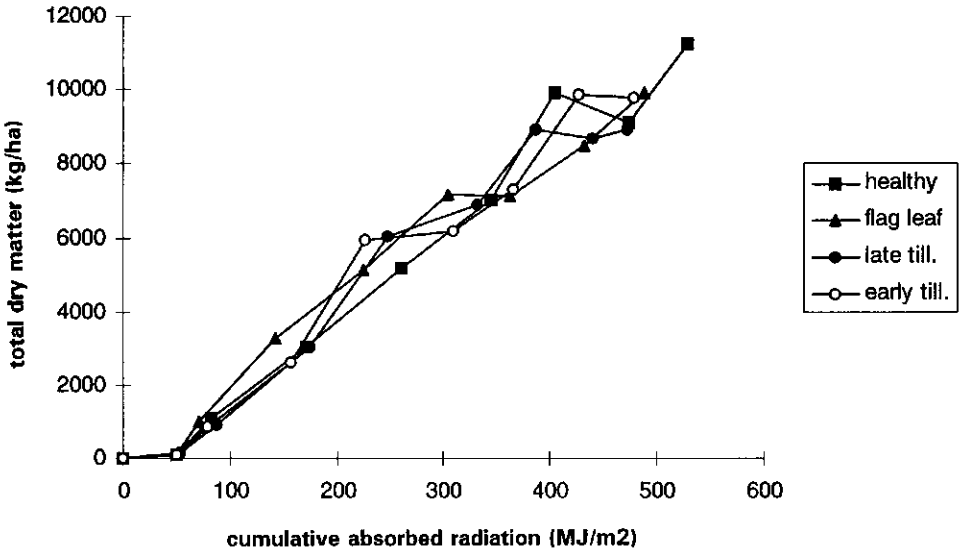


Figure 4. Simulated and observed weights of storage organs (WSO and XWPA), total dry matter (WAG and XWTDM) and stem (WST and XWST) of cultivar IR64, flag leaf inoculated treatment.

Average total dry matter weight of the healthy treatment, as a function of cumulative absorbed radiation by green leaf area, linearly increased up to 11246 kg ha^{-1} (Figure 5). In the early tillering inoculated plots in which the disease pressure was continuously maintained, total dry matter production during the early phase of disease development was similar to that of the healthy average. There was a slight increase in light use efficiency just before flowering, after which it reduced. In the late tillering inoculated plots, light use efficiency reduced during the later phase of crop development, probably as a consequence of disease built-up. Light use efficiency also reduced from flowering to maturity in the plot inoculated at flag leaf appearance. In conclusion, however, light use efficiency appeared to vary through the growing season, however, total dry matter production appeared to be reduced by lower cumulative light interception, rather than by lower light use efficiency in the presence of disease.



Discussion

Different BLB epidemics caused different reductions in total dry matter production. This reduction was lowest in the plot inoculated at flag leaf appearance, viz. 856 kg ha^{-1}, and highest in the two plots inoculated at late tillering stage, viz. 1630 and 1814 kg ha^{-1}, respectively. The reduction in total dry matter production ranged from 1095 to 1466 kg ha^{-1} in the three early tillering inoculated plots.

Similar results were found for reductions in final grain yield. The lowest reduction was 659 kg ha^{-1} in the plot inoculated at flag leaf appearance. Late tillering inoculated plots showed reductions of 1360 and 1526 kg ha^{-1}. The reductions in grain yield in the three early tillering inoculated plots ranged from 1035 to 1182 kg ha^{-1}. Therefore, with respect to reductions in total dry matter and grain yield, the three BLB epidemics viz., in-

oculations at early tillering, late tillering and flag leaf appearance, could be classified correctly through simulation. In general, observed reductions in total dry matter production and grain yield were greater than the simulated values.

Simulated and observed results indicate that disease presence, as quantified by the amount of diseased leaf area from late tillering stage to maturity, damages the crop more than during other phases. Although in the early tillering inoculated treatments, disease initiation was earlier, and duration was longer, the damage caused was slightly lower, due to the relatively high green leaf area in the vegetative crop development stage. Total LAI in the initial stages of disease development was in the early tillering inoculations was higher than in the other inoculated treatments. However, total LAI decreased with increase in diseased leaf area in the late tillering inoculations. In the flag leaf inoculated treatment, disease was present for a shorter duration, and caused a lower diseased leaf area (Table 1). Thus, yield reductions were in accordance with the disease behaviour at different growth stages of crop.

Teng (1988) has reported that a decline in disease severity level has often been observed due to fast formation of new leaves, which may compensate the earlier losses. This has also been observed in the present experiment in the treatment of early disease initiation, which was characterized by increased leaf area. In the late tillering inoculations, remaining growth duration may have been too short to compensate by increase of leaf area. Therefore, diseased leaf area and disease severity increased if infection was initiated at late tillering stage, which lead to increased yield reductions. The effect of a given level of disease severity on the production will depend upon the crop growth stage at which infection occurs and compensating capacity of different rice cultivars.

There is variation in green leaf area reduction as a consequence of variation in disease pressure. Different BLB epidemics in the present experiment caused reduction of photosynthetically active green leaf area at different growth stages of crop, which explained reduction of total dry matter production. Apparently, there was no effect beyond reduction in green leaf area.

References

Elings, A., 1993. Damage by bacterial leaf blight and sheath blight in rice: a joint experimental approach In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 119-128.

Elings, A. & E.G. Rubia, 1994. Models for the crop-pathosystems. Rice-Bacterial leaf blight, Sheath Blight and Stem Borer. Simulation and systems analysis for rice production. AB-DLO and TPE-WAU, Wageningen, The Netherlands and IRRI, Philippines, 102 pages.

Exconde, O.R., O.S. Opina & Ohanomsawaran, 1973. Yield losses due to bacterial leaf blight of rice. Philippine Agriculturist. Vol. LVII, No. 3 and 4.

Kauffman, H.E., A.P.K. Reddy, S.P.Y. Hseih & S.D. Merca, 1973. An improved technique for evaluating resistance of rice varieties to *Xanthomonas oryzae.* Plant Dis.Reptr. 57:537-541.

Kropff, M.J., H.H. van Laar & H.F.M. ten Berge, 1993. ORYZA1 - A basic model for irrigated low land rice production. Simulation and systems analysis for rice production. IRRI, Philippines, AB-DLO and TPE-WAU, Wageningen, The Netherlands.

Mohanty, S.K. 1981. Influence of host nutrition on the development of bacterial leaf blight disease of rice. Ph.D. thesis submitted to Utkal University, Bhubaneswar, India

Reddy, A.P.K., 1974. Epidemiology and variability of *Xanthomonas oryzae* in India. Paper presented at Annual International Research Conference held at IRRI, Philippines.

Srivastava, D.N., Y.P. Rao, & J.C. Durgapal, 1966. Can Taichung Native 1 stand up to bacterial blight. Indian Farming XVI. 15-17.

Teng, P.S., 1988. Pests and Pest-loss Models. Agrotechnology Transfer. No. 8, October, 1988, ISSN 0883-8631

Exploration of the effect of bacterial leaf blight disease on crop growth and yield of rice through simulation

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Introduction

Systems analysis and simulation can be used to understand the mechanism of damage due to the bacterial leaf blight disease, and to analyse the effects on crop growth and yield of rice. Disease occurs under field conditions at different levels of disease severity, at different growth stages of crop. Also the nitrogen application rate influences disease build-up. The BLIGHT model, developed by Elings & Rubia (1994) can be used for scenario studies. The model was calibrated on the basis of data from field experiments at Cuttack, India, during 1991 and 1993 (Reddy, 1994). Actual data on crop and disease characteristics that were obtained in these field experiments, were used as default input. The effect of nitrogen x disease interaction on crop growth and yield was analyzed.

Materials and Methods

Simulation model

The BLIGHT model (Elings & Rubia, 1994) which was based upon the ORYZA1 model (Kropff et al., 1993), was used to analyse the effects of the bacterial leaf blight disease on total dry matter production and grain yield. The crop characteristics of cultivars IR64 and Annada, which were used earlier for model calibration (Reddy, 1994), were also used for scenario studies. Disease levels were introduced in the model as fractions healthy and diseased leaf area in three layers of the crop canopy and as disease severity of the fractions diseased leaf area. Leaf area was simulated by the model. For the relative growth rate of leaf area, a value of 0.006 was used. Crop development rates for the vegetative and reproductive phases, which were computed from observed phenology of the two cultivars, were 0.000603 and 0.001509, respectively, for IR64, and 0.000719 and 0.001522, respectively, for Annada. For the fraction carbohydrates allocated to the stems as reserves, a value of 0.3 was used.

Disease scenarios were created for three moments of infection, viz. early tillering (early onset), late tillering (mid onset) and flag leaf appearance (late onset). Yield reductions were studied at various levels of leaf nitrogen content viz., 0.06, 0.04, 0.02 and 0.01 g g^{-1}. For each level of leaf nitrogen content, different disease epidemics were assumed (Tables 1 and 2) because of the earlier initiation and faster spread of the disease at higher nitrogen application rates.

Simulation of early disease onset in the wet season was initiated at the early tillering stage, at a fraction diseased leaf area in the lower canopy layer or 0.05. This fraction increased up to 1. Later, the second and third canopy layers are infected, which results in 85 to 90% of the leaf area infected at harvest.

Simulation of mid disease onset was initiated at the late tillering stage, at a fraction diseased leaf area in the second canopy layer of 0.15. The bottom layer was assumed to remain healthy. Disease spread to the top canopy layer, resulting in a fraction diseased leaf area of 0.9 at harvest.

Simulation of late disease onset was initiated at flowering, in the middle and top canopy layers. The top layer was more diseased than the middle layer. Fractions diseased leaf area of both layers varied between 0.50 and 0.80 (Tables 3 and 4).

Table 1. Simulated scenarios. The overall fraction diseased leaf area at different crop developmental stages cultivar Annada, under different levels of leaf nitrogen.

Leaf nitrogen ($g\ g^{-1}$)	Disease onset	Development stage								
		0.51	0.69	0.80	0.90	1.0	1.20	1.45	1.70	2.00
0.06	Early	0	0.02	0.10	0.33	0.55	0.68	0.75	0.88	0.58
	Mid	0	0	0.05	0.22	0.37	0.43	0.50	0.55	0.58
	Late	0	0	0	0	0.12	0.25	0.33	0.38	0.40
0.04	Early	0	0	0.05	0.20	0.38	0.52	0.67	0.76	0.50
	Mid	0	0	0	0.05	0.17	0.28	0.33	0.38	0.47
	Late	0	0	0	0.05	0.08	0.15	0.22	0.25	0.25
0.02	Early	0	0	0.03	0.15	0.27	0.45	0.56	0.65	0.75
	Mid	0	0	0.02	010	0.20	0.28	0.35	0.43	0.50
	Late	0	0	0	0.05	0.08	0.17	0.18	0.25	0.25
0.01	Early	-	-	-	-	-	-	-	-	-
	Mid	0	0	0	0.08	0.13	0.18	0.23	0.28	0.43
	Late	0	0	0	0.05	0.08	0.12	0.15	0.18	0.22

Table 2. Simulated scenarios. The overall fraction diseased leaf area at different crop developmental stages of cultivar IR64, under different levels of leaf nitrogen.

Leaf nitrogen ($g\ g^{-1}$)	Disease onset	Development stage							
		0.39	0.57	0.74	0.93	1.13	1.46	1.74	2.00
0.06	Early	0	0.02	0.10	0.33	0.55	0.72	0.88	0.58
	Mid	0	0	0.05	0.22	0.37	0.47	0.55	0.58
	Late	0	0	0	0	0.13	0.25	0.37	0.43
0.04	Early	0	0	0.05	0.17	0.38	0.62	0.75	0.75
	Mid	0	0	0	0.08	0.23	0.40	0.50	0.50
	Late	0	0	0	0.05	0.12	0.17	0.25	0.25
0.02	Early	0	0	0.02	0.07	0.18	0.37	0.53	0.55
	Mid	0	0	0	0.02	0.10	0.18	0.32	0.33
	Late	0	0	0	0.02	0.12	0.15	0.25	0.25
0.01	Early	-	-	-	-	-	-	-	-
	Mid	-	-	-	-	-	-	-	-
	Late	0	0	0	0.05	0.08	0.12	0.17	0.17

In the dry season (January-April), bacterial leaf blight generally initiates in a later in the crop growth stage, dependent on the susceptibility of the rice cultivar. However, a susceptible cultivar like Annada is infected even in the early tillering stage, whereas a more resistant cultivar like IR64 may be infected only at late tillering or flowering stage. Therefore, all three moments of infestation were simulated for Annada, and only mid and late onsets for IR64. The maximum fraction diseased leaf area of IR64 varied between 0.50 and 0.65, and disease severity varied between 0.35 and 0.45. Maximum fraction diseased leaf area in different canopy layers of Annada varied between 0.50 and 0.75 at harvest. Disease severity varied between 0.35 to 0.65 (Tables 5 and 6).

Weather data of Cuttack, India, of the years 1991 and 1993 were used. Crop growth was simulated for the wet and for the dry season.

Table 3. Simulated scenarios. Fraction diseased leaf area, and disease severity, for different moments of disease onset, for cultivar IR64, for the 1993 wet season.

Treatment	Layer	Development stage							
		0.39	0.57	0.74	0.93	1.13	1.46	1.74	2.00
		Day of the year							
		190	205	219	235	245	256	265	273
Early onset									
Fraction	Layer 1	0	0.05	0.15	0.35	0.55	0.75	1.0	1.0
diseased	Layer 2	0	0	0.15	0.50	0.65	0.75	0.85	0.85
	Layer 3	0	0	0	0.15	0.45	0.65	0.80	0.90
Severity	Layer 1	0	0.15	0.25	0.45	0.65	0.75	0.90	0.90
	Layer 2	0	0	0.20	0.35	0.50	0.65	0.80	0.80
	Layer 3	0	0	0	0.15	0.50	0.75	0.85	0.85
Mid onset									
Fraction	Layer 2	0	0	0.15	0.50	0.65	0.75	0.85	0.85
diseased	Layer 3	0	0	0	0.15	0.45	0.65	0.80	0.90
Severity	Layer 2	0	0	0.20	0.35	0.50	0.65	0.80	0.80
	Layer 3	0	0	0	0.15	0.50	0.75	0.85	0.85
Late onset									
Fraction	Layer 2	0	0	0	0	0.15	0.30	0.45	0.50
diseased	Layer 3	0	0	0	0	0.25	0.45	0.65	0.80
Severity	Layer 2	0	0	0	0	0.10	0.25	0.30	0.30
	Layer 3	0	0	0	0	0.15	0.35	0.50	0.75

Table 4. Simulated scenarios. Fraction diseased leaf area, and disease severity, for different moments of disease onset, for cultivar Annada, for the 1991 wet season.

Treatment	Layer	Development stage								
		0.51	0.69	0.80	0.90	1.00	1.20	1.45	1.70	2.00
		Day of the year								
		203	216	224	232	239	246	254	262	272
Early onset										
Fraction	Layer 1	0	0.05	0.15	0.35	0.55	0.75	0.75	1.0	1.0
diseased	Layer 2	0	0	0.15	0.50	0.65	0.75	0.85	0.85	0.85
	Layer 3	0	0	0	0.15	0.45	0.55	0.65	0.80	0.90
Severity	Layer 1	0	0.15	0.25	0.45	0.65	0.75	0.90	0.95	0
	Layer 2	0	0	0.20	0.35	0.50	0.65	0.80	0.80	0.80
	Layer 3	0	0	0	0.15	0.35	0.50	0.75	0.85	0.85
Mid onset										
Fraction	Layer 2	0	0	0.15	0.50	0.65	0.75	0.85	0.85	0.85
diseased	Layer 3	0	0	0	0.15	0.45	0.55	0.65	0.80	0.90
Severity	Layer 2	0	0	0.20	0.35	0.50	0.65	0.80	0.80	0.80
	Layer 3	0	0	0	0.15	0.35	0.50	0.75	0.85	0.85
Late onset										
Fraction	Layer 2	0	0	0	0	0.15	0.30	0.45	0.55	0.55
diseased	Layer 3	0	0	0	0	0.25	0.45	0.55	0.60	0.65
Severity	Layer 2	0	0	0	0	0.10	0.25	0.30	0.35	0.35
	Layer 3	0	0	0	0	0.15	0.35	0.45	0.50	0.65

Table 5. Simulated scenarios. Fraction diseased leaf area, and disease severity, for different moments of disease onset, for cultivar IR64, for the 1993 dry season.

Treatment	Layer	Development stage								
		0.39	0.50	0.61	0.73	0.84	0.98	1.22	1.57	2.0
		Day of the year								
		57	67	75	84	92	102	110	120	132
Mid onset										
Fraction diseased	Layer 2	0	0	0.05	0.15	0.25	0.35	0.50	0.50	0.50
	Layer 3	0	0	0	0.15	0.25	0.35	0.45	0.45	0.45
Severity	Layer 2	0	0	0.05	0.10	0.15	0.25	0.30	0.30	0.35
	Layer 3	0	0	0	0.10	0.20	0.25	0.30	0.35	0.35
Late onset										
Fraction diseased	Layer 3	0	0	0	0.15	0.25	0.35	0.50	0.65	0.65
Severity	Layer 3	0	0	0	0.10	0.20	0.25	0.30	0.35	0.35

Results

Cultivar effect

Scenario studies were carried out for two rice cultivars, viz. IR64 and Annada. Annada is more susceptible to bacterial leaf blight than IR64, and therefore, Annada is likely to become infected in the dry season in most growth stages, whereas IR64 may become infected only in later growth stages. In the wet season, the damage due to the disease is higher for Annada than for IR64.

Simulated total dry matter productions at a high leaf nitrogen content of 0.06 g g^{-1} in the dry and wet season of IR64 were 15701 and 14066 kg ha^{-1}, respectively, and simulated total dry matter productions of Annada were 11808 and 8778 kg ha^{-1}, respectively. Simulated grain yield at high leaf nitrogen content in the dry and wet season of IR64 were 9681 and 9507 kg ha^{-1}, respectively, and simulated grain yields of Annada were 7904 and 6597 kg ha^{-1}, respectively. The difference in production between the two cultivars in different seasons may be due to the green leaf area index. The maximum simulated green leaf area of IR64 was 12.9 in the dry season, and 8.45 in wet season, and 3.05 and 4.7 for Annada in the wet and the dry seasons, respectively.

Table 6. Simulated scenarios. Fraction diseased leaf area, and disease severity, for different moments of disease onset, for cultivar Annada, for the 1991 dry season.

Treatment	Layer	Development stage								
		0.39	0.49	0.61	0.75	0.88	1.00	1.27	1.60	2.00
		Day of the year								
		60	68	76	85	94	102	110	120	132
Early onset										
Fraction diseased	Layer 1	0	0	0.05	0.15	0.25	0.25	0.35	0.50	0.50
	Layer 2	0	0	0.15	0.25	0.25	0.35	0.40	0.50	0.55
	Layer 3	0	0	0	0.15	0.25	0.45	0.65	0.75	0.75
Severity	Layer 1	0	0	0.07	0.10	0.15	0.25	0.30	0.35	0.35
	Layer 2	0	0	0.05	0.15	0.20	0.25	0.25	0.35	0.35
	Layer 3	0	0	0	0.10	0.25	0.25	0.30	0.45	0.65
Mid onset										
Fraction diseased	Layer 2	0	0	0.15	0.25	0.25	0.35	0.40	0.50	0.55
	Layer 3	0	0	0	0.15	0.25	0.45	0.65	0.75	0.75
Severity	Layer 2	0	0	0.05	0.15	0.20	0.25	0.25	0.35	0.35
	Layer 3	0	0	0	0.10	0.25	0.25	0.30	0.45	0.65
Late onset										
Fraction diseased	Layer 3	0	0	0	0.15	0.25	0.45	0.65	0.75	0.75
Severity	Layer 3	0	0	0	0.10	0.25	0.25	0.30	0.45	0.65

Nitrogen effect

Higher levels of leaf nitrogen generally increase growth and yield of rice. IR64 gave a simulated total dry matter production of 15701 and 14066 kg ha^{-1} in dry and wet season, respectively, at a leaf nitrogen content of 0.06 g g^{-1}. There was a gradual reduction in total dry matter production as leaf nitrogen content decreased from 0.06 to 0.01 g g^{-1}. However, this decrease was more stronger in wet season, viz. from 14066 to 4936 kg ha^{-1}, than in dry season, viz. from 15701 to 7108 kg ha^{-1} (Figures 1a and 1b).

Total dry matter production of Annada at a leaf nitrogen level of 0.06 g g^{-1} was 11808 kg ha^{-1} in the dry season, and 8778 kg ha^{-1} in the wet season. With decreasing leaf nitrogen content, total dry matter production gradually decreased in both the wet and the dry season, e.g. from 11808 kg ha^{-1} at a leaf nitrogen content of 0.06 g g^{-1} to 3752 kg ha^{-1} at a leaf nitrogen content of 0.01 g g^{-1} in dry season. Corresponding values for the wet season are 8778 and 2842 kg ha^{-1}, respectively (Figures 2a and 2b).

Grain yield of IR64 at a leaf nitrogen content of 0.06 g g^{-1} was 9681 kg ha^{-1} in dry season, and 9507 kg ha^{-1} in the wet season. Reduction of leaf nitrogen content caused reduction of grain yield. This reduction was greater in the wet season than in the dry season, viz. to 4926 and 3773 kg ha^{-1} at a leaf nitrogen content of 0.01 g g^{-1} in the dry and the wet season, respectively.

Grain yield of Annada at a leaf nitrogen content of 0.06 g g^{-1} was 7904 kg ha^{-1} in dry season, and 6597 kg ha^{-1} in the wet season. Reduction of leaf nitrogen content caused reduction of grain yield, viz. to 2340 and 1924 kg ha^{-1} at a leaf nitrogen content of 0.01 g g^{-1} in the dry and the wet season, respectively.

Effect of disease built-up

Introduction of the disease at three growth stages of crop gave an overview of the effects of disease presence on total dry matter production and grain yield in wet and dry seasons. In general, the effects variation in disease onset and intensity were stronger in the wet season than in the dry season. Disease initiation at early growth stages of crop caused most damage, followed by mid and late onsets.

Simulated total dry matter production of IR64 in the dry season at a leaf nitrogen content of 0.06 g g^{-1} was 15701 kg ha^{-1}. In case of mid and late disease onsets, total dry matter production was reduced to 11249 and 11362 kg ha^{-1}, respectively. Total dry matter production decreased with decreasing leaf nitrogen content (Figure 1a).

Simulated total dry matter production of IR64 in the wet season at a leaf nitrogen content of 0.06 g g^{-1} was 14066 kg ha^{-1}. In case of early, mid, and late onset, total dry matter production was reduced to 7027, 6855, and 8215 kg ha^{-1}, respectively. With a decrease in leaf nitrogen content, total dry matter production decreased also (Figure 1b). Reductions due to the earlier disease onset were lower at lower levels of leaf nitrogen content (Table 7).

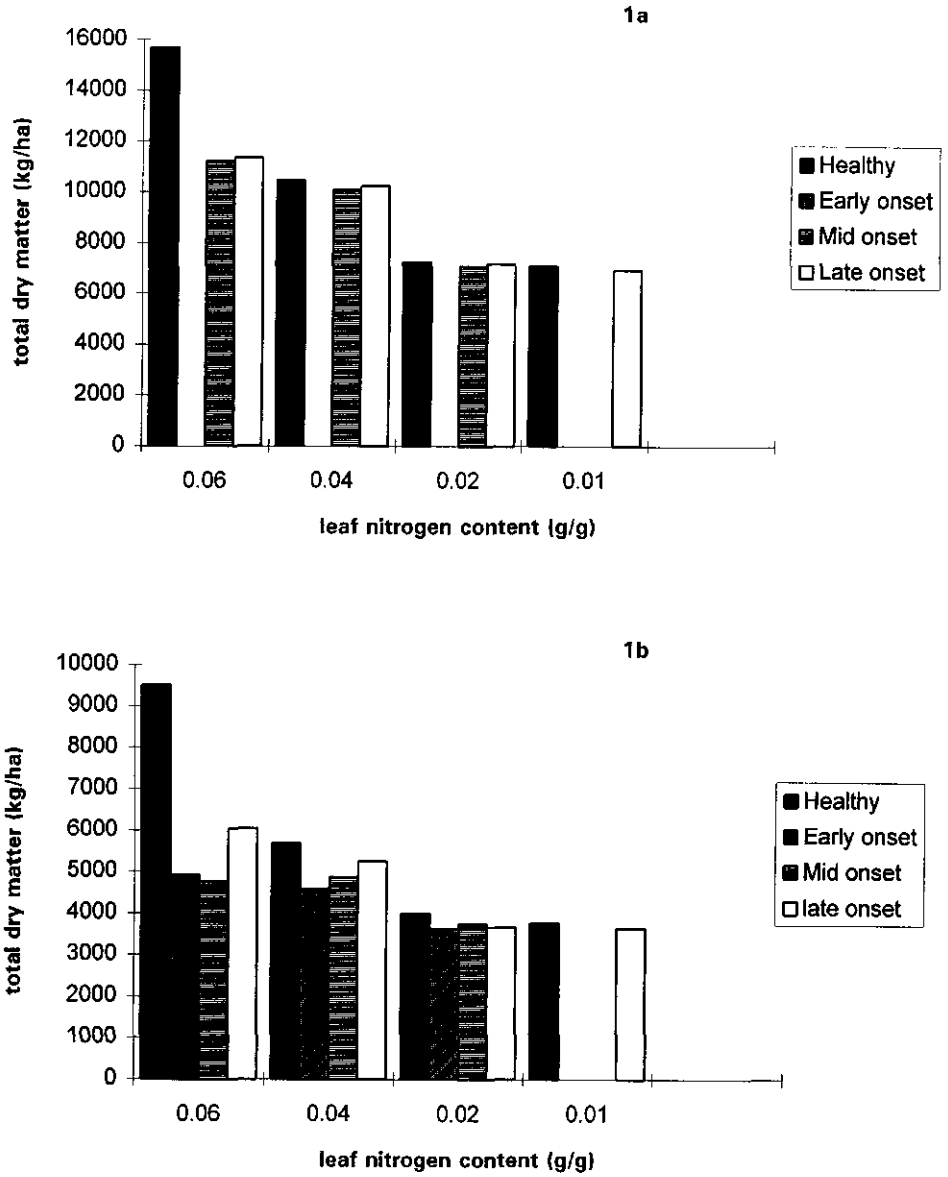

Figure 1. Simulated total dry matter production of IR64, during the dry (a) and wet (b) seasons of 1993, for different moments of disease onset.

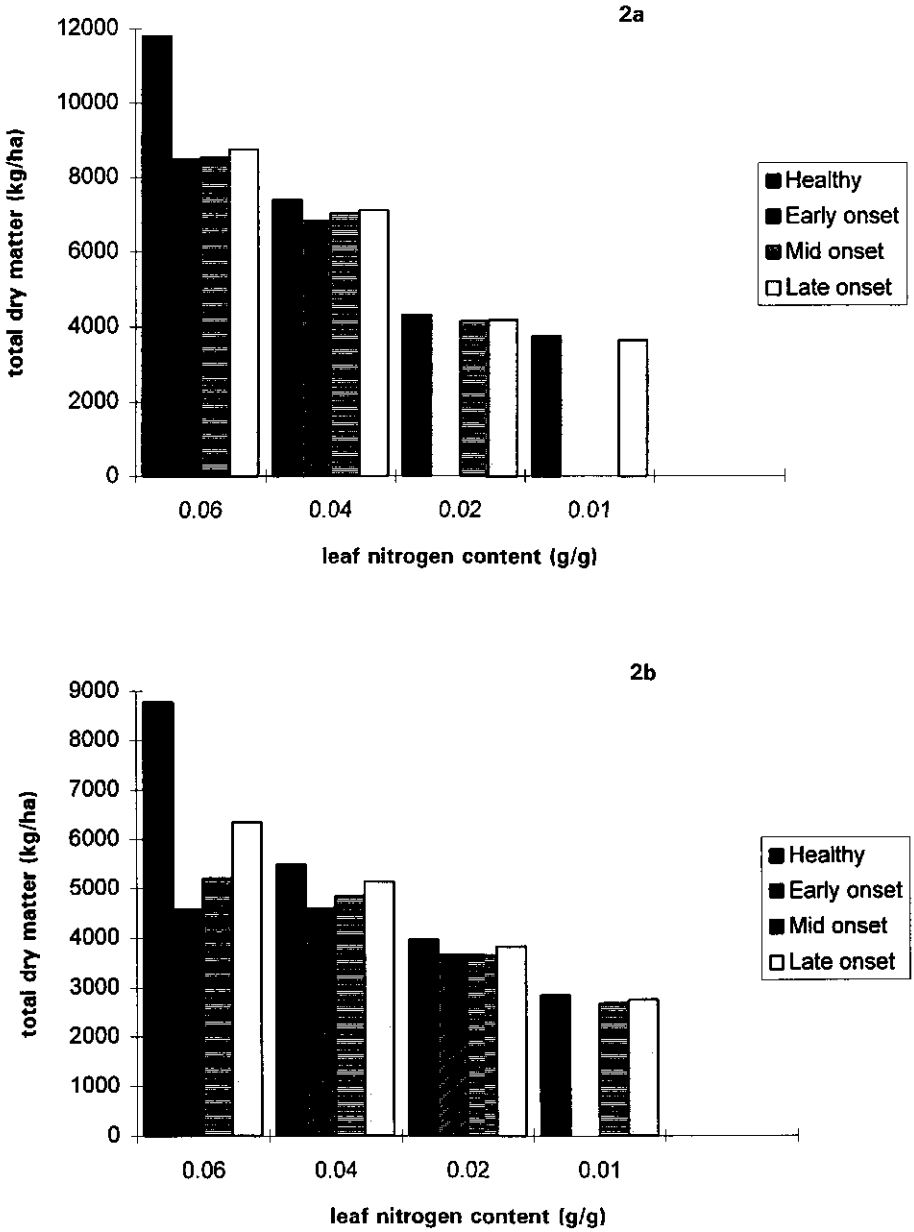

Figure 2. Simulated total dry matter production of Annada, during the dry (a) and wet (b) seasons of 1993, for different moments of disease onset.

Table 7. Simulated reductions (kg ha^{-1}) in total dry matter (WAG) and grain yield (WSO), in comparison with a heathy crop, for different different moments of disease onset and different levels of leaf nitrogen content, for cultivar Annada.

Disease onset	Leaf Nitrogen							
	0.06		0.04		0.02		0.01	
	WSO	WAG	WSO	WAG	WSO	WAG	WSO	WAG
DRY SEASON								
Early	2847	3313	532	575	-	-	-	-
Mid	2813	3270	347	365	156	170	-	-
Late	2650	3056	269	285	112	130	97	105
WET SEASON								
Early	4039	4204	861	888	304	317	-	-
Mid	3463	3570	632	647	308	318	159	164
Late	2428	2436	340	348	137	142	90	93

Simulated total dry matter productions of Annada in the dry and the wet season at a leaf nitrogen content of 0.06 g g^{-1} were 11808 kg ha^{-1} and 8778 kg ha^{-1}, respectively. Early, middle and late disease onset reduced total dry matter production to 4574, 5208 and 6342 kg ha^{-1}, respectively, in the wet season, and to 8495, 8538 and 8752 kg ha^{-1}, respectively, in the dry season (Figures 2a and 2b). Decrease in leaf nitrogen content caused decrease in total dry matter production.

Simulated grain yield of a healthy crop of IR64 in the dry season at a nitrogen content of 0.06 g g^{-1} was 9681 kg ha^{-1}. In case of middle and late onset, grain yields were 7476 and 7565 kg ha^{-1}, respectively. Therefore, grain yield reductions were 2205 and 2116 kg ha^{-1}, respectively. At a nitrogen content of 0.04 g g^{-1}, grain yield of a healthy crop was 7471 kg ha^{-1}, which reduced to 6725 and 6963 kg ha^{-1}, respectively. Yield reductions were 746 and 508 kg ha^{-1}. At a nitrogen content of 0.02 g g^{-1}, grain yield of a healthy crop was 4983 kg ha^{-1}, which reduced to 4813 and 4903 kg ha^{-1}, respectively. Yield reductions were 80 and 170 kg ha^{-1}, respectively (Figure 3a and Table 7).

Simulated grain yield of a healthy crop of IR64 in the wet season at a leaf nitrogen content of 0.06 g g^{-1} was 9507 kg ha^{-1}. In case of early, mid, and late onset, grain yields were 4925, 4757, and 6045 kg ha^{-1}, respectively (Figure 3b). Therefore, grain yield reduction ranged between 3462 and 4850 kg ha^{-1}. At a nitrogen content of 0.04 g g^{-1}, grain yield of a healthy crop was 5687 kg ha^{-1}, which reduced to 4594, 4879 and 5256 kg ha^{-1}, respectively. Yield reduction varied between 431 and 1093 kg ha^{-1}. At a nitrogen content

of 0.02 g g^{-1}, grain yield of a healthy crop was 4005 kg ha^{-1}, which reduced to 3633, 3757 and 3673 kg ha^{-1}, respectively. Yield reduction varied between 249 and 374 kg ha^{-1}. At a nitrogen content of 0.01 g g^{-1}, grain yield of a healthy crop was 3773 kg ha^{-1}, which reduced to 3647 kg ha^{-1}, in case of late disease onset (Figure 3b and Table 7). Therefore, highest yield reductions were simulated at high levels of leaf nitrogen content, in combination with early disease onset.

Simulated grain yield of a healthy crop of Annada in the dry season at a nitrogen content of 0.06 g g^{-1} was 7904 kg ha^{-1}. In case of early, mid, and late onset, grain yields were 5057, 5091, and 5254 kg ha^{-1}, respectively. Therefore, grain yield reduction ranged between 2650 and 2847 kg ha^{-1}. At a leaf nitrogen content of 0.04 g g^{-1}, grain yield of a healthy crop was 4557 kg ha^{-1}, which reduced to 4025, 4210 and 4288 kg ha^{-1}, respectively. Further decrease in leaf nitrogen content caused further reduction of grain yield. In general, yield reductions were lowest at low levels of leaf nitrogen content, in combination with late disease onsets (Figure 4a and Table 8).

Simulated grain yield of a healthy crop of Annada in the wet season at a nitrogen content of 0.06 g g^{-1} was 6597 kg ha^{-1}. In case of early, mid, and late onset, grain yields were 2558, 3134, and 4169 kg ha^{-1}, respectively (Figure 4b and Table 8). Therefore, grain yield reduction ranged between 2428 and 4039 kg ha^{-1}. At a nitrogen content of 0.04 g g^{-1}, grain yield of a healthy crop was 3556 kg ha^{-1}, which reduced to 2795, 3024 and 3316 kg ha^{-1}, respectively. Yield reduction varied between 340 and 861 kg ha^{-1}. At a nitrogen content of 0.02 g g^{-1}, grain yield of a healthy crop was 2563 kg ha^{-1}, which reduced to 2259, 2255 and 2426 kg ha^{-1}, respectively. Yield reduction varied between 137 and 308 kg ha^{-1}. Therefore, lowest yield reductions were simulated at low levels of leaf nitrogen content.

The simulation results show that higher leaf nitrogen content increases green leaf area, which, however, is more susceptible to bacterial leaf blight than leaf area with a lower nitrogen content. Therefore, green leaf area reduces due to increased disease pressure, which reflects in the significant reduction of total dry matter production and grain yield. Green leaf area also varies as a result of different moments of disease onset. Delayed disease initiation causes less reduction of green leaf area available for crop production. In general, early and mid disease onsets cause a relatively large reduction of green leaf area, and consequently large reduction of total dry matter production and grain yield. A later disease onset has the consequence that a limited period of the crop growth period is available for disease spread, and therefore, the consequences for grain yield are smaller.

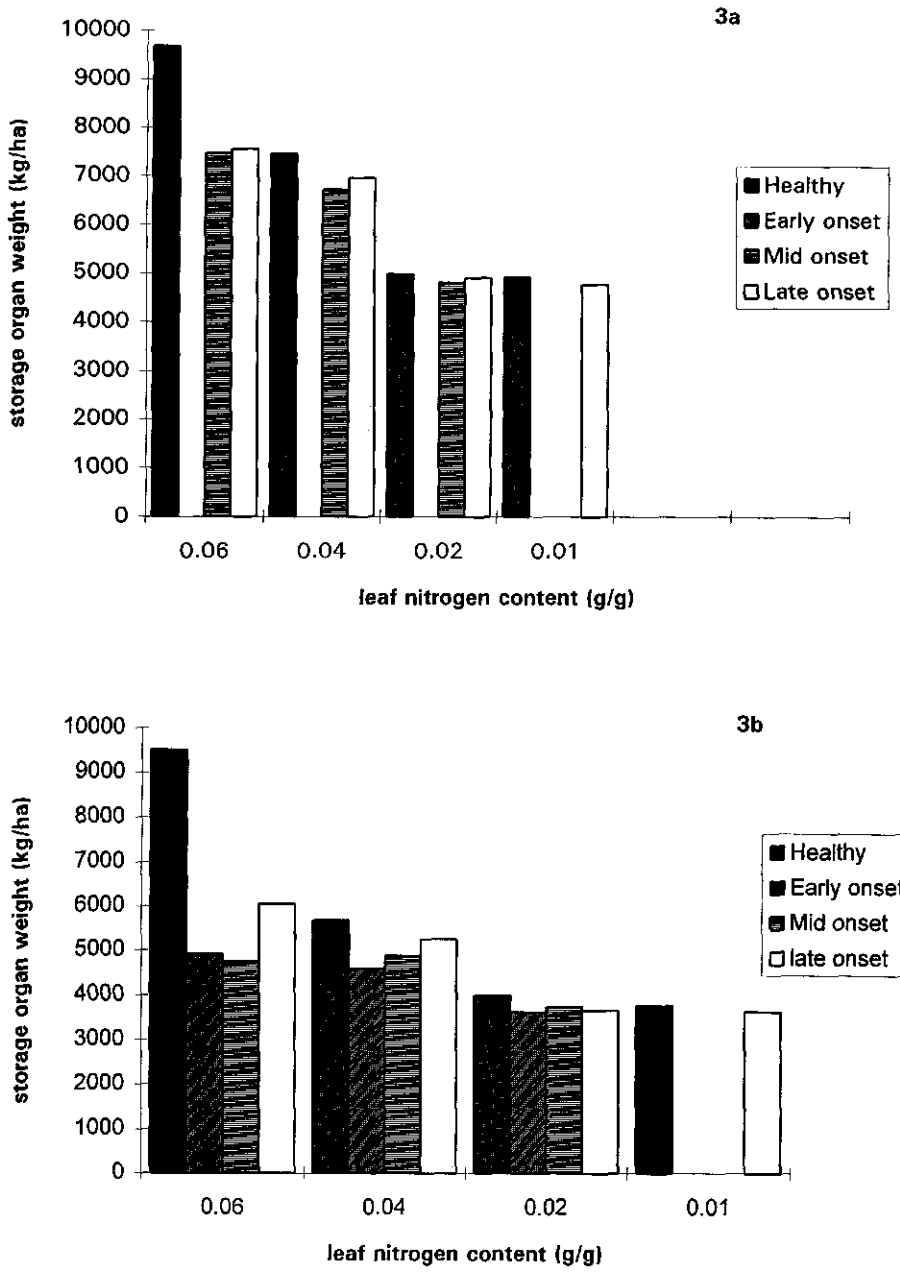

Figure 3. Simulated storage organ weight of IR64, during the dry (a) and wet (b) seasons of 1993, for different moments of disease onset.

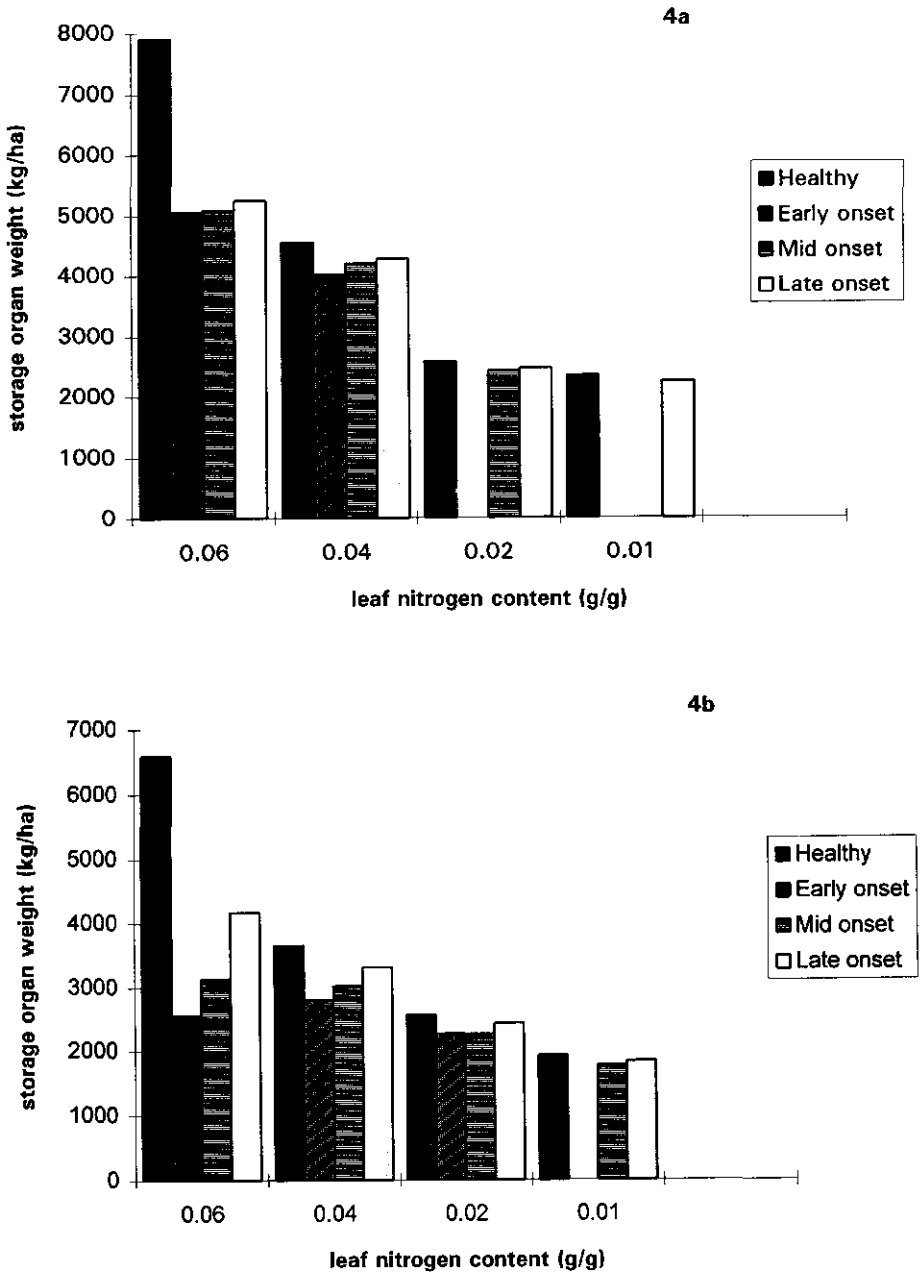

Figure 4. Simulated storage organ weight of Annada, during the dry (a) and wet (b) seasons of 1993, for different moments of disease onset.

Table 8. Simulated reductions (kg ha^{-1}) in total dry matter (WAG) and grain yield (WSO), in comparisonwith a heathy crop, for different different moments of disease onset and different levels of leaf nitrogen content, for cultivar IR64.

Disease onset	Leaf Nitrogen							
	0.06		0.04		0.02		0.01	
	WSO	WAG	WSO	WAG	WSO	WAG	WSO	WAG
DRY SEASON								
Mid	2205	3429	746	358	170	178	-	-
Late	2116	3316	508	228	80	79	152	174
WET SEASON								
Early	4582	7039	1093	1110	372	374	-	-
Mid	4850	7211	808	818	248	249	-	-
Late	3462	5851	431	437	322	336	126	135

Discussion

The two rice cultivars IR64 and Annada differ in simulated potential yield both in the wet and in the dry season. One of the reasons for the difference in production appears to be the difference in green leaf area, which is partly a varietal characteristic. Maximum green leaf areas of 12.9 and 8.45 were simulated for IR64 in the dry and wet season, respectively, and maximum green leaf areas of 4.7 and 3.05, respectively, were simulated for Annada.

The two varieties also differ in their susceptibility to bacterial blight disease. In general, Annada is more susceptible than IR64. Annada becomes infected at earlier growth stages in both seasons, whereas IR64 is less susceptible, and is normally infected in middle or late growth stages.

Different disease scenarios were created for the two cultivars, in order to obtain a more realistic assessment of their performance. Simulation results showed highest yield losses for both the varieties in case of early disease onset, at high nitrogen levels. Simulations suggest that a crop that is grown with a higher leaf nitrogen content is subjected to an earlier disease initiation and faster disease spread. With decreasing leaf nitrogen content, disease onset presumably delays, and disease severity presumably reduces. Therefore, yield losses may be lower at lower nitrogen levels. Maximum yield loss was between 2428 and 4039 kg ha^{-1} for Annada, and between 3462 to 4850 kg ha^{-1} for IR64. With decreasing leaf nitrogen content, total dry matter production generally reduces, however, the effects of the disease generally also reduce. Therefore, it may be most appropriate to grow a

rice crop with a moderate leaf nitrogen content between 0.04 and 0.02 g g^{-1}. This may help in delaying disease onset and reducing disease severity, which may increase production.

References

Elings, A. & E.G. Rubia, 1994. Models for the crop-pathosystems. Rice-Bacterial leaf blight, Sheath Blight and Stem Borer. Simulation and Systems Analysis for Rice Production. AB-DLO and TPE-WAU, Wageningen, The Netherlands and IRRI, Philippines, 102 pages.

Kropff, M.J., H.H. van Laar & H.F.M. ten Berge, 1993. ORYZA_1 - A basic model for irrigated lowland rice production. Simulation and Systems Analysis for Rice Production. IRRI, Philippines, AB-DLO and TPE-WAU, Wageningen, The Netherlands.

Reddy, P.R., 1994. Simulation of the effect of bacterial blight disease on crop growth and yield of rice. Simulation and Systems Analysis for Rice Production, internal publication, 46 pages + appendices.

Simulation of the effect of bacterial leaf blight infection on yield reduction in rice

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Introduction

The bacterial leaf blight disease (BLB), caused by *Xanthomonas campestris* pv. *oryzae*, is an important disease that can cause serious damage to the rice crop. Grain yield reduction varies from 2 to 74 per cent, depending on the cultivar, season and moment of infection (Reddy et al., 1979a and b). However, quantitative knowledge on the effects of the disease on crop physiology, crop growth rate, and grain yield reduction in relation to the crop development stage at which infection takes place, is lacking. Narasimhan et al. (1991) have earlier simulated the effect of BLB infection on yield reduction in rice, using the MACROS.L1D simulation model, in which BLB was assumed to have effects on crop photosynthesis and respiration. However, grain yield was over-estimated. Reddy et al. (1991) showed that introduction of several canopy layers, each characterized by fractions healthy, diseased and dead leaf area, and disease severity of diseased leaf area, and that introduction of leaf N content as model input, improved simulation of grain yield reduction due to BLB.

The objectives of the present study are to quantify the effect of BLB infection on crop physiology, crop growth rate and yield reduction in rice, using the L1DFDE model for foliar diseases (Bastiaans, 1991).

Materials and Methods

Field experiment

A field experiment was conducted with cultivar IR50 during the wet season of 1991-92 at the Tamil Nadu Rice Research Institute, Aduthurai, India, which is situated at an altitude of 19 m above sea level. The experiment was laid out in a randomized block design with 3 treatments and 5 replicates. The three treatments were:

T1. Inoculated on 8 January, 1992 (booting, DVS 0.78).
T2. Inoculation on 24 January, 1992 (flowering, DVS 0.98).
T3. Control (healthy crop).

The plot size was 5 × 3 m, and hill spacing was 20 × 10 cm. Plants were sown on day 309, 1991, and transplanted on day 333 at a rate of 2 seedlings per hill. The crop reached flowering on day 26, 1992, and was harvested on day 58.

A pure culture of the BLB pathogen *X. campestris* pv. *oryzae* (Aduthurai isolate) was grown on an artificial medium, and the bacterium suspension was prepared in water and used to inoculate the rice plants by the clip inoculation method (Morinka et al., 1978).

Observations were taken at periodic intervals, viz. on days 10, 22, 45, and 56, and included: weights of shoots, roots, leaves, stems and panicles; total leaf area; fractions healthy, diseased and dead leaf area; disease severity of diseased leaf area; leaf nitrogen content of healthy and diseased leaf area; and specific leaf weight of healthy and diseased leaf area.

Observations on leaves were recorded per canopy layer. The canopy was divided in three layers, viz. a bottom layer L3 (< 20 cm), a middle layer L2 (21 - 40 cm) and a top layer L1 (> 40 cm). In early crop growth stages (up to day 361) the canopy was formed by only one layer, and at later stages by two (up to day 10) or three layers (from day 22 onwards).

For each set of periodic observation, 15 hills were harvested, of which 11 hills were used for measuring weights of leaves, stems and panicles. Dry weight of healthy, diseased and dead leaf area, and disease severity were determined per layer on the basis of the remaining 4 hills, which were selected at random from the above 15 hills.

Data were averaged per treatment (5 replicates). Simulations were made on the basis of average values.

Simulation

The L1DFDE model for foliar diseases (Bastiaans, 1991), which is an extended version of the MACROS.L1D model (Penning de Vries et al., 1989) was used for simulations. This model is characterized by the following:

- Effects of the disease on leaf physiology (photosynthesis and respiration) are introduced as forcing functions.
- Canopy characteristics (LAI, SLW, N content) and disease intensity (fractions healthy, diseased and dead leaf area, and disease severity of diseased leaf area) are determined in the field and introduced in the model as forcing functions. These characteristics of the canopy, which is divided into three layers, are specified per layer.
- Leaf nitrogen content is introduced, as it is strongly related to the rate of photosynthesis at light saturation (Penning de Vries et al., 1990).
- Calculation of canopy photosynthesis is based on the photosynthesis of individual leaves. The CO_2 light response curve is characterized by the initial light use efficiency (EFF), the assimilation rate at light saturation (AMAX), and dark respiration. EFF and AMAX, and the maintenance respiration rate are multiplied with a correction factor, which is related to disease severity.
- Subroutine FUPHOT is replaced by subroutine SUPHOD, which distinguishes three types (viz. healthy, diseased and dead) of leaf area per layer.

Weather data collected at TNRRI, during 1991 and 1992, which were characteristic for the predominant weather, were used.

Radiation use efficiency was calculated on the basis of total dry matter production, and on the basis of final grain yield, by dividing weight (kg ha^{-1}) by total intercepted photosynthetically active radiation (PARTOT).

Results

Field experiment

Total above-ground dry matter production was significantly lower in the crop inoculated at booting than in the healthy crop, however total above-ground dry matter production of the crop inoculated at flowering and the healthy crop were similar (Table 1). Grain yield of the healthy crop was highest, followed by the crop inoculated at flowering and booting, respectively.

Table 1. Observed and simulated total above-ground dry matter production, and final grain yield.

Treatment	Day of the year	Total above-ground dry matter (kg ha^{-1})		Grain yield (kg ha^{-1})	
		Observed	Simulated	Observed	Simulated
Healthy	10	4208	5195		
	22	6458	6388		
	45	10042	8781		
	56	11833	9057		
	harvest			4626	4032
Inoculation at booting	10	4416	5241		
	22	5333	6623		
	45	5625	8674		
	56	8583	8630		
	harvest			3793	3464
Inoculation at flowering	10	4750	5345		
	22	5750	6641		
	45	8833	8951		
	56	12038	9015		
	harvest			4209	3804

Table 2. Leaf area (ha ha^{-1}) of the three canopy layers, and total leaf area, of the various treatments, during the growing season.

Day of the year	Healthy				Inoculated at booting				Inoculated at flowering			
	L1	L2	L3	Total	L1	L2	L3	Total	L1	L2	L3	Total
10	0	2.33	2.11	4.44	0	2.23	1.59	3.82	0	2.62	2.15	4.77
22	0.42	0.85	1.41	2.68	0.55	1.18	1.32	3.05	0.36	0.99	1.17	2.52
45	0.87	1.68	0.43	2.98	1.13	2.18	0.77	4.08	1.43	2.69	0.52	4.64
56	1.02	1.80	0.68	3.50	0.95	0.84	0.71	2.50	1.14	2.15	1.07	4.36

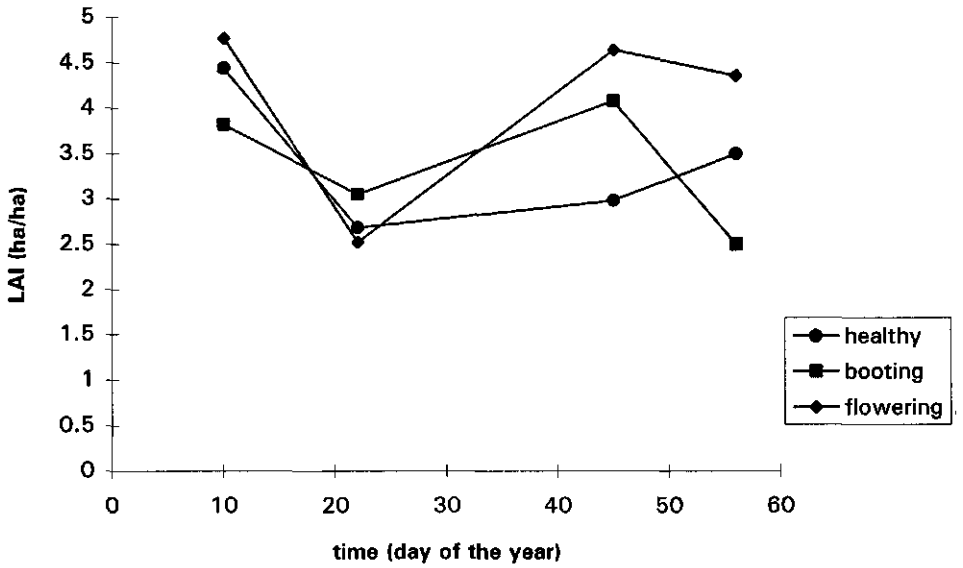

Figure 1. Average leaf area index of the various treatments during the growing season.

Total leaf area of the three canopy layers, of all treatments, is presented in Table 2 and Figure 1. Total leaf area of the crop inoculated at booting reduced at the end of the growing season, whereas total leaf area of the healthy crop slightly increased. Total leaf area of the crop inoculated at flowering was highest.

Specific leaf weight of healthy leaf area was, on the average, highest in the healthy crop, and lowest in the crop inoculated at booting (Table 3). Specific leaf weight of diseased leaf area was lower in the crop inoculated at booting than in the crop inoculated at flowering.

Table 3. Specific leaf weight (kg ha^{-1}) of leaf area of healthy (SLWL) and diseased leaf area (SLWLD) of three canopy layers, of the various treatments, during the growing season.

Day of the year	Healthy			Inoculated at booting			Inoculated at flowering		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
SLWL									
10	-	313	348	-	398	349	-	404	420
22	434	456	263	533	393	444	409	386	497
45	460	423	377	330	408	375	335	284	364
56	561	465	377	305	354	364	258	559	364
SLWLD									
10	-	-	-	-	312	103	-	0	0
22	-	-	-	360	312	103	224	465	210
45	-	-	-	296	389	158	224	465	310
56	-	-	-	222	314	247	515	398	310

Table 4. Fraction healthy (FHLT) and diseased (FDIS) leaf area and severity of diseased leaf area (SEVD), of the various treatments, during the growing season.

Treatment	Day of the year	FHLT (%)			FDIS (%)			SEVD (%)		
		L1	L2	L3	L1	L2	L3	L1	L2	L3
Healthy	10	-	100	93	-	-	-	-	-	-
	22	100	100	91	-	-	-	-	-	-
	45	100	85	30	-	-	-	-	-	-
	56	90	84	22	-	-	-	-	-	-
Inoculation at booting	10	-	100	94	-	0	0	-	0	0
	22	78	93	85	20	0	9	3	3	3
	45	65	52	5	12	28	22	36	36	41
	56	88	39	4	1	49	8	30	50	64
Inoculation at flowering	10	-	100	95	-	0	0	-	0	0
	22	100	100	93	0	0	0	0	0	0
	45	62	78	30	38	12	0	19	39	0
	56	21	59	22	39	20	17	27	39	66

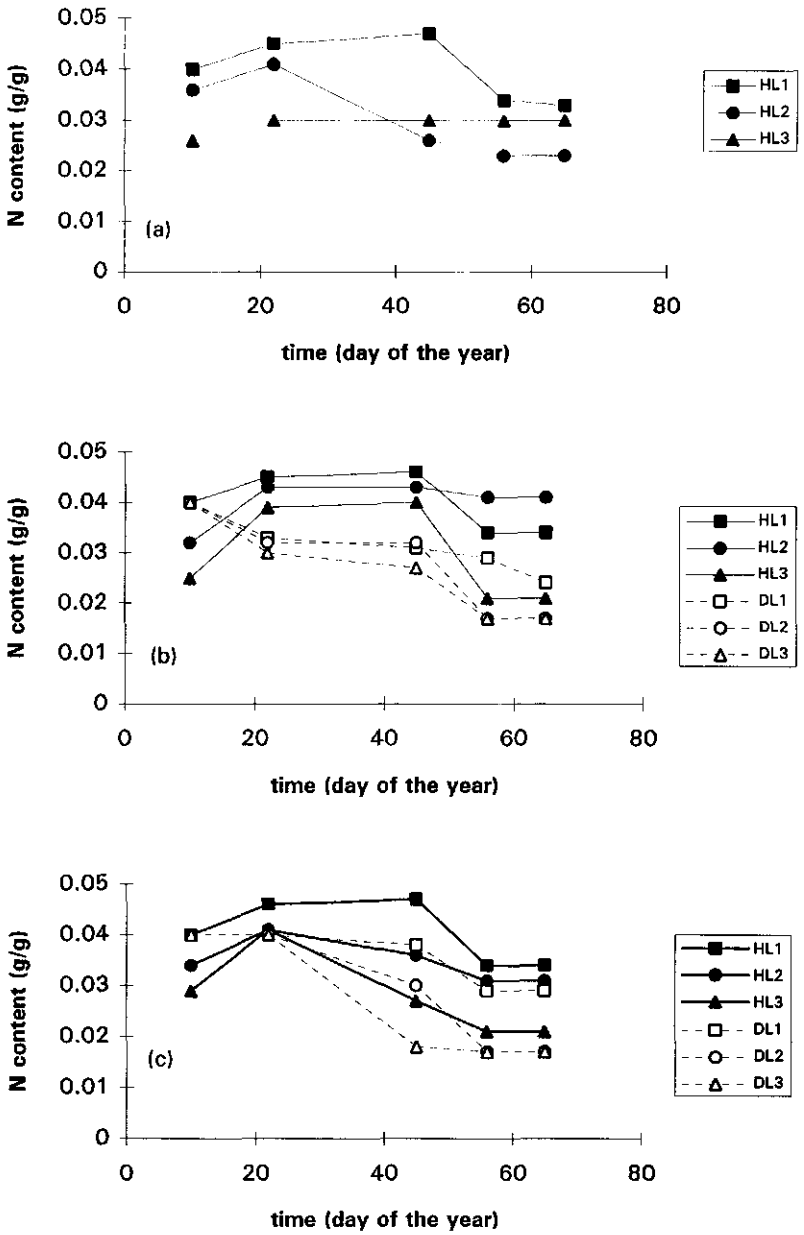

Figure 2. Average leaf nitrogen content of the healthy treatments (a), the treatments inoculated at booting (b), and the treatments inoculated at flowering (c).
HL = healthy leaf area
DL = diseased leaf area
1, 2, 3 = canopy layers 1, 2, and 3, respectively

Leaf nitrogen content of healthy and diseased leaf area for all treatments is presented in Figures 2a, b, and c. Significant differences in leaf N content existed between the healthy and inoculated treatments in different layers. Leaf nitrogen content was lower in all three canopy layers of both inoculated treatments than of the healthy treatment. Leaf nitrogen content was generally highest in the top layer, followed by the middle and bottom layers. Leaf nitrogen increased up to day 20, remained constant up to day 45, and decreased afterwards. This decrease was largest in the bottom layers of the inoculated treatments.

Fractions healthy and diseased leaf area, and disease severity for each leaf layer are given in Table 4. Fraction healthy leaf area of the top layer L1 reduced after inoculation, however, in case of the crop inoculated at booting, it increased again after day 45. Fractions healthy leaf area of the middle and bottom layers reduced more than this fraction of the top layer, and did not increase again later in the season. A reduction in fraction healthy leaf area corresponded with an increase in fraction diseased leaf area. Fraction diseased leaf area of the top layer was highest for the crop inoculated at booting, and this fraction of the middle and bottom layers was highest for the crop inoculated at flowering. Disease severity of the fraction diseased leaf area gradually increased in both inoculated treatments. However, maximum disease severity was higher in the crop inoculated at booting than in the crop inoculated at flowering. Disease severity was highest in the bottom layers, followed by middle and top layers in both inoculated treatments.

Simulations

Partitioning coefficients were derived from plant organ weights of the healthy crop (Table 5).

Table 5. Partioning coeffecient of newly produced assimilates in shoot, leaf, root and panicle in relation to devolopment stages for cv. IR 50.

DS	Shoot	Root	Leaf	Stem	Panicle
0.00	0.599	0.401	0.577	0.423	0.000
0.44	0.599	0.401	0.507	0.423	0.000
0.74	0.667	0.333	0.405	0.595	0.000
0.89	0.729	0.271	0.373	0.627	0.000
0.99	0.823	0.177	0.304	0.215	0.481
1.19	1.000	0.000	0.000	0.167	0.833
1.40	1.000	0.000	0.000	0.000	1.000
2.50	1.000	0.000	0.000	0.000	1.000

Total dry matter production was under-estimated for the healthy crop and for the crop inoculated at flowering, by 13% and 10%, respectively (Table 5). Total dry matter production for the crop inoculated at booting was initially over-estimated, however, reached a final value similar to the observed one. Grain yields were slightly under-estimated, however, this under-estimate was consistent (Table 5).

Total intercepted photosynthetically active radiation of the healthy crop and the crop inoculated at flowering were similar, and higher than PARTOT of the crop inoculated at booting (Table 6). Radiation use efficiency on the basis of grain yield was slightly higher for the healthy crop than for both inoculated crops, however, if calculated on the basis of total dry matter production, was lowest for the crop inoculated at booting, and similar for the two other treatments.

Simulated gross canopy photosynthesis of the inoculated treatments was lower after inoculation, than of the un-inoculated crop (Figure 3). Reduction of photosynthesis of the crop inoculated at booting was higher than of the crop inoculated at flowering.

Table 6. Total intercepted photosynthetically active radiation (PARTOT), and radiation use efficiency (RUE) on the basis of total dry matter production and grain yield, for the three treatments.

Treatment	PARTOT ($MJ\ m^{-2}$)	RUE ($g\ MJ^{-1}$)	
		total dry matter production	grain yield
Healthy crop	233	5.08	1.99
Inoculation at booting	207	4.15	1.83
Inoculation at flowering	234	5.14	1.80

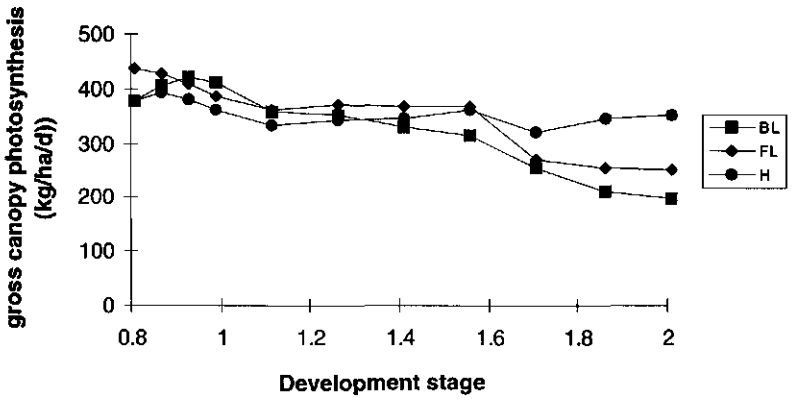

Figure 3. Gross canopy photosynthesis of the various treatments during the growing season.

Discussion

Inoculation with BLB at booting and flowering stages resulted in a grain yield reductions of 18% and 8%, respectively, in comparison with the healthy crop. The high grain yield reduction of the crop inoculated at booting can attributed to the relatively high reduction in leaf area and fraction healthy leaf area, to the relatively high disease severity of diseased leaf area, and to the lower leaf nitrogen content (Figure 2), which caused reduction in photosynthetic rate (Figure 3) and total dry matter production (Table 1). This is reflected in a relatively low radiation use efficiency for total dry matter production for the crop inoculated at booting.

The effect of BLB on reduction in photosynthesis rate was reported earlier by Reddy et al. (1991). Increased application of nitrogen fertilizer, and earlier inoculation, can result in increased BLB disease severity (Reddy et al., 1979a and 1979b). Scenario studies which incorporate different moments of infection, different disease intensities and different nitrogen levels, can help in exploring the consequences for grain yield.

References

Bastiaans, L. 1991. Quantification of crop growth and yield reduction due to foliar diseases using simulation and systems analysis; description of an approach. SARP - Plant Protection group co-ordinated experiment on bacterial leaf blight, 21 pages.

Morinka, T.H., H. Kaku, M. Hori & T. Kimura, 1978. Applying conditions of the clipping inoculation technique for evaluating resistance of rice to *Xanthomonas oryzae*. Bull. Chugoku Agric. Exp. St. Ser. E. 13: 1- 16.

Narasimhan, V., S. Mohandass, A. Abdul Kareem & S. Palanisamy, 1991. Simulation of the effect of bacterial leaf blight infection at different growth stages on rice yield. In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production (SARP), Pudoc, Wageningen, p. 332-339.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of Ecophysiological Processes of Growth in Several Annual Crops. Simulation Monograph 29, Pudoc, Wageningen and IRRI, Los Baños, 271 pages.

Penning de Vries, F.W.T., H. van Keulen & 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, pp. 513 - 520.

Reddy, A.P.K., D.R. Mackenzie, D.I. Rouse & A.V. Rao, 1979a. Relationship of bacterial leaf blight severity to grain yield of rice. Phytopathology 69: 967-969.

Reddy, A.P.K., J.C. Katyal, D.I. Rouse & D.R. Mackenzie, 1979b. Relationship between nitrogen fertilizer, bacterial leaf blight severity and rice yield. Phytopathology 69: 970-973.

Reddy, P.R., S. Nayak & L. Bastiaans, 1991. Simulation of the impact of bacterial leaf blight disease on rice crop growth and yield. Abstract of paper presented at the International Symposium on Systems Approaches for Agricultural Devolopment, held at the Asian Institute of Technology, Bangkok, Thailand, 2-6 December, 1991.

Simulation of yield loss due to sheath blight of rice in Uttar Pradesh, India

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Introduction

Uttar Pradesh is one of the most important rice growing states in India, where the rice crop is cultivated during the *Kharif* season (May-November) on 5.5 million hectare, and where an average yield of 1.75 t ha^{-1} is reached. The transfer of rice production technology in 19 districts of the state where rice productivity is higher than the state average is one of the responsibility of the G.B. Pant University of Agriculture and Technology (PUAT). One of the major constraints in increasing productivity in these districts is the severe incidence of sheath blight (ShBl), caused by Rhizoctonia solani, which occurs in epidemic form in the irrigated rice ecosystems. The pathogen infects the leaf sheath and blade, and thereby reduces photosynthetic area. In addition, it also interferes with the translocation of photosynthates and increases maintenance respiration. Damage mechanisms and yield reductions caused by the pathogen have not been fully quantified as yet, however, 25% yield reduction has been reported (Hori, 1969).

Most cultivated varieties are susceptible to the disease, and, as a resistant donor is not available, a tolerant/resistant variety will not be developed in the near future. In the absence of resistant varieties, cultural practices, and the use of effective fungicides are the only options left to manage the disease in farmer's field.

Simulation of potential yield loss due to the disease at different levels of disease incidence and at different levels of fertiliser use would be helpful in deciding on application of fungicide(s) to economically control the disease.

Materials and Methods

Field experiment

A field experiment was conducted at Pantnagar, India, in 1992, in a randomized block design with four replications and three treatments, viz. healthy (H), inoculation at maximum tillering (MT) and inoculation at panicle initiation (PI). Cultivar PD4 was sown on June 17 in a nursery and transplanted to a well-puddled field, with plots of 5 × 4.6 m and a hill distance of 20 × 15 cm. Fertilizers were applied at a rate of 120 kg N ha^{-1} and 60 kg P ha^{-1}. N and P were both applied at rates of 60 kg ha^{-1} at transplanting. The remaining 60 kg N ha^{-1} was top dressed in 2 equal splits at maximum tillering and panicle initiation.

Inoculum was prepared from rice stem pieces of 1-1.5 cm length, which were put in conical flasks of 500 ml that contained a 2% sucrose solution. The material was autoclaved for 15 min. at a pressure of 1.05 kg cm^{-2}. The stem pieces were inoculated with the sclerotia of the pathogen and incubated for 7 days at 28 ^{o}C. Inoculations were carried out at 26 August (70 DAS, MT) and at 6 September (80 DAS, PI) by placing infected rice stem pieces in the heart of each hill at the water level.

Each plot was divided in a number of sub-plots, from which samples were collected periodically by harvesting 15 plants at an interval of 15 days. Observations were taken on the phenological development stage of the crop, number of tillers per hill, and plant height.

The leaf canopy was divided into 3 layers, viz. layer 1: canopy below 25 cm; layer 2: canopy between 25 and 40 cm; and layer 3: canopy above 40 cm. The transition of the leaf sheath to the leaf blade was used as reference point.

Plant material was separated in stems + leaf sheaths, panicles, and leaves of the 3 canopy layers. For each canopy layer distinction was made among healthy, diseased (= healthy and dead) and dead leaf area, which resulted in 9 leaf area categories. Leaf area of each category was determined. Disease severity was defined as fraction dead leaf area of diseased leaf area.

Leaves, stems and panicles were oven dried separately, and their dry weights were determined. From this, total dry weight and dry matter partitioning among plant organs were determined. Specific leaf area (SLA) was determined by dividing leaf area and leaf dry weight. SLA × total dry weight on a hectare basis gave an estimate of total leaf area index.

At maturity, final harvest date were obtained from an area of 3.2 × 2 m, which is larger than the areas used for periodic harvests, to increase reliability of data on yield and yield components. The following yield components were observed per replication: number of panicles per hill, number of filled grains per panicle, percentage filled grains per panicle, and 1000 grain weight. Data were averaged to treatment values.

Simulation

L1DFDE was the first version of the standard model for foliar diseases (Bastiaans, 1991) and was an extension of the L1D model (Penning de Vries et al., 1987). With the introduction of ORYZA1, the new model for potential production (Kropff et al., 1994), a new model BLIGHT was developed (Elings, 1994). It requires disease development in time as input, and does not simulate this. A number of other plant characters are determined experimentally and are used as input to the model as forcing functions. Total leaf area (LAI), leaf nitrogen content, and specific leaf weight are model input.

Three types of leaf are distinguished: healthy, diseased and dead leaf area. These are introduced in the model as fractions healthy and diseased leaf area, from which the fraction dead leaf is calculated. Diseased leaf area is additionally described by disease severity of diseased leaf area. The canopy is divided into three leaf layers, which allows a more precise analysis of events, as the disease is not evenly distributed over canopy depth. Daily total gross canopy photosynthesis is calculated per leaf layer (Elings, 1994).

The effect of sheath blight on photosynthesis and respiration of diseased leaf area are introduced in the model as correction factors (between 0 and 1) on initial light use efficiency, assimilation rate at light saturation, and dark respiration, through an effect on maintenance respiration. The values of the correction factors are related to disease severity. Photosynthesis of healthy and dead leaf area are assumed to be unaffected and zero, respectively (Elings, 1994).

Results and Discussion

Field experiment

Leaf area index of the crop inoculated at MT was lower than of both other treatments (Figure 1). Both inoculated treatments were characterized by lower total above-ground dry matter production (Figure 2), green leaf weight (Figure 3), and storage organ weight (Table 1) than the healthy treatment, however, by a higher stem weight. These differences were influenced by the growth stage of the crop at which it was inoculated.

The reduction in panicle density due to the disease in comparison with the healthy crop, although statistically not significant, may be related to the differences in grain yield. The fractions empty grains were significantly higher in the inoculated treatments than in the healthy treatments, and the 1000 kernel weights were significantly lower (Table 1). Inoculation at MT resulted in a higher fraction unfilled grains than inoculation at PI. The 1000 kernel weight and grain yield did not differ significantly between both inoculated treatments (Table 1). This indicates that the moment of inoculation and disease appearance has no significant influence on these yield components. This may be due to the fast spreading nature of the disease, due to which the extent of damage was similar in both treatments.

Table 1. Effect of sheath blight infection on chaffiness, 1000 grain weight and grain yield of cultivar PD4, during the 1992 Kharif season at PUAT, Pantnagar, for the healthy and both inoculated treatments.

Treatment	panicle density	chaffiness	1000 grain weight	grain yield (kg ha^{-1})	
	(m^{-2})	(%)	(g)	observed	simulated
Healthy	285.5	11.49	27.34	5694	7151
Inoculation at MT	257.5	29.36	25.91	4266	6059
Inoculation at PI	269.0	25.77	26.60	4725	4709
CD 5%	52.3	6.64	1.35	553.9	
CV	11.2	13.4	3.0	6.3	

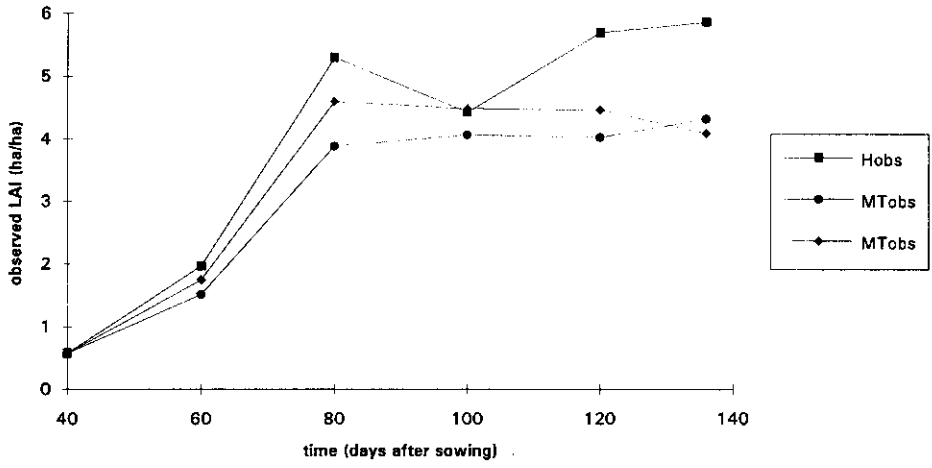

Figure 1. Observed leaf area index for cultivar PD4, during the Kharif season at PUAT, Pantnagar, for the healthy (H) treatment, and the treatments inoculated at maximum tillering (MT) and panicle initiation (PI).

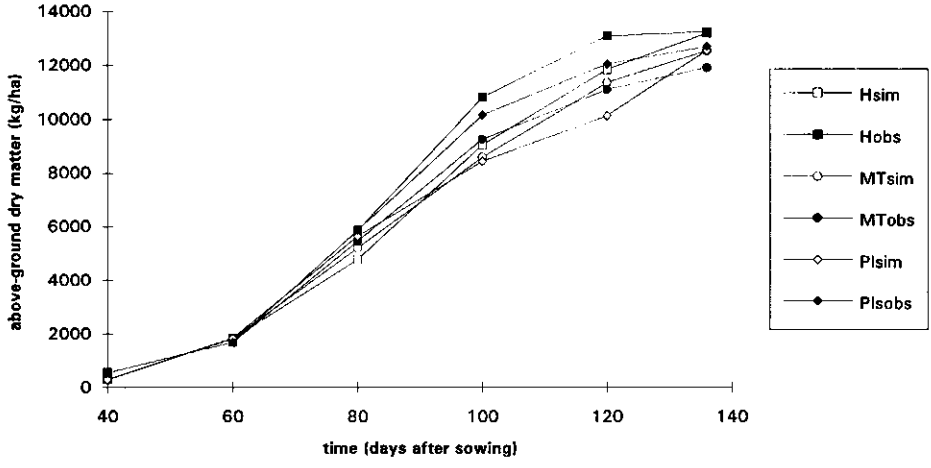

Figure 2. Observed and simulated total above-ground dry matter for cultivar PD4, during the Kharif season at PUAT, Pantnagar, for the healthy (H) treatment, and the treatments inoculated at maximum tillering (MT) and panicle initiation (PI).

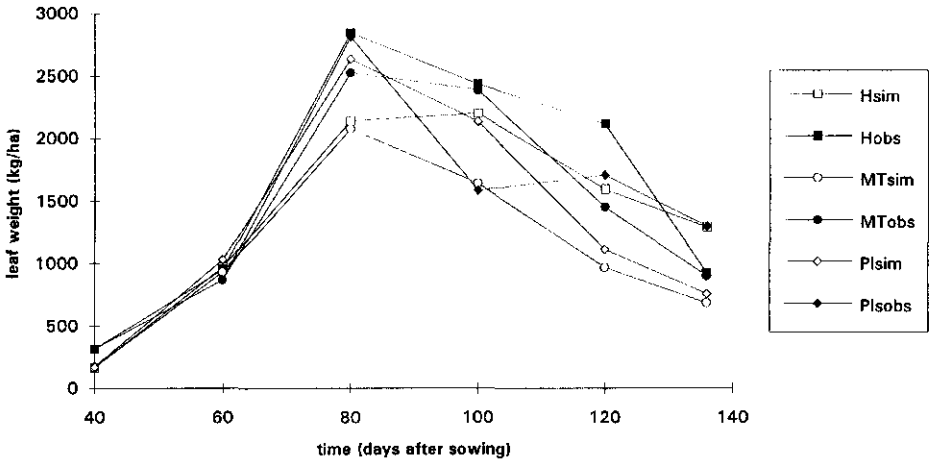

Figure 3. Observed and simulated green leaf weight for cultivar PD4, during the Kharif season at PUAT, Pantnagar, for the healthy (H) treatment, and the treatments inoculated at maximum tillering (MT) and panicle initiation (PI).

Simulation

Simulated and observed total above-ground dry matter in the healthy and inoculated treatments were similar for the MT treatment. For the H and PI treatments, simulated total above-ground dry matter was over-estimated between 80 and 120 DAS (Figure 2).

Green leaf area is the main source of photosynthates. Sheath blight infects leaf sheaths and blades, and therefore reduces the photosynthetic active area. In the un-inoculated healthy treatment, simulated green leaf weight was lower than the observed green leaf weight, except at maturity, when simulated was slightly larger than observed green leaf weight. However, in both inoculated treatments, simulated was lower than observed green leaf weight for the entire growing period (Figure 3).

Simulated stem weight was lower than observed stem weight in the healthy treatment between 80 and 120 DAS. However, observed stem weight dropped considerably (which may be due to some error in observations), and therefore, simulated stem weight was higher than observed stem weight at harvest. In the inoculated treatments, observed and simulated stem weights were similar, which indicates that the model simulates stem weight correctly (Figure 4).

Simulation grain yield was higher than observed grain yield in the healthy and the MT treatment, however was similar to observed grain yield in the PI treatment (Table 1).

On the whole, simulated and observed total above-ground dry matter of all treatments were similar, however, there were differences between simulated and observed storage

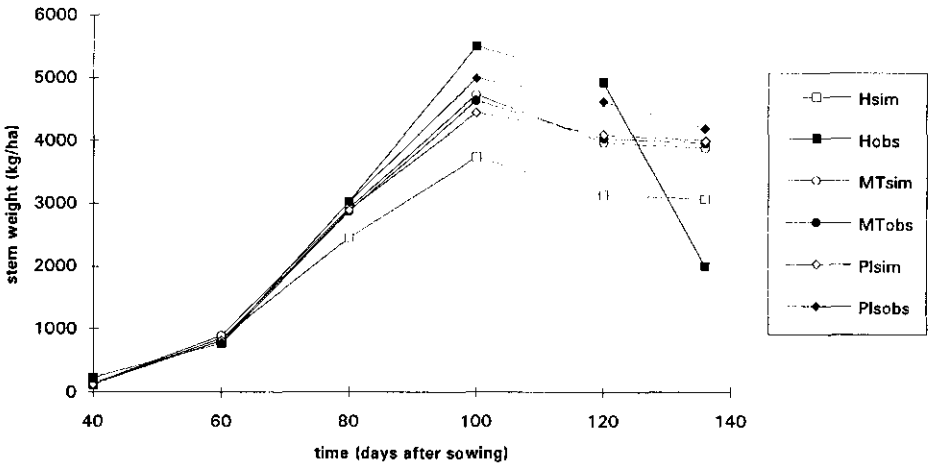

Figure 4. Observed and simulated stem weight for cultivar PD4, during the Kharif season at PUAT, Pantnagar, for the healthy (H) treatment, and the treatments inoculated at maximum tillering (MT) and panicle initiation (PI).

organ weights in the healthy and MT treatments, and between simulated and observed stem weights in the healthy treatment. This may the due to an error in partitioning. Differences were also observed between simulated and observed storage organ weights between the healthy and inoculated treatments at maximum tillering.

Conclusions

1. The BLIGHT model simulated total above-ground dry matter and green leaf weight well in healthy and inoculated treatments. However, simulated stem weight for the healthy treatment differed from observed stem weight.
2. Simulated storage organ weights were higher than observed weights in the healthy and the inoculated treatment at MT. However, simulated storage organ weights of both inoculated treatments were similar. This shows that the simulated crop is sensitive to loss of foliage due to disease at a late crop development stage, but is less sensitive at earlier stages, which may be due to compensation by the plant.
3. The disease caused reduction of panicle density and 1000 grain weight, and increased the fraction unfilled grains.

Model application

Modelling is useful to assess potential yield loss due to sheath blight. However, this study has been conducted for only two disease treatments, at one level of nitrogen application, whereas farmers use sub-optimal to supra-optimal rates of nitrogen application. Nitrogen fertilization increases the rate of disease development. Therefore, it is desirable to study yield losses at different rates of nitrogen application, and for more epidemics, which would enable wider model calibration. After further validation, the model could be integrated in the decision making process for fungicide application.

References

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.

Elings, A. & E.G. Rubia, 1994. Models for the Crop - Pathosystems Rice - Bacterial Leaf Blight, Sheath Blight and Stem Borer. SARP, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños, 102 pages.

Kropff, M.J., H.H. van Laar, R.B. Matthews & H.F.M. ten Berge, 1994. ORYZA1, an ecophysiological model for irrigated rice production. Simulation and Systems Analysis for Rice Production (SARP), IRRI, TPE-WAU, CABO-DLO, 100 pages.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of Ecophysiological Processes of Growth in Several Annual Crops, Simulation Monographs 29, Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, 271 pages.

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

Update of the experimental protocol for bacterial leaf blight and sheath blight experiments

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This text is an update of: A. Elings, 1993. Damage by bacterial leaf blight and sheath blight in rice: a joint experimental approach. In: W.A.H. Rossing, E.G. Rubia, K.L. Heong, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, December 1993, page 119-128. The most important change in the experimental protocal is the reduction of the number of canopy layers from 3 to 2.

Sub sampling

The standard sub-plot size is 15 hills (3 × 5 hills), planted at the distance you desire. As long as resources allow, sample all these 15 hills of the sub-plot for each periodic harvest. When time, labour or other resources become limiting, you can decide to take sub-samples. In sub-sampling, it is important that the harvested plant material is representative for all 15 hills.

This is achieved by splitting each of the 15 hills in 2 parts. You harvest each hill separately, and put the plant material of each hill separately in a plastic bag for transport to the laboratory. Before splitting, you should carefully consider what share of the total amount of harvested tillers you can manage. This may be, for example, 80% in the beginning, when resources are just not sufficient, and may decrease to lower values later on, when the amount of plant material to be analyzed has increased considerably. It is not advisable to analyze less than 25-30% of the total amount of plant material, as otherwise the sub-sample becomes too small to be representative. If you have to reduce the amount of harvested plant material even more, you can better increase the time interval between sampling dates. Somewhere you have to compromise.

Suppose that at some moment you want to split each hill on a 40/60 basis. You do not need to count the number of tillers, but you can take the entire bundle of tillers in your hands, position your fingers such that the 40/60 split is obtained, and pull both parts apart. Repeat this procedure with all 15 hills, which will results in 15 '40%' bundles, and 15 '60%' bundles. Combine all '40%' bundles, and all '60%' bundles, and you obtain two amounts of plant material.

One part, for example the 60% part, will be analyzed for leaf area of fractions healthy, diseased and dead leaf tissue, weights of these fractions and of stem and storage organs, disease severity, and N content of healthy and diseased leaf tissue.

Of the other, 40% part, only the total dry matter will be determined. This is easy to obtain, and will be used later to determine total above-ground dry matter production.

The 60% part of the plant material is split into:
- panicles,
- stems + sheaths,
- leaf layer 1,
- leaf layer 2.

(– leaf layer 3 is optional, see below)

Of the panicles, you determine:
  - dry weight.

Of the stems + sheaths, you determine:
  - dry weight.

Each leaf layer is separated into:
  - healthy leaves (i.e. fully green leaves)
  - diseased leaves (i.e. leaves partly green, partly dead), which is further separated in:
    - green leaf tissue of diseased leaves
    - dead leaf tissue of diseased leaves
  - dead leaves (i.e. fully dead leaves)

For each leaf layer, you determine:
- leaf area of healthy leaves
- leaf area of green leaf tissue of diseased leaves
- leaf area of dead leaf tissue of diseased leaves
- leaf area of dead leaves
- leaf weight of healthy leaves
- leaf weight of green leaf tissue diseased leaves
- leaf weight of dead leaf tissue diseased leaves
- leaf weight of dead leaves
- N content of healthy leaves
- N content of green leaf tissue of diseased leaves

The data can be processed with the EXCEL data sheet and the RAKETJE conversion programme that have been distributed, or can be obtained from the author.

In the case of studies devoted to the natural spread of Sheath Blight, it may be useful to determine the N content of the leaf sheaths, as this may be related to the rate of disease spread.

Leaf layers

Instead of the 3 leaf layer approach adopted so far, in future you may observe two leaf layers, if your research resources are limited. Please bear in mind that a 3 layer split is still better.

Preliminary calculations have indicated that a split in a top canopy layer of 1/3 and a bottom canopy layer of 2/3 of the total leaf area, results in an about similar amounts of light absorption by the two canopy layers.

It is problematic to work with canopy layers as would be obtained if you would simply cut the canopy with a sharp knife in two parts, as then single leaves would be cut in two parts. This would make it difficult to establish the fractions healthy, diseased and dead leaf area. Therefore, the base of the leaf blade is taken as reference, and an entire leaf is assigned to the layer in which its leaf blade base is situated (Figure 1).

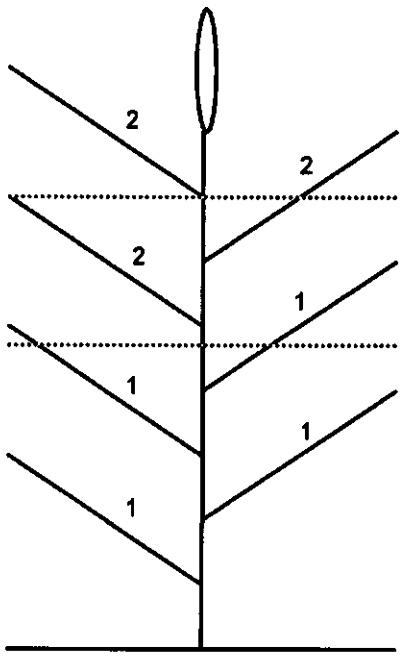

Figure 1. An entire leaf blade is assigned to the canopy layer in which the base of the leaf blade is situated. In this example, the lower 4 leaves are assigned to the bottom layer, and the upper 3 leaves to the top layer.

Please adopt the following approach:

1. Estimate at the beginning of the season, on the basis of your experience with local growing conditions, the height of the base of the flag leaf at anthesis (it is assumed that maximum plant height is reached at anthesis). For example: 90 cm above the root crown.
2. The split will be at 2/3 of this height: 60 cm.
3. As long as the crop is low (less than 60 cm), there is only one canopy layer (Figure 2).

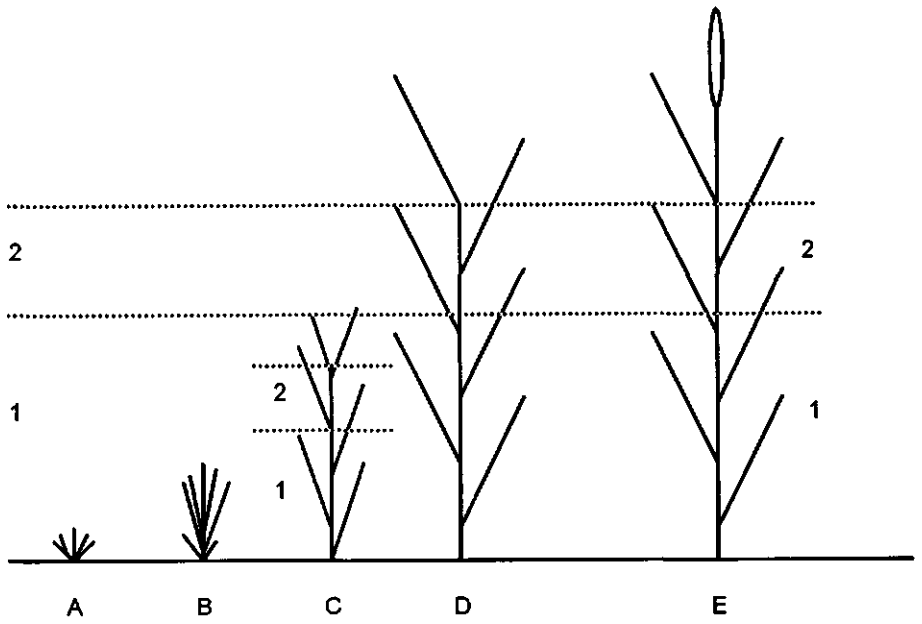

Figure 2. If the plant height exceeds 2/3 of the expected final height, 2 canopy layers are observed. Also, at the date that the crop has been inoculated, the canopy is split in 2 layers.

4. You assume two canopy layers if the highest leaf base is above 2/3 of the estimated height, or if you have inoculated your crop. Whichever comes first (Figure 2).

a. As soon as one leaf blade base is above 2/3 of the estimated height (60 cm), you assume 2 canopy layers. Canopy layer 1, the bottom layer, contains the leaves of which the base is below 2/3 of the expected height (60 cm), and canopy layer 2, the top layer, contains the leaves above this point. As long as the crop has not reached its maximum height, leaf layer 2 may is thinner than the finally expected 1/3 of the final height.

b. As soon as you have inoculated the crop with the disease, you assume two leaf layers. In this case, you establish a 2/3 - 1/3 split on the basis of the actual height of the highest leaf base at the moment of inoculation. A new 2/3 - 1/3 split is made on each observation day.

To run the BLIGHT model, update in the PEST.DAT file the value that defines the number of leaf layers:

IN = 2

Functions that characterize the 3rd leaf layer are still read, however, not used by the model. Do not delete these input functions, as this will cause model termination. Best is to give dummy values, for example:

1.	, 1.,	or	1. , 0.,
366.	, 1.		366. , 0.

Section B

Stem borer

SBORER, a model for the rice - stem borer system

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Introduction

The SBORER model is developed to support the analysis of field experiments in which the effects of the insect pest Stem Borer (SB) on plant growth are determined, to identify research goals, and to explore scenarios with respect to insect population development and grain yield reduction. For that purpose, SBORER accounts for the effects of SB on crop growth and grain yield of rice. With modifications, the model can be applied to other pests as well, such as brown plant hopper.

Within the SARP project, stem borer damage was first simulated by Rubia & Penning de Vries (1990) and Xu & Wang (1991). Xia et al. (1991) coupled the MACROS crop growth model with a population dynamics model. L1DT, which was on MACROS-L1D (Penning de Vries et al., 1989), was the first standard version of a model for stem borer damage (Bastiaans, 1993). With the introduction of ORYZA1, a new model for the production of rice under irrigated lowland conditions (Kropff et al., 1993), version 1 of a new stem borer - rice combination model, based upon ORYZA1, was developed, and distributed within the SARP network. Version 2 of the SBORER model is presented here. The main differences between versions 1 and 2 are:

- Some of the improvements and additions that are included in the latest version of ORYZA1 (Kropff et al., 1994), are incorporated, viz. loss of weight at transplanting, improved simulation of LAI, model termination after a certain number of cold days, and an improved simulation of an N gradient in the ASSIM subroutine.
- If leaf area development is made input, then the relevant input table is read starting at the date that first field observations are available. Before that moment, leaf area is simulated.
- Tiller and grain dynamics have been improved, and are now easier to calibrate.
- Intercepted photsynthetically active radiation and crop light use efficiency are calculated.
- Facilities for simple sensitivity analysis and exploration studies have been introduced.

SBORER was originally written in CSMP, however, version 2 is only available in FORTRAN77, and is compatible with the support software Fortran Simulation Environment (FSE) (van Kraalingen, 1991) and the SARP 'COME-ON' Shell (van Riethoven, 1994), which facilitate application of FORTRAN models, and offer a wide range of op-

tions with respect to data management and generating reruns. The Fortran Simulation Environment (FSE) is an environment for continuous simulation of crop growth. It consists of a main program (MAIN), a general model subroutine (MODELS), weather data and utilities to perform specific tasks. The WEATHER system (van Kraalingen et al., 1990) is used to read weather data, and utilities from the TTUTIL library (Rappoldt & van Kraalingen, 1990) are used for performing specific tasks, such as handling of input and output files, and integration of states. The model equations are defined in one or more subroutines. FSE distincts four main tasks (ITASKs) which control the order of calculations in the crop growth program, and which resemble the structure of crop growth models written in CSMP (ITASK 1 to 4, for initialization, rate calculations, state calculations, and terminal, respectively). Relevant subroutines are called under each of the tasks, to compute task-specific variables.

Model structure

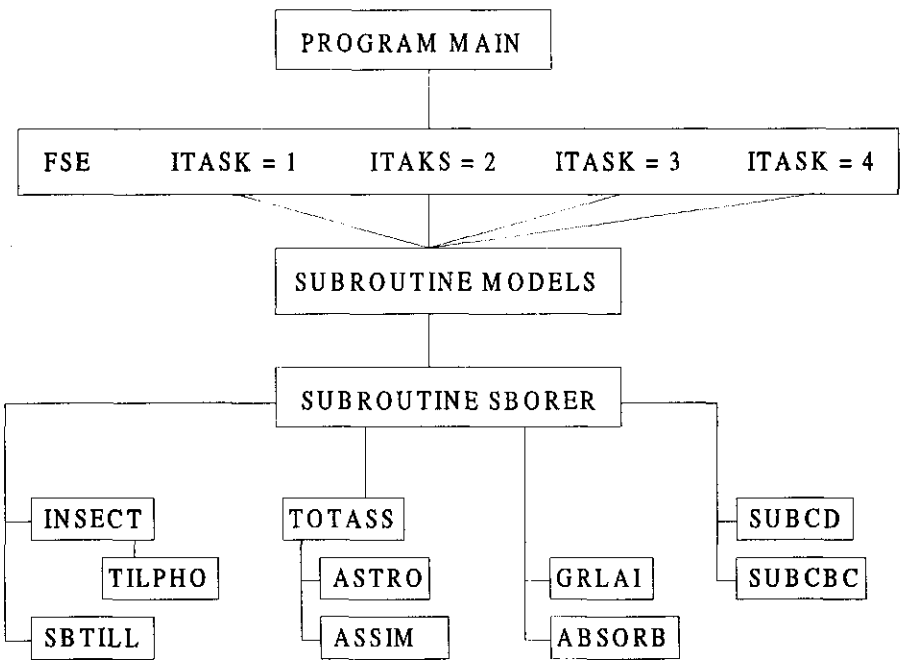


Figure 1. The SBORER model under the FSE simulation environment.

SBORER is a model with sections on crop growth and development, and sections which account for plant x pest interactions. The basic structure of the model is similar to ORYZA1 (see for a full explanation Kropff et al., 1994). However, because of many inter-

actions between host and pathogen, statements have been re-arranged considerably. The complexity of the model is increased by the many growth rates, loss rates, weights, and photosynthesis and maintenance calculations for all tiller classes. The model structure is given in Figure 1. The SBORER subroutine is called by the general MODELS subroutine, and SBORER calls directly or indirectly subroutines with specific tasks. Subroutine INSECT calculates growth and loss rates of plant organ weights, and integrates these rates; subroutine SBTILL accounts for the interaction between stem borer infestation and tiller dynamics; and subroutine TILPHO calculates assimilation and maintenance respiration rates of different plant organs. In addition, subroutine ABSORB calculates intercepted photosynthetically active radiation and light use efficiency. Subroutines TOTASS, ASTRO, and ASSIM compute canopy photosynthesis. Leaf area dynamics are computed by GRLAI; model termination after a certain number of cold days is handled by subroutine SUBCD; and subroutine SUBCBC performs the carbon balance check

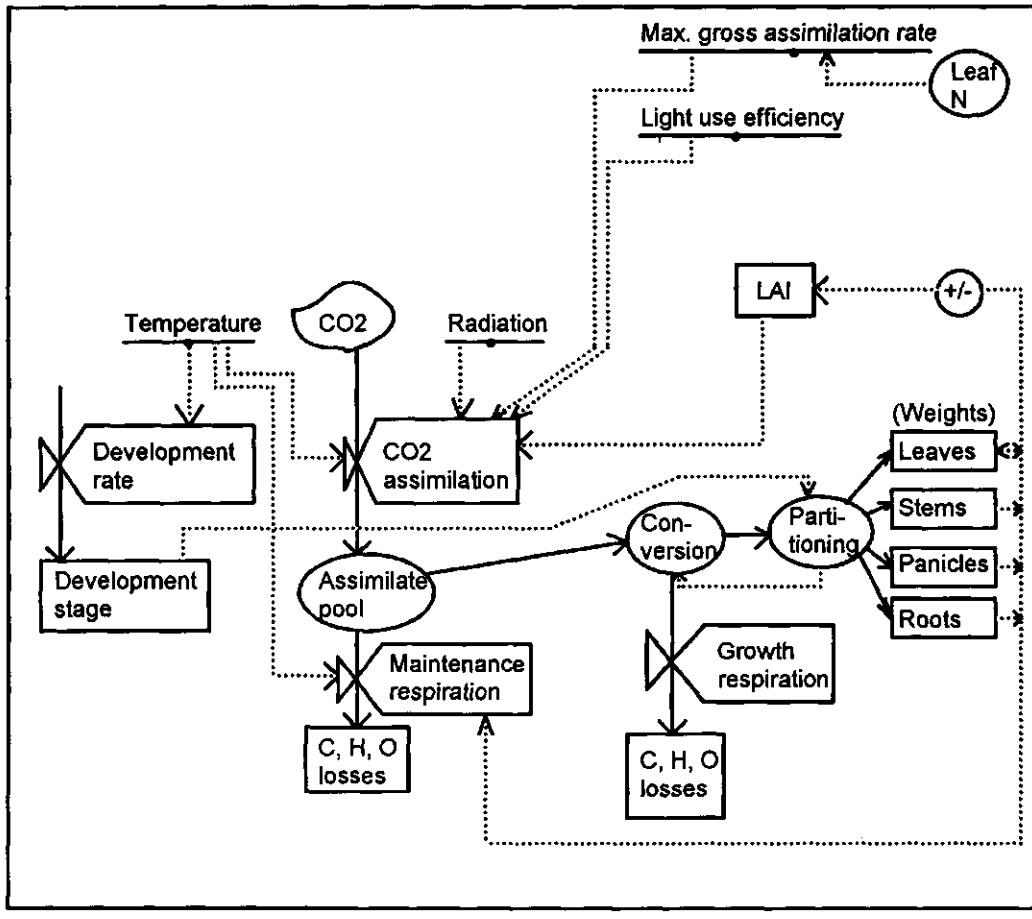
The general structure of the SBORER (Figure 2) is very similar to that of ORYZA1. Total daily rate of canopy CO_2 assimilation is calculated from the daily incoming radiation, temperature and leaf area index, by integrating instantaneous CO_2 assimilation. Photosynthesis characteristics of a single leaf depend upon leaf nitrogen concentration. After subtraction of respiration requirements, the net daily growth rate is obtained. The dry matter produced is partitioned among the various plant organs. The SBORER model is detailed with respect to calculation of growth and loss rates and weights of plant organs (leaves, structural stem material, stem reserves, roots, storage organs) of healthy tillers, dead hearts and white heads. Phenological development is tracked as a function of ambient daily average temperature. When the canopy is not yet closed, leaf area increment is calculated from the daily average temperature, as carbohydrate production does not limit leaf expansion. After canopy closure, 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. High and low temperatures result in spikelet sterility and sink limited grain filling (after Kropff et al, 1994).

Healthy tillers are potentially productive tillers (i.e. a tillers bearing a panicle with filled grains) if they are formed before a certain crop development stage, and healthy tillers that are formed later are defined as unproductive tillers. Stem borer infestation may result in dead hearts and white heads, dependent on the crop development stage. A dead heart is an infested tiller without a panicle, which dies after a given time. A white head is an infested tiller with a panicle, which dies at the same relative rate as uninfested tillers. Dead hearts and white heads are formed roughly during the crop vegetative and reproductive phases, respectively. An unproductive tiller that is infested becomes by definition a dead heart, a productive tiller that is infested becomes either a dead heart or a white head, dependent on the moment of infestation in relation to crop development stage. Potentially productive tillers are subjected to stem borer infestation and natural death only if unproductive tillers are not present.

Productive tiller density and the temperature regime determine the growth of grain density, and loss of productive tillers due to stem borer infestation or crop condition causes reduction of grain density. Grain density and carbohydrate production after onset of grain filling determine sink and source capacity, respectively. Sink and source capacity are compared, and the growth rate of storage organs is computed.

The SBORER model does not simulate insect dynamics, but requires stem borer infestation rate (SBINFR) as input, just as a number of plant characteristics need to be determined experimentally and introduced in the model as forcing functions. SBINFR is a relative rate, which is a function of the day of the year, and which defines the fraction of healthy tillers that is infested at particular dates. SBINFR is also used to determine the weight increments of the plant organs of infested tillers. The same input function is used in case of a clipping experiment (for which a switch, viz. SWICLI, has to be set to 1).

For the analysis of experimental data, or specific data that serve the study of a certain event, leaf area index (LAI) is preferably made input. However, there is a large difference between the analysis of experiments, in which damage mechanisms are studied, and exploration studies or sensitivity analyses, in which the effect of variation in infestation on



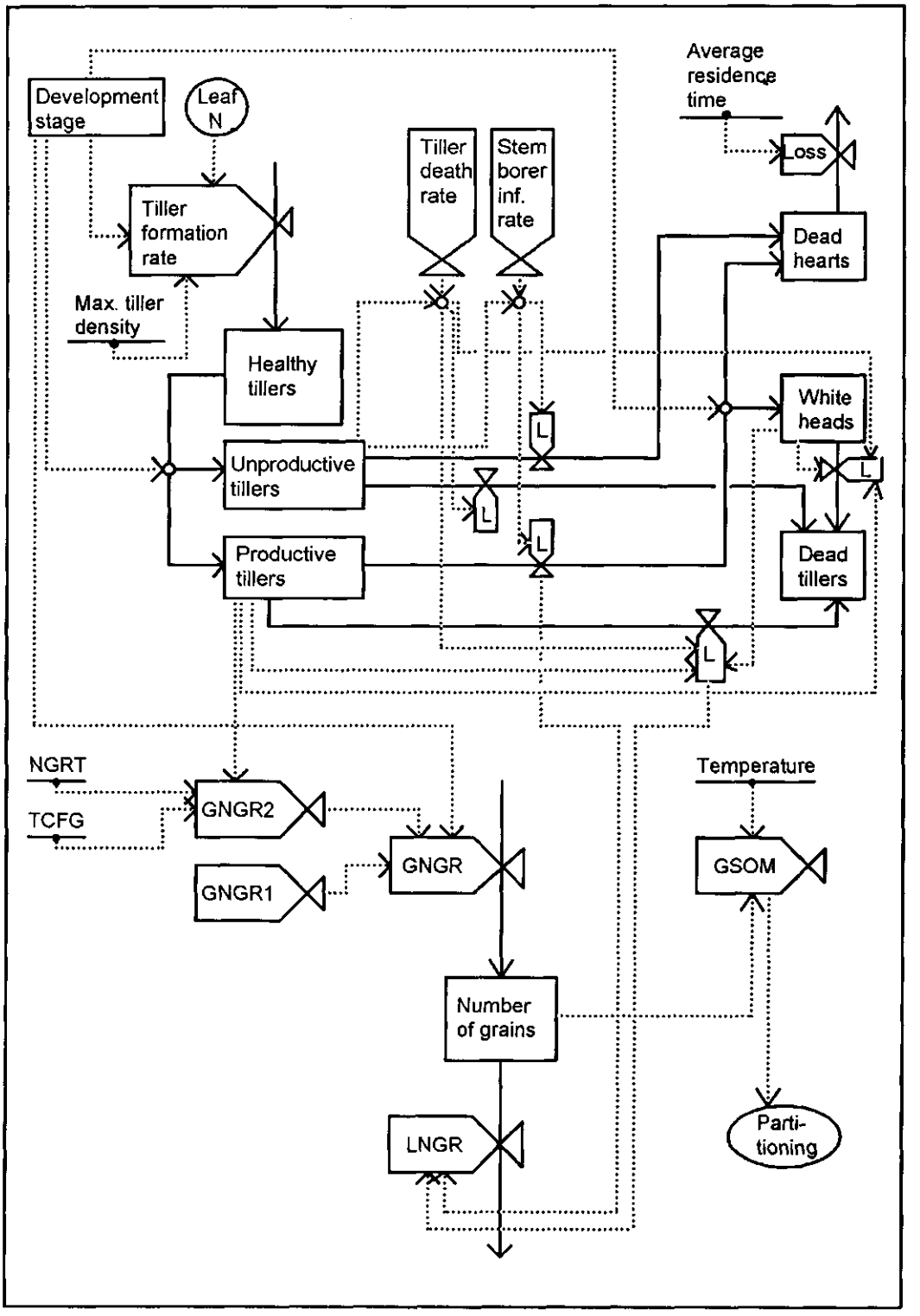


Figure 2. A schematic presentation of the model SBORER.

green leaf area and growth are studied. The latter require feed backs between growth and leaf area. For instance, an earlier onset of the epidemic may cause reduced growth, which results in a lower leaf area, which subsequently may cause even more reduced growth, etcetera. A fixed LAI in this case would probably lead to an over-estimation of crop growth.

Photosynthesis

Leaf photosynthesis can be described by an asymptotic exponential, the photosynthesis light response curve (Goudriaan, 1982):

$A_{net} = (A_{max} - R_d) \bullet (1 - e^{-I_a \cdot \varepsilon / A_{max} - R_d})$, in which

A_{net}:	net CO_2 assimilation rate for leaves	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}],
A_{max}:	maximum rate of net CO_2 assimilation rate for leaves at high light intensities,	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}]
I_a:	absorbed photosynthetic active radiation	[J m^{-2} s^{-1}], (PAR)
ε:	initial light use efficiency	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}/(J m^{-2} s^{-1})],
R_d:	dark respiration	[kg CO_2 ha (leaf)$^{-1}$ h^{-1}].

The SBORER model does not account for any effect of insect infestation on crop photosynthesis. However, there are indications (Rubia, in press) that the green leaves of infested tillers show an increased net rate of leaf photosynthesis, which could be related to nitrogen translocation from infested to healthy tillers.

Daily total gross assimilation (DTGA) is calculated in the subroutines ASTRO, ASSIM and TOTASS on the basis of the total green (leaf and stem) area. Total green area is the sum of the green areas of healthy tillers, dead hearts and white heads. For a detailed approach, in which growth and loss of all plant organs for all tiller classes are monitored, it is necessary to determine assimilation per tiller class. Therefore, crop DTGA is distributed over these three tiller classes proportionally to their green leaf weights. It is assumed that the specific leaf weight of leaves of all tiller classes is similar.

Just as photosynthesis, maintenance respiration has to be distributed over the three tiller classes. This is done on the basis of their plant organ weights. Dead hearts do not carry grains, and therefore have no maintenance costs related to WSO.

Like in ORYZA1, light interception by dead leaf area is ignored, assuming that most senescence occurs low in the crop profile where the consequences for photosynthesis are relatively low.

Photosynthesis and maintenance calculations per tiller class and plant organ are placed in a separate subroutine, TILPHO, which is called by subroutine INSECT.

Light use efficiency

Crop growth rate is approximately linearly related to absorbed photosynthetically active radiation (PAR_a) by green foliage (Monteith, 1977) under conditions of unlimited availability of moisture and nutrients, and absence of pests and diseases, which results in a constant amount of biomass produced per PAR_a (Biscoe and Gallagher, 1977), or crop light use efficiency (CLUE, Rossing et al., 1992). The effects of stem borer infestation on crop growth can be analyzed in terms of intercepted light (LI) and CLUE, thus distinguishing between effects on photosynthetic area and activity per unit photosynthetic area, respectively (Rossing et al., 1992). Absorbed photosynthetically active radiation by total green area is calculated per canopy layer with Beer's law:

$$PAR_a = (1-r_c) \cdot PAR_0 \cdot (1-e^{-k \cdot LAI})$$

PAR_a:	absorbed photosynthetically active radiation		($J\ m^{-2}\ s^{-1}$)
PAR_0:	photosynthetically active radiation above the crop canopy		($J\ m^{-2}\ s^{-1}$)
r_c	:	reflection coefficient for a green crop surface averaged over a day	(-)
k	:	extinction coefficient	(-)

Subroutine ABSORB, which is called by the BLIGHT subroutine, uses a value of r_c of 0.08, and calculates PAR_a. Crop light use efficiency is daily calculated as the slope of the relation between daily PAR_a (independent variable) and daily crop growth (dependent variable). As daily CLUE tends to be very variable, average CLUE over the last 10 days is calculated.

Stem borer infestation

Stem borer infestation (SBINFR) is a relative rate, introduced in the model as the fraction healthy tillers that is infested by stem borers, as a function of the day of the year, and not (!) as insect density in the crop, or number of egg masses introduced per hill.

By setting the switch SWITIL to 0, numbers of healthy tillers, dead hearts and white heads that have been observed are made model input. In that case, the number of observed new dead hearts or white heads on a particular day, in relation to the number of healthy tillers, is used to calculate SBINFR, which is subsequently used elsewhere in the model. SWITIL = 1 invokes simulation of tiller dynamics (see next section).

Tiller and grain dynamics

Tiller and grain dynamics, as influenced by stem borer infestation, ambient temperature, and leaf nitrogen content, are accounted for by subroutine SBTILL. This subroutine is based upon the MACROS-TIL module (Penning de Vries et al., 1989), the SWHEAT model by van Keulen & Seligman (1987), and the subroutine SUBGRN in the ORYZA1

model (Kropff et al., 1994). The subroutine SBTILL determines densities of healthy tillers, dead hearts, white heads, and kernels, and sink-limited maximum grain filling rate. The dependency of tiller formation rate on leaf nitrogen content is central to the model.

The tiller module must be carefully calibrated, as the grain density determines the crop's sink capacity, which limits the grain filling rate at high stem borer infestation rates in the crop reproductive phase.

Tiller formation and death

Tiller formation is influenced by three factors: crop development stage, leaf nitrogen content, and maximum tiller density. Tiller formation is restricted to the period between development stages DVST1 and DVST2 (see Table 1), and is further limited to the period after the transplanting shock. Maximum tiller density (TILMX) is the maximum number of tillers per ha that can be achieved under given growing conditions, i.e. the maximum that has been observed in the concerned experiment, as it is difficult to determine the genetic maximum. Possible tiller formation in the seed bed is not accounted for. Tiller formation comes to an end at the moment TILMX, or DVST2, is reached.

Table 1. Observed and calibrated parameter values that are used in simulation of tiller and grain dynamics, for three experiments. Calibration results are given elsewhere in this volume.

Parameter	Dimension	Value				
		Rubia IR64	Rubia Binato	Xu IR64	Elings IR64	Average of range
DVST1	(-)	0.43*	0.28*	0.27*	0.52	0.40
DVST2	(-)	0.84*	0.69*	0.58*	1	0.79
DVST3	(-)	0.43*	0.69*	0.35*	0.52	0.52
DVST4	(-)	1.44*	1.37*	0.75*	1.57	1.16
DVST5	(-)	0.75*	0.75*	0.50*	-	0.63
DVSWH	(-)	1.25*	1.20*	1.07*	-	1.16
ARTDH	(d)	14	14	14	-	-
WGRMX	(kg)	25.5E-6*	24.0E-6*	21.1E-6*	23.5E-6*	-
NGRT	(tiller^{-1})	60*	130*	96.4*	100	-
TILMX	(hill^{-1})	40*	36*	48*	26	-
TILDTH	(d^{-1} ha^{-1})	1.E5	2.E4	2.5E4*	2.5E4*	-

* = observed value

Tiller formation rate is calculated as a function of leaf nitrogen content. Makarim et al. (1994) have related tiller formation and death to straw nitrogen content. In early tillering phases, when stem weight is relatively small, leaf nitrogen and straw nitrogen contents will be about similar. Although the data presented by Makarim et al. (his Figure 8) show much data scatter, the thick line in Figure 3 was derived from their data set. This corresponds with data from Xu et al. (this volume).

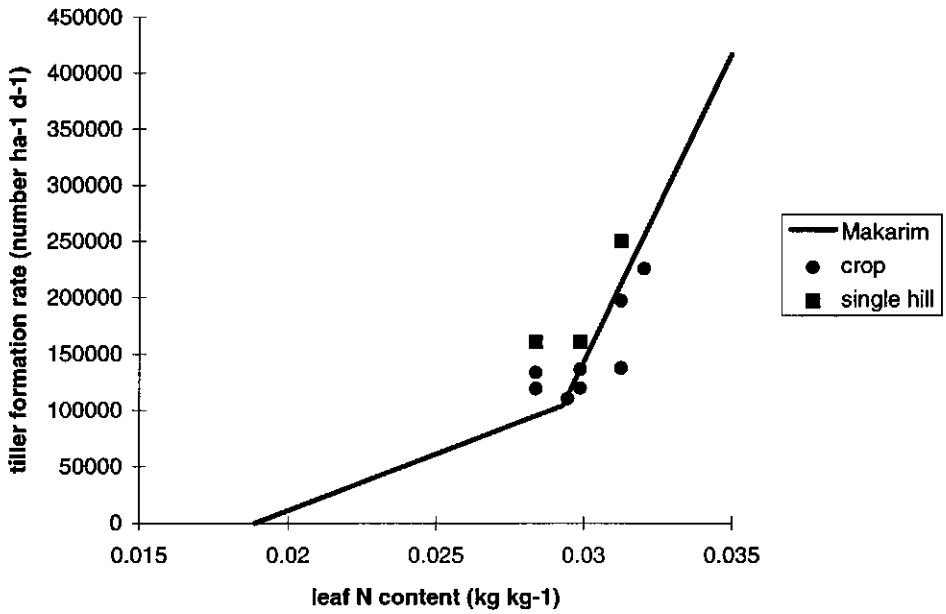


Figure 3. Tiller formation rate as a function of leaf nitrogen content (data from Makarim et al., 1994; Xu et al., 1994).

Tiller death due to crop condition is determined by the crop development stage, and is restricted to the period between development stages DVST3 and DVST4 (see Table 1). From the data presented by Makarim et al. (1994), which show wide variation, an average death rate of 50,000 ha^{-1} d^{-1} can be calculated (with a maximum of about 100,000 ha^{-1} d^{-1}); and Xu et al. (this volume) present an average tiller death rate of 20,000 - 25,000 ha^{-1} d^{-1} (with a maximum of about 50,000 $^{-1}$ d^{-1}). As tiller death due to crop condition affects both healthy tillers and white heads, the number of dying tillers on a certain day is distributed proportionally over healthy tillers and dead hearts at that day.

Xu et al. (this volume) have reported 7% reduction in tiller density during the a transplanting shock of 9 days duration. As other data are lacking, this process in not accounted for.

It is assumed that stem borers only infest healthy tillers; therefore, tiller loss rate due to stem borer infestation is calculated on the basis of healthy tiller density and stem borer

It is assumed that stem borers only infest healthy tillers; therefore, tiller loss rate due to stem borer infestation is calculated on the basis of healthy tiller density and stem borer infestation rate. The loss rate of healthy tillers due to stem borer infestation is equal to the growth rate of dead hearts or white heads, dependent on the crop development stage. Dead hearts are formed before crop development stage DVSWH (see Table 1), and white heads are formed after that stage.

(Field observation may give rise to some confusion. Infestation of a tiller during booting results in a dead heart, as the panicle has not yet emerged. As the panicle may or may not emerge, this tiller may remain a dead heart, or become a white head. DVSWH is therefore a particular development stage that represents a longer period, and is difficult to determine exactly.)

Loss off dead hearts is determined by the average residence time of a dead heart (ARTDH), with a default value of 14 days. Loss due to crop condition, if existing, is incorporated in the average residence time.

Total tiller density is the sum of the densities of healthy tillers, dead hearts, white heads, and dead tillers.

Productive and unproductive tillers

Not all tillers will bear a productive panicle. Explanatory simulation of productive panicle density would require a detailed approach of organ formation. Here, a more descriptive approach is taken. It is assumed that all tillers that are present at development stage DVST5 (see Table 1), will bear a productive panicle, and that all tillers that are formed afterwards, will not bear a panicle, or will bear an unproductive panicle. As only the number of productive panicles is important, no distinction is made between tillers without a panicle, and tillers with an unproductive panicle. Both groups are referred to as 'unproductive tillers'.

Reduction in number of healthy tillers, due to stem borer infestation, or due to crop condition, affects first the number of unproductive tillers. Only after the number of unproductive tillers has reduced to zero, the number of productive tillers reduces. This approach takes into account that a rice crop will give priority to maintenance of its (re)productive tillers, and that stem borer insects have preference for young, relatively small tillers (Rubia, in press).

The various crop development stages, and tiller formation and loss rates that they determine, are illustrated in Figure 4, which is based on the average DVST1-5 values given in Table 1. Tillering starts at DVS 0.4 and continues up to DVS 0.79. Tiller death starts at DVS 0.52, and ends at DVS 1.16. The number of productive tillers is fixed at DVS 0.63, and continued tiller formation between DVS 0.63 and 0.79 results in unproductive tillers. Tiller death first affects the density of unproductive tillers, however, as the amount of unproductive tillers is not sufficient, the density of productive tillers also reduces slightly after DVS 0.79 (Figure 4a). Densities of healthy and productive tillers are similar at the end of the season in this example; in case of a lower tiller death rate, the final density of

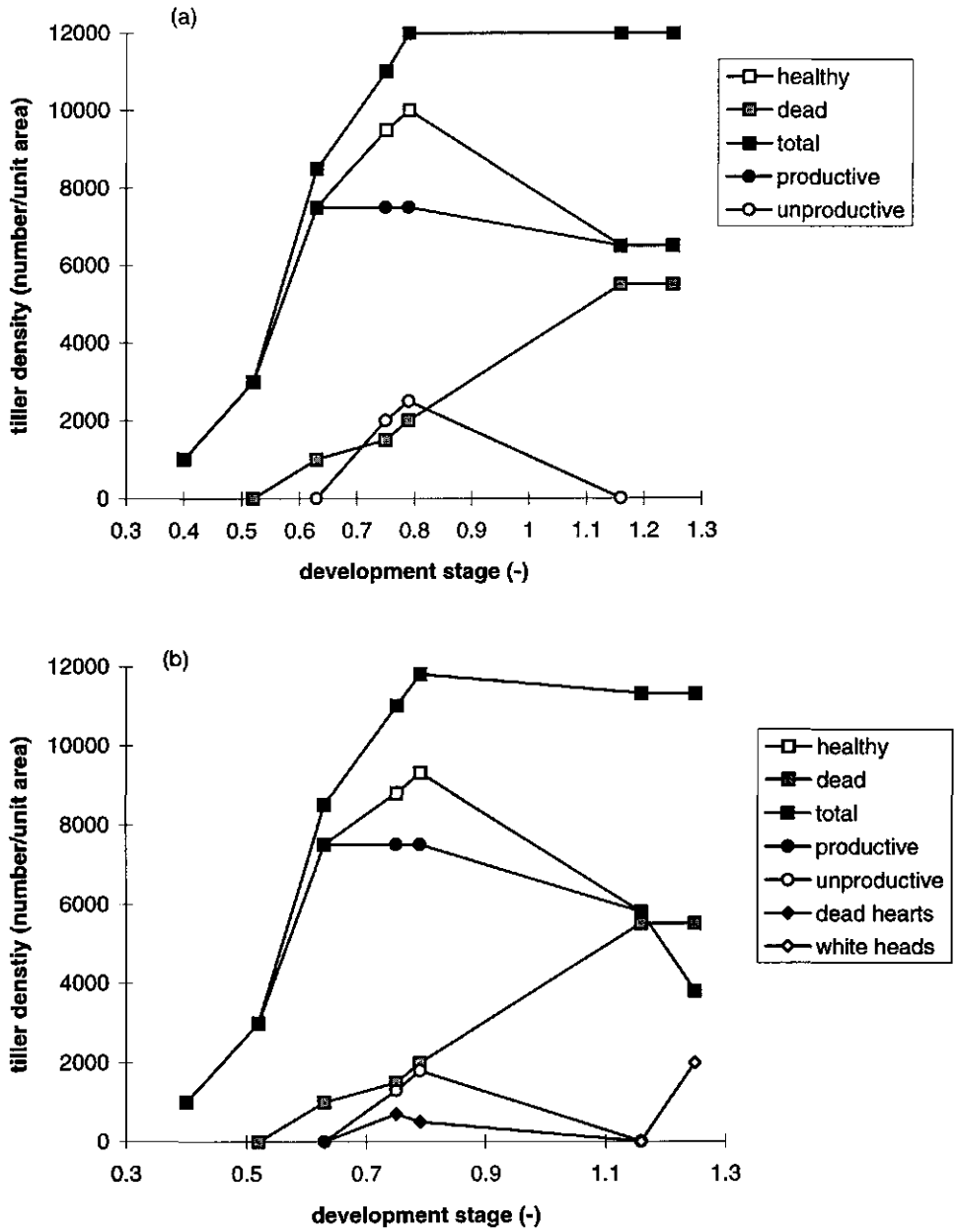


Figure 4. Examples of tiller dynamics of a healthy (a) and infested crop (b).

In case of stem borer infestation (Figure 4b), dead tiller density does not change. Dead hearts are formed at the cost of unproductive tillers, which reach a lower density than in case of a healthy crop (cf. Figure 4a). Dead hearts disappear from the crop, and therefore, total tiller density reduces. White heads are formed after DVS 1.16, and as the amount of unproductive tillers is lower than the amount of white heads formed, the number of productive tillers reduces.

Grain dynamics

Simulation of grain dynamics in ORYZA1 and SBORER are similar. The purpose of simulation of grain dynamics is to determine the sink's demand for carbohydrates, which is compared with the source's supply. This comparison results in determination of the actual grain filling rate (storage organ growth rate).

The maximum growth rate of one grain (GGRMX) has a maximum potential of 1 mg d^{-1} (estimated from Yoshida, 1981, figures on page 58), and is related to the maximum weight of one grain (WGRMX) and the filling period of one grain (GFP). WGRMX is model input, and can best be based on the highest observed 1000 kernel weight in a particular experiment. GFP is calculated from the post-anthesis crop development rate (DVR).

The maximum sink-limited grain filling rate (GSOM) is determined by grain density (NGR), a temperature effect (TEFG, Figure 5, Penning de Vries et al., 1989), and GGRMX.

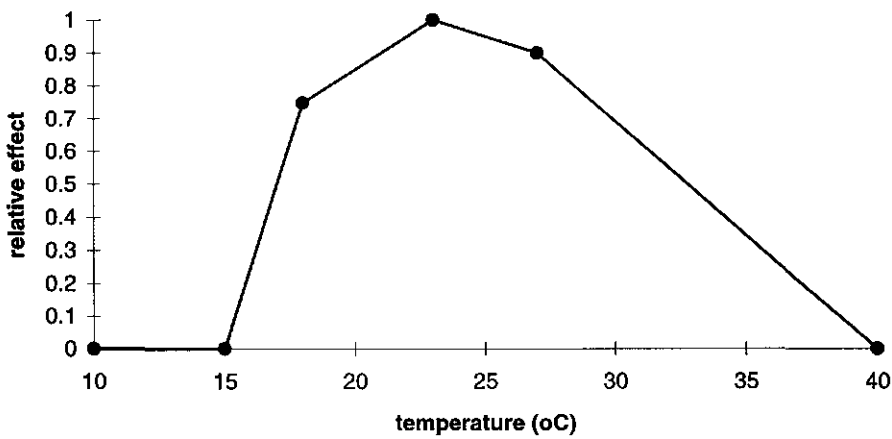


Figure 5. The temperature effect on grain filling rate (data from Penning de Vries et al., 1989).

```
GFP    = 1./(1.33*DVR)
GGRMN  = WGRMX/GFP
GGRMX  = AMIN1(GGRMN*2.,1.E-6)
GSOM   = NGR*GGRMX*TEFG
```

The temperature-dependent grain formation rate (GNGR1), which is calculated as in ORYZA1 (Kropff et al., 1994), accounts for the effects of low temperatures on fertility. In addition to this limitation, the number of grains is determined by the number of productive tillers (PROD), the maximum number of grains per productive tiller (NGRT) as observed in the particular experiment, and the time constant for grain formation (default value 3 d^{-1}). Stem borer infestation may reduce the number of productive tillers, and therefore grain density.

```
NGRMX  = PROD * NGRT
GNGR2  = (NGRMX-NGR)/TCFG
GNGR   = MAX(0.,MIN(GNGR1,GNGR2))
```

Reduction of grain density occurs if there is loss of productive tillers. In that case, relative loss rate of grains (LNGR) and productive tillers are assumed equal. Integration of the difference between grain growth and loss rates, over time, results in grain density.

```
NGR    = INTGRL(NGR,GNGR-LNGR,DELT)
```

Finally, the minimum of GSOM and the source limited growth rate of storage organs (GSOX) is the simulated growth rate of storage organs (GSO).

Validation

Simulation of tiller and grain dynamics was calibrated on three data sets that are presented in this Volume, viz. Elings (IRRI, 1993), Rubia (IRRI, 1993) and Xu (Hangzhou, 1993). As far as possible, observed data were used for model calibration (Table 1). The calibration results are presented elsewhere in this volume, in the respective contributions of the authors. The range that the calibrated parameters can take is wide.

Plant organs and tiller classes

SBORER calculates the weights of five plant organs, viz. leaves, structural stem material, stem reserves, storage organs, and roots. Healthy tillers and white heads possess all these organs, whereas dead hearts can by definition not possess storage organs (Table 2). White heads can theoretically possess storage organs in case of a stem borer infestation after grain filling has started. Roots are not considered to be linked to a particular tiller, and root

weight is distributed over all tiller classes to enable detailed calculation of maintenance respiration.

Table 2. Plant organs of healthy tillers, dead hearts and white heads.

tiller class	leaves	structural stem material	stem reserves	storage organs	roots
healthy tillers	x	x	x	x	x
dead hearts	x	x	x		x
white heads	x	x	x	(x)	x

Growth and loss rates

Growth and loss rates, and weights of all plant organs of healthy tillers, dead hearts and white heads are calculated in subroutine INSECT, which is called from the SBORER subroutine.

Growth rates

Carbohydrate requirement for dry matter production of the entire crop (CRGCR) is in ORYZA1 calculated on the basis of the fractions of total dry matter allocated to the plant organs and carbohydrate requirements for organ production. CRGCR is used, together with crop maintenance respiration rate (RMCR) and daily total gross assimilation (DTGA), to calculate crop growth rate (GCR). Subsequently, GCR is split in plant organ growth rates on the basis of the fractions of total dry matter allocated to the respective plant organs.

This compact approach to calculate crop and organ growth rates can not be used in SBORER. The fractions total dry matter allocated to the organs are in fact potential fractions. In case of a severe stem borer infestation after anthesis, a substantial part of the grains can not be filled, and as a consequence grain filling becomes a sink-limited process with a lower actual fraction of carbohydrates allocated to the storage organs. Calculation of CRGCR with potential fractions is therefore not accurate, and will cause a error in the carbon balance check and termination of simulation. Therefore, first, various organ growth rates are calculated from their respective carbohydrate requirements and actual fractions carbohydrates allocated. Subsequently, crop growth rate is obtained by adding plant organ growth rates.

Per tiller class, the amount of carbohydrates needed for growth is calculated. In the case of dead hearts, the effect of loss of stem reserves does not need to be accounted for, as this occurs only after anthesis, when dead hearts are not formed. It is assumed that particular fractions of carbohydrates formed by dead hearts and white heads are translocated to

healthy tillers. Gines et al. (1994) have reported 30-50 % translocation from white heads to productive tillers. The translocation fractions (FTRDH and FTRWH, respectively) are input parameters, and include the assimilates required for root growth (if any) of white heads. The values of FTRDH and FTRWH are set to 0.5 and 0.75, respectively, however, the model has to be calibrated for these parameters on the basis of observed tiller weights.

Table 3. Growth rates in SBORER. Particular fractions (model input) of assimilates produced by dead hearts and white heads is translocated to healthy tillers. Dead hearts do not have storage organs. All roots are allocated to healthy tillers to calculate root growth.

Tiller class plant organ	assimilation	translocation within tiller	translocation from dead hearts	translocation from white heads
Healthy tillers				
leaves	x	x	x	x
structural stem material	x	x	x	x
stem reserves	x	x	x	x
storage organs	x	x	x	x
roots	x	x	x	x
Dead hearts				
leaves	x	x		
structural stem material	x	x		
stem reserves	x	x		
roots	allocated to healthy tillers			
White heads				
leaves	x	x		
structural stem material	x	x		
stem reserves	x	x		
storage organs	set to 0	set to 0		
roots	allocated to healthy tillers			

Growth rate of storage organs of healthy tillers (GSOHL) is limited by the supply from the source (GSOX), and the maximum growth rate (GSOM) set by grain density and potential grain filling rate. The difference (DIFF) is added to the growth rate of stem reserves of healthy tillers (GSTRHL).

```
GSOX   = GCRHL2 * FSH * FSO
GSOHL  = AMIN1(GSOM*CRGSO,GSOX)                /CRGSO
DIFF   = AMAX1(0.,GSOX-GSOM*CRGSO)
GSTRHL = (GCRHL2 * FSH * FST * FSTR + DIFF)    /CRGSTR
```

It is assumed that assimilates formed by white heads and not translocated to healthy tillers, are equally distributed over stems and leaves. White heads are formed after DVSWH, when allocation of assimilates to leaves and stems has reduced in favour of storage organs. It is not clear whether growth of storage organs continues, or whether this process stops and most assimilates are translocated to the healthy tillers. In the model, growth of storage organs of white heads (GSOWH) is set to 0.

Finally, overall growth rates are calculated. Any root growth is directly supported by healthy tillers, and indirectly by infested tillers through translocation of assimilates to the healthy tillers. Partitioning tables have to be based upon partitioning of assimilates in healthy tillers only. Partitioning in a healthy and in an infested crop may differ, and therefore are experiment-specific.

An overview of all growth rates is given in Table 3.

Loss rates

Dry matter loss of plant organs of healthy tillers due to stem borer infestation or clipping are obtained by multiplication of the plant organ weights of healthy tillers with the relative loss rate SBINFR. In order to simulate a clipping experiment, the switch SWICLI has to be set to 1. In case of a stem borer experiment, there is growth of plant organ weights of infested tillers, which is equal to the respective loss rates of healthy tillers. In case of a clipping experiment, removal rates are calculated.

Leaf weights of healthy tillers and white heads will reduce due to senescence. This is in both cases determined by the relative senescence rate DRLV, which is an input function of crop development stage.

The average residence time of dead hearts (14 days) is used to calculate loss rates of plant organs of dead hearts. As the disappearance includes all forms of death, no additional calculations are made (such as for senescence).

Stem reserves of healthy tillers and dead hearts are lost due to translocation, which is determined by a time coefficient (TCLSTR). This approach is similar to the one of ORYZA1.

Various loss rates are summarized in Table 4.

Table 4. Loss rates in SBORER. Roots do not die; roots of disappeared dead hearts are re-distributed to healthy tillers and white heads. Structural stem material and storage organs of white heads do not disappear.

Tiller class & plant organ	infestation	senescence	disappearance	translocation
Healthy tillers				
leaves	x	x		
structural stem material	x			
stem reserves	x			x
storage organs	x			
Dead hearts				
leaves			x	
structural stem material			x	
stem reserves			x	
White heads				
leaves		x		
structural stem material				
stem reserves				x
storage organs				

Leaf area development

Leaf area can be simulated by setting SWILAI to 1, which activates subroutine GRLAI. This option can best be chosen for scenario studies, sensitivity analyses, and other situations which require a feed backs between crop growth and leaf area development. If an experiment is analyzed, and if leaf area has been observed, then this can be made input by setting SWILAI to 0. Up to the day that first observations have been taken, LAI is simulated, and afterwards, LAI is read from the PEST.DAT input file.

References

Bastiaans, L., 1993. Damage by Stem Borer in Rice: a Quantitative Simulation Model. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 61-77.

Biscoe, P.V. & J.N. Gallagher, 1977. Weather, dry matter production and yield. In: J.J. Landsber & C.V. Cutting (Eds.), Environmental Effects on Crop Physiology, Academic Press, London, pp. 75-100.

Gines, H.C., Descalsota, J.P. & K.G. Cassman, 1994. Fertilizer inputs and yield loss from stem borer on rice. Poster presented at the 1994 Scientific Meeting of the Federation of Crop Science Societies of the Philippines.

Goudriaan, J., 1982. Potential Production Processes. In: Simulation of Plant Growth and Crop Production, Eds. F.W.T. Penning de Vries & H.H. van Laar, Simulation Monographs, Centre for Agricultural Publishing and Documentation, Wageningen, p. 98-113.

Keulen, H. van & 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.

Kraalingen, D.W.G. van, W. Stol, P.W.J. Uithol & M.G.M. Verbeek, 1990. User manual of CABO/TPE Weather System. CABO/TPE internal communication, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 27 pages.

Kraalingen, D.W.G. van, 1991. The FSE System for Crop Simulation. CABO-TT Simulation Report no. 21, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 77 pages.

Kropff, M.J., H.H. van Laar & R.B. Matthews (Eds.), 1994. ORYZA1, a ecophysiological model for irrigated rice production. SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. 110 pages.

Makarim, A.K., Sismiyati Roechan & Ponomin Pw., 1994. Nitrogen requirement of irrigated rice at different growth stages. In: H.F.M. ten Berge, M.C.S. Wopereis & J.C. Shin (Eds.), Nitrogen Economy of Irrigiated Rice: Field and Simulation Studies, SARP Research Proceedings, April 1994, AB-DLO, TPE-WAU, IRRI, pp.70-82.

Montheith, J.L., 1977. Climate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. London, Ser. B, 281: 277-294.

Penning de Vries, F.W.T., H. van Keulen & J.C. Alegos, 1988. Nitrogen redistribution and potential production in rice. In: S.K. Sinha (Ed.), Proceedings of the International Congress of Plant Physiology, New Delhi, India, February 15-20, 1988, Society for Plant Physiology and Biochemistry, New Delhi, pp. 513-520.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of Ecophysiological Processes of Growth in Several Annual Crops, Simulation Monographs 29, Centre for Agricultural Publishing and Cocumentation (Pudoc), Wageningen, 271 pages.

Rappoldt, C. & D.W.G. van Kraalingen, 1990. Reference manual for the FORTRAN utility library TTUTIL with applications. CABO- TT Simulation Report no. 20, Centre for Agrobiological Research and Department of Theoritical Production Ecology, Wageningen, 122 pages.

Riethoven, J.J.M., 1993. The SARP-Shell, a crop growth simulation environment. Simulation and Systems Analysis for Rice Production (SARP), revision 2, version 1.0. CABO-DLO, TPE-WAU, IRRI.

Rossing, W.A.H., M. van Oijen, W. van der Werf, L. Bastiaans & R. Rabbinge, 1992. Modelling the 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 Scientific Publishers, Oxford, pp. 161-180.

Rubia, E.G. & F.W.T. Penning de Vries, 1990. Simulation of yield reduction by stem borers in rice. J. Plant Prot. Trop. 7: 87-102.

Rubia, E.G., 199x. The pest status and management of white stem borer, *Scirpophaga innota* (Walker) (Pyralidae: Lepidoptera) in West Java, Indonesia. PhD thesis, University of Queensland, Brisbane. 221 pages (submitted).

Xia, J.Y., F.W.T. Penning de Vries & J. Litsinger, 1991. Model of population dynamics of *Scirpophaga incertulas* (Walker) (Lepidoptera: Pyralidae). Envrion. Entomol. 20: 832-840.

Xu Zhihong & Wang Zhaoqian, 1991. Simulation of reduction in rice yields due to striped stem borer In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production (SARP), Selected Papers at Workshops on Crop Simulation of a Network of National and International Agricultural Research Centres of several Asian Countries and The Netherlands, PUDOC, Wageningen, pp. 353-360.

Yoshida, S., 1981. Fundamentals of Rice Crop Science. The International Rice Research Institute, Los Baños, 269 pages.

Calibration of the SBORER model for cultivars IR64 and Binato

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Introduction

So far, three versions of the stem borer model have been developed. The first one was developed by Rubia & Penning de Vries (1989), and was written in CSMPIII. It made use of the L1Q module to simulate crop growth at a quarter-day time interval, and of the TIL module to simulate development of tillers, florets, and grains. The shading effect was accounted for in the SUPHOL subroutine, by partitioning dead leaf area due to stem borer infestation equally over canopy layers. This model was applied to account for yield reduction caused by varying levels of nitrogen, and the shading effect caused by dying deadhearts in the field.

The second version of the model, L1DTSB, was developed by Bastiaans (1993). He made use of the L1D module to simulate crop growth at a time interval of one day. It was assumed that deadhearts disappear from the canopy after 14 days, whereas whiteheads remain in the canopy until crop maturity. Nutrients were translocated from deadhearts and whiteheads to neighbouring healthy tillers. The Pest and Disease Management Programme adopted this model as the first standard version of the stem borer model.

With the introduction of ORYZA1 (Kropff et al., 1994), a new version of the stem borer model, SBORER model, written in FORTRAN, was developed (Elings & Rubia, 1994, and this volume). ORYZA1 takes into account the loss of weight at transplanting, has an improved simulation of the leaf area index (LAI), and an improved simulation of the canopy nitrogen gradient in the ASSIM subroutine (Kropff et al., 1994). The adaptations incorporated in L1DTSB were also incorporated in the third version of the stem borer model.

In the current SBORER model, tillers are divided in three classes, viz. healthy tillers, deadhearts, and whiteheads. Tiller dynamics is simplified. Tiller formation is mainly influenced by nitrogen concentration in the leaves. For each tiller class, growth rates, loss rates, and dry matter weights of each plant organ (leaves, stems, storage organs, and roots) are calculated. Also, photosynthesis rates and maintenance respiration rates are calculated for each tiller class. The stem borer infestation rate (SBINFR), which defines the formation rate of deadhearts and whiteheads, is model input. Part of the plant organ weights are classified to deadhearts of whiteheads at the moment that stem borer injury is observed in the field. An option to simulate clipping to mimic stem borer injury is available.

The objective of this paper is to calibrate the SBORER model using the data from the irrigated treatment of the experiment discussed in Rubia et al. (1994). This is useful in understanding the stem borer-crop system.

Materials and Methods

The results of the irrigated treatment of two cultivars, viz. IR64 and Binato, which were grown under ample supply of water and nitrogen, as discussed by Rubia et al. (1994), were used. Some summarized field observations are:

Development stage after which stem borer infestation leads to the formation of whiteheads (DVSWH). Whitehead formation started at DVS 1.2 (73 DAS). Infestation occurred at 10 days after panicle initiation, however, whiteheads appear after flowering. This is supported by field observations on moment of egg laying, which show that eggs that cause whiteheads are laid during stem elongation. Larvae emerge from the eggs and develop from 1st to 3rd instar larvae before whitehead symptoms are observed (Rubia, 1994). Panicles flower, but their grains do not fill, which causes about 100% unfilled grains.

Deadhearts. Deadhearts were observed also after maximum tillering stage. IR64 responds to stem borer injury by increased tiller production, also after maximum tillering stage. These tillers are not productive and do not contribute to yield, and therefore, in the model, they are classified as unproductive tillers.

Average residence time of deadhearts (ARTDH) was set to 14 days (Xu et al., this volume). Rubia (1994) showed that there is translocation of carbohydrates from deadhearts to healthy tillers. The fraction of carbohydrates translocated from deadhearts to healthy tillers (FTRDH) was set to 0.2.

Whiteheads. There is also translocation of carbohydrates from whiteheads to healthy tillers (Rubia, 1994). The fraction translocated carbohydrates (FTRWH) was set to 0.5.

Using the parameters obtained from the field experiment (Tables 1, 2 and 3), the SBORER model was calibrated. The model's performance was tested with respect to leaf area, dry matter weights (total above-ground dry matter, leaves, stems, and panicles), and tiller dynamics of all tiller classes, of the un-infested, deadheart and whitehead treatments.

Results and Discussion

IR64, healthy plots

Observed (XWTDM) and simulated (WAG) total above-ground dry matter showed similar trends (Figure 1). Simulated stem, green leaf, and panicle dry weights (XWST, XWLVG, XWPA, respectively) were close to observed weights (WST, WLVG, WSO, respectively; Figure 2). Stem and green leaf weights were slightly under-estimated after DVS 1.08 and 1.21. Simulated and observed panicle weights were similar, except at the onset of grain filling. Simulated (XNHL) and observed number of healthy tillers (NHL) were similar, except between DVS 1.21 and 1.87, when tiller death rate was over-estimated (Figure 3).

There was good agreement between the observed (XNDH) and simulated number of deadhearts (NDH), except at DVS 0.75, when all deadhearts were considered whiteheads. After the start of whitehead formation, whitehead density was over-estimated, as infested tillers were added to the whiteheads. Otherwise, there is good agreement between observed (XNWH) and simulated (NWH) whitehead density.

IR64, deadheart plots

Total above-ground dry matter was over-estimated after DVS 0.54, however, trends of observed and simulated values are similar (Figure 4). As the model was calibrated on leaf and panicle weight, stem weight was slightly over-estimated between DVS 0.69 and 0.91 (Figure 5). Panicle weight is simulated well, except at harvest. Tiller formation rate was over-estimated, and tiller death rate was under-estimated (Figure 6).

IR64, whitehead plots

Total above-ground dry matter was over-estimated after DVS 1.21 (Figure 7). There is good similarity between trends of observed and simulated stem, leaf, and panicle dry weights, except for some over-estimation at the end of the growing period (Figure 8). Tiller death rate after DVS 1.34 was over-estimated (Figure 9).

Binato, healthy plots

Total above-ground dry matter was under-estimated after DVS 0.87 (Figure 10), which resulted in an under-estimation of stem weight (Figure 11). Tiller formation rate was over-estimated, however, maximum tiller density and tiller death rate were well estimated (Figure 12). The model estimates death of tillers better for Binato than for IR64.

Binato, deadheart plots

Similar to the healthy treatment, the model under-estimated total above-ground dry matter and stem weight after DVS 0.87 (Figs. 13 and 14). Leaf weight was well simulated, but there was a slight under-estimation of panicle weight. Healthy tiller density was over-estimated, however, trend of observed and simulated values were similar (Figure 15).

Binato, whitehead plots

Total above-ground dry matter was over-estimated after DVS 1.44 (Figure 16). Again, this reflects in a higher stem dry weight (Figure 17). Leaf dry weight was simulated well, whereas the difference between simulated and observed panicle weight at DVS = 1.68 is higher. Similar to the healthy treatment, tiller formation rate was over-estimated, however, death rate was simulated well (Figure 18).

Summary

The SBORER model was calibrated, and performed well. Also tiller dynamics performed well. The development stages indicating start and end of tiller formation (DVST1, DVST2) and start and end of tiller death (DVST3, DVST4), and tiller death rate (TILDTH) varied between both cultivars in this experiment. The development stage after which stem borer cause whiteheads (DVSWH) varies from 1.07 to 1.3 for cultivar IR64, but is stable at DVS 1.2 for cultivar Binato. Average residence time of deadhearts (ARTDH) is 14 days. Fraction carbohydrates that is translocated from deadhearts to healthy tillers (FTRDH) and from whiteheads to healthy tillers (FTRWH) were set to 0.2 and 0.5, respectively.

References

Bastiaans, L., 1993. Damage by Stem Borer in Rice: a Quantitative Simulation Model. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 61-77.

Elings, A & E. G. Rubia, 1994. Models for the crop-pathosystems rice-bacterial leaf blight, sheath blight and stem borer, AB-DLO, TPE-WAU, IRRI 102 pages.

Kropff, M.J., H.H. van Laar & R.B. Matthews (Eds.), 1994. ORYZA1, a ecophysiological model for irrigated rice production. SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. 110 pages.

Rubia, E.G., 1994. The pest status and management of white stem borer, *Scirpophaga innotata* (Walker) (Pyralidae: Lepidoptera) in West Java, Indonesia. PhD thesis, University of Queensland, Brisbane, Australia. 221 pages. (submitted)

Rubia, E.G., L.P. Almazan, L.T. Fabellar, E.B. Yambao, K.L. Heong & K.T. Ingram, 1994. Field experimentation: effect of stem borer infestation on grain yield of tow cultivars IR64 and Binato, under irrigated conditions. In: E.G. Rubia & Zhihong Xu, Simulation of the influence fo stem borer injury on grain yield of rice. SARP Report.

Rubia, E.G. & Penning de Vries, F.W.T., 1990. Simulation of yield reduction caused by stem borers in rice. J. Plant Prot. Trop. 7: 87-102.

Table 1. Observed parameters values for the SBORER model

Parameter	Dimension	Cultivar	
		IR64	Binato
Date of sowing	-	28 Dec. 1992	28 Dec. 1992
Date of transplanting	-	15 Jan. 1993	15 Jan. 1993
Number of plants per hill (NPLH)	$hill^{-1}$	8.	8.
Number of hills per m2 (NH)	m^{-2}	25.	25.
Development rates			
in vegetative phase (DVRV)	d^{-1}	0.000834	0.000689
in reproductive phase (DVRR)	d^{-1}	0.001387	0.001170
Maximum number of tillers per hill (TILMX)	$hill^{-1}$	40.	36.
Maximum weight of one kernel (WGRMX)	g	25.5 x 10-6	24.0 x 10-6
Development stages			
start tiller formation (DVST1)	-	0.43	0.28
end tiller formation (DVST2)	-	0.84	0.69
start of tiller death (DVST3)	-	0.43	0.69
end of tiller death (DVST4)	-	1.44	1.37
end formation of productive tillers (DVST5)	-	0.75	0.75
after which whiteheads are formed (DVSWH)	-	1.25	1.20
Average tiller death rate (TILDTH)	d^{-1}	1.0 x 105	2.0 x 104
Maximum number of grains per productive tiller (NGRT)	$tiller^{-1}$	60	130

Table 2. Stem borer infestation rates for cultivar IR64

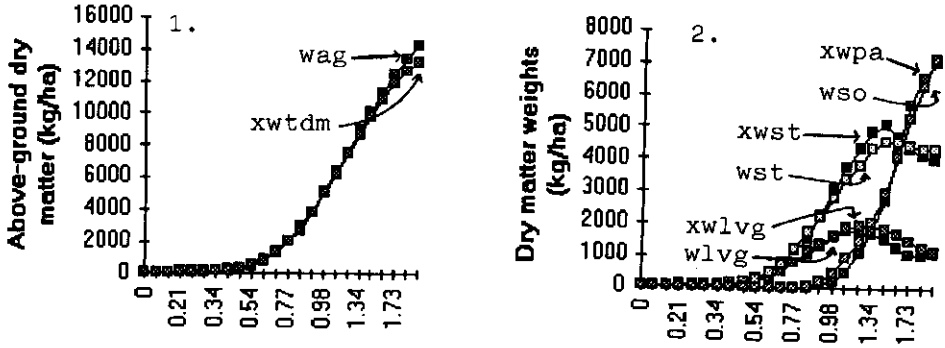
Healthy		Deadhearts		Whiteheads	
Day of year	Relative rate	Day of year	Relative rate	Day of year	Relative rate
50.	0.0027	49.	0.0332	81.	0.0048
55.	0.03	50.	0.000473	85.	0.0062
60.	0.0032	56.	0.00449	88.	0.0072
63.	0.0033	59.	0.00440	91.	0.0083
64.	0.0039	63.	0.00432	92.	0.0091
65.	0.0042	64.	0.00312	93.	0.039
70.	0.0050	65.	0.	95.	0.0046
75.	0.0059	78.	0.	105.	0.0045
77.	0.0062	90.	0.		
78.	0	91.	0.00705		
90.	0	92.	0.0029		
91.	0.0035	105.	0.0029		
92.	0.0015				
105.	0.0015				
106.	0.0014				
112.	0.002				

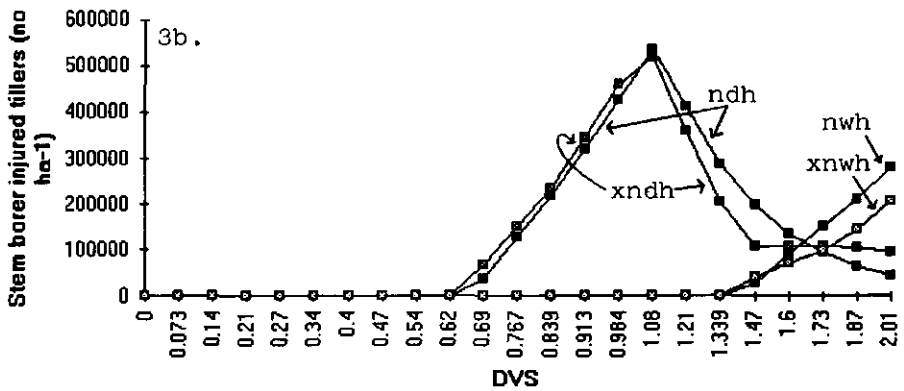
Table 3. Stem borer infestation rates for cultivar Binato

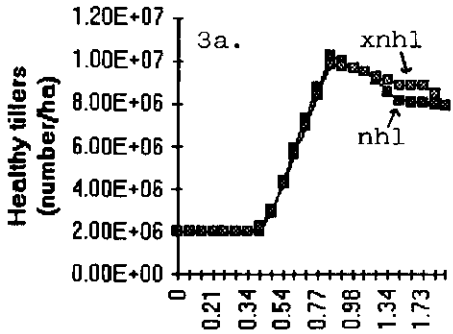
Healthy		Deadhearts		Whiteheads	
Day of year	Relative rate	Day of year	Relative rate	Day of year	Relative rate
36.	0.0015	29.	0.002	78.	0.0044
49.	0.0014	32.	0.0025	81.	0.0055
50.	0.00325	35.	0.0031	82.	0.0058
75.	0.0041	36.	0.00406	89.	0.0083
78.	0.0073	40.	0.0035	90.	0.0086
82.	0.0087	63.	0.0026	91.	0.009
85.	0.00986	64.	0.	92.	0.0028
86.	0.0102	77.	0.	102.	0.0035
91.	0.0123	78.	0.0053	105.	0.0037
92.	0.000846	81.	0.0060	106.	0.0048
105.	0.0011	86.	0.00714	119.	0.00476
106.	0.0026	91.	0.0082		
115.	0.0028	92.	0.003		
120.	0.00094	105.	0.0037		
131.	0.00085	106.	0.00245		
		119.	0.00254		

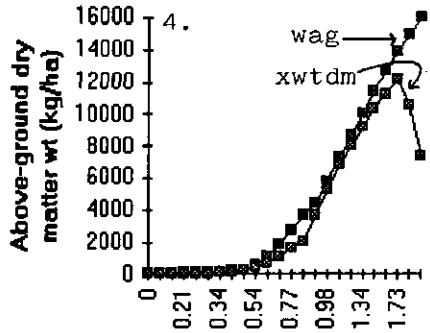
Key to figures 1-18: NDH: simulated dead heart density; NHL: simulated tiller density; NWH: simulated white head density; WAG: simulated total above-ground dry matter; WLVG: simulated green leaf weight; WSO: simulated storage organ weight; WST: simulated stem weight; XNDH: observed dead heart density; XNHL: observed tiller density; XNWH: observed white head density; XWLVG: observed green leaf weight; XWPA: observed panicle weight; XWTDM: observed total above-ground dry matter; XWST: observed stem weight

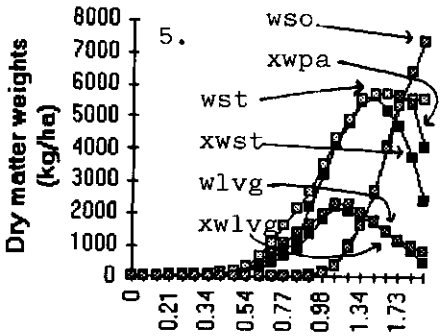
Fig. 1-3: Healthy treatment of cultivar IR64. **Fig 4-6:** Deadheart treatment of cultivar IR64. **Fig 7-9:** Whitehead treatment of cultivar IR64. **Fig 10-12:** Healthy treatment of cultivar Binato. **Fig 13-16:** Deadheart treatment of cultivar Binato. **Fig 17-19:** Whitehead treatment of cultivar Binato.

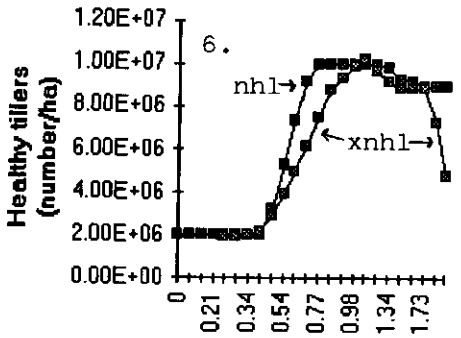





3a.
Healthy tillers (number/ha)
1.20E+07
1.00E+07
8.00E+06
6.00E+06
4.00E+06
2.00E+06
0.00E+00
xnhl
nhl
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73


4.
Above-ground dry matter wt (kg/ha)
16000
14000
12000
10000
8000
6000
4000
2000
0
wag
xwtdm
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73


5.
Dry matter weights (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
wso
xwpa
wst
xwst
wlvg
xwlvg
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73


6.
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6.00E+06
4.00E+06
2.00E+06
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nhl
xnhl
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0.21
0.34
0.54
0.77
0.98
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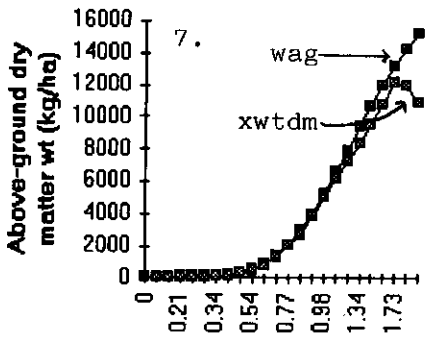
1.73


7.
Above-ground dry matter wt (kg/ha)
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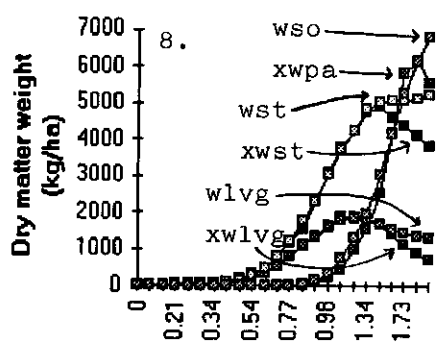
14000
12000
10000
8000
6000
4000
2000
0
wag
xwtdm
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73


8.
Dry matter weight (kg/ha)
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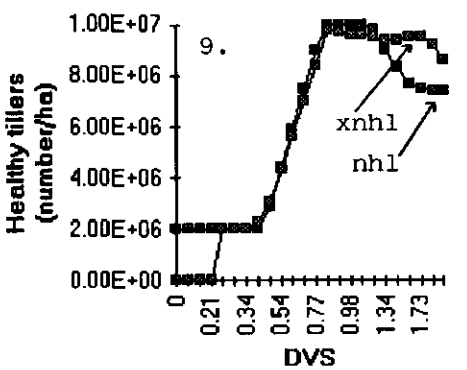
5000
4000
3000
2000
1000
0
wso
xwpa
wst
xwst
wlvg
xwlvg
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73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Healthy tillers (number/ha)
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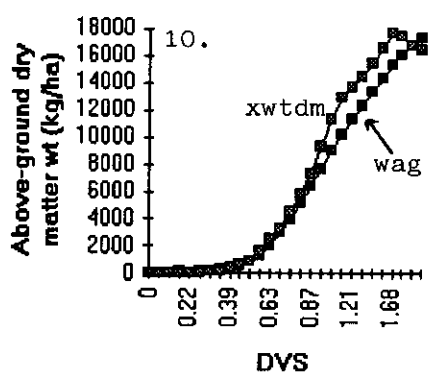
8.00E+06
6.00E+06
4.00E+06
2.00E+06
0.00E+00
xnhl
nhl
0
0.21
0.34
0.54
0.77
0.98
1.34
1.73
DVS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Above-ground dry matter wt (kg/ha)
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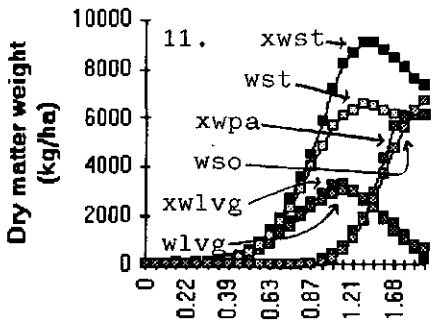
14000
12000
10000
8000
6000
4000
2000
0
xwtdm
wag
0
0.22
0.39
0.63
0.87
1.21
1.68
DVS


11.
Dry matter weight (kg/ha)
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8000
6000
4000
2000
0
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wst
xwpa
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wlvg
0
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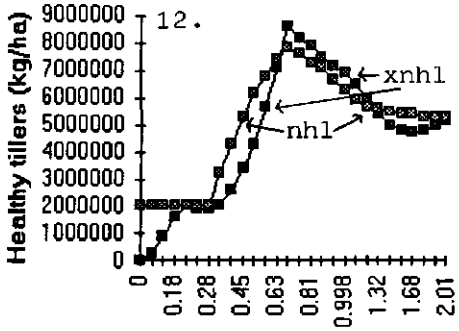
0.39
0.63
0.87
1.21
1.68


12.
Healthy tillers (kg/ha)
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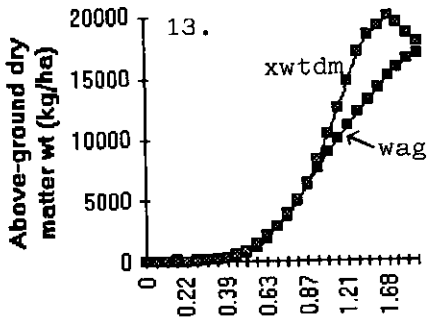
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
xnhl
nhl
0
0.18
0.28
0.45
0.63
0.81
0.998
1.32
1.68
2.01


13.
Above-ground dry matter wt (kg/ha)
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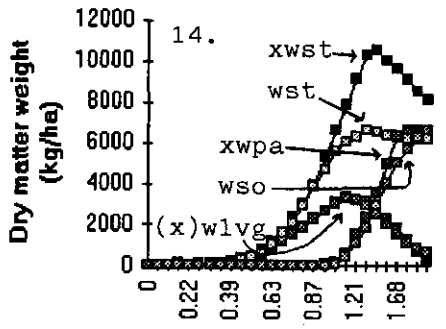
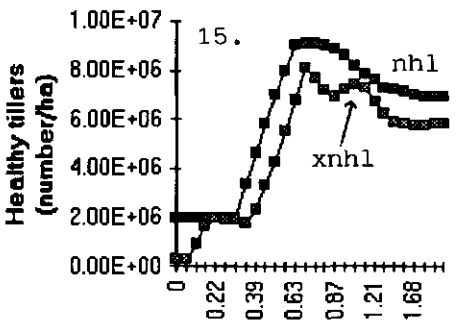
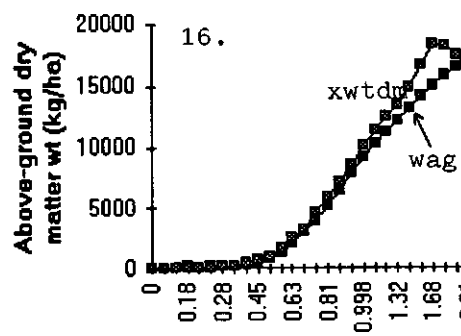
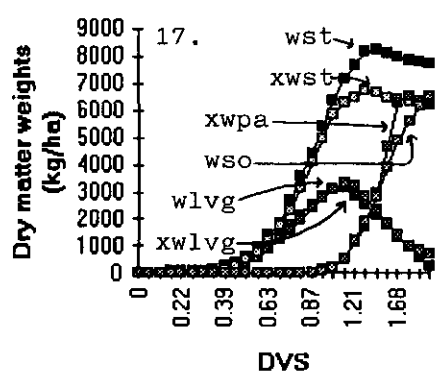
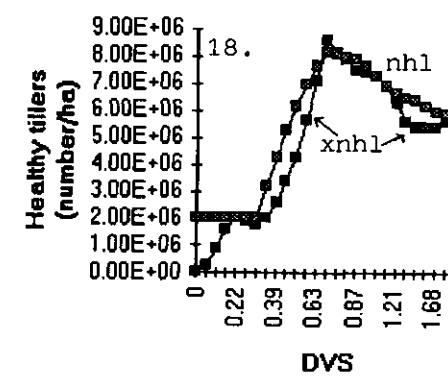
15000
10000
5000
0
xwtdm
wag
0
0.22
0.39
0.63
0.87
1.21
1.68


14.
Dry matter weight (kg/ha)
12000
10000
8000
6000
4000
2000
0
xwst
wst
xwpa
wso
(x)wlvg
0
0.22
0.39
0.63
0.87
1.21
1.68


15.
Healthy tillers (number/ha)
1.00E+07
8.00E+06
6.00E+06
4.00E+06
2.00E+06
0.00E+00
nhl
xnhl
0
0.22
0.39
0.63
0.87
1.21
1.68


16.
Above-ground dry matter wt (kg/ha)
20000
15000
10000
5000
0
xwtdm
wag
0
0.18
0.28
0.45
0.63
0.81
0.998
1.32
1.68
2.01


17.
Dry matter weights (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
wst
xwst
xwpa
wso
wlvg
xwlvg
0
0.22
0.39
0.63
0.87
1.21
1.68
DVS


18.
Healthy tillers (number/ha)
9.00E+06
8.00E+06
7.00E+06
6.00E+06
5.00E+06
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
nhl
xnhl
0
0.22
0.39
0.63
0.87
1.21
1.68
DVS

Tiller dynamics of IR64 and the effects of stem borer injury

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Introduction

Feeding of stem borers, such as striped stem borer (SSB) *Chilo suppressalis* (Walker), on tillers results in dead hearts and white heads. Rice plants can produce new tiller to replace the infested tillers after infestation. In their early development stages, rice plants produce tillers at a higher rate than in later stages. Tiller formation, death and the underlying mechanisms due to stem borer infestation at various crop production and infestation levels are not fully quantified as yet.

The objective of this paper is to quantify the effect of stem borer injury and leaf nitrogen content on the tiller formation rate of rice. This knowledge can be applied in development of a tiller simulation module.

Materials and Methods

A field experiment was conducted during the middle cropping season (May to November 1993) in Hangzhou, China. Rice (*Oryza sativa* L.) var. IR64 was sown on May 30, and transplanted on June 29 at a rate of 2 plants per hill, with a hill spacing of 0.2 × 0.2 m (500,000 plants, or tillers, per hectare). The field measured 35 × 12 m, and was divided into 10 plots of 5 × 4 m, which were separated by border rows of 2 m width. The two treatments, viz. without and with artificial introduction of SSB egg masses, were laid out in 5 replicates.

SSB moths were collected from light traps. After 24 hours of oviposition, egg masses were collected and kept at 5 °C, until the desired number of egg masses were obtained. Rice plants were infested at a rate of 1 egg mass per 8 hills (equivalent to 31,250 egg masses ha^{-1}) on 23 July, which was 25 days after transplanting (DAT). The plots were divided into 4 sets of sub-plots, viz. areas for periodic harvests (P-areas), areas for monitoring (M-areas), and one plot for final harvest (F-area, not relevant here) (see Bastiaans, 1993).

The crop reached anthesis on 24 September and was harvested on 1 November. Standard fertilizer and water management were applied. A drainage after maximum tillering was used to control tiller density. No chemicals were sprayed. Leaf nitrogen content was measured at 15, 30, 45, 60, 75 and 90 DAT.

P-areas. Twelve hills of a sub-plot were destructively sampled at two weeks interval. Densities of healthy tillers, dead hearts, white heads were recorded.

M-areas. Observations were made on 16 hills per plot at a weekly interval. The observed hills and surrounding plants were touched as less as possible. Densities of healthy tillers, dead hearts, white heads were recorded.

T-area (single hill tracking area). A different field of 8 × 8 m was divided into 16 plots of 2 × 2 m. Ten plots were selected, and five treatments were laid out in 2 replicates. The 5 treatments were:

- control,
- introduction of 1 egg mass per hill at DAT 10,
- introduction of 3 egg masses per hill at DAT 10,
- introduction of 1 egg mass per hill at DAT 40,
- introduction of 3 egg masses per hill at DAT 40.

Newly emerged tillers were marked with a label. Densities of healthy tillers, dead hearts, white heads were recorded.

Results and Discussion

Development stage

Rice plants of the three areas were transplanted 30 at days after sowing, reached anthesis (50% of the panicles flowering) at 87 DAT; and reached maturity at 43 days after flowering. The vegetative stage was prolonged by 27 days (54%), and the reproductive stage was prolonged by 13 days (20%) in comparison with the Philippines (Yambao et al, 1993). The period between moments that the first panicle flowered and that 50% of the panicles flowered, lasted 31 days (from 24 August to 24 September).

Transplanting shock

Tiller formation was affected by the transplanting shock. Tiller density had decreased with 4.4% (to 480,000 ha^{-1}, s.d. = 22) in the M-areas, and with 7.1% (to 460,000 ha^{-1}, s.d. = 91,000) in the T-area at 7 DAT. No samples was taken at this date in the P-areas. Tiller density had increased with 27.2% (to 636,000 ha^{-1}, s.d. = 73,000), and with 25% (to 625,000 ha^{-1}, s.d. = 187,500) at 14 DAT in the M and T-areas, respectively. At 15 DAT, tiller density had increased by 30.4% (to 652,000 ha^{-1}, s.d. = 67,000) in the P-areas. Hence, tiller density had decreased with a death rate of 4113 tillers ha^{-1} day^{-1} during the first week of the transplanting shock. In the second week, tiller density increased with a formation rate of 24,000 tillers ha^{-1} day^{-1} (Figure 1). As some plants produced a tiller be-

fore transplanting, the end of the transplanting shock is indicated by resumption of tiller formation. Results indicate that the transplanting shock lasted 9 -10 days. Afterwards, new tillers were formed at a high rate, which was relative stable for 4 weeks. Then, tiller formation rate decreased, up to the moment that maximum tiller density was reached.

The period between sowing and transplanting lasted 767.85 day degrees, and the period from transplanting to the end of the transplanting shock lasted 214.9 to 244.45 day degrees.

No natural and artificial infestations were observed during the transplanting shock.

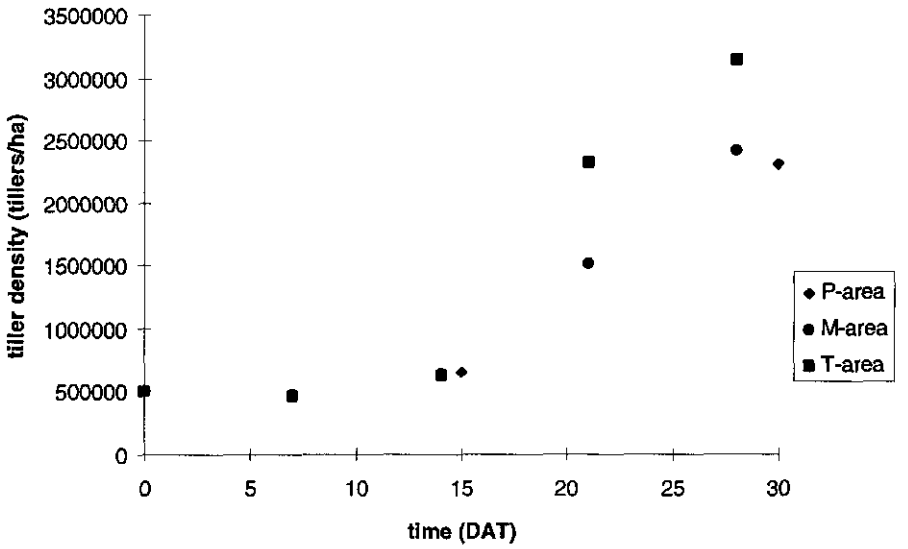

Figure 1. Tiller densities during, and just after the transplanting shock.

Maximum tiller density

Maximum tiller density in un-infested and infested M-areas occurred at the same moment, viz. at 49 DAT (DVS = 0.66, Figure 2, Table 1). Maximum tiller densities in un-infested and infested P-areas was observed at 45 DAT (DVS = 0.62). No observations were made at 49 DAT. Maximum tiller density in the T treatment with 3 egg masses inoculated at 10 DAT was observed at 91 DAT. In all other treatment, maximum tiller density was observed at 49 DAT. Hence, maximum tiller number occurred on the average at DAT 49.

The moment that maximum tiller density is reached, appears to be postponed by a heavy stem borer infestation (Figure 2).

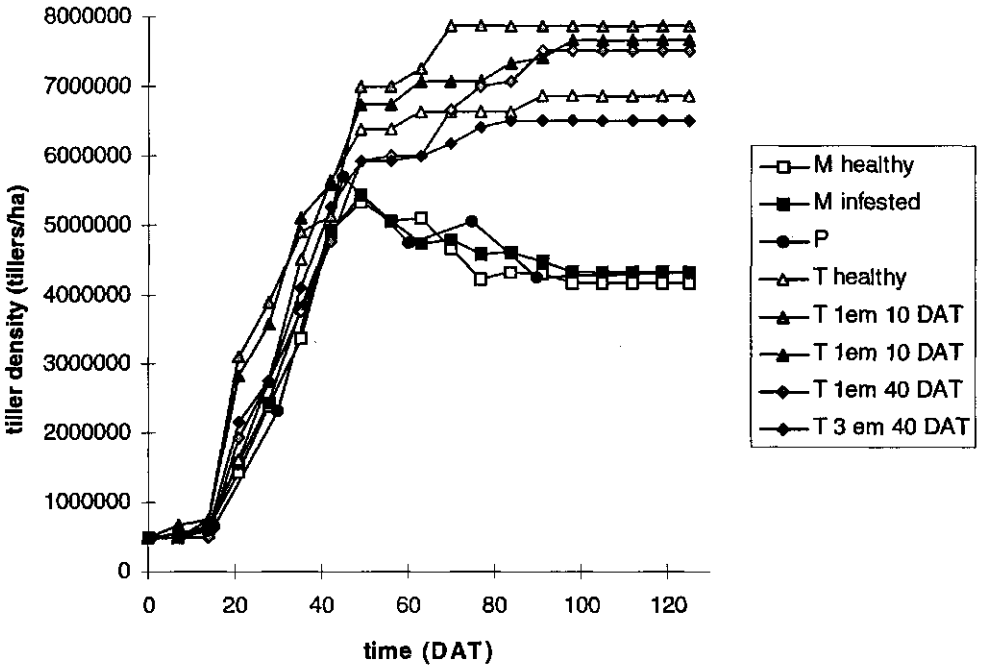

Figure 2. Tiller densities of all treatments through time.

Table 1. Maximum total tiller density (tiller ha^{-1}), per treatment, for three areas. em = egg mass

Area	treatment	average	se	remark
P-area	average	5,692,005	556,171	45 DAT, 10 replicates
M-Area	uninfestation	5,321,875	274,952	49 DAT, 5 replicates
	infestation	5,428,125	140,935	49 DAT, 5 replicates
T-area	uninfestation	6,875,000	625,002	49 DAT, 2 replicates
	1 em at DAT 10	7,875,000	1,875,018	49 DAT, 2 replicates
	3 em at DAT 10	7,500,000	1,443,335	91 DAT, 3 replicates
	1 em at DAT 40	7,666,667	881,892	49 DAT, 3 replicates
	3 em at DAT 40	6,500,000	1,154,668	49 DAT, 3 replicates

Final healthy tiller density

Final healthy tiller density in the P-areas was 3,485,000 tiller ha^{-1} (13.9 tillers $hill^{-1}$). In the M-area, final healthy tiller density in the infested plots was higher than in the un-infested plots, viz. 4.0×10^6 and 3.9×10^6 tillers ha^{-1}, respectively. The healthy T treatment had a final healthy tiller density of 4.9×10^6 tiller ha^{-1}. The treatments with introduction of 1 egg mass per hill had a higher final healthy tiller density, viz. 5.1×10^6 and 4.9×10^6 tillers ha^{-1} for inoculation at 10 and 40 DAT, respectively. The treatments with introduction of 3 egg masses per hill had a lower final healthy tiller density than the healthy treatment, viz. 4.2×10^6 and 4.1×10^6 tillers ha^{-1} for inoculation at 10 and 40 DAT, respectively (Table 2).

Table 2. Final healthy tiller density (tillers ha^{-1}), per treatment, for three areas. em = egg mass.

Area	treatment	average	se
P-area	average	3,485,000	119,965
M-Area	uninfestation	3,934,375	142,475
	infestation	4,015,625	245,616
T-area	uninfestation	4,875,000	125,000
	1 em at DAT 10	5,125,000	1,375,000
	3 em at DAT 10	4,167,500	71,141
	1 em at DAT 40	4,917,500	546,453
	3 em at DAT 40	4,082,500	91,667

Tiller formation rate in relation to leaf N content

Tiller formation rate (TFR) was calculated on the basis of observations with an interval of 7 days for the P-areas, and with an interval of 15 days for the M and T-areas. TFR between 14 and 42 DAT was related to leaf nitrogen content (LNC). TFR increased with increasing LNC in infested and un-infested treatments of the P, M, and T-areas (Figure 3). No significant difference between infested and un-infested treatments was observed, possibly due to low infestation rates. TFR was significantly higher in T-area than in the P and M-areas, possibly due to higher photosynthesis rates, caused by reduced competition for light by surrounding hills, which were mechanically damaged.

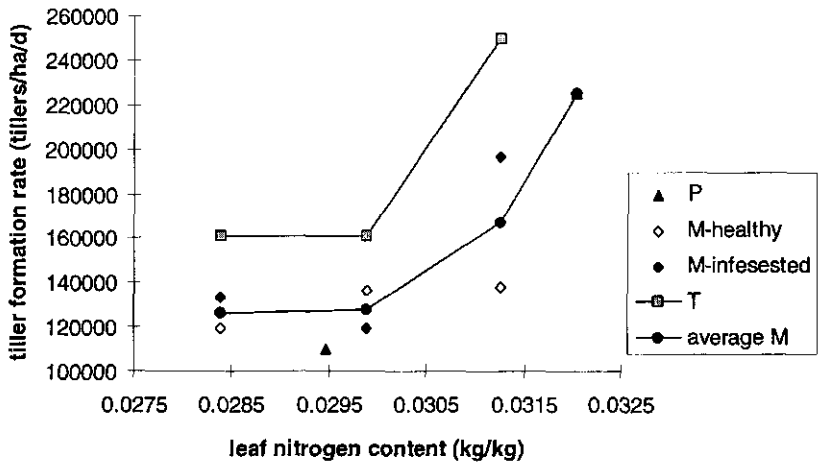

Figure 3. Tiller formation rate in relation to leaf nitrogen content.

Tiller death rate

Tiller death rate (TDR) was calculated on the basis of tiller density after maximum tillering (49 DAT), similar to the calculation of TFR. In the P and M-areas, no significant difference between infested and un-infested treatments was observed. In the T treatments, TDR varied between 0 and 35,714 tillers ha^{-1} day^{-1}. In the P and M-areas, TDR varied between 20,000 to 50,000 tillers ha^{-1} d^{-1}, with an average of 25,000 tillers ha^{-1} d^{-1}.

These results can be used to parameterize the tiller module, which forms and essential part of the SBORER model.

References

Bastiaans, L., 1993. Damage by Stem Borer in Rice: a Joint Experimental Approach. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 111-117.

Yambao, E.B., K.T. Ingram, E.G. Rubai & B.M. Shepard, 1993. Case Study: Growth and Development of Rice in Response to Artificial Stem Borer Damage. In: Mechanisms of Damage by Stem Borer, Bacterial Leaf Blight and Sheath Blight, and their Effects on Rice Yield, W.A.H. Rossing, E.G. Rubia, M. Keerati-kasikorn & P.R. Reddy (Eds.), SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen, IRRI, Los Baños. p. 33-50.

Application of the SBORER model to analyze combined stem borer and leaf folder infestation

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1. Department of Plant Protection, Zhejiang Agricultural University, Hangzhou 310029, P.R. China.
2. Philippine Rice Research Institute, Muñoz Ecija, Philippines; International Rice Research Institute, PO. Box 933, 1099 Manila, Philippines.
3. DLO-Research Institute for Agrobiology and Soil Fertility, P.O. Box 14, 6700 AA Wageningen, The Netherlands.

Introduction

The feeding effect of stem borers such as striped stem borer (SSB) *Chilo suppressalis* (Walker), on yield of the rice crop was studied by many authors (Gomez & Bernardo, 1974; Luo, 1987; Xu & Zhang, 1988). The larvae bore and feed into tillers, which causes dead hearts at the vegetative stage, and bore and feed inside the peduncle at the reproductive stage, which causes white heads. The rice crop may compensate for tiller loss due to stem borer injury (Rubia & Penning de Vries, 1990). Yield reduction due to stem borer infestation at various crop production and infestation levels of compensation, and the underlying mechanisms, are not fully quantified as yet.

Yield reduction due to infestation by leaf folder (LF) *Cnaphalocrosis medinalis* Guenee has also been studied (Fan & Lu, 1988; Heong & Fabellar, 1988). Leaf folder larvae cause folding of leaves, and feed on the green leaf tissue of the folded parts, which causes a green leaf area reduction of 0.4-7.1 cm^2 $larva^{-1}$ day^{-1} (Cheng, 1987). The net photosynthesis rate per unit green leaf area in folded leaves is reduced by 50% (de Jong, 1992; de Jong & Daamen, 1992). The rice crop can also compensate for loss of leaf are caused by leaf folder (Fabellar et al., 1994). Much research on yield reduction caused by leaf folder, e.g. Bautista et al. (1984) and Murugesan & Chelliah (1986), did not take into account such compensatory mechanisms. Studies on yield reduction due to leaf folder injury should also consider compensation, to understand and explain the effect of infestation on grain yield.

In many rice growing areas of Zhejiang, China, both of the above-mentioned pests may occur simultaneously, at tillering and heading, whereas leaf folder may also occur at booting (Li, 1982). The consequences of interaction of the effects of simultaneous infestation by these two rice pests for rice growth and production have not been quantified as yet (Dai & Guo, 1992).

The objective of this paper is to determine the effect of combined stem borer and leaf folder injury on rice production; and using simulation techniques, to analyze the effects of

variation in injury levels for each pest, on yield. This may be useful in developing pest management rules for a multi-pest ecosystem.

Materials and Methods

Field experiment

A field experiment was conducted during middle cropping season (May to November) of 1993 in Hangzhou, China. The 35 × 12 m field was divided into 10 plots of 5 × 4 m, separated by border rows of 2 m width. The two treatments, viz. without and with artificial introduction of SSB egg masses, were laid out in 5 replicates.

SSB moths were collected from light traps. After 24 hours oviposition, egg masses were collected and kept at 5 °C, until the desired number of egg masses were obtained. Rice cultivar IR64 was sown on May 30, and transplanted on June 29 at a rate of 2 plants per hill, at 0.2 × 0.2 m hill spacing. The crop was infested at a rate of 1 egg mass per 8 hills (equivalent to 31250 egg masses per hectare) on 23 July (25 days after transplanting, DAT). The crop reached anthesis on September 24, and was harvested on November 1. Standard fertilization and water management were applied. The field was drained at maximum tillering for one week, which causes termination of tillering. No chemicals were sprayed.

A sample of 12 hills was taken at 14 days interval, to measure the following crop parameters: leaf area, dry matter weight (green + dead leaves, stem, panicles), and leaf nitrogen content. The following data were recorded weekly: number of healthy tillers, dead hearts, white heads due to the stem borer and rolled leaves due to natural leaf folder infestation.

Simulation

The Continuous System Modelling Program (CSMP) version of the SBORER model (Elings & Rubia, 1994), was adapted. Leaf folder damage was introduced to the model as follows:

(1) To account for biomass loss due to leaf folder feeding, a leaf area of 6 cm^2 $larva^{-1}$ d^{-1} was converted into a biomass loss rate. Four leaves per tiller were assumed.

```
LFFD  = (NTI * 4 * LFINFR * 6.E-8)/(SLA+NOT(SLA))
LLVSB = WLVGHL*SBINFR + LFFD
```

LFFD = dry matter loss per day due to leaf folder
LLVSB = loss of leaf weight due to stem borer and leaf folder

(2) To account for leaf folding due to leaf folder infestation, 1% of infested leaf number due to leaf folder resulted in 0.5% leaf area loss, which was introduced to the GRLAI subroutine.

```
LFLA  =  1. - LFINFR * 0.5
LAI   =  LAII * NPLH * NH * LFLA / NPLSB * (EXP(RGRL*(TSLVTR....
```

(3) It was assumed that leaf tissue consumption by the insect occurs during a period of 10 days (with a constant consumption rate), which is equivalent to the duration of the 4^{th} plus 5^{th} instar phases, after leaf folding occurs. Infestations before and after the period were set to zero. For example:

```
LFINFR              =  AFGEN (LFIRTB, DOY)/10.
FUNCTION LFIRTB =  0., 0., 249., 0., 260., 0.1, 269., 0.1, 270., 0., 365., 0.
```

LFINFR = leaf folder infestation rate
LFIRTB = leaf folder infestation rate related to day of the year

Infestation rates

Observed tiller loss (dead hearts and white heads) caused by stem borer at various crop development stages is shown in Table 1. The observed leaf rolling rates caused by leaf folder at various crop development stages is given in Table 2. These data were used to calculate the stem borer and leaf folder infestation rates and were used as model inputs (Tables 3 & 4).

Table 1. Total fraction of infested tillers and fraction newly infested tillers.

day number	total fraction	new fraction
224	0.01172	0.01172
231	0.03182	0.02010
238	0.05274	0.02092
245	0.05010	
252	0.05264	0.00254
259	0.04528	
266	0.04312	
273	0.06790	0.02478
280	0.07238	0.00448

Table 2. Observed infestation rates of leaf folder in infestation plots.

day number	total fraction	new fraction
210	0.02	0.02
260	0.14	0.12
304	0.22	0.08

Table 3. Simulated infestation rates of stem borer inthe model (%).

date	sb low	SB 1	SB 2	SB 3
224	0.1	0.01	0.05	0.100
231	0.0	0.02	0.10	0.200
238	0.0	0.02	0.10	0.200
252	0.0	0.0025	0.0125	0.025
273	0.0	0.025	0.125	0.250
280	0.0	0.0045	0.0225	0.045

Table 4. Simulated infestation rates of leaf folder in the model (%).

date	lf low	LF 1	LF 2	LF 3
210	0.1	0.01	0.04	0.08
260	0.0	0.06	0.24	0.48
304	0.0	0.04	0.16	0.32

Model calibration

The SBORER model was calibrated for the above described experiment. Partitioning tables were built on the basis of observed plant organ weights; relative leaf death rate was determined on the basis of observed dead leaf weights (which included leaf material that had died due to SSB infestation, and other causes); and development rates before and after flowering were calculated on the basis of observed crop development. Observed stem borer and leaf folder infestation rates were used.

Model application

After calibration, the model was applied to simulate the effects of combined SSB and LF infestation on grain yield. Since the SBORER model does not simulate pest dynamics, SSB and LF infestation rates as observed in the field were used (Table 1).

Four different scenarios were simulated for each combination of infestation rates viz. no infestation, only stem borer infestation, only leaf folder infestation, and combined stem borer and leaf folder infestation. The outcomes of the scenario simulations were compared with respect to 6 variables, viz. total above-ground dry matter, dry weight of green leaves, stems, storage organs, leaf area, and total tiller density.

Nine combinations of stem borer and leaf folder infestation rates were simulated, viz.

- low stem borer + low leaf folder,
- middle stem borer + low leaf folder,
- high stem borer + low leaf folder,
- low stem borer + middle leaf folder,
- middle stem borer + middle leaf folder,
- high stem borer + middle leaf folder,
- low stem borer + high leaf folder,
- middle stem borer + high leaf folder,
- high stem borer + high leaf folder.

Results

Field experiment

In control plots (without artificial infestation), there was natural infestation, which causedstem borer injury of 4% dead hearts and 17% white heads, and leaf folder injury of 11% leaf folding, This is within the range of natural infestation rates of stem borer and leaf folder, which vary from 5% to 30% tiller loss, and from 5% to 30% rolled leaf number, respectively. In plots with artificial stem borer introduction, 8% dead hearts and 22% white heads were observed. The difference between infested and uninfested plots was 4% dead hearts and 5% white heads. Grain yield was 6678 kg ha^{-1} in untreated plots, and 6338 kg ha^{-1} in infested plots, which implies 5.09% grain yield reduction caused by artificial infestation.

Simulation

Model calibration

With observed leaf area as model input, simulated above-ground dry matter (WAG) at maturity was 8.19% higher than observed WAG, however, in case of leaf area simulation, simulated WAG was over-estimated by 34.29% (Figure 1). Observed and simulated leaf

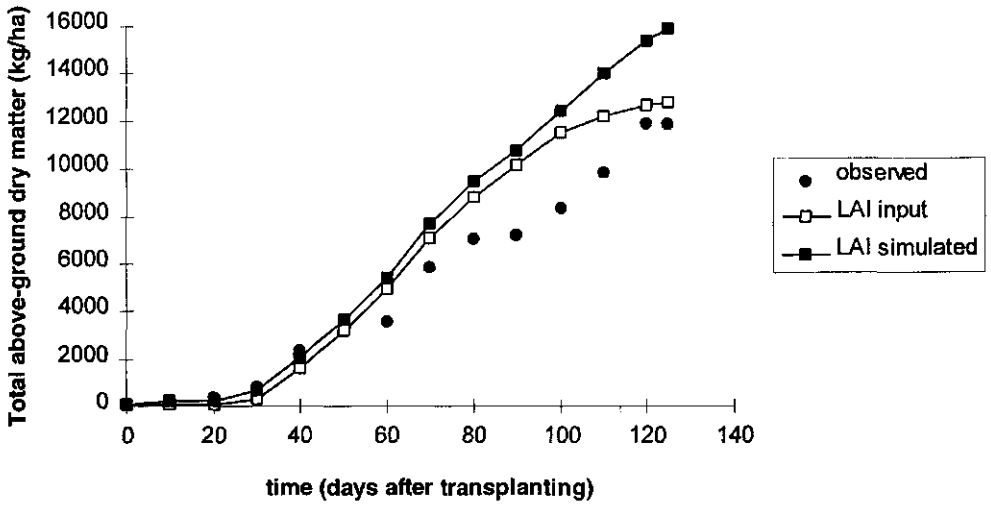

Figure 1. Observed and simulated total above-ground dry matter production of IR64. Simulation results are based on LAI input, and simulated LAI.

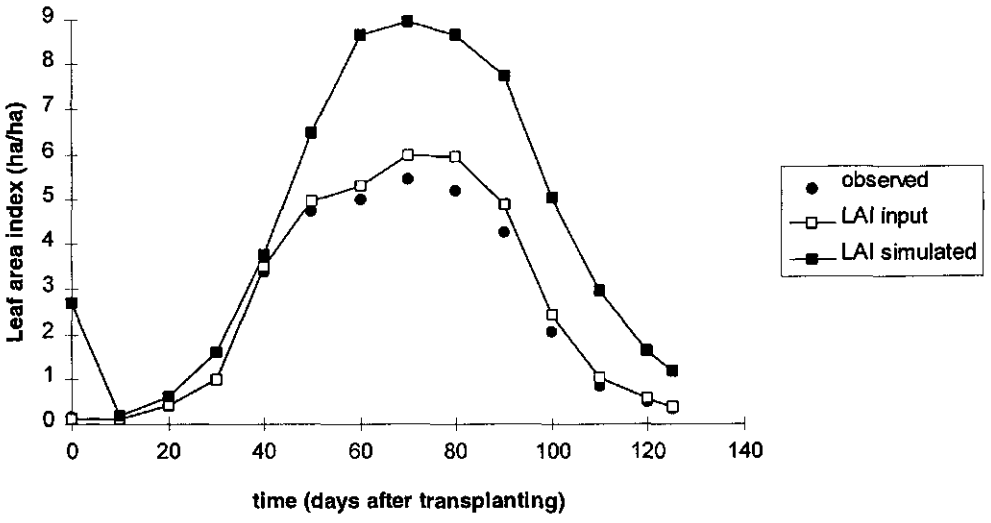

Figure 2. Observed and simulated leaf area index of IR64. Simulation results are based on LAI input, and simulated LAI.

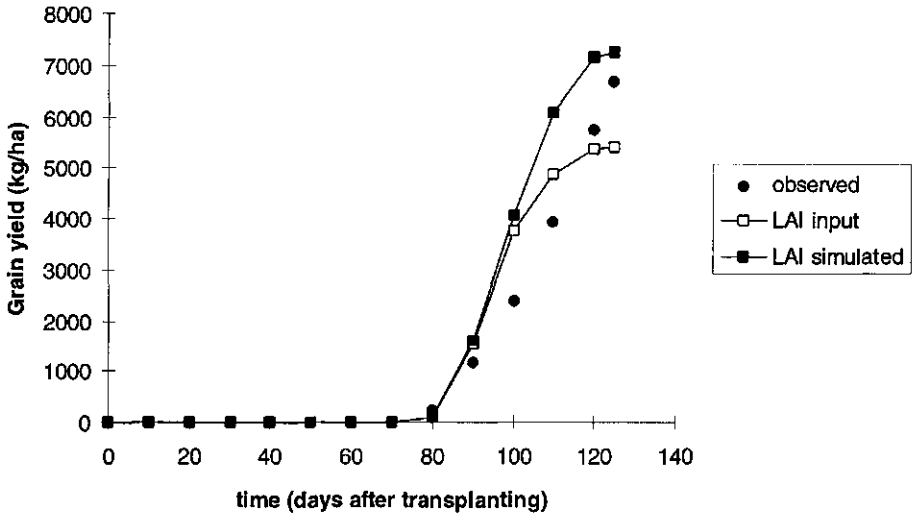

Figure 3. Observed and simulated weight of storage organs of IR64. Simulation results are based on LAI input, and simulated LAI.

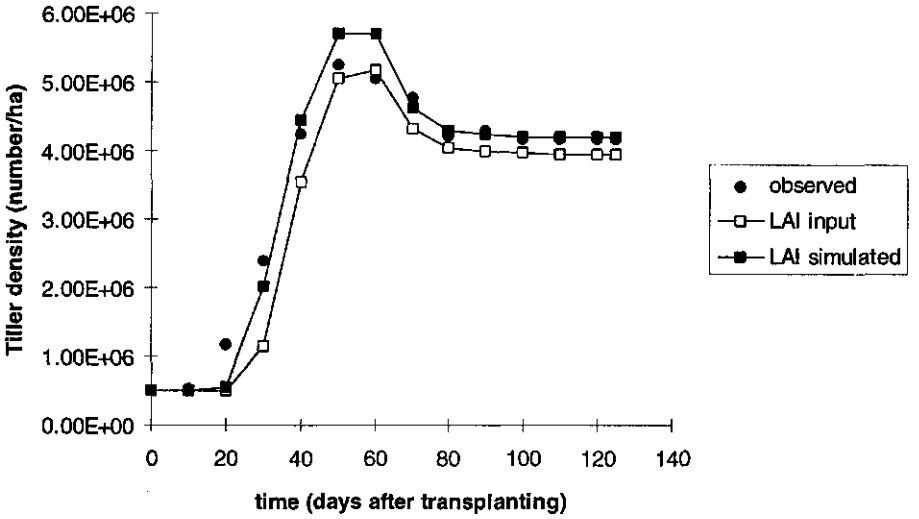

Figure 4. Observed and simulated tiller density of IR64. Simulation results are based on LAI input, and simulated LAI.

area reached maximum values at the same moment, however, simulated leaf area was over-estimated with 65% (Figure 2). The initial rates of increase of leaf area were similar, however, after 40 DAT, this rate decreased for observed leaf area and remained constant for simulated leaf area.

Storage organ weight (WSO), if leaf area was simulated, was well simulated (Figure 3). If observed leaf area was made input, WSO was under-estimated by 19%.

Simulated and observed maximum tiller density occurred at the same moment. The length of the transplanting shock was over-estimated by 7 days (Figure 4). Simulated rate of tiller formation , and simulated maximum tiller density were also over-estimated, the latter by 11.6%.

The model was calibrated by adapting the relative growth rate of leaf area (RGRL), the development stages of initialisation and end of tiller formation and senescence (DVST1~4), and by multiplying AMAX with 0.56.

Model application

Stem borer infestation

Simulated grain yield decreased as stem borer infestation rate increased, viz. 1.28%, and 16.07% for medium and high tiller loss rate, respectively, (Table 3), whereas grain yield increased by 0.04% at low tiller loss rate. This suggests that a significant compensation can occur at low infestation rates. Moreover, 1% of tiller loss resulted in 0.0049% to 0.20% grain yield reduction, from low to high infestation (Figure 5).

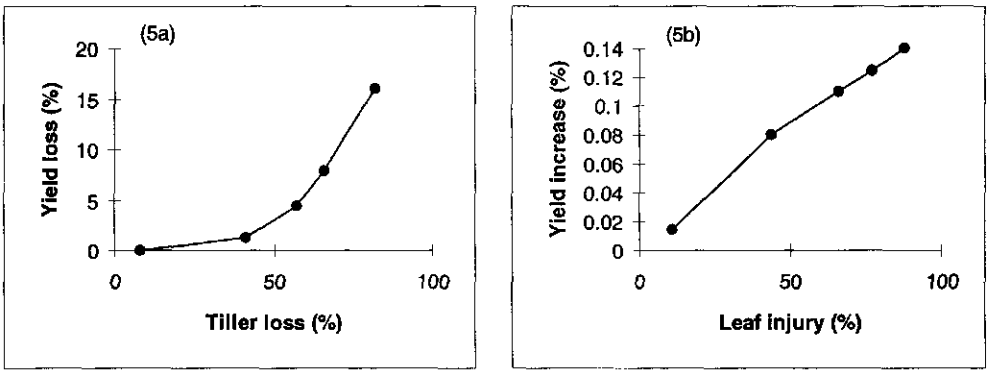

Figure 5. Yield loss due to tiller loss (a) and leaf injury (b).

Simulated above-ground dry matter weight increased slightly with increasing stem borer infestation rate, viz. 0.37%, 1.47% and 3.01% for low, middle and high tiller loss rates, respectively (Table 5). Stem weight significantly increased with increasing stem borer infestation rate. This may be caused by translocation, whereby stem weight increases in response to SSB tiller injury. Leaf weight and leaf area decreases with increasing stem borer infestation rate. Tiller density decreased with 1.4%, 2.8%, and 4.1%, for low, middle

and high infestation rates, respectively; whereas observed tiller loss was 2.1% for low infestation rate.

Leaf folder infestation

Rice plant showed a strong compensation to leaf folder infestation, as there was no yield loss, but a slight increased in yield, simulated for various infestation rates. Stem weight increased with 0.02%, 0.12% and 2.2% for low, middle and high leaf folding rate, respectively; leaf weight decreased with 0.05%, 0.22% and 0.44% for low, middle and high leaf folding rate, respectively; total above-ground dry matter increased with 0.06%, 0.2% and 0.39% for low, middle and high leaf folding rates, respectively. Tiller density was not affected by infestation.

In comparison with only SSB infestation, green leaf weight and leaf area were slightly lower.

Stem borer and leaf folder infestation

Simulated effects of SSB and LF infestation on grain yield were not additive. For low stem borer infestation rates, the combined effect of simultaneous SSB and LF infestation on grain yield, which varied from 0 to 0.12%, was similar or lower (0 to 33.3%) than the sum of the separate effects (Figure 6). For middle and high stem borer infestation rates, the combined effect of simultaneous infestation on grain yield, which varied from 1.3% to 16.1%,was similar or larger (0 to 14%) than the sum of the separate effects.

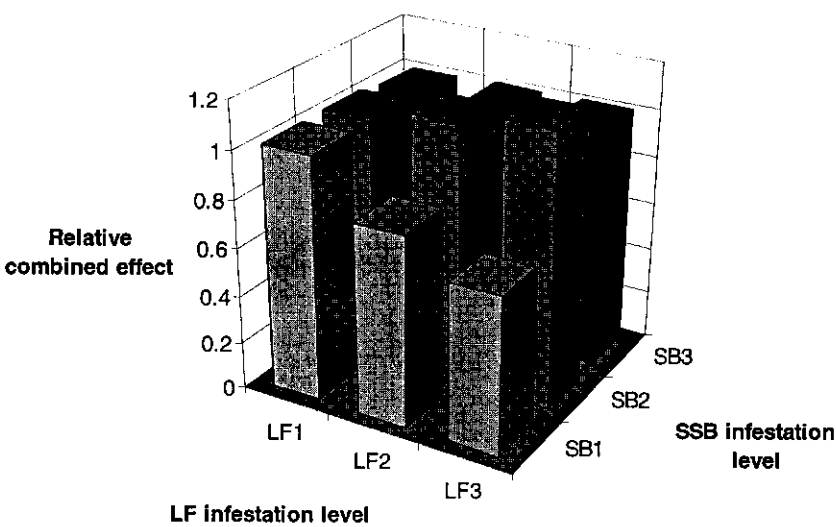

Figure 6. Multiple effects on grain yield due to combined stem borer and leaf folder injury. For each combination of stem borer and leaf folder effects, the sum of the separate effects is set equal to unity.

Simulated stem weight showed highest reduction at middle SSB infestation, without LF infestation. The combined effect of simultaneous infestation on stem weight were 21% (low SSB + high LF) to 433% (middle SSB + high LF) higher that the sum of the separate effects.

The effects of combined infestation on green leaf weight, total above-ground dry matter, leaf area, and tiller density were similar to the sum of the separate effects, however, with a few exceptions: WLVG was 33% higher for the combination of low SSB + high LF, and LAI was 36% lower for the combination of low SB + low LF, than the sum of the separate effects.

Table 5. The effect of various combinations of stem borer and leaf folder infestations on total above-ground dry matter (WAG, kg ha^{-1}), storage organ weight (WSO, kg ha^{-1}), stem weight (WST, kg ha^{-1}), green leaf weight (WLVG, kg ha^{-1}), total leaf+stem area (LAI, ha ha^{-1}), and maximum tiller density (ha^{-1}).

treatment	WSO	WST	WLVG	WAG	LAI	NTI
control	7280	5566	3633	15862	9.13	5.81E+6
SB low	7286	5563	3624	15872	9.11	5.79E+6
SB inf 1	7283	5535	3543	15920	8.95	5.72E+6
SB inf 2	7187	5410	3202	16094	8.25	5.64E+6
SB inf 3	6110	6001	2817	16339	7.77	5.56E+6
LF low	7295	5580	3613	15894	9.09	5.81E+6
LF inf 1	7281	5567	3631	15870	9.13	5.81E+6
LF inf 2	7286	5572	3625	15893	9.12	5.81E+6
LF inf 3	7290	5578	3617	15923	9.10	5.81E+6
SB1+LF1	7284	5537	3541	15927	8.95	5.72E+6
SB2+LF1	7186	5411	3200	16099	8.25	5.64E+6
SB3+LF1	6110	6000	2816	16341	7.77	5.56E+6
SB1+LF2	7287	5541	3535	15949	8.93	5.72E+6
SB2+LF2	7185	5414	3195	16113	8.24	5.63E+6
SB3+LF2	6111	5997	2813	16346	7.75	5.56E+6
SB1+LF3	7289	5547	3528	15976	8.91	5.72E+6
SB2+LF3	7182	5419	3189	16130	8.22	5.63E+6
SB3+LF3	6112	5991	2808	16352	7.74	5.55E+6

Of the five crop characters stem weight, green leaf weight, total above-ground dry matter, leaf area and tiller number at harvest, green leaf weight was most related to yield reduction. Maximum grain yield reduction corresponded with a maximum green leaf weight reduction of 23%, with a stem weight increase of 8%, with an increase in total above-ground dry matter of 3%, and with a reduction of leaf area at flowering of 15%. This occurred in 'stem borer only' scenarios, however, not in 'leaf folder only' scenarios, in which green leaf weight and stem weight decreased slightly. The probable explanation is that in the model is assumed that assimilates that can not be translocated to the storage organs, are added to the stem reserves.

The trends in decrease of grain yield, green leaf weight, leaf area, tiller density, and in increase of total above-ground dry matter and stem weight, are similar for combined infestation and only stem borer infestation (Table 5). Hence, SSB contributed more to the combined effect on grain yield than LF. For low and middle LF infestation levels, for different SSB infestation levels, reduction in stem weight was similar to reduction in case of only stem borer infestation. For high LF infestation levels, for different SSB infestation levels, reduction in stem weight was similar to reduction in case of only leaf folder infestation.

For all simulated combinations of infestations, crop growth rate increased slightly, with increasing insect infestation, which resulted in an increase in total above-ground dry matter production of 0.4 to 3.1%. This also occurred in case of only stem borer (0.37~3.01%) and only leaf folder (0.06~0.39%) infestation.

Discussion

The calibrated SBORER model over-estimated total dry matter production, which could partly be explained by sub-optimal water management. Simulated green leaf weight corresponded well with observed values, whereas leaf area was over-estimated with 65%. The model simulated tiller dynamics well, apart from a 10 days longer transplanting shock.

Simulations indicated that 1% tiller loss resulted in 0.0049 to 0.1959% grain yield reduction, depending on the infestation rate. This is low in comparison with otherreports, i.e. 1% tiller loss causing 0.89-1.58% grain yield reduction in Zhejiang province, 0.80-0.91% in Jiangxi province, and 0.77-0.85% in Hunan province (National cooperation group to study yield loss and economical threshold of striped stem borer, 1987). The latter data on tiller loss were based on one sampling, whereas our data made use of bi-monthly observations on tiller loss, for the entire rice growing season. This clearly illustrates the importance ofdynamics of tiller loss caused by SSB and/or LF presence in the field.

In previous studies, tiller loss due to stem borer and leaf folding due to leaf folder infestation were quantified once for the entire rice growing season, and as one infestation observation can not be used to quantify infestation dynamics during the entire growing season, this often caused difficulties in estimating infestation rates, determining infestation phase, and comparing infestation rates with yield reduction. To avoid this, infestation rates were made input to the model, on the basis of field observations.

At low SSB infestation rates, the rice crop shows over-compensation, as storage organ weight increases. As stem borer infestation rates increase, reduction in storage organ weight, green leaf weight, leaf area and tiller number increase, whereas total above-ground dry matter increases. However, simulated stem weight did not increase with increasing stem borer infestation rate. At low and middle SSB infestation rates, reduction in stem weight increases as the infestation rate increases; whereas at high infestation rate, simulated stem weight increases. Moreover, in case of combined stem borer and leaf folder infestation, simulated stem weight follows the same pattern as in the 'stem borer only' scenario.

At low leaf folder infestation levels, rice plant showed strong compensation, viz. as infestation rates increased, storage organ weight increased. Also, leaf folder injury did not influence density of healthy tillers. Leaf folder infestation also had limited effect on green leaf weight and leaf area. This is the reason why some crop protectionists consider leaf folder a minor pest.

Simulations indicate that, under particular conditions, a rice crop has compensation ability for the effects of stem borer, leaf folder, and combined stem borer and leaf folder infestations. The degree of compensation varies over conditions. The combined effect of the simultaneous infestation on grain yield varied from -33.3% (low SSB + high LF) to +14.04% (middle SSB + high LF), in comparison with the sum of the separate effects (Figure 6). Existing economic thresholds may over- or under-estimate grain yield reduction. Hence, it is recommended that new economic thresholds are developed for combined stem borer and leaf folder infestations.

Further leaf folder field experiments are required. The relations between leaf weight, leaf area loss and leaf injury rates must be quantified. The compensatory mechanisms of rice plant to leaf folder infestation are likely to be different with those of stem borer. This should be quantified with field experiment.

References

Bautista, R. C, Heinrichs, E.A. and Rejesus, R.S. 1984. Economic injury levels for the rice leaffolder *Cnaphalocrocis medinalis* (Lepdoptera: Pyralidae) : insect infestation and artificial leaf removal. Environmental Entomology 13: 439-443.

Cheng, C.H. 1987. Investigation on bionomics of the rice leaffolder, *Cnaphalocrocis medinalis* (Guenee) in the south of Taiwan. Plant Protection Bulletin, Taiwan 29: 135-146.

Dai, X.F & Y.Y. Guo, 1992. Multiple-species economic threshold in pests control: theory and approach. Transactions of the ecological society of Chinese Youths, vol. 2:48-55 (in Chinese).

Elings, A & E.G. Rubia, 1994. Models for the crop-pathosystems rice-bacterial leaf blight, sheath blight and stem borer, AB-DLO, TPE-WAU, IRRI. 102 pages.

Fabellar, L.T., N.G. Fabellar & K.L. Heong. 1994. Simulating rice leaffolder feeding effects on yield using MACROS. Int. Rice Res. Newsl. 19: 7-8.

Fan, Y.D. & C.Y. Lu, 1988. Yield loss and economic threshold for striped stem borer in rice tillering stage. Kunchongzhishi 25: 1-4 (in Chinese).

Gomez, K.A. & R.C. Bernardo, 1974 Estimation of stem borer damage in rice field. J.Econ. Entomol. 67: 509-513.

Heong, K.L., & L. T. Fabellar, 1988. Modelling feeding rates of rice leaffolder *Cnaphalocrocis medinalis* (Lepdoptera: Pyralidae) on different plant stages. Int. Rice Res. Newsl. 13: 38.

Jong, P.D. de, 1992. Effect of folding and feeding by *Cnaphalocrocis medinalis* on photosynthesis and transpiration of rice leaves. Entomol. Exp. Appl. 63: 101-102.

Jong, P.D. de & R.A. Daamen, 1992. Simulation of yield loss by the rice leaffolder *Cnaphalocrocis medinalis* under different growing conditions. J. Plant Prot.Trop. 9: 117-123.

Li, X.L. (Ed.), 1982. Agricultural Entomology, Shanghai Scientific & Technology Press, 398 pages (in Chinese).

Luo, S.F. 1987. Studies on the compensation of rice to the larval damage caused by the Asian rice borer (*Chilo supressalis* (WK)). Sci.Agric. Sinica 20: 67-72 (in Chinese).

Murugesan, S. & S. Chellian, 1986. Yield loss and economic injury by rice leaf folder. Indian J. Agric. Sci. 56: 282-285.

National cooperation group to study yield losses and economy threshold of striped stem borer, 1987. Study on yield loss and economic threshold of striped stem borer. Prediction of disease and pests 1987 (2): 1-8.

Rubia, E.G. & Penning de Vries, F.W.T., 1990. Simulation of yield reduction caused by stem borers in rice. J. Plant Prot. Trop. 7: 87-102.

Xu, W. & Z.S. Zhang, 1988. Study on yield loss and economic threshold for striped stem borer. Zhejiang Agricultural Science 2: 75-79 (in Chinese).

Methods of estimating yield loss due to yellow stem borer in Thailand

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Abstract

Yield loss due to the the rice yellow stem borer (*Scirpophaga incertulas* (Walker)) and other stem borer species was assessed, during the dry and wet seasons of 1986, and dry season of 1987, at the Suphan Buri Rice Experiment Station, Central Plain, Thailand. Variety RD7 was used, and the single hill and microplot methods in were applied in 1986 and 1987, respectively. Infestation was determined on 500 hills by counting the number of injured and healthy tillers per hill. Number of dead hearts per hill was counted at weekly intervals, starting at 35 days after transplanting (DAT) in the wet season, and at 24 DAT in the dry season, respectively, until 70 DAT. Grain yield per hill was determined. Observations were grouped into classes of the same stem borer damage. On the basis of these classes, regression functions that describe the relationship between the number of dead hearts per hill at three crop development stages, and fraction grain yield reduction, were derived.

Introduction

Rice ecosystems are in a very complicated manner affected by biotic and abiotic factors. Stem borer infestation is one of the biotic factors that influences rice production. Yield loss assessment is a tool to determine crop-pest relationships, and can indicate the pest densities at which grain yield is not affected, resulting in the definition of a damage threshold. Regressions models can describe the relationship between pest density and yield reduction.

Stem borers belong to the most important rice pests in Thailand. Of the four stem borer species that exist in Thailand, the yellow stem borer, *Scirpophaga incertulas* (Walker) is the most important (Sindhusake, 1993). An important constraint in studying crop-pest relationships is a low infestation, and therefore. This paper presents a method for assessment of yield loss due to stem borers at various levels of infestation during the wet and dry season in Thailand.

Materials and methods

Yield loss assessment on the basis of single hills

Yield loss experiments were conducted during the 1986 dry and wet seasons at Suphan Buri Rice Experiment Station, in the Central Plain, which is one of the important rice production areas in Thailand. In both seasons the same experimental procedure was used. Rice variety RD7, which matures in 120 days, was transplanted to a plot of 900 m^2. The transplanting date of was one month earlier than normal, in order to enhance stem borer infestation by making use of the higher insect density earlier in the year. Five hundred hills, in 20 rows of 25 hills were systematically selected by marking every fifth hill. Half of the field was sprayed with monocrotophos at a dosage of 375 ml ha^{-1} to keep stem borer infestation at a low level. Natural stem borer infestation was recorded during the 1986 dry season 6 times at weekly intervals, from 35 to 70 DAT. Ten observations were made during the 1986 wet season from 24 to 70 DAT. Numbers of healthy and infested tillers per hill were recorded. Number of panicles and grain yield were determined per hill.

Crop loss assessment on the basis of microplots

A different procedure was used in the 1987 dry season. The experiment was conducted at the same location and with the same variety, however, the field was divided into small plots of 25 hills (5×5) each. The central 9 hills of each plot were weekly observed for the presence of stem borers and other pests. Pest density and yield components were recorded for the 9 central hills of each plot. To induce different levels of stem borer infestation, plots were treated 0 to 5 times with monocrotophos. Each treatment was replicated 4 times.

Results and discussion

Correlation and regression of stem borer infestation and yield loss

A severe stem borer infestation was observed during the 1986 dry season, whereas infestation rates were lower in the 1986 wet and 1987 dry seasons. Average numbers of dead hearts for the three seasons were different, however, maximum amounts of dead heart were observed in all three experiments at the end of the vegetative crop development stage.

In both the 1986 dry and wet seasons, all 500 hills showed at least at one moment in time symptoms of stem borer feeding. As yield loss could not be determined on the basis of the experiments, grain yield of an uninfested crop, was estimated by regression of grain yield on stem borer infestation. High variation in grain yield per hill due to factors other than stem borer infestation resulted in non-significant regression models when the analysis was based on the individual hill data. Therefore, all observations were grouped on the basis of number of dead hearts per hill.

Linear regression lines with correlation coefficients of 0.89 or higher were derived from the grouped data, taken on 49, 56 and 63 DAT, of the 1986 dry season, whereas analysis of stem borer injury at 35 and 42 DAT did not result in significant relationships. The first group of regression functions were used to determine fraction crop loss as the result of given numbers of dead hearts per hill. In the second regression analysis, percent grain yield reduction was related to number of dead hearts per hill. The obtained results are given in Table 1. Statistical precision and amount of explained variation are satisfactory for all three regression functions.

Table 1. Relationships between number of dead hearts and fraction grain yield reduction at various moments during crop growth. Data are derived from a single hill experiment, during the 1986 dry season, using RD7, at Suphan Buri Rice Experiment Station.

Date of observation	Regression line	SE	F	r^2	N
49 DAT	y = -0.02 + 4.93 x	0.57	74.0***	0.89	11
56 DAT	y = 0.002 + 6.01 x	0.39	240.7***	0.96	12
63 DAT	y = 10.16 + 8.27 x	0.86	92.7***	0.95	7

y = % grain yield reduction
x = number of dead hearts per hill
*** = $p < 0.001$

Contrary to previous reports from the Philippines (Gomez & Bernado, 1974) and Bangladesh (Catling et al., 1978), the linear regression lines obtained in this study described well the relation between stem borer injury and crop loss.

One infested tiller per hill at 49, 56 and 63 DAT resulted in a grain yield reduction of 4.9, 6.0 and 8.3 % respectively. The significant yield reduction at low infestation levels, as observed for 63 DAT, indicates an effect of time on the relationship between infestation level and grain yield reduction at low infestation levels. Damage is more severe if infestation occurs later. All three regression lines indicate more that one dead heart results in a yield reduction of more than 1% (Tables 1 and 2).

Data collected during 1986 wet season were analyzed similarly. The derived regression equations are given in Table 2.

Table 2. Relationships between number of dead hearts and fraction grain yield reduction at various moments during crop growth. Data are derived from a single hill experiment, during the 1986 wet season, using RD7, at Suphan Buri Rice Experiment Station.

Date of observation	Regression line	SE	F	r^2	N
38 DAT	y = 5.86 + 4.64 x	1.28	13.1*	0.72	7
52 DAT	y = 8.20 + 5.94 x	0.82	65.2**	0.94	6
59 DAT	y = 3.00 + 7.60 x	1.59	22.9*	0.92	4

y = % grain yield reduction * = $p < 0.05$
x = number of dead hearts per hill ** = $p < 0.01$

Regression analysis of data collected in the microplots during the 1987 dry season, and transformed to treatment means, did not yield a useful predictive model. Grouping of the individual hill data, in the same way as described for 1986, neither resulted in significant relations between number of dead hearts and fraction grain yield reduction. This was caused by the very low stem borer densities, and the low number of groups that could be formed per set of observations. Therefore, differences in grain yield between the group of hills without stem borer injury at a particular time, and the groups with various numbers of dead hearts or white heads, were calculated (Table 3). Except for the observations at 62 DAT, data in Table 3 relate to a later period of crop growth than the equations derived from the 1986 dry season results. There appears to be no further increase in yield reduction per infested tiller over this part of the growing season, and significant correlations and regressions could not be found. Similar fractions yield reduction were associated with given injury levels at the four moments of observation.

Table 3. Average fraction yield reduction per hill due to stem borer infestation, for variety RD7, during the 1987 dry season, at Suphan Buri Rice Experiment Station.

Number of infested tillers per hill	Percent yield reduction				
	62 DAT	69 DAT	76 DAT	83 DAT	average
1	3	15	5	16	9.8
2	9	18	17	21	16.3
3	29	32	27	34	30.5
4	–	–	31	16	23.5
5	–	–	38	37	37.5

Conclusion

The yield loss estimates indicate that the fraction yield loss caused by stem borers is not only determined by the growth stage of the crop, but also by the environment. A different environment will result in a different attainable yield level, and in different yield loss by stem borer infestaion. This appears to be particularly the case in periods during which stem borer control measures are carried out. As many environmental factors have an effect on dry matter production and grain yield, the effect of plant age, in interaction with other factors, on these two variables, has to be studied with physiologically based simulation models. Based on variables as mentioned above, the use of a crop growth model may stimulate exchange of information between different disciplines, and may lead to comprehensive hypotheses on plant-environment interactions.

References

Catling, H.D., S. Alam, & S.A. Minh, 1987. Assessing losses in rice due to insects and diseases in Bangladesh. Expl. Agric.14: 277-287.

Gomez, K.A. & R.C. Bernado, 1974. Estimation of stemborer damage in rice fields. J. Econ. Entomol. 67: 509-513.

Sindhusake, Ch., 1993. Assessment of yield losses due to rice insect pests and their economic threshold levels. In Integrated Pest Management Control Component. BIOTROP Spec. Publ. No. 50. p. 49-61.

Section C

Brown plant hopper

Damage mechanisms of brown planthopper infestation: modelling approaches under a paradigm shift in pest management

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Aims and approaches

The effects of insect infestation on crop growth and production are complex and variable. Interactions among onset, duration and intensity of insect infestation, environmental conditions and crop growth, cause variation in the effects of infestation on crop yield. A pest-crop combination model is a useful tool for quantitative analysis of the reductions in total dry matter production and grain yield, which are the results of dynamic interactions among pest, crop and climate conditions. Use of a model also enables better understanding of the cause-effect relationships in a host-pathogen system.

Identification and prioritization of damage mechanisms are the first, essential steps in building a pest-crop combination model. For instance, in the case of feeding insects, damage to the crop caused by insect infestation may be directly or indirectly related to the insect feeding. The feeding behaviour determines how the link between the two trophic systems with respect to energy flows from plants to herbivores is modelled.

The brown planthopper (BPH) is originally a successful monophagous herbivore on rice, which exploits nutrients and carbohydrates from rice plants. Whereas chewing insects destroy the crop's photosynthetic system by eating crop tissue, sucking insects withdraw assimilate solutes from the crop without destroying the crop's photosynthetic systems. Host and pathogen have, in a process of co-evolution, formed a sustainable paddy ecosystem. Integrated Pest Management (IPM) practitioners are aiming at maintaining such sustainable ecosystems. However, the pesticide-dependent crop protection technologies which were promoted in the 'Green Revolution' induced resurgence of BPH populations. These large populations caused feeding damage to the rice crop, commonly referred to as hopperburn, and destroyed the ecological balance between the two trophic systems.

Along with increased attention for, and understanding of, the ecological aspects of BPH population dynamics in tropical paddy fields, the IPM paradigm has shifted from pesticide-dependent to ecosystem-dependent, which is currently by common agreement characterized by 'the maximum conservation of natural enemies and minimal reliance on pesticides'. Also, the status of BPH is changing from a primary to a secondary rice pest.

A good understanding by researchers of the effects of certain pest management strategies on the pest population, is essential to the practical value of SARP's output. This is important, as SARP should provide advisory tools for judicious and judicial pest management, and analytical tools to investigate damage to the crop due to the pest infestation.

Evaluation of the impact of BPH feeding on rice production under different pest management systems could be a significant contribution of SARP to BPH management in tropical rice agriculture. The technical implication of application of the economic threshold level (ETL) concept to BPH management, and the possible role of resistant varieties can be explored by simulation, which would enable better determination of their roles in BPH management.

The brainstorming technique was employed to encourage members of SARP's Pest and Disease Management Application Theme to discuss above-mentioned issues, to design the concepts of a BPH-rice combination model, and to stress the application of models to practical conditions. The following 3 questions were discussed:

1. How does BPH feeding cause damage to the rice crop?
2. Is ETL essential to BPH management?
3. Are BPH resistant varieties still needed?

Modelling approaches to the effects of BPH sucking

A brown planthopper is an actively sucking insect, which is visible through excretion of large amounts of honeydew. Its feeding behaviour is characterized by stylet insertion in the phloem of rice plants, through which photosynthates are translocated. Therefore, BPH insects feeding on rice can be considered as an 'extra sink' for photosynthates, or as 'assimilate consumers'. BPH feeding causes two major symptoms, viz. reduction of crop growth rate, and hopperburn, in the vegetative and reproductive crop development phase, respectively. Before anthesis, N and C are removed from the crop, which results in reduced photosynthesis and growth. Generally, crop N levels before anthesis are sufficiently high to avoid early senescence. Hopperburn is the accelerated senescence of a crop after anthesis. This process quickly reaches the flag leaf, and causes termination of grain fill. Drain of nitrogen, which is remobilized from the leaves to the grains during grain filling, may cause the accelerated senescence. In addition to feeding effects, mechanical injury due to stylet probings and injection of toxic saliva may be causes of damage. Injury caused by egg laying in plant tissue, and increased incidence of stem rot and sheath blight were also suggested as secondary causes of damage. All ideas and opinions were summarized in a relational block diagram (Figure 1).

Although full identification, ranking and quantification of possible BPH damage mechanisms has not been completed as yet, highest priority must be given to sucking of phloem sap, as this directly interferes with the assimilate flow in the host plant. In modelling terms, the sucking of phloem sap by BPH insects can be considered as a functional valve (rate variable), affiliated to the assimilate pool of the rice crop. The increase in dry matter weight of the insect population does not account for the reduction in total aboveground dry matter due to BPH infestation (IRRI-Japan Shuttle Research

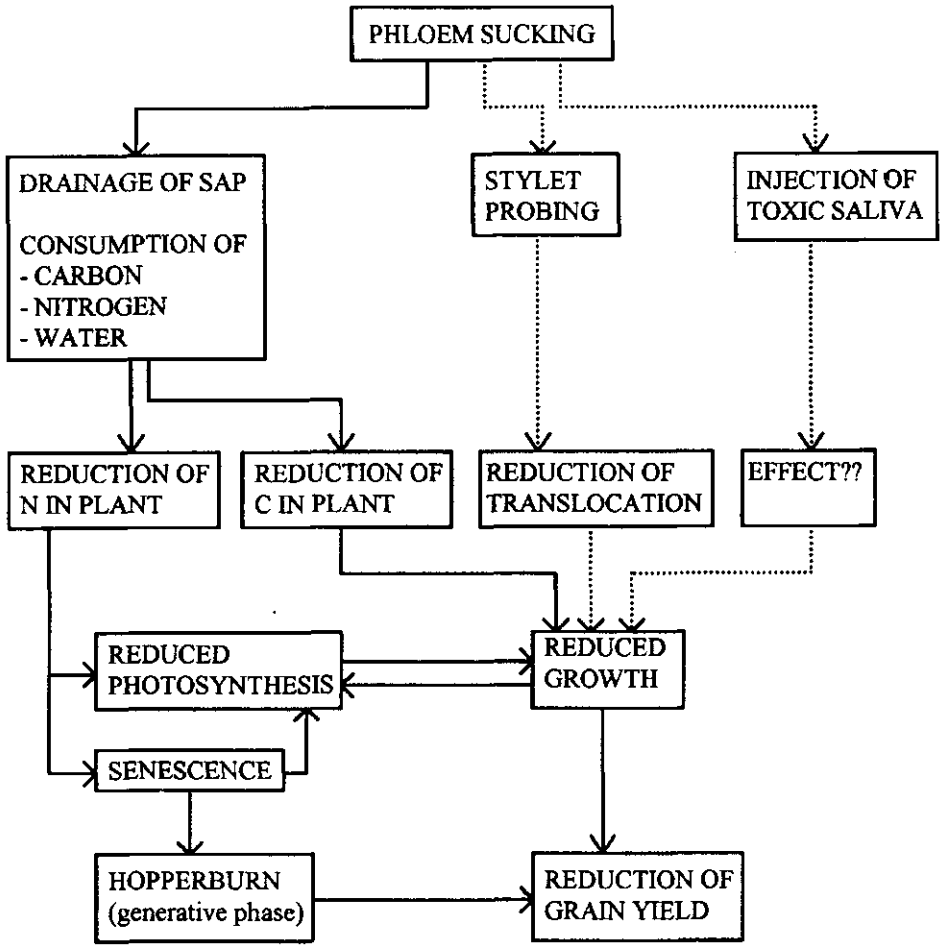

Figure 1. Possible damage mechanisms with respect to brown planthopper sucking on rice.

Project 1992-1993). In addition to the drain of photosynthates, nitrogen, and other phloem sap constituents, the effects of BPH sucking on physiological processes in rice plants such as photosynthesis, respiration, translocation, and senescence have to be further investigated to describe the damage mechanisms. Also, the phloem sucking probably has different effects on rice growth and production at different crop development stages. Sucking could reduce crop growth rate during the vegetative phase of the crop, and accelerate crop senescence, leading to hopperburn, in the reproductive phase of the crop.

Further interdisciplinary collaboration between planthopper specialists and rice physiologists is required, to investigate the important cause-effect relationships between insect feeding and plant physiological processes, and to design experiments for obtaining parameters values that are required for modelling.

Paradigm shift in BPH management, and the consequences for modelling

Application of a pest-crop simulation model enables assessment of yield loss, and evaluation of the effects of various pest management strategies. The results can be used to generate pest and crop management advises. A good understanding by researchers with regard to the paradigm shift in BPH management, and to the change of the BPH pest status, are elementary to the applicability of models. In order to generate pest management advises, two topics were raised during the brainstorming, viz. the ETL concept, and varieties resistant to BPH, which are both closely related to the recent paradigm shift in BPH management strategies.

Pesticides and resistant varieties were previously the major components of crop protection in rice farming. An ETL defined the amount of injury that would cause a certain amount of damage that justified the cost of pest control, which was equivalent to the cost of pesticides. ETL based advises specified in most cases the moments of pesticide application. Therefore, the ETL concept was a strong tool in justification of the pesticide technology, which was particularly utilized in advertising campaigns that promoted pesticide use. It is now well documented that preventive pesticide use tends to cause serious resurgence of the BPH populations (e.g. Heinrichs & Mochida, 1984). As a supplementary control measure, resistant varieties had been planted widely to areas prone to BPH outbreaks. However, as the rice-ecosystems here were pre-conditioned by intensive pesticide application, sequential release of rice varieties with different genetic resistance to BPH attributed only to the development of other, more virulent BPH biotypes.

For example, devastating outbreaks of BPH in Indonesia during 1974-1979 were successfully suppressed by wide-spread planting of IR36, the rice variety resistant to BPH. However, pesticide use increased strongly, which increased the risk of BPH outbreaks as it stimulated development of new biotypes. The second surge of BPH outbreaks started with a sudden spread of more virulent biotypes to 200,000 ha of paddy fields in 1986. A possible reduction in national rice self-sufficiency, which was attained in 1985, became a serious political problem. Finally, the pesticide that had induced the BPH resurgence were banned from use in paddy fields by Presidential Instruction in November, 1986. By this powerful political intervention, further BPH outbreaks were effectively avoided, and since then, IPM has been implemented successfully in Indonesia.

Because of compatibility with natural enemies, cultivation of resistant varieties may be an insurance against pest outbreak when biological control fails. However, resistant varieties should not be used as a safeguard to BPH resurgence as a consequence of heavy pesticide application for the control of another pest. For example, chemical control may be recommended for the management of leaf feeders, such as the rice leaf folder. However, damage caused by leaf feeders is usually aggravated, because farmers tend to be over-anxious for the conspicuous but actually insignificant syndromes. Therefore, pesticide application is often not needed. SARP has to contribute to break the vicious cycle of such pesticide-dependent syndromes.

As a consequence of the paradigm shift, BPH management in tropical paddy fields has shifted from pesticide-oriented to ecosystem-oriented. IPM is founded on the ecological principle that BPH populations can be kept at densities below the ETL by natural enemies, unless these are destroyed by prophylactic pesticide spraying. Therefore, ETLs that are based upon the use of pesticides and cultivation of resistant rice varieties are now posing a basic question with regard to their practical value for BPH management.

The majority of the participants supported the importance of ETLs as a decision tool or action threshold in BPH management, and as a criterion to reduce unnecessary insecticide application. A few participants pointed out that an ETL may alarm the farmers to spray, or induce the habit of preventive spraying. Most participants considered that resistant varieties are still necessary to suppress BPH, interrupt insecticide-induced resurgence of BPH populations, ensure biological control, and reduce pesticide use. Researcher's perception of the pest status of BPH, and of the technical approach to BPH management changes slowly, in spite of the significant paradigm shift in pest management strategies.

The ETL concept must be applied carefully to secondary insect pests, particularly to those pests for which the chance of outbreak in case of prophylactic pesticide use exists, as then the application of an ETL may lead to even larger pesticide use, as has been pointed out above. Instead, simulation of yield losses due to the BPH infestation, which may be limited, would strengthen sound implementation of IPM.

Conclusions

The brainstorming stimulated thinking about major phenomena in relation to the damage mechanisms of the BPH-rice system. Phloem sucking by the insect was identified as a prime mechanism causing damage to the rice crop. BPH was, therefore, in mechanistic terms, characterized as an 'extra sink' or 'assimilate sapper'. It was further hypothesized that the effects of intensive phloem sucking can explain reduced crop growth in the vegetative phase of the crop, and enhanced leaf senescence in the generative phase. However, available research data on the different plant physiological reactions are insufficient to quantitatively incorporate the effects of BPH sucking effects to the rice model. Physiological processes of damage mechanisms must be identified, prioritized and quantified in experiments, in order to fill the existing knowledge gaps with respect to insect feeding activities, injury symptoms, and damage, and to evaluate assumptions on BPH-rice interactions, which are so far based on field observations and empirical information. Different modelling concepts can be developed during this process of experimentation, dependent upon the emphasis researchers wish to give to the various material flows that connect the BPH and rice systems, such as carbon, nitrogen and water flows.

Dynamic crop growth models provide advisory tools for pest management. Therefore, thorough understanding of the target pests and recommended pest management strategies are indispensable for a useful contribution by SARP to integrated pest management. Despite a large change in the pest status of BPH, and a paradigm shift in BPH management in tropical paddy ecosystems, some researchers tended to confine themselves to their old ap-

proaches. Further changes should be stimulated, by transferring knowledge from other disciplines, in order to develop a practical role for the SARP project, to improve its scientific perspectives, and to develop tools that provide insight into the dynamic mechanisms of pest infestation to a crop.

References

Heinrichs, E.A. & O. Mochida, 1984. From secondary to major pest status: the case of insecticide-induced rice brown planthopper, *Niliparavata lugens*, resurgence. Protection Ecology 7: 201-218.

Feeding behaviour and damage mechanism of the rice planthoppers

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Introduction

The brown planthopper (BPH), *Nilaparvata lugens* Stal, and the white-backed planthopper (WBPH), *Sogatella furcifera* Horvath, are the most important herbivorous insect pests on rice in the south-western part of Japan (Suenaga & Nakatsuka, 1958). These Delphacid planthoppers are characterized by a monophagous interaction with their host plant, rice (*Oryza sativa* L.), and by migration over a long distance from tropical to temperate latitudes. This migration is influenced by the monsoon climate prevalent in East Asia (Kisimoto, 1981; Sogawa & Watanabe, 1992).

BPH and WBPH invade simultaneously, in several massive surges, the newly transplanted paddy fields in Japan in the months of June and July during the Baiu season (the rainy season). The immigration peak usually occurs in late June to early July. Both planthoppers species cause feeding damage to the rice crop, however, because of their different life histories, which are related to the age of the host plant and injury symptoms, the physiological backgrounds of damage caused by the two species are different. BPH and WBPH are generally known by Japanese farmers as the 'summer' and 'autumn' planthopper, respectively, for the seasons in which the populations are largest and most injurious.

The densities of the immigrating WBPH populations is several tens to hundreds times higher than that of the BPH population. WBPH prefers rice plants which are in the early tillering stage, and the insect's reproduction is restricted to one or two generations during the vegetative development phase of the rice crop. Therefore, damage caused by an immigrating WBPH population and its progeny is restricted to young rice plants in the vegetative phase. Furthermore, damage is only caused if the density of the immigrating population is higher than 5 planthoppers per hill. Intensive oviposition by immigrant females causes conspicuous discolouration of the outer leaf sheaths of newly transplanted rice seedlings. Sucking by immigrants and their progeny limits vegetative growth, which results in reduced plant height, tiller density, crop biomass, LAI, etcetera (Naba, 1991). However, plant growth is mostly sufficient to limit the effects of these symptoms on grain yield.

The population dynamics of BPH is different. The densities of the BPH populations that immigrate into paddy fields are very low, and 2 or 3 generations are produced during the generative development phase of the rice crop. Brachypterous females play an important role in the population build-up in paddy fields. Economic damage may be caused by

their progeny if the density of brachypters is higher than 0.2 to 0.3 per hill. In contradiction to WBPH, a BPH population does not cause any visible injury to rice plants during vegetative development, but causes irreversible damage to the crop the during its reproductive development phase. The typical BPH symptom is commonly referred to as hopperburn (Cagampang et al., 1974). The first symptom of hopperburn is chlorosis of old leaf blades. Chlorosis extends progressively to all plant parts, and plants eventually turn brown and fully deteriorate. Browning of plants initially shows as patches in paddy fields, which spread rapidly in case of severe hopperburn. The ecology of BPH, with special reference to the causes of hopperburn damage, has been studied in detail by Kisimoto (1965) and Kuno (1968).

Damage caused by planthoppers has been evaluated by determining the yield components of the rice crop, such as panicle density, number of grains per panicle, fraction filled grains, and final grain weight (Sogawa & Cheng, 1979). Also, statistical relations between insect density and yield loss have been determined, which formed the basis of static thresholds. However, the effects of insect infestation on crop growth and production are very complex and dynamic in time, and depend upon interactions among crop, insect population, and environmental factors affecting crop growth and insect activities (Bardner & Fletcher, 1974). A crop-pest simulation model is a useful tool to analyse these dynamic processes, and provide tactical information for pest management (Boote et al., 1983; Johnson et al., 1986).

This paper summarized available information on planthopper feeding behaviour and damage levels, and discusses possible damage mechanisms of planthopper infestation. This may facilitate incorporation of planthopper feeding into crop growth models, which can be used for simulation of the dynamic interactions between insect population and rice crop.

Phloem sucking by the planthoppers: 'assimilate sappers'

Interactions between an insect and its host plant are mostly determined by the insect's feeding. Feeding is the activity of the insect that causes most damage to the crop, as nutrients are removed, physiological activities are disrupted, and pathogens are inoculated. The feeding behaviour of BPH and WBPH is characterized by stylet feeding on the leaf sheath. The planthopper insert its capillary stylet in the leaf sheath, in which it deposits coagulable salivary secretions, and where it sucks from the phloem at very localized spots (Sogawa, 1973, 1982). Both the nymphs and adults feed on rice plants in the same manner. BPH and WBPH feed preferably on the phloem sap of leaf sheaths at the base of the plant, and of the upper leaves, respectively.

The phloem is the vascular system of a plant in which photosynthates and other nutrients that have been synthesized are translocated from source to sink organs (Zimmermann, 1960). The acquisition of energy (in the form of photosynthates) and nutrients for the planthopper's own assimilation depends upon the ingestion of phloem sap from the host plant. Therefore, the rice planthoppers are herbivores which exploit energy and nutrients

from the host plants by establishing a direct physical connection with the phloem streams of the plant without destroying the plant's metabolic system. The feeding activity of a planthopper is visible through the excretion of large amounts of sugary honeydew during the sustained sucking. The planthopper population on the rice crop can be considered as an extra sink in the host-pathogen system, in which the transport of nutrients and energy from the rice crop to the planthopper population by a direct connection of the planthopper alimentary canal to the phloem system of the rice plant (Sogawa, 1992b).

The photosynthates are transported through the phloem in the form of sucrose, from the leaves to the sink organs. Sucrose and amino acid concentrations in the rice phloem sap collected from BPH stylets, were 17-25 g ml^{-1} and 3-8 g ml^{-1}, respectively (Fukumorita & Chino, 1982). Potassium had a concentration of about 5900 ppm, and was the major inorganic component of the phloem sap (Fukumorita et al., 1983). However, honeydew is excreted by BPH as clear droplets and contains high amounts of sugars and amino acids (Sogawa, 1982). The principal carbon and nitrogen sources utilized by the planthoppers are sucrose and amino acids may originate from the phoem of the host plant, as has been reported for aphids (Auclair, 1963). Each female BPH adult excretes 10 to 60 ml honeydew per day. As the insects ingest and egest a large quantity of photosynthesized carbohydrate (sucrose) by linking up with the phloem of the rice plant, planthoppers can be classified as 'assimilate sappers'. A potential damage mechanism is the transport of plant assimilates from the phloem in the host plant to the alimentary canal of the planthoppers by sucking (Figure 1).

Hopperburn and 'senescence acceleration'

The symptoms caused by BPH infestation to the rice plants during the reproductive development phase are characterized by upward progression of leaf chlorosis, which is not conspicuous during the earlier vegetative phase. When chlorosis reaches the flag leaf, grain filling ceases, and eventually the plant dies. This condition is known as 'hopperburn'. Therefore, grain yield reduction under hopperburn conditions is largely determined by the moment of cessation of grain fill (Kisimoto, 1976). If the BPH population density remains below the level that causes hopperburn, plants survive until harvest. However, grain yield declines as a consequence of reduction in green leaf area. The symptoms of leaf chlorosis due to the BPH infestation, and due to senescence, are similar, except for the fact that chlorosis due to BPH infestation is very acute and causes rapid senescence of green leaf area. This 'senescence acceleration' by BPH is an additional damage mechanism during the crop's reproductive development phase (Sogawa & Cheng, 1979).

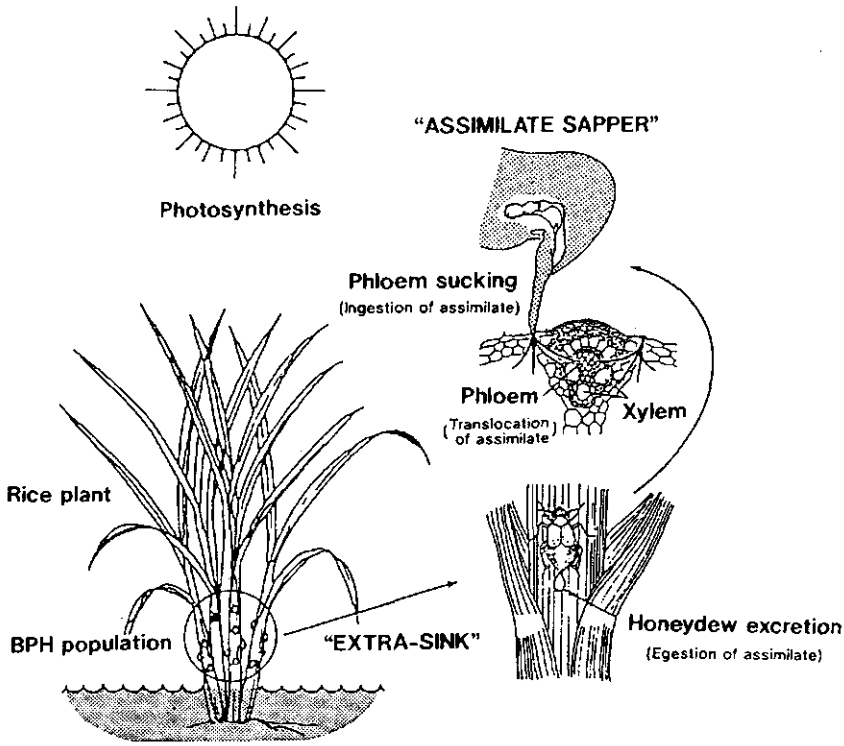

Figure 1. The trophic interaction between BPH and rice plants. The BPH population is defined as an 'extra-sink' or 'assimilate sapper', linked to the photosynthetic system of rice plants by phloem sucking.

Quantification of planthopper sucking

The sucking rate of a planthopper varies, depending upon insect developmental stage, sex, age and nutrient status of the host plant, and environmental factors. Quantification of insect sucking is the first step in investigation of the damage mechanisms. To measure honeydew excretion and changes in body weight during sucking, a small clip-on parafilm sachet (of about 2.0 × 1.5 × 0.5 cm) was devised, which confines an individual insect on a selected position on the plant (Sogawa, 1992a).

The rate of honeydew excretion by BPH nymphs increases exponentially as they develop to nymphal instars, and is closely related to the increase in dry weight of the nymphs. Newly emerged nymphs and 5^{th} instar nymphs excrete about 0.05 mg and 1-1.5 mg honeydew (dry weight) per day, respectively. Female adults maintain a high level of honeydew excretion, whereas honeydew excretion by males declined sharply. Therefore,

large nymphs (4^{th} and 5^{th} instars) and adult females form the major extra sink of a planthopper population colonizing on a rice crop (Sogawa, 1992b).

The rates at which dry matter is drained from a rice plant in its early tillering phase by large nymphs and adult females of BPH and WBPH are given in Table 1, in mg dry matter $insect^{-1}$ day^{-1} at 25 °C (Sogawa 1992b). BPH drains 2 to 3 times more dry matter from the rice plant than WBPH. Eighty per cent of the total amount of dry matter removed from the phloem was directly excreted in the form of honeydew. Only 10 to 15% of the dry matter ingested was assimilated to insect biomass.

Table 1. Rates of dry matter consumption (mg d^{-1} $insect^{-1}$) at 25 °C by the 4^{th} and 5^{th} instar nymphs and adult females of BPH and WBPH that suck on rice plants in their early vegetative development stage (Sogawa, 1992b).

	BPH		WBPH	
Fractions	Nymph	Adult	Nymph	Adult
Honeydew	0.54	1.54	0.28	0.65
Insect biomass	0.10	0.31	0.06	0.07
Respiration	0.04	0.14	0.03	0.06
Total	0.68	1.99	0.37	0.78

The rate of honeydew excretion by both planthopper species varies significantly, depending upon crop age. In general, the rate reaches a maximum at 2 weeks after transplanting (WAT). The maximum rate is maintained up to maximum tillering, and then declines, until booting or flowering is reached (Figure 2) (Sogawa, 1992b). The amino N concentration in the phloem may determine the insect sucking rate, since amino acids stimulate the sucking by planthoppers (Sogawa, 1982). Also nitrogen fertilization has a significant effect on planthopper sucking and insect population growth (Kanno et al., 1977). Therefore, the effect of the nitrogen status of the host plant on insect sucking, in relation to plant age and crop fertilization, may be one of the important mechanisms that influence the dynamic interactions between planthoppers and plants (Cook & Denno, 1994).

The rate of honeydew excretion (y, in mg per insect per day) is a linear function of temperature (x, in °C). The function has a validity domain of 17.5 to 30 °C (Sogawa, 1992b):

$y = 2.1 \times - 18.4$ ($r=0.95$).

This equation can be incorporated in a host-pathogen combination model, to enable computation of amount of dry matter drained from the crop on the basis of insect density.

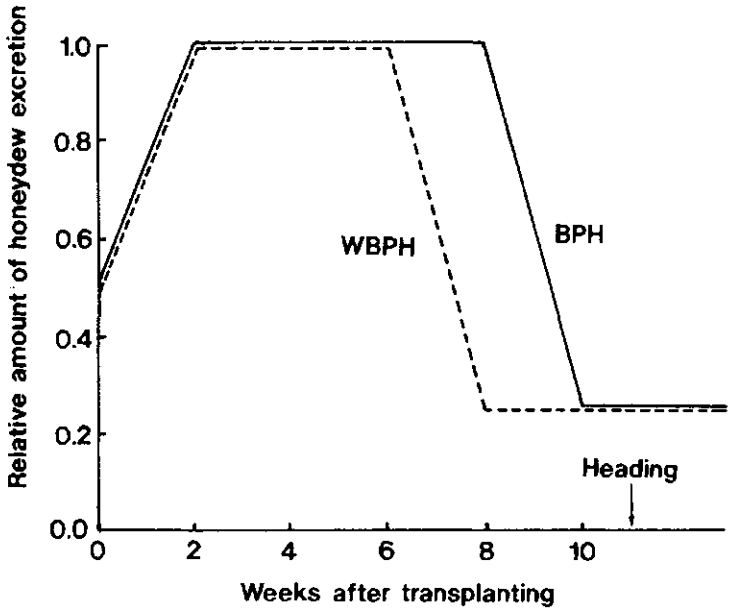

Figure 2. Relative sucking activity of BPH and WBPH as a function of host plant age (Sogawa, 1992b).

Quantification of damage due to sucking

In addition to diagnostic and morphological information, quantitative analysis of the metabolic changes in the host plant due to insect infestation can be used to quantify damage to the host plant. The data given below were obtained through outdoors or greenhouse experiments with *japonica* variety Reihou at the Kyushu National Agricultural Experiment Station (Sogawa, unpublished). Plants were transplanted at a density of one plant per pot of 0.02 m^2. Each plant was infested with a nymph population that had emerged from eggs deposited by 2 to 5 pairs of BPH adults. Insects were confined to the plants with nylon gauze cages.

(1) **Vegetative development phase.** Planthopper infestation during vegetative development results in reduction of host plant growth, which before had generally been determined by measuring the physical dimensions of the plants. Instead of such morphometric data, dry matter weights of the rice plants and planthoppers were determined to quantify the effect of planthopper infestation on the metabolism of rice.

Rice plants were infested with a nymph population of BPH at 2 WAT for the duration of one month. Dry weight of one uninfested plant increased from 0.24 g to 5.73 g (an increase of 5.49 g). Dry weight of one infested plant increased from 0.24 g to 3.94 g (an in-

crease of 3.70 g), however, dry weight increase of the BPH population was only 0.057 g (Table 2). Therefore, an increase in BPH dry weight of 0.057 g caused a reduction in plant growth of 1.79 g (or, 1 mg insect and 31.4 mg plant dry matter, respectively). Since only about 15% of the dry matter ingested is assimilated into nymphal biomass, in total about 0.38 g dry matter was taken up from the plants to produce 0.057 g BPH biomass. The amount of dry matter ingested by the BPH nymphs was only about 21% (0.38/0.0179) of the dry matter reduction of the infested rice plants.

Similar experiments with rice plants at maximum tillering stage (5 WAT) gave similar results (Table 2). Dry matter production of an infested plant reduced with 4.7 g. A BPH population ingested 1.327 g dry matter from one plant, however, its dry weight increased with 0.199 g. An increase in BPH dry matter of 1 mg caused a reduction in plant growth of 24 mg. About 28% of the dry matter reduction the infested plants can be explained by the dry matter drain by the BPH. These results indicate that the drain of dry matter by planthopper sucking is not sufficient to account for the growth reduction of the infested plants.

Table 2. Dry matter (DM, mg plant^{-1}) balance between BPH nymph populations and rice plants at early and maximum tillering stage (Sogawa, unpublished).

	Age of rice plants	
Factor	2 WAT	5 WAT
DM increase of uninfested plants	5490	9790
DM increase of plants infested with BPH	3700	5090
Reduction of plant DM due to BPH infestation	1790	4700
DM increase of BPH population	57	199
plant DM decrease per mg BPH insects	31.4	23.6
total plant DM drained by BPH population[1)]	380	1327
% plant DM drained of plant DM reduction	21	28

Note:

[1)] Calculated on the basis of the assumption that 15% of the total DM drained by the BPH nymphs is assimilated into the insect biomass.

(2) **Reproductive development phase**. The panicles form the major sink for carbohydrates in the reproductive phase of the rice crop. Carbohydrate demand by the panicle is largely (for 60-90%) supported by photosynthesis of the upper green leaves (Wada, 1969). At the same time, leaf N is remobilized and translocated to the panicles, which triggers senescence of lower leaves during the ripening process (Mae & Ohira, 1981).
Rice plants suffer from hopperburn if the BPH biomass increase is 1.5 to 3.0% of the host plant biomass. Lower leaves show chlorosis at lower levels of BPH biomass increase. The extent of chlorosis depends upon the increase in BPH biomass: 1 mg of BPH biomass in-

crease caused 6 mg dead leaves. The percentages increase in dry weight of BPH (x) and dead leaves (y), on the basis of total host plant dry weight, were closely related:

$y = 4.63 + 6.98\ x$ ($r = 0.95$, Figure 3).

The percentage grain weight (y) of the total plant weight was also highly correlated with the percentage weight of dead leaves (x):

$y = 45.9 - x$ ($r=0.88$, Figure 4).

The total amount of dry matter drained by the BPH population was almost equivalent to the amount of dead leaves, however, accounted for only about 18% of grain yield reduction.

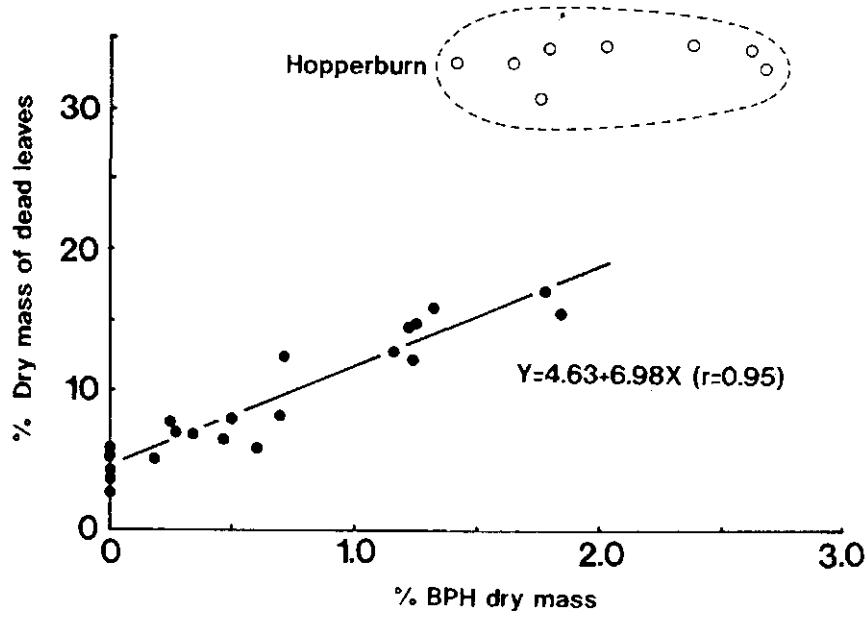

Figure 3. Relation between fraction increase in BPH dry matter, and fraction dry matter of dead leaves, for rice plants infested by BPH at reproductive phase. The fractions are defined as percentages of the total plant dry matter (Sogawa, unpublished). Open circles indicate observations on plants which suffered from hopperburn, and which were excluded from the regression analysis.

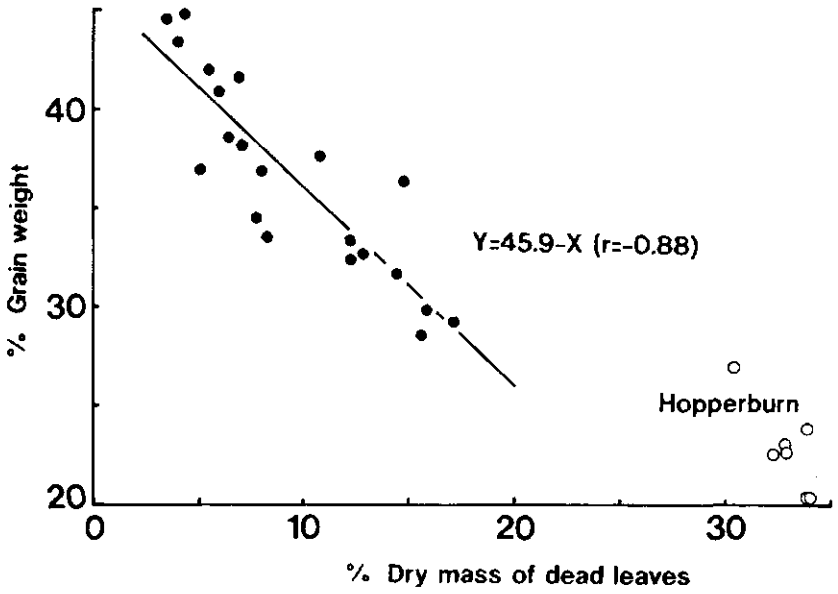

Figure 4. Relation between fraction dry matter of dead leaves and fraction grain dry matter, for rice plants infested yb BPH at the reproductive phase (Sogawa, unpublished). Open circles indicate observations on plants which suffered from hopperburn, and which were excluded from the analysis.

Incorporation of planthopper sucking into crop models

The planthoppers were regarded as an extra sink (or assimilate sappers) because they withdraw carbohydrates and nutrients from the plant's phloem. BPH was also regarded as a senescence accelerator, because it hastens leaf senescence at the reproductive phase. These functions provide a number of basic concepts on damage mechanism that can be used to formulate planthopper - rice combination models that simulate yield reduction caused by these insects.

To evaluate the direct effects of planthopper infestation as assimilate sapper, insect sucking was quantified in terms of dry matter drained from the host plants. However, the difference between the amount drained by the insects, and the growth reduction of the infested plants, was large: the amount of drained dry matter explained only 20 - 30% of the dry matter reduction in the infested plants at both vegetative and reproductive phase. This indicates that biomass production of the infested plants is not only reduced by draining assimilates from the phloem, but also by other effects of the insect sucking on the metabolic systems of the plant.

Plant biomass largely consists of carbohydrates photosynthesized in the leaves, and proteins synthesized with N absorbed by the root system. The photosynthesis rate is closely correlated with the protein content in the leaves (Yoshida & Coronel, 1976). Free amino acids and amides are the major nitrogenous constituents in the phloem sap (Fukumorita & Chino, 1982). Therefore, N uptake from the phloem by sucking planthopper may reduce crop photosynthesis, which may lead to reduction of biomass production. Acceleration of leaf senescence in the rice plants infested at the reproductive phase could also be attributed to removal of remobilized N (Mae and Ohira, 1981).

Therefore, phloem sucking by planthoppers can be introduced in a crop model as rate variables ('valves'), which account for the drain of carbohydrates from the assimilate pool, and for the drain of N. This influences photosynthesis rate and biomass production. The effects of N removal by insect sucking on plant metabolic processes, e.g. photosynthesis, respiration, N uptake by the root system, N remobilization, etcetera, have to be quantified.

References

Auclair, J.L., 1963. Aphid feeding and nutrition. Ann. Rev. Ent. 8: 439-490.

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

Boote, K.l., J.W. Jones, J.W. Mishoe & R.D. Berger, 1983. Coupling pests to crop growth simulators to predict yield reductions. Am. Phytopath. Soc. 73:1581-1587.

Cagampang, G.B., M.D. Pathak & B.O. Juliano, 1974, Metabolic changes in the rice plant during infestation by the brown planthopper, *Nilaparvata lugens* Stal (*Hemiptera: Delphacidae*). Appl. Ent. Zool. 9:174-184.

Cook, A.G. & R.F. Denno, 1994. Planthopper/plant interactions: feeding behavior, plant nutrition, plant defense, and host plant specialization. In: R. F. Denno & T. J. Perfect (Eds.): Planthoppers, their ecology and management, Chapmann & Hall, New York, London, pp. 114-139.

Fukumorita, T. & M. Chino, 1982. Sugar, amino acid and inorganic contents in rice phloem sap. Pl. Cell Physiol. 23: 273-273.

Fukumorita, T., Y. Noziri, H. Haraguchi & M. Chino, 1983. Inorganic content in rice phloem sap. Soil Sci. Pl. Nutr. 29:185-192.

Johnson, K.B., S.B. Johnson & P.S. Teng, 1986. Development of a simple potato growth model for use in crop-pest management. Agr. Syst. 19:189-209.

Kanno, H., M. Kim & S. Ishii, 1977. Feeding activity of the brown planthopper, *Nilaparvata lugens* Stal, on rice plants manured with different level of nitrogen. Jap. J. Appl. Ent. Zool. 21: 110-112 (in Japanese).

Kisimoto, R., 1965. Studies on the polymorphism and its role playing in the population growth of the brown planthopper, *Nilaparvata lugens* Stal. Bull. Shikoku Agr. Exp. Stat. 13: 1-106 (in Japanese with English summary).

Kisimoto, R., 1976. Bionomics, forecasting of outbreaks and injury caused by the rice brown planthopper. In: The rice brown planthopper, Food & Fertilizer Technology Center, Taipei, Taiwan, pp. 27-41.

Kisimoto, R., 1981. Development, behavior, population dynamics and control of the brown planthopper, *Nilaparvata lugens* Stal. Rev. Pl. Prot. Res.14: 26-58.

Kuno, E., 1968. Studies on the population dynamics of rice leafhoppers in a paddy field. Bull. Kyushu Agr. Exp. Stat. 14: 131-246 (in Japanese with English summary).

Mae, T. & K. Ohira, 1981. The remobilization of nitrogen related to leaf growth and senescence in rice plant (*Oryza sativa* L.). Pl. Cell Physiol. 22: 1067-1074.

Naba, K., 1991. Frequent outbreaks and population growth patterns of the white-backed rice planthopper, *Sogatella furcifera* Horvath, in recent years. Pl. Prot. 45: 41-45 (in Japanese).

Sogawa, K., 1973. Feeding of the rice plant- and leafhoppers. Rev. Pl. Prot. Res. 6: 31-43.

Sogawa, K., 1982. The rice brown planthopper: Feeding physiology and host plant interactions. Ann. Rev. Ent. 27: 49-73.

Sogawa, K., 1992a. A change in biotype property of brown planthopper populations immigrating into Japan and their probable source areas. Proc. Assoc. Pl. Prot. Kyushu, 38: 63-68 (in Japanese with English summary).

Sogawa, K., 1992b. Modeling of dry matter drain by the rice planthoppers on rice. Kyushu Agr. Res., No.54: 104 (in Japanese).

Sogawa, K. & C. H. Cheng, 1979. Economic thresholds, nature of damage, and losses caused by the brown planthopper. In: Brown planthopper: Threat to rice production in Asia, IRRI, Los Baños, Philippines, pp. 125-142.

Sogawa, K. & T. Watanabe, 1992. Redistribution of rice planthoppers and its synoptic monitoring in East Asia. Food & Fertilizer Technology Center Tech Bull. No.131, Taipei, Taiwan, 9 pages.

Suenaga, H. & K. Nakatsuka, 1958. Review on the forecasting of leaf- and planthoppers infesting rice. Spec. Rep. Forecasting Diseases Insects, Jap. Minist. Agr. For. No.1, 468 pages (in Japanese).

Wada, G., 1969. The effect of nitrogenous nutrition on the yield determining process of rice plant. Bull. Nat. Inst. Agr. Sci., Series A, No.16: 27-167 (in Japanese with English summary).

Yoshida, S. & V. Coronel, 1976. Nitrogen nutrition, leaf resistance, and leaf photosynthetic rate of the rice plant. Soil Sci. Pl. Nutr., 22: 207-211.

Zimmermann, M.H., 1960. Transport in the phloem. Ann. Rev. Pl. Physiol. 11: 167-190.

The use of simulation models for brown plant hopper management in Japan

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Introduction

The brown planthopper (BPH), *Nilaparvata lugens* (Stal), and the white-backed planthopper (WBPH), *Sogatella furcifera* (Horvath) (Homoptera: Delphacidae), are known as important rice pests in Asia. They do not winter in Japan, and rice crops are infested when hoppers migrate from overseas regions to Japan in the Baiu (rainy) season in June and July.

The population dynamics of these planthoppers in Japan were studied in the 1960's by Kuno (1968). He found a usually very low mean BPH immigrant density of 0.01 insect per hill. After the paddy field has been invaded, the BPH population has 3 generations during the rice growing season, and usually reaches highest density in the 3rd generation. Population growth rate is very high, and the spatial distribution of the population is very clumped. The autumn population may cause severe damage to the rice crop, which is called 'hopper burn'.

The WBPH immigrant density is about ten times higher than that of BPH, viz. 0.1 insect per hill (Kuno, 1968). WBPH also has 3 generations, however, highest density is reached in the 2nd generation.

Population dynamics of BPH and WBPH were studied in Kyushu from 1987 to 1991 (Watanabe & Tanaka, unpublished). BPH and WBPH immigrant densities were 6 and 23 times higher, respectively, than in the 1960-ies. Annual fluctuations in the occurrence of these hoppers were obtained with light traps recorded at our institute, located in the southern part of Japan, for 40 years from 1951 to 1990. WBPH immigrant density increased from the mid 1970-ies. Variation in BPH immigrant density in the 1980-ies was wider than during the other decades (Watanabe et al., 1994).

Immigrant density of both hoppers showed annual fluctuation in the 1990-ies, and therefore, accurate monitoring and prediction of population growth and damage to the rice crop are necessary for integrated management of the planthoppers. Simulation models are powerful tools that can help to predict population dynamics of the planthoppers and the effect on crop production. In this paper, an outline of our BPH population growth and dynamics model, and for a growth model of a rice crop under BPH presence, are introduced.

BPH population growth model

The BPH population growth model is based upon data obtained for literature and field studies, and is written in BASIC. The relational diagram is given in Figure 1. Population growth starts when immigrants invade the rice crop. Oviposition rate depends upon crop development stage. Insect development rate is influenced by temperature, which fluctuates during the season in temperate areas as Japan.

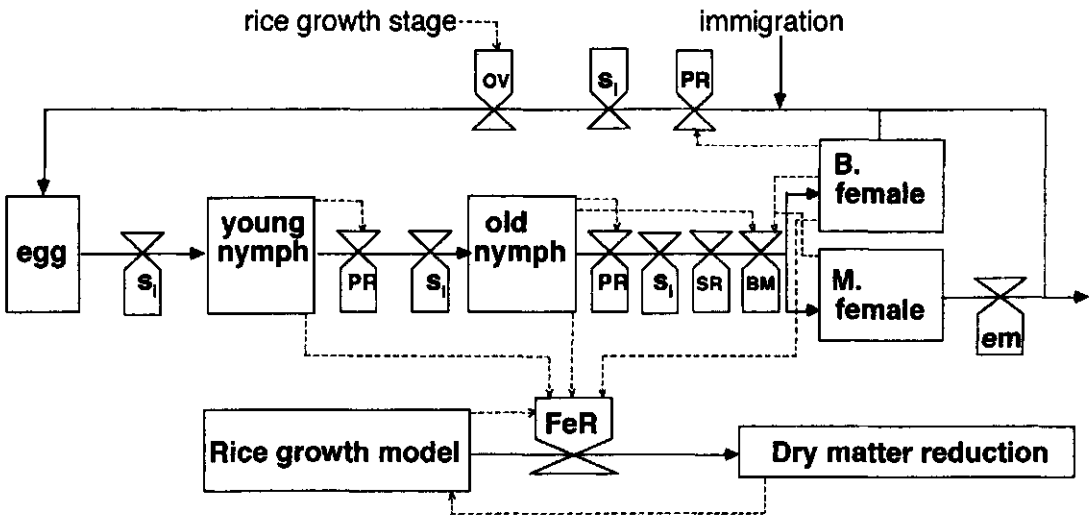

Figure 1. Relational diagram of a population growth model for the brown planthopper, *Nilaparvata lugens*.

s_i : survival rate
PR : total mortality by natural enemies
SR : sex ratio
BM : wing form ratio
em : emigration rate
ov : oviposition rate
FeR : feeding rate

A modified Leslie-matrix, developed by Miyai and Hokyo (1992), is used in the model to predict development of BPH. Developmental stages are: egg, young nymph, old nymph, and adult stage. In the matrix, each development stage has 10, 8, 12, 10 units, respectively, and one unit is characterized by a certain number of day degrees.

BPH adults have two morphological types, brachypterous and macropterous. The macropterous type is characterized by long wings and emigrates from the field, whereas the brachypterous type is characterized by short wings, can not fly, remains in the field, and is therefore the main contributor to population growth. The wing form ratio is determined by density dependent responses.

Population dynamics and rate of parasitism of some natural enemies were also studied in the field, however, there exists little knowledge on the functional relationship between hoppers and their natural enemies in the field. A constant mortality rate due to natural enemies was introduced to the model.

Figure 2 shows two examples of observed and simulated population dynamics of BPH, for 1988 and 1989. Annual differences in population dynamics are caused by differences in immigrant density, length of immigration period, and temperature.

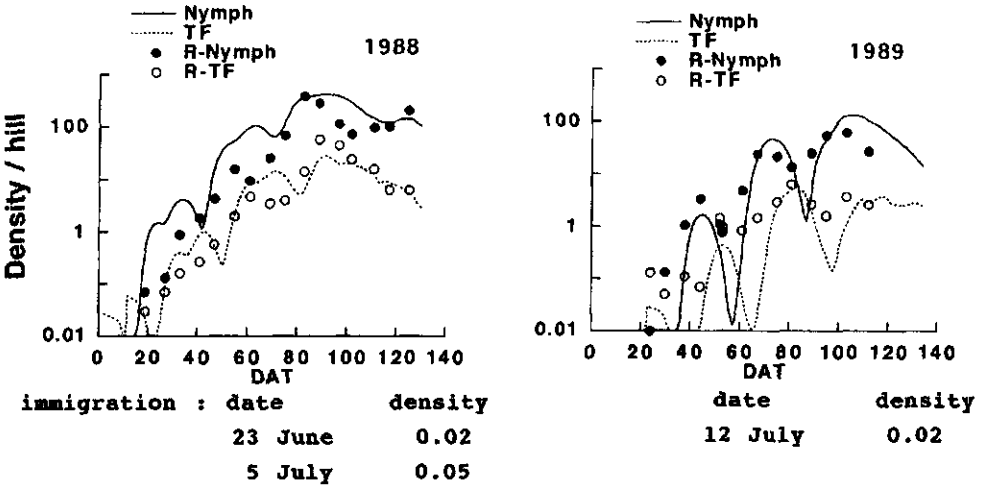

Figure 2. Simulated and observed population dynamics of BPH, for 1988 and 1989.

Nymph and R-Nymph: simulated and observed number of 4th and 5th nymphs
TF and R-TF: simulated and observed number of adult females
DAT: days after transplanting

A rice growth model accounting for BPH feeding

The feeding rate of BPH depends on body size of the insect, development stage of rice plant, and temperature (Sogawa, 1992). Combination of a population dynamics model and a feeding rate per insect, enables estimation of the amount of dry matter that is drained by the BPH population from the phloem (Figure 3). However, crop growth may additionally be affected by reduction of the photosynthesis rate and change in other physiological processes related to biomass production. For instance, reduction of leaf nitrogen content due to planthopper feeding on the phloem may play a role here.

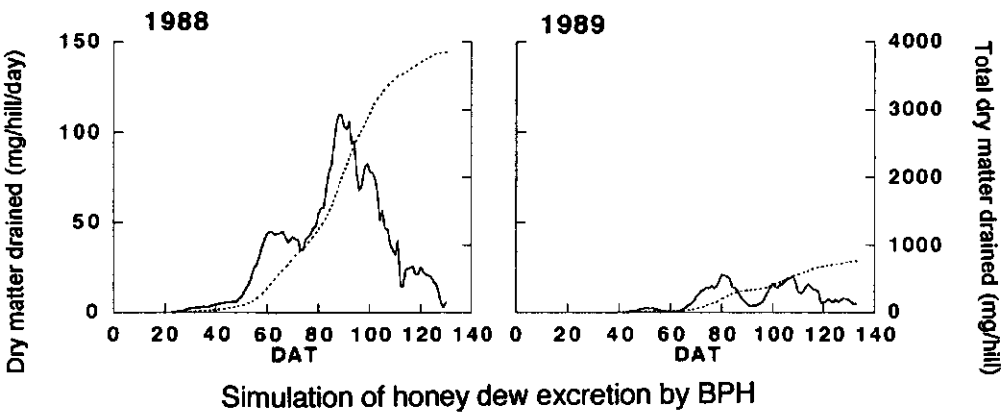

Figure 3. Simulated daily (solid line), and accumulated (broken line) amounts of dry matter drained by a simulated number of BPH, for 1988 and 1989.

An extended version of the MACROS-L1D model (Penning de Vries et al., 1989) was used to simulate the effects of BPH feeding on rice production. The model was initialized at flowering, as the 3rd generation (with the highest density) usually occurs after flowering. A constant sucking rate of 1 mg phloem sap dry matter per mg BPH dry weight per day was assumed. Honeydew excretion by hoppers before flowering was dependent on rice development stage and temperature, however, after flowering, it stabilized.

Initially, the reduction of the amount of crop dry matter was the only damage mechanism introduced to the model (model 1). Simulated grain weight decreased linearly with increase in the BPH density (Figure 4, left). However, reduction of simulated total aboveground dry matter was limited, and therefore, the phenomenon of 'hopperburn', which occurs at a BPH density of more than 200 per hill (Watanabe, unpublished), was not simulated satisfactory.

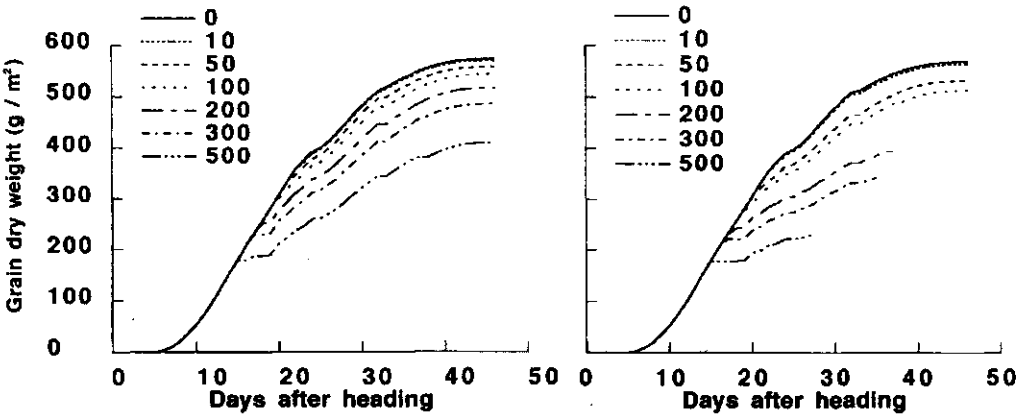

Figure 4. Simulated effects of BPH feeding on grain yield. Left: model 1; right: model 2 (see text). Numbers indicate BPH density per hill. In model 2, simulation stops during the grain filling, due to death of the rice crop.

BPH nymphs and adults usually stay on the lower sheaths near the water surface. It was assumed that the sucking rate by BPH on the lower sheaths was much higher than on the higher sheaths. This hypothesis was introduced to the rice growth model, of which a relational diagram is given in Figure 5. The canopy was divided in to 5 leaf layers, with similar leaf areas. The SUPHOL photosynthesis subroutine (Penning de Vries et al., 1989) was introduced for calculation of photosynthesis per leaf layer. Each leaf layer has a carbohydrate pool, and daily produced assimilates are preserved in the respective carbohydrate pools. Hoppers initially feed from the lowest carbohydrate pool. If more carbohydrates are removed by the insects than produced by the plant, the relative leaf death rate increases. After the entire lowest leaf layer has died, the BPH population moves to the next leaf layer and continues feeding there.

Simulation shows a dying rice crop during the grain filling, if the infestation rate is higher than 200 BPH insects per hill (Figure 4, right). Temperature and solar radiation are key variable in this simulation, as simulation results that were obtained with weather conditions of several years, showed that biomass reduction fluctuated at similar BPH infestation rates. Model improvement requires better quantitative analysis of the indirect effects of planthopper feeding on rice growth.

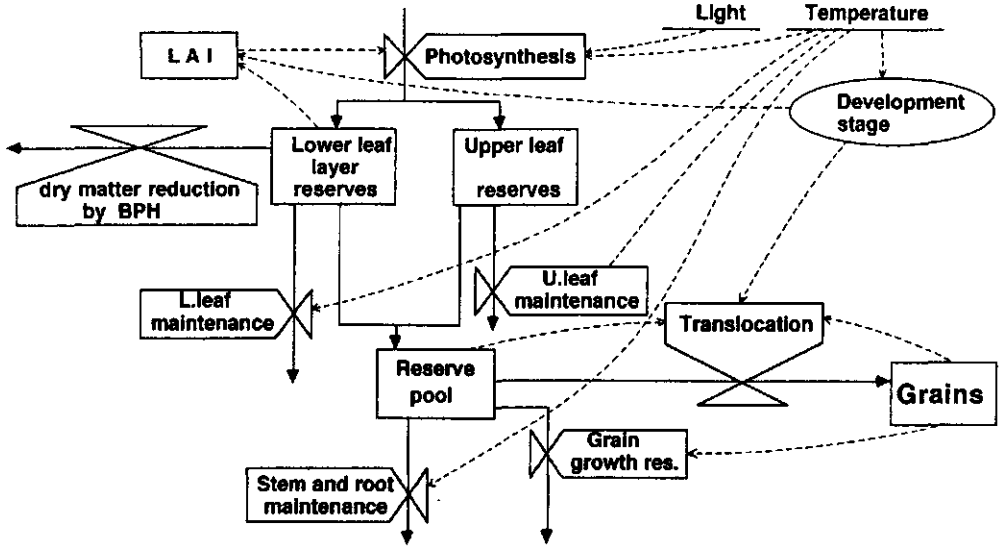

Figure 5. Relational diagram of a rice growth model accounting for BPH feeding (model 2).

References

Kuno, E., 1968. Studies on the population dynamics of rice leafhoppers in a paddy field. Bull. Kyushu Agric. Exp. Sta. 14: 131-246.

Miyai, S. & N. Hokyo, 1992. Modelling approach to simulate the progress of insect-borne rice virus disease in paddy fields. In: National Institute of Agro-Environmental Sciences Series No. 1., Tukuba, Japan, pp. 139-154.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of ecophysiological processes of growth in several annual crops. Pudoc, Wageningen, 271 pages.

Sogawa, K., 1992. Modelling of dry matter drain by the rice planthoppers on rice. Kyushu Agric. Res. 54: 104 (in Japanese).

Watanabe, T., K. Sogawa & Y. Suzuki, 1994. Analysis of yearly fluctuations in the occurrence of migratory rice planthoppers, *Nilaparvata lugens* Stal and *Sogatella furcifera*

Horvath, based on light-trap data in northern Kyushu. Jpn. J. Appl. Entomol. Zool. 38: 7-15 (in Japanese with English summary).

The effect of the weather system on BPH migration in China

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Introduction

The so-called 'Green Revolution', with the introduction of semi-dwarf varieties and hybrid rice, brought about large changes in rice agriculture in many Asian countries. One of the changes was the increased importance of the plant hopper pests. Since then, most countries have paid attention to this pest problem. Kisimoto (1971) documented the white-backed plant hopper (WBPH) *Sogatella furcifera* (Horvath) and brown plant hopper (BPH) *Nilaparvata lugens* (Stal) migration from China to Japan over the East China Sea in 1968. He studied the relation between the weather system and plant hopper migration (1976) and summarized (1991) several migration routes accross the Chinese continent and from China to Japan. Chinese entomologists, in a national collaborative research project in the early 1980's (Jian, 1981), identified several weather phenomena that are associated with plant hopper migration, including moving cold front and stationary front systems. Seino and Watanabe (1987, 1991) showed that the low level jet streams play an important role in the plant hopper migration from China to Japan. This knowledge is now successfully used in forecasting plant hopper migration from China to Japan.

Table 1. The effect of weather systems on the number of BPH immigrations in 1984, 1980, 1987, and 1991.

Weather system	Number of immigrations				
	1980	1984	1987	1991	Total
Stationary front system	12	2	13	11	38
Cold front system	7	7	8	4	26
Tropical streams	4	3	4	4	15
Subtropical high and LLJET	2	0	2	1	5
Total	25	12	27	20	84

Weather systems inducing migration

The relation between the weather system and long-distance plant hopper migration has been studied by Kisimoto (1971, 1976, 1991) Jiang (1981), Sogawa (1988), Watanabe (1991) and Cheng (1992). Air-trap studies with air planes located plant hoppers generally at 1000 to 2000 m above the ground surface, at about 850 hPa (Deng, 1981). Therefore, plant hopper migration can be analyzed by using 850 hPa weather synoptic chart. The impact of weather systems on the BPH immigration in Southwest China has been analyzed for 1980, 1984, 1987 and 1991 (Table 1). Severity of BPH was highest in 1991, and decreasingly lower in 1987, 1980, and 1984, respectively.

Cold front systems

Changes in weather and climate are closely related to changes in weather systems. Cold front systems play an important role in weather systems. Cold air masses from Siberia accumulate continuously in the polar zone, and are moved from the polar high pressure zone to the tropical low pressure zone by air currents. As the cold front moves, air pressure at the ground surface increases sharply, strong winds occur, temperature decreases and precipitation occurs. Therefore, moving cold fronts are important factors in weather forecasting.

When plant hoppers that migrate from south to north meet the cold front, then rainfall brings them downwards to the ground. The vertical transect of a cold front meeting migrating plant hoppers is shown in Figure 1. When the cold front line meets the plant hoppers, the fast movement of the cold front causes fall of the plant hoppers, and light trap data show a rapid increase in the amount of plant hoppers. When the cold front line moves further, light trap data show a sharp decrease in the amount of plant hoppers.

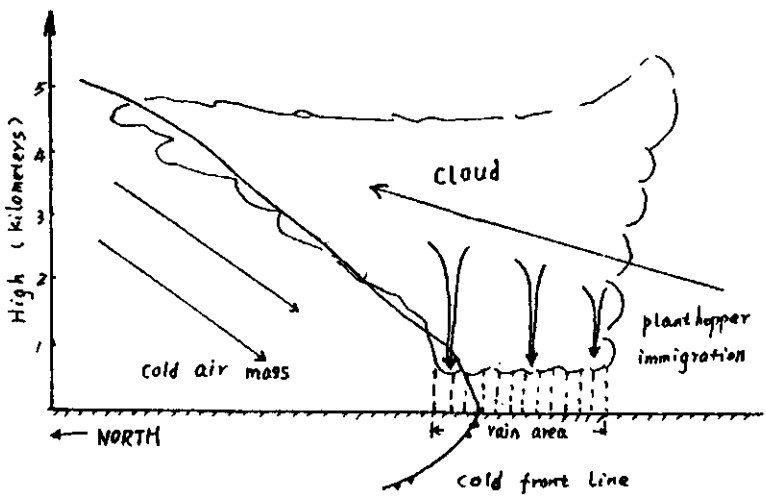

Figure 1. Downward movement of plant hoppers due to cold air movements

Stationary front system and shear

The stationary front system is the most important weather system that influences BPH immigration in Southwest China. When temperature rises, the flows of warm and cold air become stronger and weaker, respectively, causing a halt of the cold front, which then becomes stationary. The stationary front line separates warm and cold air masses (Figure 2), and is usually characterized by successive days with rainfall. Such a stationary cold front is another major factor in weather forecasting. This is a stationary front line on the weather chart of the ground surface, and a shear line on the weather chart of the high level.

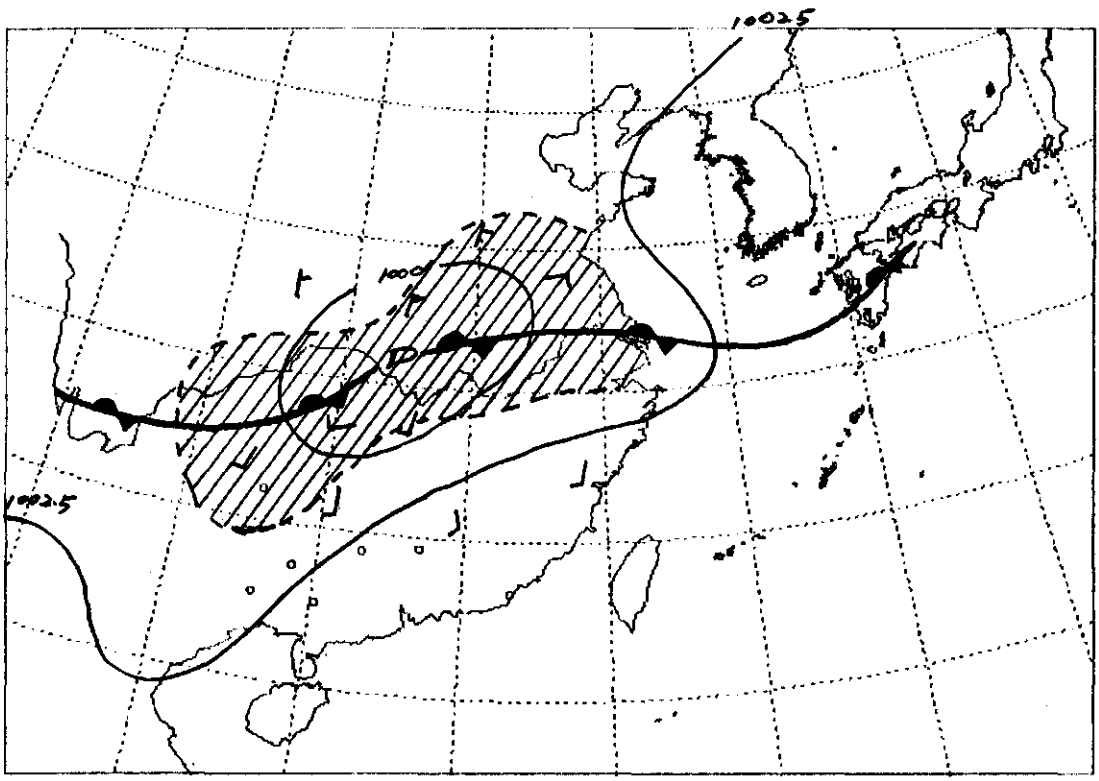

Figure 2. A stationary front line on the ground surface weather chart

A stationary front causes many plant hoppers coming from the south to fall down continuously in this area, in a similar way as described for a cold front (Figure 1). Light trap data show for 3 to 5 or more days a continuous increase in the number of plant hoppers. If another cold front moves from north to south, the stationary front will move or disappear, and the increase in the number of plant hoppers stops.

Tropical streams

From May to September, the tropical stream usually moves to the South and East China Sea, and influences South and East China. A typhoon is characterized by high wind speeds and heavy precipitation around its centre. There is high wind speed zone around the tropical stream centre from the ground surface to 5 km altitude. So, it causes plant hopper migration along the high wind speed zone and immigration in the rainfall area. Data of light trap show a sharp increase in the amount of plant hoppers, which is maintained for a short period at a high level (Figure 3).

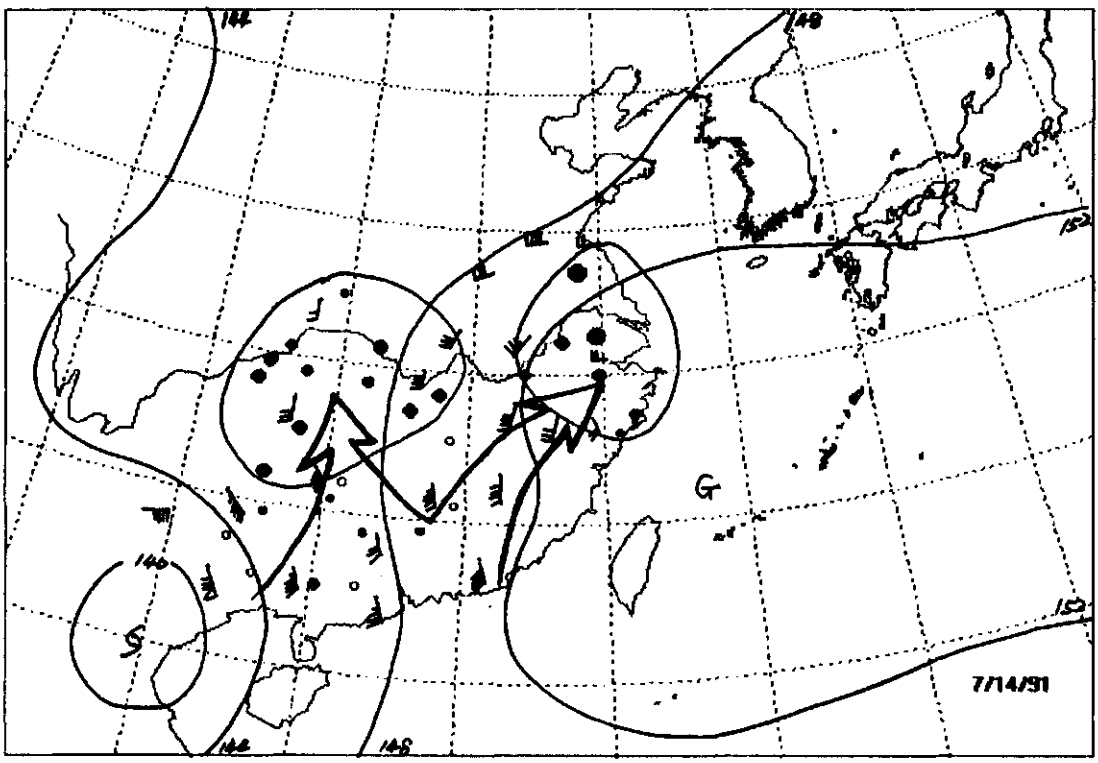

Figure 3. Plant hopper migration influenced by tropical streams

Subtropical high pressure zone and low level jet stream

From May to August, the subtropical high pressure zone moves northwest and controls the eastern part of the Chinese continent. In this area, it is dry and hot. Sometimes, in the western area of the subtropical high pressure zone, there are long and narrow zones with high wind speeds, which usually exceed 12 m s^{-1}. This is the so-called low level jet stream

(LLJET). This low-level jet stream occurs between 1000 and 4000 m altitude, and is 1000 to 2000 km long and several hundreds km wide. The low level jet stream is located over eastern China. Therefore, southeast of the low level jet stream is usually a precipitation zone, which is associated with plant hopper landing.

The speed of subtropical high pressure zone that moves from south to north is variable. The ridge line of the subtropical high pressure zone is in winter located near 15 N degree latitude, and moves slowly from south to north, while temperature rises. The first immigration area of the plant hopper appears at the north-west area of the subtropical high pressure zone, which is located south of 25 N degree latitude in China from March to April. In the middle of June, when the ridge line moves from 15 to 20 N degree latitude, the first immigration area of the plant hopper also moves, to the area south of 30 N degree latitude in China, and when the ridge line moves in mid-July from 25 to 30 N degree latitude, the first immigration area moves to the 35 N degree latitude (Figure 4).

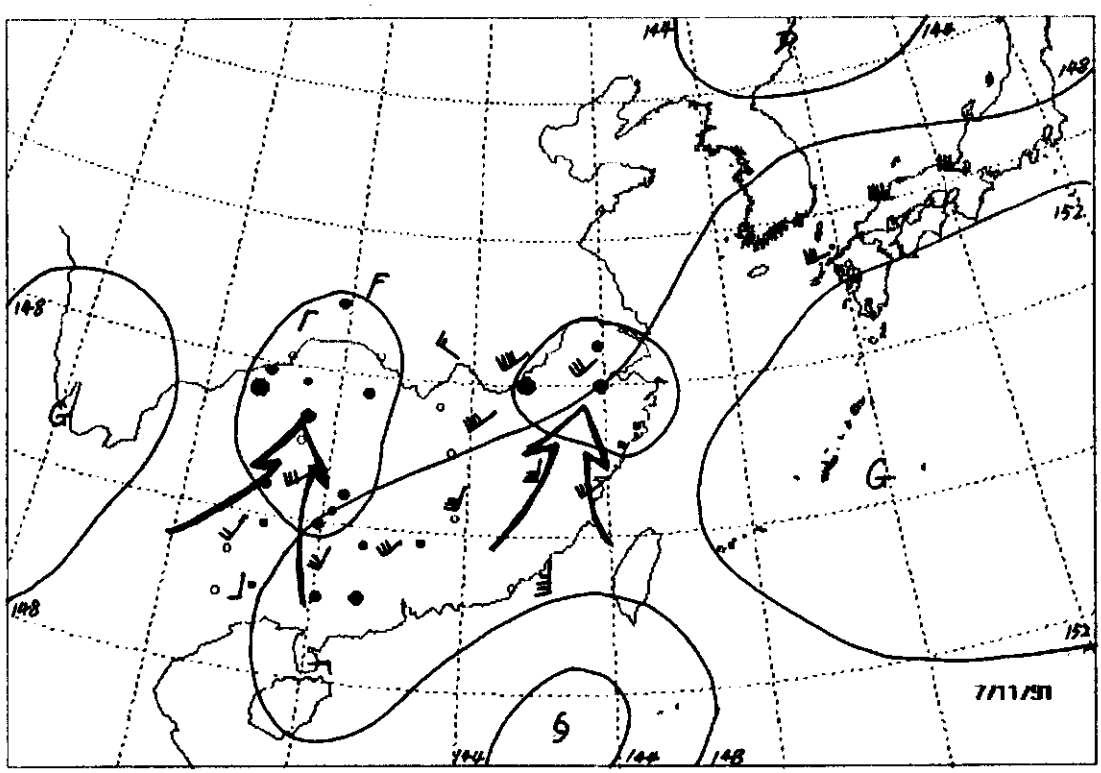

Figure 4. Plant hopper migration influenced by a subtropical high pressure zone

Conclusion

The weather systems play an important role in long-distance migration of the rice plant hopper. It is possible to forecast and analyze the long-distance migration of the rice plant hopper by using weather charts and light traps. For the region of rice plant hopper immigration, models can be developed, on the basis of existing models that have been developed by meteorological centres, to forecast the weather system and the rice plant hopper migration.

References

Cheng, C.H., 1991. Trans-oceanic immigrations of brown plant hopper and their influence on the population abundance in Taiwan. Proceedings of International Seminar on Migration and Dispersal of Agriculture Insects, Tuskuba, Japan, September 199. pp. 167-181.

Deng, W.X., 1981. A general survey of seasonal migrations of *Nilaparvata lugens* (Stal) and *Sogatella furcifera* (Horvath) (Homoptera: Delphacidae) by means of airplane collections. Acta Phytophylacica Sinica 8: 73-82 (in Chinese with English summary).

Jiang, G.H., H.Q. Tan, W.Z. Shen, X.N. Cheng & R.C. Chen, 1981. The relation between long-distance northward migration of the brown plant hopper (*Niliparvata lugens* Stal) and synoptic weather conditions. ACTA, Entomological Sinica 3: 251-262 (in Chinese with English summary).

Kisimoto, R., 1971. Long-distance migration of plant hoppers, *Sogatella furcifera* and *Niliparvata lugens*. Proc. Symp. Rice Insects, 1971, Trop. Agric. Res. Centre, Tokyo, pp. 201-216.

Kisimoto, R., 1976. Synoptic weather conditions inlcuding long-distance immigration of planthopper, *Sogatella furcifera* Horvath and *Niliparvata lugens* Stal. Ecol. Ent. 1: 95-109.

Kisimoto, R., 1991. Long distance migration of rice insects. In: E.A. Heinrichs & T.A. Miller (Eds.), Rice Entomology. Springer Verlag, New York.

Seino, H., Shiotsuki, S. Oya & Y. Hiral, 1987. Prediction of long distance migration of rice plant hoppers to northern Kyushu considering low-level jet stream. J. Agr. Met. 43: 203-208.

Sogawa, K., T. Watanabe & M. Tsrumachi, 1988. Emigration areas and meteological factors inducing overseas migration of the brown plant hopper. Proc. Assoc. Pl. Prot. Kyushu 34: 79-82 (in Japanese).

Watanabe, T. & H. Seino, 1991. Correlation between immigration areas of rice plant hoppers and low-level jet streams in Japan. Appl. Ent. Zool. (in press).

Section D

Malayan black bug

Predicting a dynamic economic threshold level for Malayan black bug infestation on rice in Malaysia

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Introduction

The Malayan black bug (MBB), *Scotinophora coarctata* F., can cause significant yield reduction in rice. In Malaysia, MBB is one of the most important rice pests, especially in Sungai Manik and Kerian (Perak) rice growing areas. Table 1 gives the yearly acreage of rice fields that were infested by MBB and other major pests from 1978 to 1992 (Department of Agriculture, Malaysia, 1993). The exact yield reduction depends upon the number of MBB per hill, the period of infestation, cultivar, and crop development stage. Heinrich et al. (1987) found that 40 MBB per hill at reproductive stage resulted in 54 to 83% yield loss.

Insecticide application is the only control measure recommended for the management of MBB infestation. The Economic Injury Level (EIL) is defined as the lowest insect density that causes economic loss (Stern et al., 1959), and is for MBB set at 3 insects per hill (Heinrich et al, 1987). However, control action should be initiated at a lower insect density in order to prevent that the insect density exceeds the EIL. This insect density is known as the economic threshold level (ETL). Although the ETL concept serves as a basis for decision making in IPM, quantitative information on thresholds is limited. This is due to the fact that most of the factors involved in determining the ETL are dynamic, and are influenced by the crop (i.e. cultivar characteristics and crop phenology), the environment (i.e. weather and human practices) and pest behaviour (i.e. intra- and inter-specific competition).

Mumford & Norton (1984) introduced the following formula to calculate the ETL:

$$ETL = C/P \cdot D \cdot K \qquad (1)$$

C = costs of the control measure ($ ha^{-1})
P = price of produce ($ kg $^{-1}$)
D = damage caused by a unit of insect (kg ha^{-1} insect^{-1})
K = insect mortality due to application of the control measure (fraction).

Their ETL depends upon several dynamic variables, such as costs of a particular control measure, amount of produce, damage caused by the insect, and pest mortality due to application of the control measure. These variables are functions of several other dynamic variables. For instance, the amount of produce can be affected by the amount of available produce in the market, and insect damage can, for instance, depend on the condition of the crop. Definition of an ETL becomes more complex if human behaviour, which is difficult to predict, is also taken into consideration. Involvement of dynamic interactions between crop, pest, environment and human behaviour make quantification of ETLs challenging.

Definition of ETLs for a wide range of conditions requires a large number of field experiments. This problem can be addressed by application of a crop growth model, which enables identification and understanding of the causes of damage, i.e. the damage mechanisms. In addition, models also can be a useful tool to understand the interactions between crop, pests, and environment.

Therefore, a crop growth model was used to analyze yield reduction due MBB infestation. This paper presents a preliminary study on the utilisation of a rice growth model to predict a dynamic ETL for MBB management in rice.

Table 1. Acreage affected by various pests in the Sungai Manik Agricultural development project (Perak, Malaysia) from 1978 to 1992. Source: Department of Agriculture, Malaysia, 1993.

	affected acreage (ha)					
Year	MBB	rats	plant hoppers	tungro virus	leaf folder	stem borers
1978	158	283	0	263	0	74
1979	53	58	0	191	0	72
1980	185	138	0	223	0	73
1981	4919	1548	0	2256	0	7
1982	1487	640	0	1181	0	2844
1983	1457	655	0	2395	0	1150
1984	3057	191	0	755	0	0
1985	790	497	0	722	0	64
1986	3348	230	0	53	56	66
1987	7988	261	71	8	105	1049
1988	5492	1530	216	79	2153	436
1989	7531	149	13	62	942	25
1990	14048	875	91	399	326	1041
1991	13144	1073	222	78	532	20
1992	870	70	378	0	5	154

Materials and Methods

Coupling MBB damage model to ORYZA1

The rice growth model ORYZA1 (Kropff et al., 1993) was used to simulate the potential growth rate and potential grain yield of rice. Figure 1 shows schematically the calculation procedure for daily crop growth rate of a rice crop infested with MBB. Under healthy conditions, daily total gross assimilation of the crop (DTGA) is used for maintenance respiration, growth respiration, and growth. Assimilates available for growth are partitioned to roots, stems, leaves and storage organ (Spitters et al., 1989). If the crop is infested by MBB, then the sucking of assimilates by the insects results in a reduction of DTGA available for growth, which is, as a result, reduced. In addition, a continuous removal of assimilates by MBB results in drying of part of the plants, which is called hopperburn.

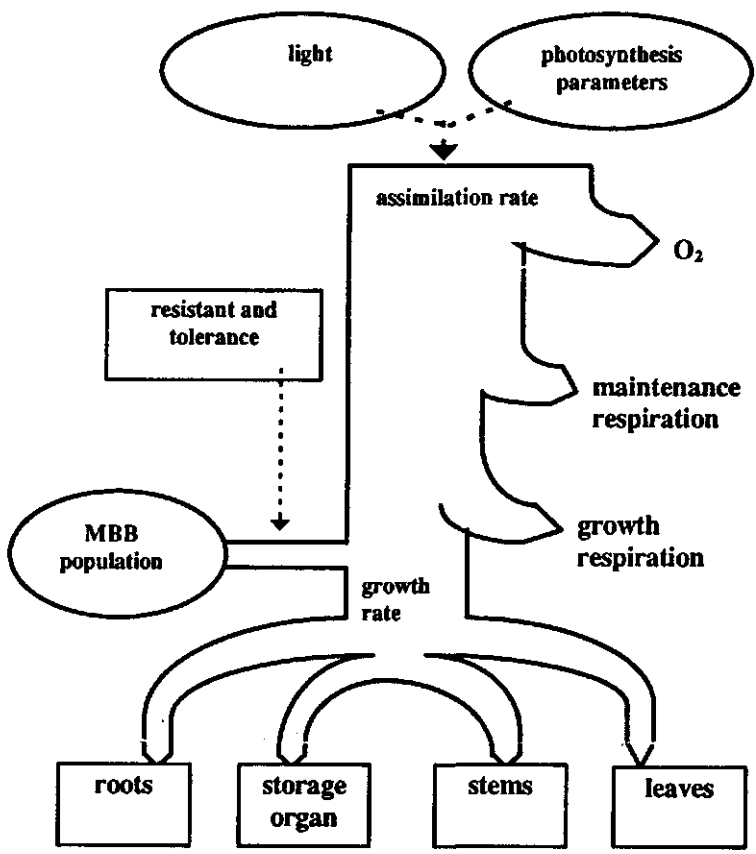

Figure 1. A schematic diagram illustrating the calculation procedure of ORYZA1 model with MBB damage component.

The MBBORYZA model was developed to predict the effect of MBB infestation on growth and production of two commonly grown rice variety in Malaysia, viz. MR84 and MR106. The model was developed by linking a MBB damage model to ORYZA1. The MBB damage model was based on a predation model of Guttierez et al. (1987):

MBBRV = RVRT*(1.-EXP(-SRCH*DTGA/RVRT)) (2)

MBBRV = the amount of energy consumed by MBB ((kg ha^{-1}) / (kg MBB organism day^{-1}))
DTGA = daily total gross assimilation (kg ha^{-1} day^{-1})
RVRT = demand for growth, respiration, and production (i.e. reproduction, excretion, and exuviae) (g g^{-1} MBB d^{-1}).
SRCH = searching rate (the probability of success in each process of predation by the organism in t trophic level on t^{-1} tropic level (i.e. level of resistance of rice against MBB infestation))

The daily demand for growth, respiration and maintenance of MBB was determined from a laboratory experiment (Mohd Norowi & Ahmad, 1991), and introduced to the model with equation 3 (Southwood, 1978).

RVRT = GRW + RES + EXC + REP (3)

GRW = MBB growth rate (g trehalose g^{-1} of MBB day^{-1})
RES = carbohydrate used for respiration (g sucrose g^{-1} MBB d^{-1})
EXC = excretion (g sucrose g^{-1} MBB day^{-1})
REP = the amount of sucrose allocated for reproduction (for hemiptran adult, more than 40% of the ingested food is allocated to the reproduction process (Slansky & Scriber, 1985).

Calculations assume that MBB preys on rice sucrose, and that increase in MBB weight is due to trehalose storage in MBB body fat (Friedman, 1985). In addition, MBB infestation was also supposed to accelerate senescence of rice plants, which results in hopperburn. Mohd Norowi & Ahmad (1991) described this effect as:

FTDR = MBBRV · 0.000608 · FACT (4)

FTDR = fraction of tiller death due to premature senescence (fraction tillers kg^{-1} DTGA removed)
TMBBRV = total amount of DTGA removed by MBB since infestation (kg ha^{-1})
FACT = tolerance of tiller senescence to DTGA removal by MBB (0 = highly tolerant, 1 = highly susceptible)

The fraction tiller loss was used to calculate loss rates of plant organ weights. Statements and parameters that were added to ORYZA1 to model MBB damage on rice are listed in Appendix A of this article.

Field experiments

Field experiments were conducted to evaluate the performance of the ORYZA1 and MBBORYZA models to predict rice growth under field conditions. For evaluation of the ORYZA1 model, a field experiment was carried out in Seberang Perak, Malaysia, under irrigated lowland conditions. Variety MR84 was direct seeded on 17 April 1993. N (in form of urea), P_2O_5 and K_2O were applied at rates of 150, 50, and 50 kg ha^{-1} respectively. Nitrogen application was given in four doses at 15, 45, 75 and 95 days after sowing (DAS). Dry weight of leaves (dead and green leaf), stems and panicles, area of leaves and number of tillers were determined at least once per 10 days, on rice plants from an area of 15 × 15 cm (one hill). Leaf area was measured with a Licor 1300 (Licor Inc., USA). Weather data were recorded by a portable weather station (Omnidata, Utah USA) which was located near the experimental site.

The MBBORYZA model was evaluated by comparing simulated and observed data of rice growth with and without MBB infestation. Two experiment were conducted under irrigated lowland conditions. The first experiment was conducted at Pasir Mas in 1991, where rice variety MR106 was transplanted on 15 November 1991. The second experiment was conducted at Kota Bharu in 1993, where rice variety MR84 was direct-seeded on 15 January 1993. In both experiments, the experimental area measured 100 m^2. The plot was divided in two sub-plots. One plot was regularly sprayed with insecticide to prevent MBB infestation, and the other plot not sprayed to allow development of a MBB population. Weather data from Pengkalan Chepa were used for both experimental locations (the distance between Pengkalan Chepa, and Kota Bharu and Pasir Mas, is about 20 and 30 km, respectively). Searching rate (SRCH) and tolerance factor (FACT) were calibrated per experiment, as MR84 and MR106 differ in their levels of resistance and against MBB infestation.

The MBB population development (number of insects per hill in transplanted rice, and per 15 × 15 cm^2 in direct-seeded rice) was monitored weekly in both experiments. Total above-ground dry matter and grain weight were determined weekly in 1991, however, were only at final harvest in 1993.

To determine yield loss caused by a single MBB infestation at various crop development stages, and for different duration of infestation, simulations were conducted for MR106 and MR84. Results were statistically analysed to obtain for each variety an equation that relates grain yield to the number of DAT of the onset, and to the duration of the infestation. This equation was used to predict the yield loss per MBB epidemic, which is one of the input parameters of equation (1). The other parameters of equation (1) were obtained by collecting information on costs and efficacy of insecticides used to control MBB infestation in Malaysia. For example, in the region of Kota Bharu, costs of insecti-

cide application are about RM 127 per hectare, the price of husk rice is RM 0.87 per kg, and the efficacy of killing MBB in the field by the insecticide is considered 90%.

Results and Discussion

Figure 2 compares simulated and observed weights of storage organs, stems and leaves for Seberang Perak 1993. The ORYZA1 model predicted growth of variety MR84 growth well, especially WSO and WLVG. The model also estimated WST well up to 100 DAS. Afterwards, simulated values decreased, whereas observed values increased.

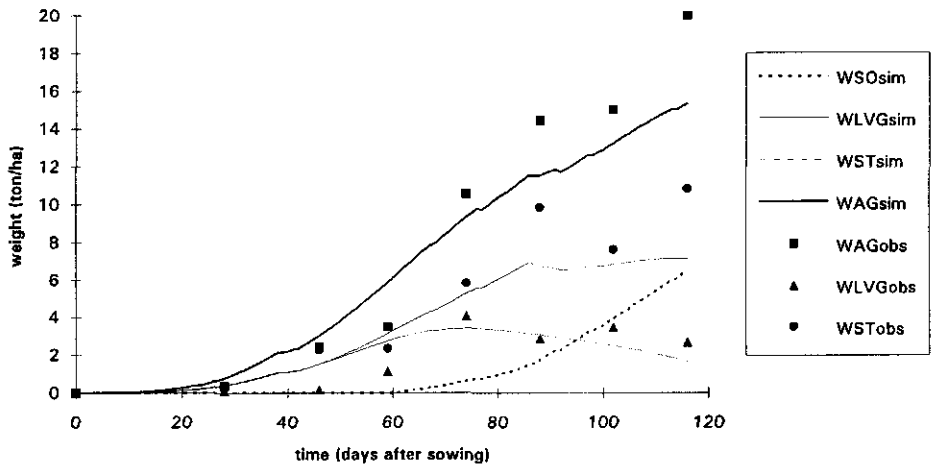

Figure 2. Simulated and observed plant organs weight for rice variety MR84 (without MBB presence) in Seberang Perak, 1993.

The difference between simulated and observed of WST can be attributed to assumptions with respect to dry matter partitioning. Continuation of stem growth up to maturity is characteristic for MR84. The model predicted the leaf area index (LAI) relatively well (Figure 3). LAI of MR84 was high (more than 4.0 ha ha^{-1}) at harvest. Overall, it can be concluded that ORYZA1 can be used to model MR84 growth under Malaysian conditions. However, calibration of the partitioning tables for direct-seeded rice is needed.

Evaluation of the MBBORYZA model show that simulated and observed values are close. Figure 4 and Table 2 compare observed and simulated results on rice growth with and without MBB infestation. Figure 4 compares observed and simulated total above-ground dry matter of MR106 grown in Pasir Mas in 1991. The model slightly under-estimated crop growth. Table 2 compares observed and simulated weights total dry matter production and grain yield of healthy and infested crops of MR84 in Kota Bharu in 1993. Simulated total dry matter production is slightly under-estimated in case of a healthy crop, however, more severely under-estimated in case of an infested crop. Grain yields, how-

ever, are fairly well simulated. Therefore, MBBORYZA model appeared able to predict MBB damage on both MR84 and MR106 rice varieties. Partitioning and specific leaf area (SLA) need better quantification.

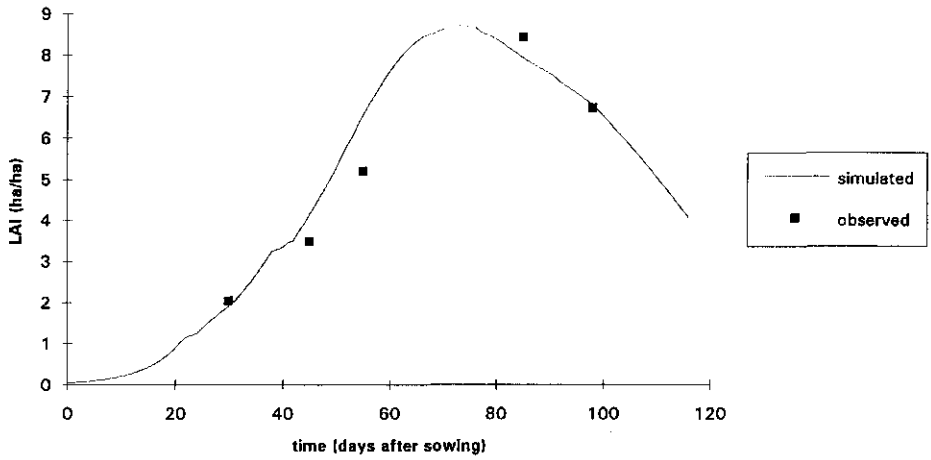

Figure 3. Simulated and observed leaf area index (LAI) for rice MR84 (without MMB presence) in Seberang Perak, 1993.

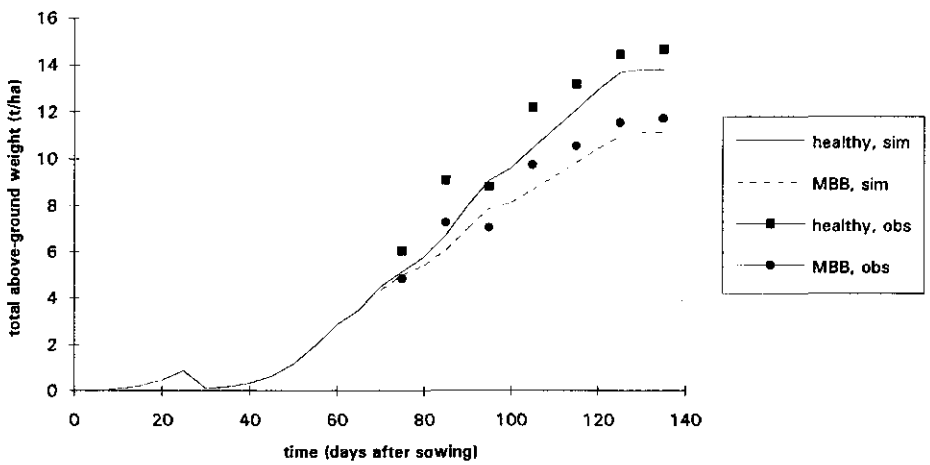

Figure 4. Simulated and total above-ground dry matter of rice variety MR106, with and without MBB infestation, in Kota Bharu, 1991.

Table 2. Observed and simulated total above-ground dry matter production and grain yield (ton ha^{-1}) for rice variety MR84, in Kota Bharu in 1993.

	Without MBB Infestation		With MBB Infestation	
	observed	simulated	observed	simulated
Total dry matter production	16.20	15.63	9.28	6.13
Grain yield	6.47	6.54	1.17	1.76

Multiple regression analysis of crop yield of varieties MR84 (equation 4) and MR106 (equation 5) on the moment and duration of MBB infestation resulted in the following second order polynomial linear model:

$$YIELD = 19202.41 - 23.44 \cdot DUR - 8.17 \cdot DUR^2 - 188.99 \cdot DAT + 0.67 \cdot DAT^2 \quad (4)$$

$$YIELD = 6057.07 - 0.50 \cdot DUR - 0.02 \cdot DUR^2 - 0.16 \cdot DAT - 0.01 \cdot DAT^2 \quad (5)$$

YIELD = predicted grain yield (ton ha^{-1})
DUR = duration of a single MBB infestation (days)
DAT = number of days after transplanting of infestation

The simulated dynamic ETL of MBB for variety MR106 is shown in Figure 5. The rice crop can compensate for MBB infestation in the vegetative phase, but is sensitive during the early part of reproductive phase, especially during spikelet formation period. This is a common phenomenon of crop compensatory mechanisms to insect infestation (Whitham et al., 1991). In soybeans, for instance, it was observed that the crop is able to compensate for high defoliation by insects, except during pod formation stage (Turnipseed, 1972). The presence of another sink may result in an increased demand for assimilates, and enhance the effect of insect infestation.

The result of this study suggest that a general equation can be used to describe the energy acquisition by an organism in a certain trophic level from a lower trophic level.

The model can be used by extension officers in Malaysia as a tool to support their decision in managing MBB infestation. The management (i.e. insecticide application) of MBB infestation is the responsibility of the extension staff in the Department of Agriculture. If MBB density exceeds the ETL, the government, through recommendation of extension agents will subsidise insecticides to farmers. Therefore, the simulation result of this model can be used by the extension agents as a guide to recommend insecticide subsidy to farmers, not only on the basis of MBB density, but also on the basis of cultivars

characteristics, crop development stage, as well as on current knowledge on advantages and disadvantages of insecticide application.

Result from this preliminary work also show that a dynamic threshold which incorporates several dynamic factors can be determined, and serve as a component for the integrated pest management of rice. Experiment to further calibrate and validate MBBORYZA model are on-going.

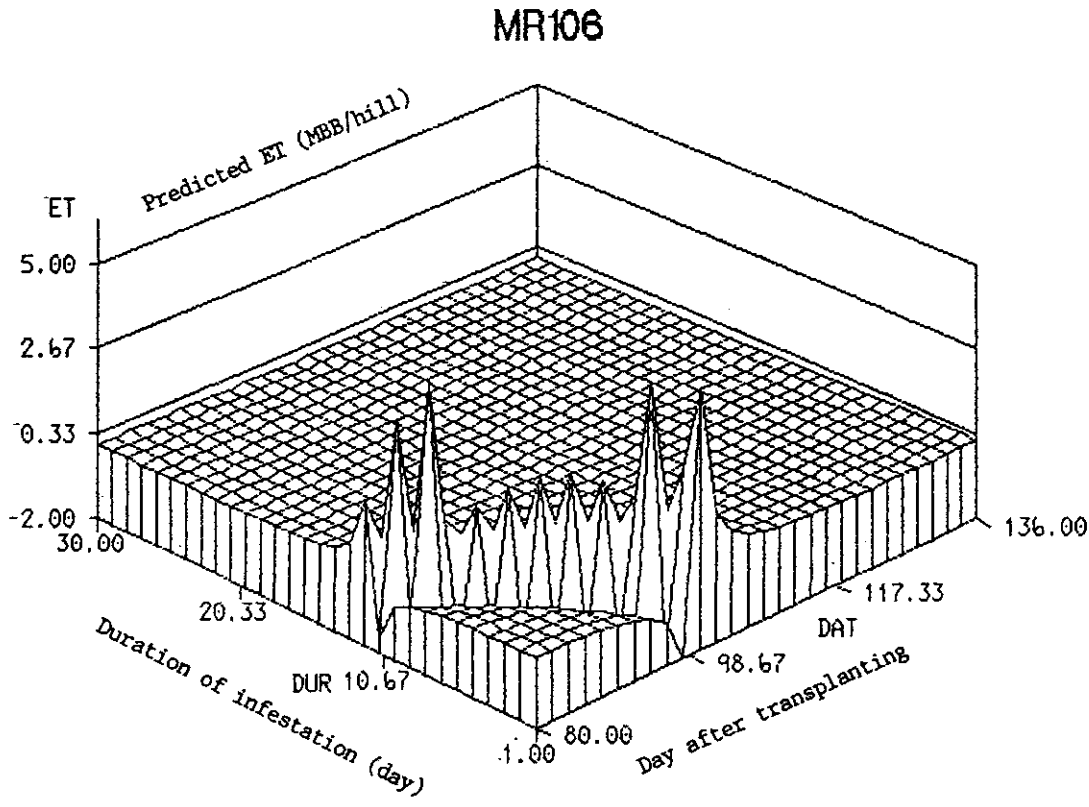

Figure 5. Dynamic ETL of MBB infestation in rice variety MR106 grown in Kota Bharu, 1991.

References

Department of Agriculture, 1993. Kawalan kutu bruang (*Scotinophora coarctata*) dengan lampu ultra violet di Projek Kerian-Sungai Manik. Briefing paper presented to Deputy of Secretary General of Ministry of Agriculture, Malaysia, April 1993.

Friedman, S. 1985. Intermediary Metabolism. In: Fundamentals of Insect Physiology. A. Blum (Ed.), John Wiley & Son, New York. pp. 467-506.

Guttierez, A.P., F. Schulthes, A.T. Wilson, A.M. Villacorta, C.K. Ellis, & J.U Baumgaertner, 1987. Energy accquisation and allocation in plant and insect: A hypothesis for possible role of hormones in insect feeding patterns. Can. Entomol. 119: 109-119

Heinrichs, E.A., I.T. Domigo & E.H. Castillo, 1987. Resistance yield response of rice cultivars to black bug *Scotinophora coarctata* (F). (Hempitera: Pentatomidae). J. Pl. Prot. Tropics 4: 55-64

Kropff, M.J., H.H. van Laar & H.F.M. ten Berge (Eds.), 1993. ORYZA1, a basic model for irrigated lowland rice production. IRRI, TPE-WAU, CABO-DLO, 89 pages.

Mumford, J.D. & G.A. Norton, 1984. Economics of decision making in pest management. Ann. Rev. Entomol. 29: 175-74.

Mohd Norowi, H. & S. Ahmad, 1991. Simulation of yield reduction due to Malayan black bugs infestation on several rice varieties. In: F.W.T. Penning de Vries, H.H. van Laar & M.J. Kropff (Eds.), Simulation and Systems Analysis for Rice Production. Pudoc, Wageningen, pp. 310-319.

Slansky Jr., F., & J.M. Scriber, 1985. Food consumption and utilization. In: Comprehensive insect physiology, biochemistry and pharmacology. Vol. 4: Regulation, Digestion, Nutrition exceretion. Pergmon Press, New York. pp. 87-163

Spitters, C.J.T., H. van Keulen, & D.W.G. van Kraalingen, 1989. A simple and universal crop growth simulator: SUCROS87. In: R. Rabbinge, S.A. Ward & H.H. van Laar (Eds.), Simulation and Systems Management in Crop Protection, Pudoc, Wageningen, pp. 147-181.

Southwood, T.R.E., 1978. Ecological methods (2nd Edition). Chapman and Hall, London. 391 pages.

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

Turnipseed, S.G., 1972. Response of soybeans to folliage losses in South Carolina. J. Econ. Entomol. 65:224-229.

Whitman, T.G., J. Maschinski, K.C. Larson & K.N. Paige, 1991. Plant responses to herbivory: The continuum from negative to positive and phisiogical mechanisms.In: P.W. Price et al. (Eds.), Plant-Animal Interactions, John Wiley & Sons, Inc. New York, p. 227- 256.

Appendix A. Equations and parameters added to the ORYZA1 model to develop the MBBORYZA model.

***Calculation of effect of MBB infestation on rice

```
MBBRV   = RVRT*(1.-EXP(-SRCH*DTGA/(RVRT+1.E-10)))
RVRT    = WTMBHA*TOTING
WTMBHA  = WTMBB*NH*1.0E4*MBPHL
MBPHL   = AFGEN(KBNO,TIME)

GCR     = (((DTGA-MBBRV)*30./44.) - RMCR +                ...
          (LSTR*LRSTR*FCSTR*30./12.))/CRGCR
```

***Calculation of fraction tiller loss

```
TMBBRV  = INTGRL(0., MBBRV)
FRTLS   = INSW(MBBRV-.1,0.,TLSRT*TMBBRV*FACT)
```

***Calculation of loss of plant components due to insect damage

***Loss rates due to insect damage

```
LLVP    = WLVG*FRTLS
LSTP    = WSTS*FRTLS
LSOP    = WSO*FRTLS
LSTRP   = WSTR*FRTLS
LRTP    = WRT*FRTLS
LOSP    = LLVP+LSTP+LSOP+LSTRP
```

***Weight loss due to insect damage

```
WLLVP   = INTGRL(0.,LLVP)
WLSTP   = INTGRL(0.,LSTP)
WLSOP   = INTGRL(0.,LSOP)
WLTRP   = INTGRL(0.,LSTRP)
WLRTP   = INTGRL(0.,LRTP)
WLOSP   = WLLVP+WLSTP+WLSOP+WLTRP
```

***Plant organ weights**

```
WLVG    = INTGRL (WLVGI, GLV - LLV-LLVP)
WLVD    = INTGRL (0.,          LLV+LLVP)
WSTS    = INTGRL (WSTI,        GST-LSTP)
WSTR    = INTGRL (0.,  GSTR -    LSTR-LSTRP)
WSO     = INTGRL (0.,          GSO-LSOP)
WRT     = INTGRL (WRTI ,       GRT-LRTP)
WST     = WSTS + WSTR
WAG     = WLVG + WST + WSO + WLVD
WCR     = WAG    + WRT
WRR     = WSO    * FGRAIN/0.86
```

*** Input data**

```
PARAM TOTING   = 0.0874964223, WTMBB=0.0264584
PARAM FACT     = 05, SRCH=.4, HIPHA = 1.6E5, TLSRT=6.08E-4
FUNCTION KBNO = 0.,0., 19.,0., 20.,0., 30.,0., 31.,0., 366.,0.
```

Appendix B: Additional list of variables in MBBORYZA models

Name	Description	Units
MBBRV	Amount of energy consumed by MBB	(kg ha^{-1}) / (kg MBB organism day^{-1})
TOTING	Food demand for growth, maintenance and respiration of MBB	g g^{-1} of MBB d^{-1}
SRCH	Searching rate (probanility of success)	-
TMBBRV	Total amount of DTGA removed by MBB since infestation	kg ha^{-1}
WTMBHA	Weight of MBB per hactare	kg ha^{-1}
MBPHL	Number of MBB per hill	
KBNO	Function MBB density against time (DOY)	
FRTLS	Fraction of tiller loss due removal of sucrose	
FACT	Tolerance factor	
L(XXXX)	Loss varoius growth components	kg ha^{-1} day^{-1}
W(XXXX)	Total weight of various components	kg ha^{-1}

Appendices

Appendix Ia. Listing of the BLIGHT model

BLIGHT.FOR

```
*-----------------------------------------------------------------------*
*                            BLIGHT - FSE                               *
*                                                                       *
* A combination model for the growth of rice under the presence of      *
* Bacterial Leaf Blight (Xanthomonas campestris pv. oryzae) or          *
* Sheath Blight (Rhizoctonia solani)                                    *
*                                                                       *
* BLIGHT is based upon:                                                 *
* - ORYZA1: M.J. Kropff, H.H. van Laar & R.B. Matthews (Eds.), 1994.    *
*           ORYZA1, an ecophysiological model for irrigated rice        *
*           production, SARP Research Prceedings, September 1994.       *
*           IRRI, AB-DLO, TPE-WAU.                                      *
* - L1DFDE: L. Bastiaans, January 1993.                                 *
*                                                                       *
* Author: A. Elings,                                                    *
*         Research Institute for Agrobiology and Soil Fertility         *
*         (AB-DLO),                                                     *
*         P.O. Box 14,                                                  *
*         6700 AA Wageningen,                                           *
*         The Netherlands                                               *
*                                                                       *
* Version 1, March 1993                                                 *
* Version 2, November 1994: first improvements                          *
*                                                                       *
* Documentation:                                                        *
* A. Elings, 1993. Damage by bacterial leaf blight and sheath blight    *
* in rice: a quantitative simulation model. In: W.A.H. Rossing, E.G.    *
* Rubia, M. Keerati-Kasikorn & P.R. Reddy (Eds.), Mechanisms of damage  *
* by stem borer, bacterial leaf blight and sheath blight, and their     *
* effects on rice yield, p. 79-109.                                     *
*                                                                       *
* A. Elings & E.G. Rubia, 1994. Models for the crop-pathosystems rice   *
* - bacterial leaf blight, sheath blight and stem borer. Manual for     *
* SARP Workshop, IRRI, April/May 1994.                                  *
*                                                                       *
* A. Elings & E.G. Rubia, 1994. Analysis of Damage Mechanisms by        *
* Pests and Diseases and their Effects on Rice Yield. SARP Research     *
* Proceedings                                                           *
*                                                                       *
* The model is programmed in FORTRAN and runs in the FORTRAN            *
* Simulation Environment (FSE).                                         *
* See D.W.G. van Kraalingen, Simulation Reports CABO-TT no 23, 77       *
* pages, AB-DLO, P.O. Box 14, 6700 AA Wageningen, The Netherlands, and  *
* TPE-WAU, P.O. Box 430, 6700 AK Wageningen, The Netherlands.           *
*                                                                       *
* It is recommended to run the program under the SARP/COME-ON shell:    *
* J.J.M. Riethoven, 1994. The SARP Shell, a crop growth simulation      *
* environment, SARP, revision 2, version 1.0, AB-DLO, TPE-WAU, IRRI.    *
* 114 pages.                                                            *
*                                                                       *
* External files needed:                                                *
* - CONTROL.DAT                                                         *
* - TIMER.DAT                                                           *
* - CROP.DAT                                                            *
* - PEST.DAT                                                            *
* - weather file(s)                                                     *
* - RERUNS.DAT (if reruns are made)                                     *
*-----------------------------------------------------------------------*

*-----------------------------------------------------------------------*
*                                                                       *
*                                                                       *
*                FORTRAN Simulation Environment (FSE 2.0a)              *
*                             September, 1993                           *
*                                                                       *
*                                                                       *
*     FSE 2.0 is a simulation environment suited for simulation of      *
*     biological processes in time, such as crop and vegetation growth, *
*     insect population development etc.                                *
*                                                                       *
*     The MAIN program, subroutine FSE and subroutine MODELS are        *
*     programmed by D.W.G. van Kraalingen, DLO Centre for               *
*     Agrobiological Research, PO Box 14, 6700 AA, Wageningen, The      *
*     Netherlands (e-mail: d.w.g.van.kraalingen@cabo.agro.nl).          *
*                                                                       *
*     A manual of FSE 2.0 is in preparation.                            *
*                                                                       *
*     Version 1.0 of FSE is described in:                               *
*     Kraalingen, D.W.G. van 1991. The FSE system for crop simulation,  *
*     Simulation Report CABO-TT No.23, Centre for Agrobiological        *
*     Research, Dept. of Theoretical Production Ecology, 77 pp.         *
```

```
*                                                                     *
*     Data files needed for FSE 2.0:                                  *
*          (excluding data files used by models called from MODELS):  *
*        - CONTROL.DAT (contains file names to be used),              *
*        - timer file whose name is specified in CONTROL.DAT,         *
*        - optionally, a rerun file whose name is specified in        *
*          CONTROL.DAT,                                               *
*        - weather data files as specified in timer file              *
*     Object libraries needed for FSE 2.0:                            *
*        - TTUTIL (at least version 3.2)                              *
*        - WEATHER (at least version from 17-Jan-1990)                *
*---------------------------------------------------------------------*

      PROGRAM MAIN
      CALL FSE
      END

      SUBROUTINE FSE

      IMPLICIT REAL (A-Z)

*-----Standard declarations for simulation and output control

      INTEGER   ITASK   , INSETS, ISET  , IPFORM, IL, ILEN
      LOGICAL   OUTPUT  , TERMNL, RDINQR
      CHARACTER COPINF*1, DELTMP*1
      INTEGER   INPRS

      INTEGER   IMNPRS
      PARAMETER (IMNPRS=100)
      CHARACTER PRSEL(IMNPRS)*11

*-----Declarations for time control
      INTEGER   IDOY, IYEAR
      REAL      DELT, DOY, FINTIM, PRDEL, STTIME, TIME, YEAR

*-----Declarations for weather system
      INTEGER   IFLAG    , ISTAT1, ISTAT2 , ISTN
      REAL      ANGA     , ANGB  , ELEV   , LAT , LONG, RDD
      REAL      TMMN     , TMMX  , VP     , WN  , RAIN
      LOGICAL   WTRMES   , WTRTER
      CHARACTER WTRDIR*80, CNTR*7, WSTAT*6, DUMMY*1

*-----Declarations for file names and units
      INTEGER   IUNITR   , IUNITD   , IUNITO   , IUNITL   , IUNITC
      CHARACTER FILEON*80, FILEOL*80
      CHARACTER FILEIC*80, FILEIR*80, FILEIT*80
      CHARACTER FILEI1*80, FILEI2*80, FILEI3*80, FILEI4*80, FILEI5*80

*-----Declarations for observation data facility
      INTEGER   INOD , IOD

      INTEGER   IMNOD
      PARAMETER (IMNOD=100)
      INTEGER   IOBSD(IMNOD)

*-----Unit numbers for control file (C), data files (D),
*     output file (O), log file (L) and rerun file (R). File name for
*     control file and empty strings for input files 1-5.
*     WTRMES flags any messages from the weather system

      DATA IUNITC /10/, IUNITD /20/, IUNITO /30/
      DATA IUNITL /40/, IUNITR /50/
      DATA FILEIC /'CONTROL.DAT'/
      DATA FILEI1 /' '/, FILEI2 /' '/, FILEI3 /' '/
      DATA FILEI4 /' '/, FILEI5 /' '/
      DATA WTRMES /.FALSE./

*-----Open control file and read names of normal output file, log file
*     and rerun file (these files cannot be used in reruns)
      CALL RDINIT (IUNITC,0, FILEIC)
      CALL RDSCHA ('FILEON', FILEON)
      CALL RDSCHA ('FILEOL', FILEOL)
      CALL RDSCHA ('FILEIR', FILEIR)
      CLOSE (IUNITC)

*-----Open output file and possibly a log file
      CALL FOPENS  (IUNITO, FILEON, 'NEW', 'DEL')
      IF (FILEOL.NE.FILEON) THEN
         CALL FOPENS  (IUNITL, FILEOL, 'NEW', 'DEL')
      ELSE
         IUNITL = IUNITO
      END IF

*-----See if rerun file is present, and if so read the number of rerun
*     sets from rerun file

      CALL RDSETS (IUNITR, IUNITL, FILEIR, INSETS)
```

```
*=====================================================================*
*=====================================================================*
*                                                                     *
*                  Main loop and reruns begin here                    *
*                                                                     *
*=====================================================================*
*=====================================================================*


      DO 10 ISET=0,INSETS

      WRITE (*,'(A)') '   FSE 2.0a: Initialize model'

*-----Select data set
      CALL RDFROM (ISET, .TRUE.)


*=====================================================================*
*                                                                     *
*                        Initialization section                       *
*                                                                     *
*=====================================================================*

      ITASK  = 1
      TERMNL = .FALSE.
      WTRTER = .FALSE.

*-----Read names of timer file and input files 1-5 from control
*     file (these files can be used in reruns)
      CALL RDINIT (IUNITC,IUNITL,FILEIC)
      CALL RDSCHA ('FILEIT', FILEIT)
      IF (RDINQR ('FILEI1')) CALL RDSCHA ('FILEI1', FILEI1)
      IF (RDINQR ('FILEI2')) CALL RDSCHA ('FILEI2', FILEI2)
      IF (RDINQR ('FILEI3')) CALL RDSCHA ('FILEI3', FILEI3)
      IF (RDINQR ('FILEI4')) CALL RDSCHA ('FILEI4', FILEI4)
      IF (RDINQR ('FILEI5')) CALL RDSCHA ('FILEI5', FILEI5)
      CLOSE (IUNITC)

*-----Read time, control and weather variables from timer file
      CALL RDINIT (IUNITD  , IUNITL, FILEIT)
      CALL RDSREA ('STTIME', STTIME)
      CALL RDSREA ('FINTIM', FINTIM)
      CALL RDSREA ('PRDEL' , PRDEL )
      CALL RDSREA ('DELT'  , DELT  )
      CALL RDSINT ('IYEAR' , IYEAR )
      CALL RDSINT ('ISTN'  , ISTN  )
      CALL RDSINT ('IPFORM', IPFORM)
      CALL RDSCHA ('COPINF', COPINF)
      CALL RDSCHA ('DELTMP', DELTMP )
      CALL RDSCHA ('WTRDIR', WTRDIR)
      CALL RDSCHA ('CNTR'  , CNTR)
      CALL RDSINT ('IFLAG' , IFLAG)

*-----See if observation data variable exists, if so read it
      IF (RDINQR('IOBSD')) THEN
         CALL RDAINT ('IOBSD' , IOBSD, IMNOD, INOD)
         IF (IOBSD(1).EQ.0) INOD = 0
      ELSE
         INOD = 0
      END IF

*-----See if variable with print selection exists, if so read it
      IF (RDINQR('PRSEL')) THEN
         CALL RDACHA ('PRSEL',PRSEL,IMNPRS,INPRS)
      ELSE
         INPRS = 0
      END IF
      CLOSE (IUNITD)

*-----Initialize TIMER and OUTDAT routines
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      CALL OUTDAT (ITASK, IUNITO, 'TIME', TIME)

*-----Open weather file and read station information and return
*     weather data for start day of simulation.
*     Check status of weather system, WTRMES flags if warnings or errors
*     have occurred during the whole simulation. WTRTER flags if the run
*     should be terminated because of missing weather

      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY  , ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      WSTAT  = '444444'
      IF (ABS (ISTAT2).GE.111111) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE IF (ISTAT2.EQ.0) THEN
         WSTAT = '111111'
      END IF
```

```
*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)


*=====================================================================*
*                                                                     *
*                     Dynamic simulation section                      *
*                                                                     *
*=====================================================================*

      WRITE (*,'(A)') '   FSE 2.0a: DYNAMIC loop'

20    IF (.NOT.TERMNL) THEN

*---------------------------------------------------------------------*
*                     Integration of rates section                    *
*---------------------------------------------------------------------*

      IF (ITASK.EQ.2) THEN

*--------Carry out integration only when previous task was rate
*       calculation

         ITASK = 3

*--------Call routine that handles the different models
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*--------Turn on output when TERMNL logical is set to .TRUE.
         IF (TERMNL) OUTPUT = .TRUE.
      END IF

*---------------------------------------------------------------------*
*                  Calculation of driving variables section           *
*---------------------------------------------------------------------*
      ITASK = 2

*-----Write time of output to screen and file
      IF (OUTPUT) THEN
         IF (ISET.EQ.0) THEN
            WRITE (*,'(13X,A,I5,A,F7.2)')
     &        'Default set, Year:', IYEAR, ', Day:', DOY
         ELSE
            WRITE (*,'(13X,A,I3,A,I5,A,F7.2)')
     &        'Rerun set:', ISET, ', Year:', IYEAR, ', Day:', DOY
         END IF
         IF (OUTPUT) CALL OUTDAT (2, 0, 'TIME', TIME)
         IF (OUTPUT) CALL OUTDAT (2, 0, 'DOY' , DOY)
      END IF

*-----Get weather data for new day and flag messages
      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY, ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      WSTAT  = '444444'
      IF (ABS (ISTAT2).GE.111111) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE IF (ISTAT2.EQ.0) THEN
         WSTAT = '111111'
      END IF

*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.

*---------------------------------------------------------------------*
*                Calculation of rates and output section              *
*---------------------------------------------------------------------*

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)
      IF (TERMNL.AND..NOT.OUTPUT.AND.PRDEL.GT.0.) THEN
```

```
*--------Call model routine again if TERMNL is switched on while
*        OUTPUT was off (this call is necessary to get output to file
*        when a finish condition was reached and output generation
*        was off)
         OUTPUT = .TRUE.
         CALL OUTDAT (2, 0, 'TIME', TIME)
         CALL OUTDAT (2, 0, 'DOY' , DOY)
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)
      END IF

*-----------------------------------------------------------------------*
*                            Time update                                *
*-----------------------------------------------------------------------*

*-----Check for FINTIM, OUTPUT and observation days
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      DO 30 IOD=1,INOD,2
         IF (IYEAR.EQ.IOBSD(IOD).AND.IDOY.EQ.IOBSD(IOD+1))
     &       OUTPUT = .TRUE.
30    CONTINUE

      GOTO 20
      END IF


*=======================================================================*
*                                                                       *
*                          Terminal section                             *
*                                                                       *
*=======================================================================*

      ITASK = 4

      WRITE (*,'(A)') '   FSE 2.0a: Terminate model'

      CALL OUTDAT (2, 0, 'TIME', TIME)
```

```
*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*-----Generate output file dependent on option from timer file
      IF (IPFORM.GE.4) THEN
         IF (INPRS.EQ.0) THEN
            CALL OUTDAT (IPFORM, 0, 'Simulation results',0.)
         ELSE
*           Selection of output variables was in timer file
*           write tables according to output selection array PRSEL
            CALL OUTSEL (PRSEL,IMNPRS,INPRS,IPFORM,'Simulation results')
         END IF
      END IF

      IF (WTRTER) THEN
         WRITE (*,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
         WRITE (IUNITO,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
         IF (IUNITO.NE.IUNITL) WRITE (IUNITL,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
      END IF

*-----Delete temporary output file dependent on switch from timer file
      IF (DELTMP.EQ.'Y'.OR.DELTMP.EQ.'y') CALL OUTDAT (99, 0, ' ', 0.)

10    CONTINUE

      IF (INSETS.GT.0) CLOSE (IUNITR)

*-----If input files should be copied to the output file,
*     copy rerun file (if present) and timer file and if there, input
*     files 1-5

      IF (COPINF.EQ.'Y'.OR.COPINF.EQ.'y') THEN
         IF (INSETS.GT.0) CALL COPFL2 (IUNITR, FILEIR, IUNITO, .TRUE.)
         CALL COPFL2 (IUNITD, FILEIT, IUNITO, .TRUE.)
         IF (FILEI1.NE.' ') CALL COPFL2 (IUNITD, FILEI1, IUNITO, .TRUE.)
         IF (FILEI2.NE.' ') CALL COPFL2 (IUNITD, FILEI2, IUNITO, .TRUE.)
         IF (FILEI3.NE.' ') CALL COPFL2 (IUNITD, FILEI3, IUNITO, .TRUE.)
```

```
         IF (FILEI4.NE.' ') CALL COPFL2 (IUNITD, FILEI4, IUNITO, .TRUE.)
         IF (FILEI5.NE.' ') CALL COPFL2 (IUNITD, FILEI5, IUNITO, .TRUE.)
      END IF

*-----Delete all .TMP files that were created by the RD* routines
*     during simulation
      CALL RDDTMP (IUNITD)

*-----Write to screen which files contain what
      IL = ILEN (FILEON)
      WRITE (*,'(/,3A)') ' File: ',FILEON(1:IL),
     &  ' contains simulation results'
      WRITE (*,'(2A)') ' File: WEATHER.LOG',
     &  ' contains messages from the weather system'
      IL = ILEN (FILEOL)
      WRITE (*,'(3A,/)') ' File: ',FILEOL(1:IL),
     &  ' contains messages from the rest of the model'

*-----Write message to screen and output file if warnings and/or errors
*     have occurred from the weather system, pause and wait for return
*     from user to make sure he has seen this message

      IF (WTRMES) THEN

         WRITE (*,'(/,A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
         WRITE (IUNITO,'(A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'

         WRITE (*,'(A)') ' Press <Enter>'
         READ  (*,'(A)') DUMMY

      END IF

*-----Close output file and temporary file of OUTDAT
      CLOSE (IUNITO)
      CLOSE (IUNITO+1)

*-----Close log file (if used)
      IF (FILEOL.NE.FILEON) CLOSE (IUNITL)

*-----Close log file of weather system
      CLOSE (91)

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
* SUBROUTINE MODELS                                                     *
* Authors: Daniel van Kraalingen                                        *
* Date   : 5-Jul-1993                                                   *
* Purpose: This subroutine is the interface routine between the FSE-    *
*          driver and the simulation models. This routine is called     *
*          by the FSE-driver at each new task at each time step. It     *
*          can be used by the user to specify calls to the different    *
*          models that have to be simulated                             *
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name   type meaning                                        units class *
* ----   ---- -------                                        ----- ----- *
* ITASK   I4  Task that subroutine should perform             -      I   *
* IUNITD  I4  Unit that can be used for input files           -      I   *
* IUNITO  I4  Unit used for output file                       -      I   *
* IUNITL  I4  Unit used for log  file                         -      I   *
* FILEI1  C*  Name of input file no. 1                        -      I   *
* FILEI2  C*  Name of input file no. 2                        -      I   *
* FILEI3  C*  Name of input file no. 3                        -      I   *
* FILEI4  C*  Name of input file no. 4                        -      I   *
* FILEI5  C*  Name of input file no. 5                        -      I   *
* OUTPUT  L4  Flag to indicate if output should be done       -      I   *
* TERMNL  L4  Flag to indicate if simulation is to stop       -     I/O  *
* DOY     R4  Day number within year of simulation (REAL)     d      I   *
* IDOY    I4  Day number within year of simulation (INTEGER)  d      I   *
* YEAR    R4  Year of simulation (REAL)                       y      I   *
* IYEAR   I4  Year of simulation (INTEGER)                    y      I   *
* TIME    R4  Time of simulation                              d      I   *
* STTIME  R4  Start time of simulation                        d      I   *
* FINTIM  R4  Finish time of simulation                       d      I   *
* DELT    R4  Time step of integration                        d      I   *
* LAT     R4  Latitude of site                             dec.degr. I   *
* WSTAT   C7  Status code from weather system                 -      I   *
* WTRTER  L4  Flag whether weather can be used by model       -      O   *
* RDD     R4  Daily shortwave radiation                    J/m2/d    I   *
* TMMN    R4  Daily minimum temperature                    degrees C I   *
* TMMX    R4  Daily maximum temperature                    degrees C I   *
* VP      R4  Early morning vapour pressure                   kPa    I   *
* WN      R4  Average wind speed                              m/s    I   *
* RAIN    R4  Daily amount of rainfall                        mm/d   I   *
*                                                                       *
* Fatal error checks: none                                              *
```

```
* Warnings         : none                                              *
* Subprograms called: models as specified by the user                  *
* File usage       : none                                              *
*----------------------------------------------------------------------*

      SUBROUTINE MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                   FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                   FILEIT, OUTPUT, TERMNL,
     &                   DOY   , IDOY  , YEAR  , IYEAR,
     &                   TIME  , STTIME, FINTIM, DELT ,
     &                   LAT   , WSTAT , WTRTER,
     &                   RDD   , TMMN  , TMMX  , VP   , WN, RAIN)
      IMPLICIT REAL (A-Z)

*     Formal parameters
      INTEGER   ITASK, IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      CHARACTER FILEI1*(*), FILEI2*(*), FILEI3*(*)
      CHARACTER FILEI4*(*), FILEI5*(*), FILEIT*(*)
      LOGICAL   OUTPUT, TERMNL, WTRTER
      CHARACTER WSTAT*(*)

*     Local variables
*     <none>
      SAVE

      CALL BLIGHT (ITASK, IUNITD, IUNITO, IUNITL ,
     &             FILEI1,FILEI3,FILEIT, OUTPUT,TERMNL, WSTAT, WTRTER,
     &             TIME,  STTIME,DOY,    IDOY, DELT, LAT,
     &             RDD,    TMMN,    TMMX,
     &             IYEAR)
      RETURN
      END

*======================================================================*
* SUBROUTINE BLIGHT                                                    *
* Date    : October 1994                                               *
* Version: 2                                                           *
* Author : A. Elings, AB-DLO                                           *
* Purpose: This subroutine simulates growth of a rice under the        *
*          presence of a foliar disease, in particular bacterial leaf  *
*          blight of sheath blight                                     *
*                                                                      *
* Fatal error checks: none                                             *
* Warnings          : none                                             *
* Subprograms called: RDLAI, RDDIS, DIS1, DIS2, GRLAI, TASSDS, ASTRO,  *
*                     ASSIMD, SENS, AVERAG, GRLAI, ABSORB, SUBCD,      *
*                     SUBCBC                                           *
* File usage        : none                                             *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning                                    units  class  *
* ----   ---- -------                                    -----  -----  *
* ITASK   I4  Task that subroutine should perform          -      I    *
* IUNITD  I4  Unit that can be used for input files        -      I    *
* IUNITO  I4  Unit used for output file                    -      I    *
* IUNITL  I4  Unit used for log  file                      -      I    *
* FILEI1  C*  Name of CROP FILE                            -      I    *
* FILEI3  C*  Name of PEST FILE                            -      I    *
* FILEIT  C*  Timer file                                   -      I    *
* OUTPUT  L4  Flag to indicate if output should be done    -      I    *
* TERMNL  L4  Flag to indicate if simulation is to stop    -     I/O   *
* WSTAT   C7  Status code from weather system              -      I    *
* WTRTER  L4  Flag whether weather can be used by model    -      O    *
* TIME    R4  Time of simulation                           d      I    *
* STTIME  R4  Start time of simulation                     d      I    *
* DOY     R4  Day number within year of simulation (REAL)  d      I    *
* IDOY    I4  Day number within year of simulation (INTEGER) d    I    *
* DELT    R4  Time step of integration                     d      I    *
* LAT     R4  Latitude of site                          dec.degr. I    *
* RDT     R4  Daily shortwave radiation (RDT)           J/m2/d   I    *
* TMX     R4  Daily minimum temperature                degrees C I    *
* TMN     R4  Daily maximum temperature                degrees C I    *
* IYEAR   I4  Year of simulation (INTEGER)               y      I    *
*======================================================================*

      SUBROUTINE BLIGHT (ITASK, IUNITD, IUNITO, IUNITL ,
     &                   FILEI1, FILEI3,FILEIT,
     &                   OUTPUT,TERMNL, WSTAT, WTRTER,
     &                   TIME,  STTIME, DOY,   IDOY, DELT, LAT,
     &                   RDT,    TMN,    TMX,
     &                   IYEAR)

      IMPLICIT REAL (A-Z)

*     Formal parameters

      INTEGER  ITASK , IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      LOGICAL  OUTPUT, TERMNL, WTRTER
      CHARACTER FILEI1*(*), FILEI3*(*), FILEIT*(*), WSTAT*7
      REAL RDT, TMN, TMX, TIME, DOY, DELT, LAT
```

```
*     Standard (FSE) local declarations

      INTEGER ITOLD, IMNP
      PARAMETER (IMNP=40)

*     standard model variables

      INTEGER IDOYS

*     local variables for BLIGHT

      DIMENSION LAILL(3),LAITL(3),LAIG(3),SAIL(3)
      DIMENSION NCNTH(3),NCNTD(3)
      DIMENSION SLWHL(3),SLWDS(3)
      DIMENSION FHLL(3),FDSL(3),FDDL(3),FHLT(3),FDST(3),FDDT(3)
      DIMENSION SEVL(3),SEVS(3),ASEV(3)
      DIMENSION AMAXH(3),AMAXD(3),EFFH(3),EFFD(3)
      DIMENSION AHLL(3),ADSL(3),ADDL(3)
      DIMENSION PARABS(3)

      INTEGER IN,I
      INTEGER SWILAI,SWISEN,LAISIM,OBS1

*-----States

      REAL XWLVG, XWLVD,  XWST,  XWPA, XWTDM
      REAL WLVGI, WLVDI,  WSTI,  WSTSI, WSTRI, WRTI
      REAL WLVG,  WLVD,    WSO, WST, WSTS, WSTR,  WRT
      REAL TS,    TSLV,   TSTR
      REAL WAG,    WRR
      REAL LAI,   LAIL, LAP0
      REAL DVS, DVSI

*-----Species parameters and rates

      INTEGER ILREDF
      INTEGER ILEFF
      REAL REDFT, REDFTT(IMNP)
      REAL EFF,   EFFTB(IMNP)

      INTEGER ILKDF
      REAL KDF,  KDFTB(IMNP), SCP
      REAL NPLH, NH, NPLSB

      REAL DVR,   DVRV,   DVRR
      REAL TSHCKD,TSHCKL

      REAL SHCKD, SHCKL
      REAL TBD,   TBLV

      REAL HU,      HULV
      REAL DTGA,    DS0
      REAL MAINLV,  MAINST,  MNDVS
      REAL MAINRT,  MAINSO

      INTEGER ILFSH, ILFLV, ILFST,   ILFRT
      INTEGER ILFSO, ILSAI
      REAL FSH,     FSHTB(IMNP)
      REAL FLV,     FLVTB(IMNP)
      REAL FST,     FSTTB(IMNP)
      REAL FSTR
      REAL FRT,     FRTTB(IMNP)
      REAL FSO,     FSOTB(IMNP)
      REAL SAI, SSGA,  SSGATB(IMNP)

      REAL CRGCR, CRGLV, CRGST,   CRGRT, CRGSO, CRGSTR
      REAL FCLV,  FCST,  FCRT,    FCSO
      REAL CO2LV, CO2ST, CO2SO,  CO2RT
      REAL CKCIN, CKCFL, TNASS, CKCDIF
      REAL GCR,  GMAINT

      INTEGER ILDRLV
      REAL DRLVT(IMNP)

      REAL LLV
      REAL GLV, GST, GSTR
      REAL GSO, GRT

      INTEGER ILXWLV, ILXWLD, ILXWST, ILXWPA, ILXWT
      REAL XWLVGT(IMNP), XWLVDT(IMNP), XWSTTB(IMNP)
      REAL XWPATB(IMNP), XWTDMT(IMNP)

      REAL RGRL

      INTEGER IWVAR
      CHARACTER WUSED*6

      SAVE

*     initial value of previous task
      DATA ITOLD /4/, WUSED /'UUU---'/
```

```
*     Check the new task against the old task, check the value
*     of DELT and check weather data
      CALL CHKTSK ('BLIGHT', IUNITO, ITOLD, ITASK)

      IF (DELT.LT.1.0) CALL ERROR
     &   ('BLIGHT','DELT too small for BLIGHT')

*     check weather data availability
      IF (ITASK.EQ.1.OR.ITASK.EQ.2.OR.ITASK.EQ.4) THEN
         DO 10 IWVAR=1,6
*        is there an error in the IWVAR-th variable ?
            IF (WUSED(IWVAR:IWVAR).EQ.'U'.AND.
     &          WSTAT(IWVAR:IWVAR).EQ.'4') THEN
               WTRTER = .TRUE.
               TERMNL = .TRUE.
               ITOLD  = ITASK
               RETURN
            END IF
10       CONTINUE
      END IF

      IF (ITASK.EQ.1) THEN

*        ----------------------
*        Initialization section
*        ----------------------

*        Send title(s) to output file

         CALL OUTCOM
     &   ('FSE-BLIGHT: Rice production under disease presence')
         CALL OUTCOM ('Version November 1994')

*        Read timerfile for some time-related parameters

         CALL RDINIT (IUNITD  , IUNITL, FILEIT)

         CALL RDSREA ('DTRP'  , DTRP)

         CALL RDSINT ('SWILAI', SWILAI)
         CALL RDSINT ('SWISEN', SWISEN)

         IF (SWISEN.EQ.1) SWILAI = 1

         IDOYS = NINT(STTIME)

         CLOSE (IUNITD)

*        Read input file

         CALL RDINIT (IUNITD  , IUNITL, FILEI1)

*--------Oryza sativa initialization

         CALL OUTCOM ('Rice/blight')

*        States

         CALL RDSREA ('WLVGI',  WLVGI)
         CALL RDSREA ('WLVDI',  WLVDI)
         CALL RDSREA ('WSTI',   WSTI)
         CALL RDSREA ('WRTI' ,  WRTI)
         CALL RDSREA ('DVSI',   DVSI)

         CALL RDSREA ('FSTR',   FSTR)

         WLVG = WLVGI
         WLVD = WLVDI

         WSTRI = FSTR      * WSTI
         WSTSI = (1.-FSTR) * WSTI
         WST   = WSTI
         WSTR  = WSTRI
         WSTS  = WSTSI

         WRT  = WRTI
         WSO  = 0.
         WAG  = WLVG + WST + WSO  + WLVD
         WCR  = WAG + WRT
         XWCR = 0.

         DVS  = DVSI
         LAI  = 0.
         SAI  = 0.

         TNASS  = 0.
         TS     = 0.
         TSTR   = 0.
         TSLV   = 0.
         MNDVS  = 1.

         CKCIN = 0.
```

```
      CKCFL = 0.

*     Rates

      DTGA   = 0.
      GCR    = 0.
      CRGCR  = 0.
      LLV    = 0.
      GSTR   = 0.
      LSTR   = 0.
      GMAINT = 0.

*     Other parameters

      CALL RDSREA ('SHCKD', SHCKD)
      CALL RDSREA ('SHCKL', SHCKL)
      CALL RDSREA ('SCP',    SCP)
      CALL RDSREA ('TBD',    TBD)
      CALL RDSREA ('TBLV',   TBLV)
      CALL RDSREA ('MAINLV', MAINLV)
      CALL RDSREA ('MAINST', MAINST)
      CALL RDSREA ('MAINSO', MAINSO)
      CALL RDSREA ('MAINRT', MAINRT)
      CALL RDSREA ('CRGLV',  CRGLV)
      CALL RDSREA ('CRGST',  CRGST)
      CALL RDSREA ('CRGSTR', CRGSTR)
      CALL RDSREA ('CRGSO',  CRGSO)
      CALL RDSREA ('CRGRT',  CRGRT)
      CALL RDSREA ('FCLV',   FCLV)
      CALL RDSREA ('FCST',   FCST)
      CALL RDSREA ('FCSTR',  FCSTR)
      CALL RDSREA ('FCRT',   FCRT)
      CALL RDSREA ('FCSO',   FCSO)
      CALL RDSREA ('TCLSTR', TCLSTR)
      CALL RDSREA ('LRSTR',  LRSTR)
      CALL RDSREA ('LAP0',   LAP0)
      CALL RDSREA ('NPLH'  , NPLH)
      CALL RDSREA ('NH'  ,   NH)
      CALL RDSREA ('NPLSB' , NPLSB)
      CALL RDSREA ('DVRV',   DVRV)
      CALL RDSREA ('DVRR',   DVRR)

      CALL RDAREA ('EFFTB',  EFFTB,  IMNP, ILEFF)
      CALL RDAREA ('KDFTB',  KDFTB,  IMNP, ILKDF)
      CALL RDAREA ('REDFTT', REDFTT, IMNP, ILREDF)
      CALL RDAREA ('SSGATB', SSGATB, IMNP, ILSAI)
      CALL RDAREA ('FSHTB',  FSHTB,  IMNP, ILFSH)
      CALL RDAREA ('FRTTB',  FRTTB,  IMNP, ILFRT)

      CLOSE (IUNITD)

      CALL RDINIT (IUNITD  , IUNITL, FILEI3)

*     Other parameters

      CALL RDSREA ('RGRL',   RGRL)

*      CALL RDSINT ('ENDEPI', ENDEPI)

      CALL RDAREA ('FLVTB', FLVTB,  IMNP, ILFLV)
      CALL RDAREA ('FSTTB', FSTTB,  IMNP, ILFST)
      CALL RDAREA ('FSOTB', FSOTB,  IMNP, ILFSO)
      CALL RDAREA ('DRLVT',  DRLVT, IMNP, ILDRLV)

*     Observed values

      XWLVG = 0.
      XWLVD = 0.
      XWST  = 0.
      XWPA  = 0.
      XWTDM = 0.
      XNFLV = 0.

      CALL RDAREA ('XWLVGT',XWLVGT,IMNP,ILXWLV)
      CALL RDAREA ('XWLVDT',XWLVDT,IMNP,ILXWLD)
      CALL RDAREA ('XWSTTB',XWSTTB,IMNP,ILXWST)
      CALL RDAREA ('XWPATB',XWPATB,IMNP,ILXWPA)
      CALL RDAREA ('XWTDMT',XWTDMT,IMNP,ILXWT)

*     Initialization disease input

      DAS    = 0.
      LAISIM = 1
      EPISTP = 0

      KDF    = LINT (KDFTB, ILKDF, DVS)

      REDFT = 1.
      EFF   = 1.
      TEFF  = 1.

      WLVHL = 0.
```

```
         WLVDS = 0.

         CALL RDLAI (DOY,ITASK,LAILL)

         CALL RDDIS (DOY,DVS,ITASK,SWISEN,
     &                  NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL,
     &                  SEVS,IN,OBS1)

         CALL DIS2(ITASK,
     &               IN,WLVHL,WLVDS,SLWHL,SLWDS,NCNTH,NCNTD,REDFT,
     &               EFF,MAINLV,WLVG,TEFF,MNDVS,SEVL,ASEVL,
     &               AMAXH,AMAXD,EFFH,EFFD,RMLV)

         CLOSE (IUNITD)

*        USE OF SUBROUTINE ABSORB IS OPTIONAL

         DO 15 I = 1,IN
         LAITL(I) = 0.
         LAIG(I)  = 0.
15       CONTINUE

         CALL ABSORB (ITASK,DELT,DAS,IN,KDF,LAITL,LAIG,RDT,GCR,
     &                ABS,CUMABS,CLUE,AVCLUE,PARABS)

       ELSE IF (ITASK.EQ.2) THEN

*        ------------------------
*        Rate calculation section
*        ------------------------

************
*** 1. INPUT, e.g. from experiment
************

         CALL RDDIS (DOY,DVS,ITASK,SWISEN,
     &               NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL,
     &               SEVS,IN,OBS1)

******************
*** 2. TEMPERATURE
******************

         TAV   = 0.5*(TMX + TMN)
         TAVD  = 0.5*(TAV + TMX)

******************
*** 3. DEVELOPMENT
******************

*--------Heat units

         HU    = MIN(30.-TBD, (MAX (0., TAV-TBD)))
         HULV  = MIN(26.-TBLV,(MAX (0., TAV-TBLV)))

*--------Development
         IF (DVS.LT.1.) THEN
            DVR = DVRV * HU
            IF (DAS.EQ.DTRP) TSTR = TS
            TSHCKD = SHCKD * TSTR
            IF (DAS.GT.DTRP .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.
         ELSE
            DVR = DVRR * HU
         ENDIF

*--------Cold days

         CALL SUBCD (DAS,DTRP,TAV,TIME,NCOLD)

*******************
*** 4. ASSIMILATION
*******************

         EFF   = LINT (EFFTB,  ILEFF, TAVD)
         REDFT = LINT (REDFTT, ILREDF,TAVD)
         KDF   = LINT (KDFTB, ILKDF, DVS)

*--------Light absorption and photosynthesis
*        Program structure is such that yesterday's AMAXH,D and
*        EFFH,D are used.

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

*****************************
*** 5. MAINTENANCE RESPIRATION
*****************************

         IF ((WLVG+WLVD).GT.0.) THEN
            MNDVS = WLVG/(WLVG+WLVD)
         ELSE
```

```
          MNDVS = 1.
        ENDIF

        Q10      = 2.
        TREF     = 25.
        TEFF     = Q10**((TAV-TREF)/10.)

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

************************************
*** 6. GROWTH AND LOSS OF DRY MATTER
************************************

*--------Dry matter partitioning

        FSH  = LINT (FSHTB, ILFSH, DVS)
        FRT  = LINT (FRTTB, ILFRT, DVS)
        FLV  = LINT (FLVTB, ILFLV, DVS)
        FST  = LINT (FSTTB, ILFST, DVS)
        FSO  = LINT (FSOTB, ILFSO, DVS)

        FTOT = FRT+FSH*(FLV+FST+FSO)
        IF ((FTOT.LT.0.99).OR.(FTOT.GT.1.01)) THEN
             WRITE (*,'(A)') ' Warning'
             WRITE (*,'(A)') ' Sum of partitioning fraction not 1'
        ENDIF

*--------Carbohydrate requirements

        CRGCR = FSH*(CRGLV*FLV  + CRGST*FST*(1.-FSTR) +
     &               CRGSTR*FSTR*FST                  +
     &               CRGSO*FSO) + CRGRT*FRT

*--------Loss of crop weight due to transplanting.

        IF ((DAS.EQ.DTRP).AND.(DAS.GT.0.)) THEN
             TRLOSS = (NPLSB-NPLH*NH)/NPLSB*(WAG+WRT)
        ELSE
             TRLOSS = 0.
        ENDIF

*--------Loss of green leaf weight.

        DRLV   = LINT(DRLVT, ILDRLV, DVS)
        LLV    = WLVG * DRLV

*--------Loss of stem reserves.

        IF (DVS.LT.1.) THEN
           LSTR  = 0.
        ELSE
           LSTR  = WSTR / TCLSTR
        ENDIF

*--------Growth rates.

        GCR    = ((DTGA*30./44.) - RMCR - TRLOSS +
     &             (LSTR*LRSTR*FCSTR*30./12.))/CRGCR
        GRT    = GCR * FRT
        GLV    = GCR * FSH * FLV
        GST    = GCR * FSH * FST * (1.-FSTR)
        GSTR   = GCR * FSH * FST * FSTR
        GSO    = GCR * FSH * FSO

************************
*** 7. GROWTH MAINTENANCE
************************

        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)

        GMAINT = ((DTGA*30./44.)-RMCR-TRLOSS)*44./30. -
     &            (GRT*CO2RT  +  GLV*CO2LV +
     &             GST*CO2ST  +  GSO*CO2SO +
     &             GSTR*CO2STR             +
     &            (1.-LRSTR)*LSTR*FCSTR*44./12.)

****************************
*** 8. LEAF AREA DEVELOPMENT
****************************

        SSGA   = LINT (SSGATB, ILSAI, DVS)
        SAI    = SSGA * WST

************************
** 8.1. SIMULATION OF LAI
************************

        IF (SWILAI.EQ.1) THEN
```

```
*-------     Averages of relevant SLW and leaf nitrogen contents.
            CALL AVERAG(ITASK,IN,SLWHL,SLWDS,NCNTH,NCNTD,
     &                  SLA,NCHAV,NCDAV)

            DO 11 I = 1,IN
               NCNTH(I) = NCHAV
               NCNTD(I) = NCDAV
11          CONTINUE

            CALL GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &                 TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

*--------    Three layers of equal depth are simulated.
            DO 20 I = 1,IN
               LAITL(I) = LAI/IN
               LAILL(I) = LAIL/IN
20          CONTINUE

            CALL DIS1(ITASK,
     &                IN,FHLL,FDSL,LAILL,SAI,SEVL,SEVS,SLWHL,SLWDS,
     &                LAIX,LAIHL,LAIDS,LAIDD,LAITL,LAIG,SAIL,GLAI,
     &                FDDL,AHLL,ADSL,ADDL,TSEVL,TSEVS,ASEV,ASEVL,
     &                FHLT,FDST,FDDT,WLVHL,WLVDS)

            CALL DIS2(ITASK,
     &                IN,WLVHL,WLVDS,SLWHL,SLWDS,NCNTH,NCNTD,REDFT,
     &                EFF,MAINLV,WLVG,TEFF,MNDVS,SEVL,ASEVL,
     &                AMAXH,AMAXD,EFFH,EFFD,RMLV)

*****************************************
** 8.2. ANALYSIS OF EXPERIMENTS, LAI INPUT
*****************************************

         ELSE

*--------   Simulation of leaf area before 1st observation isavailable.

            IF (IDOY.EQ.OBS1) LAISIM = 0

            IF (LAISIM.EQ.0) THEN

               CALL RDLAI (DOY,ITASK,LAILL)

               CALL DIS1(ITASK,
     &                   IN,FHLL,FDSL,LAILL,SAI,SEVL,SEVS,SLWHL,SLWDS,
     &                   LAIX,LAIHL,LAIDS,LAIDD,LAITL,LAIG,SAIL,GLAI,
     &                   FDDL,AHLL,ADSL,ADDL,TSEVL,TSEVS,ASEV,ASEVL,
     &                   FHLT,FDST,FDDT,WLVHL,WLVDS)

               CALL DIS2(ITASK,
     &                   IN,WLVHL,WLVDS,SLWHL,SLWDS,NCNTH,NCNTD,REDFT,
     &                   EFF,MAINLV,WLVG,TEFF,MNDVS,SEVL,ASEVL,
     &                   AMAXH,AMAXD,EFFH,EFFD,RMLV)

               LAIL   = LAIX
               LAI    = 0.5*SAI + LAIL

            ELSE

*           It is assumed that first observations are made before the
*           second leaf layer is formed, and that up to that moment the
*           crop is healthy.

               SLA    = 1./SLWHL(1)

               CALL GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &                    TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

               LAITL(1) = LAI
               LAILL(1) = LAIL
               LAITL(2) = 0.
               LAILL(2) = 0.
               LAITL(3) = 0.
               LAILL(3) = 0.

               CALL DIS1(ITASK,
     &                   IN,FHLL,FDSL,LAILL,SAI,SEVL,SEVS,SLWHL,SLWDS,
     &                   LAIX,LAIHL,LAIDS,LAIDD,LAITL,LAIG,SAIL,GLAI,
     &                   FDDL,AHLL,ADSL,ADDL,TSEVL,TSEVS,ASEV,ASEVL,
     &                   FHLT,FDST,FDDT,WLVHL,WLVDS)

               CALL DIS2(ITASK,
     &                   IN,WLVHL,WLVDS,SLWHL,SLWDS,NCNTH,NCNTD,REDFT,
     &                   EFF,MAINLV,WLVG,TEFF,MNDVS,SEVL,ASEVL,
     &                   AMAXH,AMAXD,EFFH,EFFD,RMLV)

            ENDIF

         ENDIF
```

```
************************************
** 8.3. COMPARISON WITH OBSERVED LAI
************************************

        CALL RDLAI (DOY,ITASK,LAILL)
        XLAI = LAILL(1)+LAILL(2)+LAILL(3)

***************************
*** 9. OPTIONAL SUBROUTINES
***************************

*--------Cumulative intercepted radiation
        CALL ABSORB (ITASK,DELT,DAS,IN,KDF,LAITL,LAIG,RDT,GCR,
     &               ABS,CUMABS,CLUE,AVCLUE,PARABS)

*******************
*** 10. DATA OUTPUT
*******************

        IF (OUTPUT) THEN
           CALL OUTDAT (2, 0, 'DAS',    DAS)
           CALL OUTDAT (2, 0, 'DVS',    DVS)

*           CALL OUTDAT (2, 0, 'DVR',     DVR)
*           CALL OUTDAT (2, 0, 'HU',      HU)
*           CALL OUTDAT (2, 0, 'TBD',     TBD)
*           CALL OUTDAT (2, 0, 'TBLV',    TBLV)
*           CALL OUTDAT (2, 0, 'TS',      TS)
*           CALL OUTDAT (2, 0, 'TSTR',    TSTR)
*           CALL OUTDAT (2, 0, 'TSHCKD',TSHCKD)

           CALL OUTDAT (2, 0, 'DTGA', DTGA)
           CALL OUTDAT (2, 0, 'LAI',    LAI)
           CALL OUTDAT (2, 0, 'LAIL',   LAIL)
           CALL OUTDAT (2, 0, 'XLAI',   XLAI)
           CALL OUTDAT (2, 0, 'SAI',    SAI)
           CALL OUTDAT (2, 0, 'GLAI',   GLAI)
*          CALL OUTDAT (2, 0, 'XNFLV', XNFLV)
*           CALL OUTDAT (2, 0, 'NFLV',   NFLV)
           CALL OUTDAT (2, 0, 'XWLVG',  XWLVG)
           CALL OUTDAT (2, 0, 'WLVG',   WLVG)
           CALL OUTDAT (2, 0, 'XWLVD', XWLVD)
           CALL OUTDAT (2, 0, 'WLVD',   WLVD)
           CALL OUTDAT (2, 0, 'XWST',   XWST)
           CALL OUTDAT (2, 0, 'WST',    WST)
           CALL OUTDAT (2, 0, 'WSTS',   WSTS)
           CALL OUTDAT (2, 0, 'WSTR',   WSTR)
           CALL OUTDAT (2, 0, 'XWPA',   XWPA)
           CALL OUTDAT (2, 0, 'WSO',    WSO)
           CALL OUTDAT (2, 0, 'WCR',    WCR)
           CALL OUTDAT (2, 0, 'XWCR',   XWCR)
           CALL OUTDAT (2, 0, 'XWTDM', XWTDM)
           CALL OUTDAT (2, 0, 'WAG',    WAG)
           CALL OUTDAT (2, 0, 'WRT',    WRT)
           CALL OUTDAT (2, 0, 'CKCDIF',CHCDIF)
           CALL OUTDAT (2, 0, 'GCR',    GCR)
           CALL OUTDAT (2, 0, 'CUMABS',CUMABS)
           CALL OUTDAT (2, 0, 'AVCLUE',AVCLUE)
        END IF

      ELSE IF (ITASK.EQ.3) THEN

*       -------------------
*       Integration section
*       -------------------

*--------Days after sowing.

        DAS  = TIME - STTIME

*--------Development stage.

        DVS  = INTGRL (DVS , DVR,          DELT)

*--------Plant organ weights.
*       WRR at 10% chaff weight and 14% moisture.

        WLVG = INTGRL (WLVG, GLV - LLV,    DELT)
        WLVD = INTGRL (WLVD, LLV  ,        DELT)
        WSTS = INTGRL (WSTS, GST,          DELT)
        WSTR = INTGRL (WSTR, GSTR - LSTR, DELT)
        WST  = WSTS + WSTR
        WSO  = INTGRL (WSO,  GSO  ,        DELT)
        WRT  = INTGRL (WRT , GRT  ,        DELT)
        WAG  = WLVG + WST  + WSO  + WLVD
        WRR  = WSO * 0.90 / 0.86
        WCR  = WAG + WRT
        XWCR = XWTDM + WRT
```

```
*--------Temperature sums

        TS   = INTGRL (TS  , HU   ,       DELT)
        TSLV = INTGRL (TSLV, HULV ,       DELT)

*--------Cumulative intercepted radiation

        CALL ABSORB (ITASK,DELT,DAS,IN,KDF,LAITL,LAIG,RDT,GCR,
     &               ABS,CUMABS,CLUE,AVCLUE,PARABS)

*--------Carbon balance check

        CALL SUBCBC (CKCIN,CKCFL,TIME,CBCHK)

        CKCIN  = (WLVG+WLVD-WLVGI-WLVDI)*FCLV +
     &           (WSTS-WSTSI)*FCST + (WSTR-WSTRI)*FCSTR +
     &           (WRT-WRTI)*FCRT        + WSO*FCSO
        TNASS  = INTGRL (TNASS, GMAINT, DELT)
        CKCFL  = TNASS * (12./44.)
        IF (CKCIN.LE.0.) CKCDIF = (CKCIN-CKCFL)/(1.+CKCIN)
        IF (CKCIN.GT.0.) CKCDIF = (CKCIN-CKCFL)/CKCIN

*--------Field observations

        XWLVG = LINT(XWLVGT, ILXWLV,  DOY)
        XWLVD = LINT(XWLVDT, ILXWLD,  DOY)
        XWST  = LINT(XWSTTB, ILXWST,  DOY)
        XWPA  = LINT(XWPATB, ILXWPA,  DOY)
        XWTDM = LINT(XWTDMT, ILXWT  , DOY)

*--------Finish conditions of simulation.

        IF (DVS.GE.2.0)    TERMNL = .TRUE.

      ELSE IF (ITASK.EQ.4) THEN

*       ----------------
*       Terminal section
*       ----------------

*       Define graph for output
*       Use individual scale, small plot width for output

*        CALL OUTPLT (1,'WSO')
*        CALL OUTPLT (1,'TADRW')
*        CALL OUTPLT (6, 'Printplot of BLIGHT')

        END IF

        ITOLD = ITASK

        RETURN
        END

*-----------------------------------------------------------------------*
*  SUBROUTINE SUBCBC                                                    *
*  Purpose: This function checks the Crop Carbon Balance                *
*           and stops the simulation if the difference between          *
*           CKCIN and CKCFL exceeds 0.1 %                               *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  CKCIN   R4  Accumulated C in the crop               kg C/ha  I       *
*  CKCFL   R4  Sum of integrated C fluxes              kg C/ha  I       *
*  TIME    R4  Time of simulation                          d    I       *
*  CKCHK   R4  Difference between in carbon balance        -    O       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

        SUBROUTINE SUBCBC(CKCIN,CKCFL,TIME,CBCHK)
        IMPLICIT REAL (A-Z)

        CBCHK = 2.0*(CKCIN-CKCFL)/(CKCIN+CKCFL+1.E-10)

        IF (ABS(CBCHK).GT.0.001) THEN
          WRITE (*,10) CBCHK, CKCIN, CKCFL, TIME
 10       FORMAT (/,'* * *Error in Carbon Balance, please check* * *',/,
     &    ' CBCHK=',F8.3,', CKCIN=',F8.2,', CKCFL=',F8.2,' at TIME=',F6.1)
          STOP
        ENDIF

        RETURN
        END

*-----------------------------------------------------------------------*
* SUBROUTINE SUBCD                                                      *
*                                                                       *
*  Purpose: This subroutine determines the number of consecutive cold   *
*           days and terminates simulation if the number of days with   *
*           an average temperature below 12 oC exceeds 3                *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
```

```
*  name   type meaning                                        units  class *
*  ----   ---- -------                                        -----  ----- *
*  DAS     R4  Number of days after sowing                     -      I    *
*  DTRP    R4  Number of days between sowing and transpl.      -      I    *
*  TAV     R4  Average daily temperature                      oC      I    *
*  TIME    R4  Time of simulation                              d      I    *
*  NCOLD   R4  Number of cold days                             -      O    *
*                                                                          *
*  FILE usage : none                                                       *
*--------------------------------------------------------------------------*

      SUBROUTINE SUBCD(DAS,DTRP,TAV,TIME,NCOLD)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      REAL DAS,DTRP,TIME
      REAL TAV,NCOLD

      SAVE

      IF(DAS.EQ.DTRP) NCOLD=0.

      IF(TAV.LT.12.) THEN
         NCOLD = NCOLD + 1.
      ELSE
         NCOLD = 0.
      ENDIF

      IF (NCOLD.GT.3.) THEN

        WRITE (*,10) NCOLD, TIME
 10     FORMAT (/,'* * *Number of cold days (<12 C) exceeded 3* * *',/,
     &  ' NCOLD',F8.3, ' at TIME=',F6.1)
        STOP

      ENDIF

      RETURN
      END

*--------------------------------------------------------------------------*
*  SUBROUTINE GRLAI                                                        *
*  Purpose: This subroutine calculates the total leaf area index           *
*                                                                          *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)         *
```

```
*  name   type meaning                                        units  class *
*  ----   ---- -------                                        -----  ----- *
*  SAI     R4  Stem area index                                ha/ha    I    *
*  SLA     R4  Specific leaf area                             ha/kg    I    *
*  DVS     R4  Development stage                               -       I    *
*  WLVG    R4  Weight of the green leaves                     kg/ha    I    *
*  IDOY    I4  Day of year                                     d       I    *
*  IYEAR   I4  Year                                            -       I    *
*  LAP0    R4  Plant leaf area at emergence                    m2      I    *
*  DAS     R4  Number of days after sowing                     -       I    *
*  DTRP    R4  Number of days between sowing and transpl.      -       I    *
*  TSLV    R4  Temperature sum for leaf development           oC       I    *
*  RGRL    R4  Relative growth rate for leaf development      1/(oCd)  I    *
*  SHCKL   R4  Delay parameter in development                 oCd/oCd  I    *
*  NPLSB   R4  Number of plants in seedbed                    pl/m2    I    *
*  NH      R4  Number of hills                                hills/m2 I    *
*  NPLH    R4  Number of plants per hill                      pl/hill  I    *
*  LAI     R4  Total leaf area index (including SAI)          ha/ha    O    *
*  LAIL    R4  Total leaf area index (excluding SAI)          ha/ha    O    *
*  TSHCKL  R4  Transplanting shock for phenological           oCd      O    *
*                  development                                             *
*                                                                          *
*  FILE usage : none                                                       *
*                                                                          *
*--------------------------------------------------------------------------*

      SUBROUTINE GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &                 TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      REAL DAS,DTRP
      REAL TSLV,TSHCKL,SHCKL
      REAL LAI,LAIL,LAP0,SAI,SLA
      REAL RGRL,NPLSB,NPLH,NH
      REAL WLVG
      REAL DVS

*-----Local parameters
      REAL LAPI,LAII,LAIEXS,LAIEXP
      REAL TSLVTR,WLVEXS,WLVEXP

      SAVE

      LAIEXS = 0.
```

```
      WLVEXS = 0.

      IF (DAS.LT.DTRP)                                          THEN

         IF (LAI.LT.1.)                                         THEN
             LAPI   = LAP0 * (EXP(RGRL*TSLV))
             LAII   = LAPI * NPLSB
             LAI    = LAII
             WLVEXS = WLVG
             LAIEXS = LAI
          ELSE
             LAII  = 0.5*SAI + LAIEXS + SLA*(WLVG-WLVEXS)
             LAI   = LAII
          ENDIF

      ELSEIF (DAS.EQ.DTRP)                                       THEN
             LAI    = LAII * NPLH*NH/NPLSB
             TSLVTR = TSLV
             TSHCKL = SHCKL * TSLVTR

      ELSE

         IF (TSLV.LT.(TSLVTR+TSHCKL))                           THEN
             LAI    = LAII * NPLH*NH/NPLSB
         ELSE
*            IF ((LAI.LT.1.).AND.(DVS.LT.0.6))                  THEN
            IF ((LAI.LT.1.).AND.(DVS.LT.1.0))                   THEN
                LAI    = LAII * NPLH*NH/NPLSB *
     &                        (EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
                WLVEXP= WLVG
                LAIEXP= LAI
            ELSE
                LAI    = 0.5*SAI + LAIEXP +  SLA*(WLVG-WLVEXP)
            ENDIF
          ENDIF
      ENDIF

      LAIL = LAI - 0.5*SAI

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                     *
*  Purpose: This subroutine calculates astronomic daylength,            *
*           diurnal radiation characteristics such as the daily         *
*           integral of sine of solar elevation and solar constant.     *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  DOY     R4  Daynumber (Jan 1st = 1)                    -      I      *
*  LAT     R4  Latitude of the site                     degrees  I      *
*  SC      R4  Solar constant                           J m-2 s-1 O     *
*  DS0     R4  Daily extraterrestrial radiation         J m-2 d-1 O     *
*  SINLD   R4  Seasonal offset of sine of solar height    -       O     *
*  COSLD   R4  Amplitude of sine of solar height          -       O     *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)    h       O     *
*  DSINB   R4  Daily total of sine of solar height        s       O     *
*  DSINBE  R4  Daily total of effective solar height      s       O     *
*                                                                       *
*  FATAL ERROR CHECKS (execution terminated, message)                   *
*  condition: LAT > 67, LAT < -67                                       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE ASTRO (DOY, LAT,
     &                  SC , DS0, SINLD, COSLD, DAYL, DSINB, DSINBE)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      REAL DOY,LAT,SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE

*-----Local parameters
      REAL PI,RAD
      PARAMETER (PI=3.141592654)

      SAVE

*-----Conversion factor from degrees to radians
      RAD   = PI/180.

*-----check on input range of parameters
      IF (LAT.GT.67.)  STOP 'ERROR IN ASTRO: LAT> 67'
      IF (LAT.LT.-67.) STOP 'ERROR IN ASTRO: LAT>-67'

*-----declination of the sun as function of daynumber (DOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+10.)/365.))
```

```
*-----SINLD, COSLD and AOB are intermediate variables
      SINLD = SIN (RAD*LAT)*SIN (DEC)
      COSLD = COS (RAD*LAT)*COS (DEC)
      AOB   = SINLD/COSLD

*-----daylength (DAYL)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)

      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE = 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &         12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT (1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB

      RETURN
      END

*-----------------------------------------------------------------------*
*  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.                         *
*                                                                       *
*  Adapted from TOTASS by A. Elings, March 1993, January 1994.          *
*                                                                       *
*  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      *
*  AMAXH   R4  Assimilation rate of healthy leaf area   kg CO2/   I      *
*              at light saturation, per layer          ha leaf/h        *
*  AMAXD   R4  Assimilation rate of diseased leaf and   kg CO2/   I      *
*              stem area at light saturation, per layer ha leaf/h       *
*  EFFH    R4  Initial light use efficiency of healthy  kg CO2/J/ I      *
*              leaf area, per layer                     ha/h m2 s       *
*  EFFD    R4  Initial light use efficiency of diseased kg CO2/J/ I      *
*              leaf and stem area, per layer            ha/h m2 s       *
*  KDF     R4  Extinction coefficient for diffuse light               I  *
*  LAITL   R4  Leaf + stem area index (total)          ha/ha          I  *
*  FHLT    R4  Fraction healthy leaf area                -            I  *
*  FDST    R4  Fraction diseased leaf area               -            I  *
*  IN      I4  Number of leaf layers                     -            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, AND IS COMPATIBLE WITH BLIGHT.                    *
*-----------------------------------------------------------------------*

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

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER IN
      REAL DOY,LAT,DTR,SCP,KDF,DAYL,DTGA,DS0
      REAL AMAXH,AMAXD,EFFH,EFFD,LAITL,FHLT,FDST

      DIMENSION FHLT(3),FDST(3)
      DIMENSION AMAXH(3),AMAXD(3),EFFH(3),EFFD(3)
      DIMENSION LAITL(3)

*-----Local parameters
      REAL XGAUSS(3), WGAUSS(3)
      REAL PI
      INTEGER I1, IGAUSS

      PARAMETER (PI=3.141592654)

      SAVE

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

      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   *
*           leaf 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 leaf layers    *
*           is integrated to total gross canopy photosynthesis FGROS.   *
*           Healthy, diseased and dead leaf area is taken into account. *
*                                                                       *
*  Adapted from ASSIM by A. Elings, March 1993, January 1994.           *
*                                                                       *
*  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   *
*  AMAXH   R4  Assimilation rate of healthy leaf area    kg CO2/      I   *
*              at light saturation, per layer           ha leaf/h        *
*  AMAXD   R4  Assimilation rate of diseased leaf and    kg CO2/      I   *
*              stem area at light saturation, per layer ha leaf/h        *
*  EFFH    R4  Initial light use efficiency of healthy   kg CO2/J/    I   *
*              leaf area, per layer                     ha/h m2 s        *
*  EFFD    R4  Initial light use efficiency of diseased  kg CO2/J/    I   *
*              leaf and stem area, per layer            ha/h m2 s        *
*  KDF     R4  Extinction coefficient for diffuse light                 I   *
*  LAITL   R4  Leaf + stem area index (total)             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   *
*  FHLT    R4  Fraction healthy leaf area                   -          I   *
*  FDST    R4  Fraction diseased leaf area                  -          I   *
*  IN      I4  Number of leaf layers                        -          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, AND IS COMPATIBLE WITH BLIGHT.                    *
*                                                                       *
*-----------------------------------------------------------------------*
```

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

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER IN
      REAL SCP,KDF,SINB,PARDR,PARDF,FGROS
      REAL AMAXH,AMAXD,EFFH,EFFD,LAITL,FHLT,FDST

      DIMENSION LAITL(3),LAIA(3),FHLT(3),FDST(3)
      DIMENSION AMAXH(3),EFFH(3),AMAXD(3),EFFD(3)

*-----Local parameters
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, I3, IGAUSS

      SAVE

      DATA TINY /1.E-8/

*-----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 leaf layers is calculated.
*     If more layers are simulated, then add statments.
      LAIA(1) = LAITL(2) + LAITL(3)
      LAIA(2) = LAITL(3)
      LAIA(3) = 0.

*-----Calculation of assimilation per canopy layer.
      DO 30 I3 =1,IN

      IF (LAITL(I3).GE.(-TINY).AND.LAITL(I3).LE.TINY) GOTO 30

      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(I3)/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 layer
*        assimilation (FGROSL)
         FGROSL = FGROSL + FGL * WGAUSS(I1)

10     CONTINUE

       FGROSL = FGROSL * LAITL(I3)

*-----integration of layer assimilation rate to canopy assimilation
*      rate (FGROS)
       FGROS  = FGROS + FGROSL

30     CONTINUE

       RETURN
       END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE RDLAI                                                     *
*  Purpose: This subroutine reads leaf area input data for more than    *
*           one leaf layer.                                             *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   January 1994.                                                *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- -------                                    -----  -----  *
*  DOY     R4  Daynumber (Jan 1st = 1)                     -       I    *
*  ITASK   I4  Task that subroutine should perform         -       I    *
*  LAILL   R4  Leaf area index of a leaf layer             -       O    *
*              (excluding stem area index)                              *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : PEST.DAT                                                *
*-----------------------------------------------------------------------*

      SUBROUTINE RDLAI (DOY,ITASK,
     &                  LAILL)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK
      REAL DOY,LAILL

*-----Local parameters
      INTEGER IMNP
      PARAMETER (IMNP=40)

      REAL LAILL1(IMNP),LAILL2(IMNP),LAILL3(IMNP)
      INTEGER ILL1,ILL2,ILL3

      DIMENSION LAILL(3)

      SAVE

      IF (ITASK.EQ.1) THEN

          CALL RDAREA('LAILL1',LAILL1,IMNP,ILL1)
          CALL RDAREA('LAILL2',LAILL2,IMNP,ILL2)
          CALL RDAREA('LAILL3',LAILL3,IMNP,ILL3)
```

```
      ELSE IF (ITASK.EQ.2) THEN

          LAILL(1) = LINT(LAILL1, ILL1, DOY)
          LAILL(2) = LINT(LAILL2, ILL2, DOY)
          LAILL(3) = LINT(LAILL3, ILL3, DOY)

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE RDDIS                                                     *
*  Purpose: This subroutine reads diseas input data for more than       *
*           one leaf layer.                                             *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   March 1993, January 1994.                                    *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- -------                                    -----  -----  *
*  DOY     R4  Daynumber (Jan 1st = 1)                     -       I    *
*  DVS     R4  Development stage                           -       I    *
*  ITASK   I4  Task that subroutine should perform         -       I    *
*  SWISEN  I4  Switch to enable sensitivity test           -       I    *
*  NCNTH   R4  Nitrogen content of healthy leaf area      g/g      O    *
*  NCNTD   R4  Nitrogen content of diseased leaf area     g/g      O    *
*  SLWHL   R4  Specific leaf weight of healthy leaf area  kg/ha    O    *
*  SLWDS   R4  Specific leaf weight of diseased leaf area kg/ha    O    *
*  FHLL    R4  Fraction healthy leaf area                  -       O    *
*  FDSL    R4  Fraction diseased leaf area                 -       O    *
*  SEVL    R4  Disease severity on diseased leaf area      -       O    *
*  SEVS    R4  Disease severity on stem area               -       O    *
*  IN      I4  Number of leaf layers                       -       O    *
*  OBS1    I4  Day of first observation                                 *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : SENS                              *
*  FILE usage : PEST.DAT                                                *
*-----------------------------------------------------------------------*
```

```
      SUBROUTINE RDDIS (DOY,DVS,ITASK,SWISEN,
     &                  NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL,
     &                  SEVS,IN,OBS1)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,SWISEN,IN,OBS1
      REAL DOY,DVS
      REAL NCNTH,NCNTD,SLWHL,SLWDS,FHLL,FDSL,SEVL,SEVS

*-----Local parameters

      INTEGER IMNP
      PARAMETER (IMNP=40)

      INTEGER I

      REAL NCNTH1(IMNP),NCNTH2(IMNP),NCNTH3(IMNP)
      INTEGER ILNTH1,ILNTH2,ILNTH3

      REAL NCNTD1(IMNP),NCNTD2(IMNP),NCNTD3(IMNP)
      INTEGER ILNTD1,ILNTD2,ILNTD3

      REAL SLWHL1(IMNP),SLWHL2(IMNP),SLWHL3(IMNP)
      INTEGER ILSHL1,ILSHL2,ILSHL3

      REAL SLWDS1(IMNP),SLWDS2(IMNP),SLWDS3(IMNP)
      INTEGER ILSDS1,ILSDS2,ILSDS3

      REAL FHLL1(IMNP),FHLL2(IMNP),FHLL3(IMNP)
      INTEGER ILFHL1,ILFHL2,ILFHL3

      REAL FDSL1(IMNP),FDSL2(IMNP),FDSL3(IMNP)
      INTEGER ILFDS1,ILFDS2,ILFDS3

      REAL SEVL1(IMNP),SEVL2(IMNP),SEVL3(IMNP)
      INTEGER ILSVL1,ILSVL2,ILSVL3

      REAL SEVS1(IMNP),SEVS2(IMNP),SEVS3(IMNP)
      INTEGER ILSVS1,ILSVS2,ILSVS3

      DIMENSION NCNTH(3),NCNTD(3),SLWHL(3),SLWDS(3)
      DIMENSION FHLL(3),FDSL(3),SEVL(3),SEVS(3)

      DIMENSION NCNTHX(3),NCNTDX(3),FHLLX(3),FDSLX(3),SEVLX(3),SEVSX(3)
```

```
      SAVE

      IF (ITASK.EQ.1) THEN

         CALL RDSINT ('IN'    ,IN)
         CALL RDSINT ('OBS1'  ,OBS1)

         CALL RDAREA('NCNTH1',NCNTH1,IMNP,ILNTH1)
         CALL RDAREA('NCNTH2',NCNTH2,IMNP,ILNTH2)
         CALL RDAREA('NCNTH3',NCNTH3,IMNP,ILNTH3)
         CALL RDAREA('NCNTD1',NCNTD1,IMNP,ILNTD1)
         CALL RDAREA('NCNTD2',NCNTD2,IMNP,ILNTD2)
         CALL RDAREA('NCNTD3',NCNTD3,IMNP,ILNTD3)
         CALL RDAREA('SLWHL1',SLWHL1,IMNP,ILSHL1)
         CALL RDAREA('SLWHL2',SLWHL2,IMNP,ILSHL2)
         CALL RDAREA('SLWHL3',SLWHL3,IMNP,ILSHL3)
         CALL RDAREA('SLWDS1',SLWDS1,IMNP,ILSDS1)
         CALL RDAREA('SLWDS2',SLWDS2,IMNP,ILSDS2)
         CALL RDAREA('SLWDS3',SLWDS3,IMNP,ILSDS3)
         CALL RDAREA('FHLL1' ,FHLL1 ,IMNP,ILFHL1)
         CALL RDAREA('FHLL2' ,FHLL2 ,IMNP,ILFHL2)
         CALL RDAREA('FHLL3' ,FHLL3 ,IMNP,ILFHL3)
         CALL RDAREA('FDSL1' ,FDSL1 ,IMNP,ILFDS1)
         CALL RDAREA('FDSL2' ,FDSL2 ,IMNP,ILFDS2)
         CALL RDAREA('FDSL3' ,FDSL3 ,IMNP,ILFDS3)
         CALL RDAREA('SEVL1' ,SEVL1 ,IMNP,ILSVL1)
         CALL RDAREA('SEVL2' ,SEVL2 ,IMNP,ILSVL2)
         CALL RDAREA('SEVL3' ,SEVL3 ,IMNP,ILSVL3)
         CALL RDAREA('SEVS1' ,SEVS1 ,IMNP,ILSVS1)
         CALL RDAREA('SEVS2' ,SEVS2 ,IMNP,ILSVS2)
         CALL RDAREA('SEVS3' ,SEVS3 ,IMNP,ILSVS3)

         IF (SWISEN.EQ.1) THEN
             CALL SENS (ITASK,IN,
     &                  NCNTHX,NCNTDX,FHLLX,FDSLX,SEVLX,SEVSX,
     &                  NCNTH, NCNTD, FHLL, FDSL, SEVL, SEVS)
         ENDIF

      ELSE IF (ITASK.EQ.2) THEN

         NCNTH(1) = LINT(NCNTH1, ILNTH1, DOY)
         NCNTH(2) = LINT(NCNTH2, ILNTH2, DOY)
         NCNTH(3) = LINT(NCNTH3, ILNTH3, DOY)
         NCNTD(1) = LINT(NCNTD1, ILNTD1, DOY)
         NCNTD(2) = LINT(NCNTD2, ILNTD2, DOY)
         NCNTD(3) = LINT(NCNTD3, ILNTD3, DOY)
         SLWHL(1) = LINT(SLWHL1, ILSHL1, DOY)
         SLWHL(2) = LINT(SLWHL2, ILSHL2, DOY)
         SLWHL(3) = LINT(SLWHL3, ILSHL3, DOY)
         SLWDS(1) = LINT(SLWDS1, ILSDS1, DOY)
         SLWDS(2) = LINT(SLWDS2, ILSDS2, DOY)
         SLWDS(3) = LINT(SLWDS3, ILSDS3, DOY)
         FHLL(1)  = LINT(FHLL1,  ILFHL1, DOY)
         FHLL(2)  = LINT(FHLL2,  ILFHL2, DOY)
         FHLL(3)  = LINT(FHLL3,  ILFHL3, DOY)
         FDSL(1)  = LINT(FDSL1,  ILFDS1, DOY)
         FDSL(2)  = LINT(FDSL2,  ILFDS2, DOY)
         FDSL(3)  = LINT(FDSL3,  ILFDS3, DOY)
         SEVL(1)  = LINT(SEVL1,  ILSVL1, DOY)
         SEVL(2)  = LINT(SEVL2,  ILSVL2, DOY)
         SEVL(3)  = LINT(SEVL3,  ILSVL3, DOY)
         SEVS(1)  = LINT(SEVS1,  ILSVS1, DOY)
         SEVS(2)  = LINT(SEVS2,  ILSVS2, DOY)
         SEVS(3)  = LINT(SEVS3,  ILSVS3, DOY)

         IF (SWISEN.EQ.1) THEN

            DO 10 I = 1,IN
               NCNTHX(I) = NCNTH(I)
               NCNTDX(I) = NCNTD(I)
               FHLLX(I)  = FHLL(I)
               FDSLX(I)  = FDSL(I)
               SEVLX(I)  = SEVL(I)
               SEVSX(I)  = SEVS(I)
10          CONTINUE

            CALL SENS (ITASK,IN,
     &                 NCNTHX,NCNTDX,FHLLX,FDSLX,SEVLX,SEVSX,
     &                 NCNTH,NCNTD,FHLL,FDSL,SEVL,SEVS)
         ENDIF

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE SENS                                                      *
*  Purpose: This subroutine facilitates simple sensitivity analysis     *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   February 1994.                                               *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- -------                                    -----  -----  *
*  ITASK   I4  Task that subroutine should perform          -      I    *
*  IN      I4  Number of leaf layers                        -      O    *
*  NCNTH   R4  Nitrogen content of healthy leaf area       g/g     O    *
*  NCNTD   R4  Nitrogen content of diseased leaf area      g/g     O    *
*  FHLL    R4  Fraction healthy leaf area                   -      O    *
*  FDSL    R4  Fraction diseased leaf area                  -      O    *
*  SEVL    R4  Disease severity of diseased leaf area       -      O    *
*  SEVL    R4  Disease severity of stem area                -      O    *
*                                                                       *
*  ....X   R4  Same variales as above, but intermediates                *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE SENS (ITASK,IN,
     &                 NCNTHX,NCNTDX,FHLLX,FDSLX,SEVLX,SEVSX,
     &                 NCNTH, NCNTD, FHLL, FDSL, SEVL, SEVS)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,IN
      REAL NCNTHX,NCNTDX,FHLLX,FDSLX,SEVLX,SEVSX
      REAL NCNTH, NCNTD, FHLL, FDSL, SEVL, SEVS

*-----Local parameters
      INTEGER I

      DIMENSION NCNTHX(3),NCNTDX(3),FHLLX(3),FDSLX(3),SEVLX(3),SEVSX(3)
      DIMENSION NCNTH(3) ,NCNTD(3) ,FHLL(3) ,FDSL(3) ,SEVL(3) ,SEVS(3)

      REAL SENS1,SENS2,SENS3,SENS4,SENS5

      SAVE

      IF (ITASK.EQ.1) THEN

         CALL RDSREA ('SENS1' ,SENS1)
         CALL RDSREA ('SENS2' ,SENS2)
         CALL RDSREA ('SENS3' ,SENS3)
         CALL RDSREA ('SENS4' ,SENS4)
         CALL RDSREA ('SENS5' ,SENS5)

      ELSE IF (ITASK.EQ.2) THEN

         DO 10 I = 1,3

            NCNTHX(I) = NCNTHX(I) + SENS1
            NCNTDX(I) = NCNTDX(I) + SENS1

            NCNTHX(I) = LIMIT(0.01,0.06,NCNTHX(I))
            NCNTDX(I) = LIMIT(0.01,0.06,NCNTDX(I))

            IF (FDSLX(I).GT.0.) THEN
                FHLLX(I) = FHLLX(I) + SENS2
                FDSLX(I) = FDSLX(I) + SENS3
            ENDIF

            FHLLX(I) = LIMIT(0.,1.,FHLLX(I))
            FDSLX(I) = LIMIT(0.,1.,FDSLX(I))

            IF (FHLLX(I)+FDSLX(I).GT.1.) FHLLX(I) = 1.-FDSLX(I)

            IF (SEVLX(I).GT.0.) THEN
                SEVLX(I) = SEVLX(I) + SENS4
            ENDIF

            SEVLX(I) = LIMIT(0.,1.,SEVLX(I))

            IF (SEVSX(I).GT.0.) THEN
                SEVSX(I) = SEVSX(I) + SENS5
            ENDIF

            SEVSX(I) = LIMIT(0.,1.,SEVSX(I))

10       CONTINUE

         DO 20 I = 1,IN
               NCNTH(I) = NCNTHX(I)
               NCNTD(I) = NCNTDX(I)
               FHLL(I)  = FHLLX(I)
```

```
                FDSL(I)  = FDSLX(I)
                SEVL(I)  = SEVLX(I)
                SEVS(I)  = SEVSX(I)
20          CONTINUE

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE DIS1                                                      *
*  Purpose: This subroutine calculates on the basis of input data and   *
*           simulated results variables with respect to disease         *
*           severity, fractions leaf area, etcetera. The subroutine     *
*           works for more than one leaf layer.                         *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   March 1993, January 1994.                                    *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- -------                                    -----  -----  *
*  ITASK   I4  Task that subroutine should perform          -      I    *
*  IN      I4  Number of leaf layers                        -      I    *
*  LAILL   R4  Leaf area index of a leaf layer              -      I    *
*              (excluding stem area index)                             *
*  SAI     R4  Stem area index                              -      I    *
*  GLAI    R4  Total green leaf area                        -      I    *
*  FHLL    R4  Fraction healthy leaf area                   -      I    *
*  FDSL    R4  Fraction diseased leaf area                  -      I    *
*  SLWHL   R4  Specific leaf weight of healthy leaf area  kg/ha    I    *
*  SLWDS   R4  Specific leaf weight of diseased leaf area kg/ha    I    *
*  SEVL    R4  Disease severity on diseased leaf area       -      I    *
*  SEVS    R4  Disease severity on stem area                -      I    *
*  LAIX    R4  Total leaf area index (excl. stem)         ha/ha    O    *
*  LAIHL   R4  Total healthy leaf area index (excl. stem) ha/ha    O    *
*  LAIDS   R4  Total diseased leaf area index (excl. stem) ha/ha   O    *
*  LAIDD   R4  Total dead leaf area index (excl. stem)    ha/ha    O    *
*  LAIG    R4  Total green leaf area index (excl. stem)   ha/ha    O    *
*  LAITL   R4  Total leaf + stem area index, per layer    ha/ha    O    *
*  SAIL    R4  Stem area index, per layer                 ha/ha    O    *
*  FHLLA   R4  Total fraction healthy leaf+stem area        -      O    *
*  FDSLA   R4  Total fraction diseased leaf+stem area       -      O    *
*  FDDLA   R4  Total fraction dead leaf+stem area           -      O    *
*  ASEVL   R4  Average disease severity of diseased leaf    -      O    *
*              area                                                     *
*  FHLLW   R4  Total weight fraction of healthy leaf area   -      O    *
*  FDSLW   R4  Total weight fraction of diseased leaf area  -      O    *
*  ASEV    R4  Average disease severity over leaves         -      O    *
*              and stems, per layer                                     *
*  TSEVL   R4  Total leaf area occupied by disease       ha/ha     O    *
*  TSEVS   R4  Total stem area occupied by disease       ha/ha     O    *
*  FHLT    R4  Fraction healthy leaf+stem area, per layer   -      O    *
*  FDST    R4  Fraction diseased leaf+stem area, per layer  -      O    *
*  FDDT    R4  Fraction dead leaf+stem area, per layer      -      O    *
*  FDDL    R4  Fraction dead leaf area, per layer           -      O    *
*  AHLL    R4  Healthy leaf area, per layer              ha/ha     O    *
*  ADSL    R4  Diseased leaf area, per layer             ha/ha     O    *
*  ADDL    R4  Dead leaf area, per layer                 ha/ha     O    *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE DIS1(ITASK,
     &                IN,FHLL,FDSL,LAILL,SAI,SEVL,SEVS,SLWHL,SLWDS,
     &                LAIX,LAIHL,LAIDS,LAIDD,LAITL,LAIG,SAIL,GLAI,
     &                FDDL,AHLL,ADSL,ADDL,TSEVL,TSEVS,ASEV,ASEVL,
     &                FHLT,FDST,FDDT,WLVHL,WLVDS)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER ITASK,IN
      REAL FHLL,FDSL,FDDL,FHLT,FDST,FDDT,AHLL,ADSL,ADDL
      REAL LAILL,SAI,GLAI,LAIX,LAIHL,LAIDS,LAIDD,LAITL,LAIG,SAIL
      REAL SEVL,SEVS,TSEVL,TSEVS,ASEV,ASEVL
      REAL SLWHL,SLWDS,WLVHL,WLVDS

*-----Local parameters
      INTEGER I

      DIMENSION AHLL(3),ADSL(3),ADDL(3)
      DIMENSION LAILL(3),LAITL(3),LAIG(3),SAIL(3),SLWHL(3),SLWDS(3)
      DIMENSION FHLL(3),FDSL(3),FDDL(3),FHLT(3),FDST(3),FDDT(3)
      DIMENSION SEVL(3),SEVS(3),ASEV(3)
```

```
      SAVE

      IF     (ITASK.EQ.1) THEN
      ELSEIF (ITASK.EQ.2) THEN

      LAIX  = 0.
      LAIHL = 0.
      LAIDS = 0.
      LAIDD = 0.
      ASEVL = 0.
      WLVHL = 0.
      WLVDS = 0.
      TSEVL = 0.
      TSEVS = 0.
      GLAI  = 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 leaf layer
**        (ha/ha)
          AHLL(I) = FHLL(I)*LAILL(I)
          ADSL(I) = FDSL(I)*LAILL(I)
          ADDL(I) = 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(I)
          LAIDS = LAIDS + ADSL(I)
          LAIDD = LAIDD + ADDL(I)

**        Stem area index per layer (ha/ha).
**        Is assumed proportional to leaf area distribution.
          IF (LAIX.GT.0.) THEN
            SAIL(I) = SAI * LAILL(I)/LAIX
          ELSE
            SAIL(I) = 0.
          ENDIF

**        Total area index per layer (ha/ha).
          LAITL(I) = LAILL(I) + 0.5 * SAIL(I)

**        Total leaf and stem area occupied by lesions (ha/ha).
          TSEVL = TSEVL + SEVL(I)*ADSL(I)
          TSEVS = TSEVS + SEVS(I)*SAIL(I)

**        Green leaf+stem area per layer (ha/ha).
          LAIG(I) = AHLL(I) + ADSL(I)*(1.-SEVL(I)) + SAIL(I)

**        Total green leaf area (ha/ha)
          GLAI = GLAI + AHLL(I) + ADSL(I) * (1.-SEVL(I))

**        Average severity over stem and leaves, per leaf layer (-).
          IF ((ADSL(I)+0.5*SAIL(I)).GT.0.) THEN
               ASEV(I) = SEVL(I)*ADSL(I)/(ADSL(I)+0.5*SAIL(I))+
     &                   SEVS(I)*0.5*SAIL(I)/(ADSL(I)+0.5*SAIL(I))
          ELSE
               ASEV(I) = 0.
          ENDIF

**        Weight of healthy and diseased leaf area (kg/ha).
          WLVHL = WLVHL + AHLL(I) * SLWHL(I)
          WLVDS = WLVDS + ADSL(I) * SLWDS(I)

**        Fractions healthy, diseased and dead total area,
**        per leaf layer (-).
          IF (LAITL(I).GT.0.) THEN
            FHLT(I) = (FHLL(I) * LAILL(I) + (1.-SEVS(I))
     &                                     * 0.5 * SAIL(I))/LAITL(I)
            FDST(I) =  FDSL(I) * LAILL(I) / LAITL(I)
            FDDT(I) = 1. - FHLT(I) - FDST(I)
          ELSE
            FHLT(I) = 0.
            FDST(I) = 0.
            FDDT(I) = 0.
          ENDIF
10    CONTINUE

** Fractions healthy, diseased and dead leaf area (-).
      IF (LAIX.GT.0.) THEN
        FHLLA = LAIHL/LAIX
        FDSLA = LAIDS/LAIX
        FDDLA = LAIDD/LAIX
      ELSE
        FHLLA = 0.
        FDSLA = 0.
        FDDLA = 0.
      ENDIF
```

```
** Average severity for leaves (-).
      IF (LAIDS.GT.0.) THEN
        ASEVL = TSEVL/LAIDS
      ELSE
        ASEVL = 0.
      ENDIF

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE DIS2                                                      *
*  Purpose: This subroutine accounts for the interaction between crop   *
*           and foliar disease, in particular with respect to the       *
*           characteristics of the photosynthesis light response        *
*           curve. The subroutine works for more than one leaf layer.   *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   March 1993, January 1994.                                    *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  ITASK   I4  Task that subroutine should perform        -      I      *
*  IN      I4  Number of leaf layers                      -      I      *
*  WLVHL   R4  Weight of total healthy leaf area         kg/ha   I      *
*  WLVDS   R4  Weight of total dead leaf area            kg/ha   I      *
*  SLWHL   R4  Specific leaf weight of healthy leaf area kg/ha   I      *
*  SLWDS   R4  Specific leaf weight of diseased leaf area kg/ha  I      *
*  NCNTH   R4  Nitrogen content of healthy leaf area      g/g     I      *
*  NCNTD   R4  Nitrogen content of diseased leaf area     g/g     I      *
*  REDFT   R4  Temperature effect on AMAX                 -       I      *
*  EFF     R4  Initial light use efficiency            kg CO2/J/  I      *
*                                                      ha/h m2 s         *
*  MAINLV  R4  Maintenance respiration coefficient of  kg CO2/    I      *
*              leaves                                  kg DM/d           *
*  WLVG    R4  Weight of green leaf area                 kg/ha    I      *
*  TEFF    R4  Temperature effect on maintenance resp.     -      I      *
*  MNDVS   R4  Effect of DVS on maintenance respiration    -      I      *
*  ASEV    R4  Average disease severity over leaves        -      O      *
*              and stems, per layer                                     *
*  SEVL    R4  Disease severity on diseased leaf area      -      I      *
*  AMAXH   R4  Assimilation rate of healthy leaf area   kg CO2/   O      *
*              at light saturation, per layer          ha leaf/h        *
*  AMAXD   R4  Assimilation rate of diseased leaf area  kg CO2/   O      *
*              at light saturation, per layer          ha leaf/h        *
*  EFFH    R4  Initial light use efficiency of healthy  kg CO2/J/ O      *
*              leaf area, per layer                    ha/h m2 s        *
*  EFFD    R4  Initial light use efficiency of diseased kg CO2/J/ O      *
*              leaf area, per layer                    ha/h m2 s        *
*  RMLV    R4  Maintenance respiration of leaves      kg CH2O/ha/d O     *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*
```

```
      SUBROUTINE DIS2(ITASK,
     &                IN,WLVHL,WLVDS,SLWHL,SLWDS,NCNTH,NCNTD,REDFT,
     &                EFF,MAINLV,WLVG,TEFF,MNDVS,SEVL,ASEVL,
     &                AMAXH,AMAXD,EFFH,EFFD,RMLV)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER ITASK,IN
      REAL WLVHL,WLVDS,SLWHL,SLWDS,WLVG
      REAL NCNTH,NCNTD
      REAL REDFT
      REAL AMAXH,AMAXD,EFF,EFFH,EFFD,MAINLV,TEFF,MNDVS,RMLV
      REAL SEVL,ASEVL

*-----Local parameters
      INTEGER I, IMNP
      PARAMETER (IMNP=40)

      REAL AMAXDC,EFFDC,RMAIN
      REAL AMAXDT(IMNP),EFFDT(IMNP),MAINDT(IMNP)
      INTEGER ILAMAX,ILEFFD,ILMAIN

      DIMENSION SLWHL(3),SLWDS(3)
      DIMENSION SEVL(3)
      DIMENSION NCNTH(3),NCNTD(3),NFLVH(3),NFLVD(3)
      DIMENSION AMAXH(3),AMAXD(3)
      DIMENSION EFFH(3),EFFD(3)
      DIMENSION AMAXDC(3),EFFDC(3)
```

```
      SAVE

      IF (ITASK.EQ.1) THEN

      CALL RDAREA('AMAXDT',AMAXDT,IMNP,ILAMAX)
      CALL RDAREA('EFFDT' ,EFFDT ,IMNP,ILEFFD)
      CALL RDAREA('MAINDT',MAINDT,IMNP,ILMAIN)

      ELSEIF (ITASK.EQ.2) THEN

** STEP 2: Effect of disease on photosynthesis characteristics of
**         diseased leaf area.

      DO 10 I = 1,IN
**          Correction factors for maximum photosynthesis and initial
**          light use efficiency of diseased leaves.
            AMAXDC(I) = LINT(AMAXDT,ILAMAX,SEVL(I))
            EFFDC(I)  = LINT(EFFDT, ILEFFD,SEVL(I))

10    CONTINUE

      DO 20 I = 1,IN

**          Field observations are, if the standard procedure is
**          followed, available in 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 leaf layers
**          (kg/ha/d), corrected for nitrogen and temperature and disease
**          severity.
            AMAXH(I) = AMAX1(1.,AMIN1(60.,(-6.5+32.4*NFLVH(I))*REDFT))
            AMAXD(I) = AMAX1(1.,AMIN1(60.,(-6.5+32.4*NFLVD(I))*REDFT)
     &                        * AMAXDC(I))

**          New function, used in latest ORYZA1:
**           Gives higher amax values at low N values
*            IF (NFLVH(I).GE.0.5) THEN
*                  AMAXH(I) = 9.5 + 22. * NFLVH(I) * REDFT
*            ELSE
*                  AMAXH(I) = AMAX1(0., 68.33 * NFLVH(I) * REDFT)
*            ENDIF
*
*            IF (NFLVD(I).GE.0.5) THEN
*                  AMAXD(I) = 9.5 + 22. * NFLVD(I) * REDFT
*            ELSE
*                  AMAXD(I) = AMAX1(0., 68.33 * NFLVD(I) * REDFT)
*            ENDIF

**          EFF of healthy and diseased leaf area in leaf layers
**          (kg/ha/d).
            EFFH(I) = EFF
            EFFD(I) = EFF*EFFDC(I)

20    CONTINUE

** Weight fraction of healthy and diseased leaf area of alive leaf area
** (-).
      IF ((WLVHL+WLVDS).GT.0.) THEN
        FHLLW = WLVHL/(WLVHL+WLVDS)
        FDSLW = WLVDS/(WLVHL+WLVDS)
      ELSE
        FHLLW = 0.
        FDSLW = 0.
      ENDIF

**    Ratio between respiration of diseased and healthy leaf area (-).
      RMAIN = LINT(MAINDT,ILMAIN,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

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE ABSORB                                                    *
*  Purpose: This subroutine calculates absorbed photosynthetic active   *
*           radiation for more than one leaf layer, and crop light use  *
*           efficiency                                                  *
*  A. Elings, March 1994                                                *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class  *
*  ----   ---- --------                                   -----  -----  *
*  ITASK   I4  Task that subroutine should perform          -      I    *
*  DELT    R4  Time step of integration                     d      I    *
*  DAS     R4  Number of days after sowing                  -      I    *
*  IN      I4  Number of leaf layers                        -      I    *
*  KDF     R4  Extinction coefficient for diffuse light                 I    *
*  LAITL   R4  Total leaf + stem area index, per layer     ha/ha   I    *
*  LAIG    R4  Total green leaf area index (excl. stem)    ha/ha   I    *
*  RDT     R4  Daily total of global radiation            J/m2/d   I    *
*  GCR     R4  Daily crop growth                           kg/ha   I    *
*  ABS     R4  Daily absorbed PAR                          J/m2    O    *
*  CUMABS  R4  Cumulative absorbed PAR                     J/m2    O    *
*  CLUE    R4  Crop light use efficiency                   kg/J    O    *
*  AVCLUE  R4  Average crop light use efficiency over      kg/J    O    *
*              last 10 days                                             *
*  PARABS  R4  Daily absorbed PAR per leaf layer           J/m2    O    *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*                                                                       *
*-----------------------------------------------------------------------*

      SUBROUTINE ABSORB (ITASK,DELT,DAS,IN,KDF,LAITL,LAIG,RDT,GCR,
     &                   ABS,CUMABS,CLUE,AVCLUE,PARABS)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER ITASK,IN
      REAL DAS
      REAL KDF,RDT
      REAL LAITL,LAIG
      REAL GCR
      REAL ABS,CUMABS,CLUE,AVCLUE,PARABS

*-----Local parameters
      INTEGER I3, N, TOP, M
      REAL PARTR
      REAL CLUEC,TOCLUE

      PARAMETER (M=10)

      DIMENSION LAITL(3),LAIG(3),PARABS(3)
      DIMENSION CLUEC(M)

      SAVE

      IF (ITASK.EQ.1) THEN

      CUMABS = 0.

      DO 10 N = M,1,-1
      CLUEC(N) = 0.
10    CONTINUE
      TOCLUE = 0.

      ELSEIF (ITASK.EQ.2) THEN

*-----PAR transmitted by higher leaf layers
      PARTR  = 0.5 * RDT

*-----Total absorbed PAR
      ABS = 0.

*-----Variable that indicates top layer
      TOP = 0

*-----Absorbed radiation per leaf layer
      DO 20 I3 =IN,1,-1

      IF (LAIG(I3).GT.0.) THEN
          IF (TOP.EQ.0) THEN
             PARABS(I3) = (1.-0.08) * PARTR * (1.-EXP(-KDF*LAIG(I3)))
             PARTR      = (1.-0.08) * PARTR *    (EXP(-KDF*LAITL(I3)))
             TOP        = TOP + 1
          ELSE
             PARABS(I3) = PARTR * (1.-EXP(-KDF*LAIG(I3)))
             PARTR      = PARTR *    (EXP(-KDF*LAITL(I3)))
          ENDIF
      ELSE
          PARABS(I3) = 0.
      ENDIF
```

```
*-----Daily absorbed radiation
      ABS = ABS + PARABS(I3)

20    CONTINUE

*-----Crop light use efficiency
*     = slope of relation cumabs, wag/xwtdm
      IF ((GCR.GT.0.).AND.(ABS.GT.0.)) THEN
          CLUE = GCR/ABS
      ELSE
          CLUE = 0.
      ENDIF

*-----Average crop light use efficiency for last 10 days

      TOCLUE    = 0.
      DO 30 N = 10,2,-1
      CLUEC(N)  = CLUEC(N-1)
      TOCLUE    = TOCLUE+CLUEC(N)
30    CONTINUE
      CLUEC(1)  = CLUE
      TOCLUE    = TOCLUE+CLUEC(1)
      IF (DAS.LT.10.) THEN
          AVCLUE = 0.
      ELSE
          AVCLUE = TOCLUE/10.
      ENDIF

      ELSEIF (ITASK.EQ.3) THEN

*-----Cumulative absorbed radiation
      CUMABS = INTGRL (CUMABS, ABS, DELT)

      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE AVERAG                                                    *
*  Purpose: This subroutine calculates average crop values for SLW and  *
*           nitrogen content on the basis of input data for three       *
*           leaf layers                                                 *
*                                                                       *
*  Author: A. Elings                                                    *
*  Date:   February 1994.                                               *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  ITASK   I4  Task that subroutine should perform        -      I      *
*  IN      I4  Number of leaf layers                      -      I      *
*  SLWHL   R4  Specific leaf weight of healthy leaf area kg/ha   I      *
*  SLWDS   R4  Specific leaf weight of diseased leaf area kg/ha   I      *
*  NCNTH   R4  Nitrogen content of healthy leaf area      g/g    I      *
*  NCNTD   R4  Nitrogen content of diseased leaf area     g/g    I      *
*  SLA     R4  Crop specific leaf area                    ha/kg  O      *
*  NCHAV   R4  Average nitrogen content of healthy leaf   kg/kg  O      *
*              area                                                     *
*  NCDAV   R4  Average nitrogen content of diseased       kg/kg  O      *
*              leaf area                                                *
*                                                                       *
*  SUBROUTINES and FUNCTIONS called : none                              *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE AVERAG(ITASK,IN,SLWHL,SLWDS,NCNTH,NCNTD,
     &                  SLA,NCHAV,NCDAV)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,IN
      REAL SLWHL,SLWDS,NCNTH,NCNTD,SLA,NCHAV,NCDAV

*-----Local parameters
      INTEGER I
      REAL SLWHAL,SLWHAV,COUNT1
      REAL SLWDAL,SLWDAV,COUNT2
      REAL NCHALL       ,COUNT3
      REAL NCDALL       ,COUNT4

      DIMENSION SLWHL(3),SLWDS(3),NCNTH(3),NCNTD(3)

      IF     (ITASK.EQ.1) THEN
      ELSEIF (ITASK.EQ.2) THEN

      SLWHAL = 0.
      SLWDAL = 0.
      NCHALL = 0.
```

```
      NCDALL = 0.
      COUNT1 = 0.
      COUNT2 = 0.
      COUNT3 = 0.
      COUNT4 = 0.

      DO 10 I = 1,IN
         IF (SLWHL(I).GT.0.) THEN
             SLWHAL = SLWHAL + SLWHL(I)
             COUNT1 = COUNT1 + 1.
          ENDIF

          IF (SLWDS(I).GT.0.) THEN
              SLWDAL = SLWDAL + SLWDS(I)
              COUNT2 = COUNT2 + 1.
          ENDIF

          IF (NCNTH(I).GT.0.) THEN
              NCHALL = NCHALL + NCNTH(I)
              COUNT3 = COUNT3 + 1.
          ENDIF

          IF (NCNTD(I).GT.0.) THEN
              NCDALL = NCDALL + NCNTD(I)
              COUNT4 = COUNT4 + 1.
          ENDIF

10        CONTINUE

      IF (COUNT1.GT.0.) THEN
          SLWHAV = SLWHAL/COUNT1
      ELSE
          SLWHAV = 0.
      ENDIF

      IF (COUNT2.GT.0.) THEN
          SLWDAV = SLWDAL/COUNT2
      ELSE
          SLWDAV = 0.
      ENDIF
      IF (COUNT3.GT.0.) THEN
          NCHAV  = NCHALL/COUNT3
      ELSE
          NCHAV  = 0.
      ENDIF

      IF (COUNT4.GT.0.) THEN
          NCDAV  = NCDALL/COUNT4
      ELSE
          NCDAV  = 0.
      ENDIF

      SLA = 1./((SLWHAV+SLWDAV)/2.)

      ELSE IF (ITASK.EQ.3) THEN
      CONTINUE
      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

Appendix Ib. BLIGHT input files

CONTROL.DAT

```
* CONTROL.DAT created by COME-ON 0.2b
FILEON='RESULTS.OUT'
FILEIR='RERUNS.DAT'
FILEIT='TIMER.DAT'
FILEI1='CROP.DAT'
FILEI3='PEST.DAT'
FILEOL='RESULTS.LOG'
```

TIMER.DAT

```
*****************************************************************
*  RUNCONTROL FILE for COME-ON                                  *
*****************************************************************

* Weather data specification

WTRDIR = 'C:\WEATHER\'
CNTR   = 'PHIL'
ISTN   = 1          ! Station number of weather data
IFLAG = 1101        ! Indicates where weather error and warnings go
                    ! (1100 means errors and warnings only to log file,
                    ! see FSE manual)

* Time variables
IYEAR  = 1992       ! Year of sowing
DELT   = 1.         ! Time step of integration

* Output options
COPINF = 'N'        ! Swich variable denoting what to be done with
                    ! inputfiles:
                    !    'N' = do not copy inputfiles into outputfile
                    !    'Y' = copy inputfiles into outputfile
PRDEL  = 5.         ! Time between consecutive outputs to file,
                    ! (when PRDEL=0, no output is generated, when PRDEL is
                    ! very large (i.e. 10000) only initial and terminal
                    ! output is generated).
IPFORM = 5          ! (0 = no output table, 4 = normal table,
                    !  5 = tab-delimited (for Excel), 6=TTPLOT format)
DELTMP  = 'N'       ! Switch variable what should be done with the
                    ! temporary output file:
                    !    ('N' = do not delete,
                    !     'Y' = delete)

*PRSEL = 'WSO','TADRW','<TABLE>','DVS','<TABLE>'
PRSEL = 'WAG','WSO','SEVL(1)'
*IOBSD = 1992,183
                    ! list of data for which output is required

*****************************************************************
*  DEFTIMER for use with COME-ON                                *
*****************************************************************

ANGA   = 0.25       ! Angstrom parameters: dry tropical A=0.25 B=0.45
ANGB   = 0.45       !                      humid tropical A=0.29 B=0.42
                    !                 cold and temperate A=0.18 B=0.55

* Time variables
STTIME = 361.       ! Sowing date ; Start day of simulation
FINTIM = 1000.      ! Finish time of simulation
DTRP   = 21.        ! Number of days between sowing and transplanting

************
* Switches *
************

SWILAI=1            ! 0: Analysis of experiments (LAI input)
                    ! 1: Exploration (LAI simulated)
SWISEN=0            ! 1: Simple sensitivity analysis
                    ! 0: No sensitivity analysis
```

CROP.DAT

```
************************************************************
* CROP.DAT file                                            *
*                                                          *
* BACTERIAL LEAF BLIGHT VALIDATION EXPERIMENTS             *
*                                                          *
* IRRI 1993 WET SEASON     IR 64                           *
*                                                          *
* ALL TREATMENTS                                           *
*                                                          *
* A. ELINGS, DLO-CENTRE FOR AGROBIOLOGICAL RESEARCH,       *
*            PO BOX 14, 6700 AA WAGENINGEN, THE NETHERLANDS *
************************************************************

*-------------------------------------------*
* General functions and parameters for rice. *
*-------------------------------------------*

SHCKL  = 0.25
SHCKD  = 0.4

EFFTB  = 10., 0.54,
         40., 0.36

KDFTB  = 0. , 0.4,
         0.2, 0.4,
         0.6, 0.6,
         2.1, 0.6,
         3.0, 0.6

SCP    = 0.2

REDFTT = -10., 0.,
          10., 0.,
          20., 1.,
          37., 1.,
          43., 0.

SSGATB = 0. , 0.0003,
         0.9, 0.0003,
         2.1, 0.,
         3.0, 0.

TBD    = 8.
TBLV   = 8.

MAINLV = 0.02
MAINST = 0.015
MAINSO = 0.003
MAINRT = 0.01

CRGLV  = 1.326
CRGST  = 1.326
CRGSO  = 1.462
CRGRT  = 1.326
CRGSTR = 1.111

FCSTR  = 0.444
FCLV   = 0.419
FCST   = 0.431
FCRT   = 0.431
FCSO   = 0.487

LRSTR  = 0.947
TCLSTR = 10.

FSHTB  = 0.0,  0.50,
         0.43, 0.75,
         1.0,  1.0,
         2.1,  1.,
         3.0,  1.

FRTTB  = 0.0,  0.50,
         0.43, 0.25,
         1.0,  0.0,
         2.1,  0.,
         3.0,  0.

LAP0   = 0.0001

WLVGI  = 0.
WSTI   = 0.
WRTI   = 0.
WLVDI  = 0.

DVSI   = 0.

FSTR   = 0.20
*FSTR = 0.3
```

```
*-------------------------------------------------------------------*
* Parameters and functions specific for variety IR64 in all treatments.
*-------------------------------------------------------------------*

NPLH   = 3.
NH     = 25.
NPLSB  = 1000.

DVRV   = 0.000735
DVRR   = 0.002294

*-----------------------------------------------*
* Data for variety IR64 in specific treatment. *
*-----------------------------------------------*
```

PEST.DAT

```
*****************************************************************
* PEST.DAT file                                                 *
*                                                               *
* BACTERIAL LEAF BLIGHT VALIDATION EXPERIMENTS                  *
*                                                               *
* IRRI 1993 WET SEASON     IR 64                                *
*                                                               *
* EARLY INOCULATION, HIGH SEVERITY, AVERAGE PLOTS B1 AND B3     *
*                                                               *
* A. ELINGS, DLO-CENTRE FOR AGROBIOLOGICAL RESEARCH,            *
*            PO BOX 14, 6700 AA WAGENINGEN, THE NETHERLANDS     *
*****************************************************************

*-------------------------------------------------------------------*
* Parameters and functions specific for variety IR64 in all treatments.
*-------------------------------------------------------------------*

* Calendar day of first observation.
OBS1   = 53

* AMAX, EFF and MAIN related to disease severity.
AMAXDT =  0.    , 1.    ,
          0.05  , 0.8638,
          0.45  , 0.2142,
          1.    , 0.

EFFDT  =  0.    , 1.,
          1.    , 0.

MAINDT =  0.    , 1.,
          0.108 , 1.,
          0.5   , 0.664,
          1.    , 0.

* Number of leaf layers.
IN = 3

*-------------------------------------------------------------------*
* Parameters and functions specific for var. IR64 in specific treatment.
*-------------------------------------------------------------------*

RGRL   = 0.0059

DRLVT  =  0.    , 0.,
          0.7   , 0.,
          1.    , 0.0075,
          1.5   , 0.015,
          2.    , 0.02,
          3.    , 0.31

FSTTB  =  0.0   , 0.40,
          0.6605, 0.61,
          0.755 , 0.80,
          0.846 , 0.54,
          0.9285, 0.45,
          1.0665, 0.15,
          1.3645, 0.17,
          1.6685, 0.17,
          2.004 , 0.,
          3.    , 0.

FLVTB  =  0.0   , 0.60,
          0.6605, 0.39,
          0.755 , 0.20,
          0.846 , 0.32,
          0.9285, 0.,
          1.0665, 0.,
          1.3645, 0.,
          1.6685, 0.05,
          2.004 , 0.,
          3.    , 0.
```

```
FSOTB   =  0.0    , 0.,
           0.6605, 0.,
           0.755  , 0.,
           0.846  , 0.14,
           0.9285, 0.55,
           1.0665, 0.85,
           1.3645, 0.83,
           1.6685, 0.77,
           2.004  , 1.,
           3.     , 1.

** Observed weights.

XWLVGT  =   1.,     0.,
           52.,     0.,
           53.,   533.6,
           60.,   923.3,
           68.,  1036.3,
           74.,  1380.8,
           81.,  1163.3,
           88.,   845.6,
           95.,  1193.3,
          102.,  1055.8,
          110.,   781.7,
          116.,   428.4,
          117.,  0.,
          366.,  0.

XWSTTB  =   1.,     0.,
           52.,     0.,
           53.,   619.8,
           60.,  1220.4,
           68.,  1938.4,
           74.,  2414.7,
           81.,  2883.4,
           88.,  2910.5,
           95.,  3195.8,
          102.,  3584.5,
          110.,  3516.9,
          116.,  3034.2,
          119.,  3433.8,
          120.,  0.,
          366.,  0.

XWPATB  =    0.,     0.,
            52.,     0.,
            53.,     0.0,
            60.,     0.0,
            68.,     0.0,
            74.,   126.4,
            81.,   698.9,
            88.,   850.7,
            95.,  2253.5,
           102.,  3980.7,
           110.,  6192.9,
           116.,  4929.1,
           119.,  5787.8,
           120.,  0.,
           366.,  0.

XWLVDT  =    0.,   0.,
            52.,   0.,
            53.,   0.,
            60.,   0.,
            68.,  64.5,
            74.,  55.6,
            81.,  137.7,
            88.,  198.1,
            95.,  190.8,
           102.,  445.8,
           110.,  592.8,
           116.,  512.6,
           117.,  0.,
           366.,  0.

XWTDMT  =    0.,     0.,
            52.,     0.,
            53.,  1153.4,
            60.,  2139.2,
            68.,  3039.5,
            74.,  3977.7,
            81.,  4883.4,
            88.,  4805.0,
            95.,  6833.5,
           102.,  9066.7,
           110., 11084.3,
           116.,  8904.4,
           119., 10842.9,
           120.,     0.,
           366.,     0.
```

```
** Observations for three canopy layers.

* Total leaf area (ha/ha).
LAILL1 =    1., 0.0001,
           53., 1.44,
           60., 2.38,
           68., 3.06,
           74., 2.23,
           81., 1.56,
           95., 1.30,
          102., 1.41,
          110., 1.18,
          116., 0.88,
          119., 0.88,
          361., 0.0001,
          366., 0.0001

LAILL2 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.10,
           74., 0.73,
           81., 0.87,
           95., 1.14,
          102., 0.74,
          110., 0.78,
          116., 0.47,
          119., 0.47,
          361., 0.,
          366., 0.

LAILL3 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.07,
           81., 0.48,
           95., 0.64,
          102., 0.67,
          110., 0.75,
          116., 0.49,
          119., 0.49,
          361., 0.,
          366., 0.

* Nitrogen content of healthy leaf area (kg/kg).
NCNTH1 =    1., 0.0519,
           53., 0.0519,
           60., 0.0381,
           68., 0.0249,
           74., 0.0334,
           81., 0.0284,
           88., 0.0323,
           95., 0.0281,
          102., 0.0246,
          110., 0.0237,
          116., 0.0219,
          119., 0.0219,
          361., 0.0519,
          366., 0.0519

NCNTH2 =    1., 0.,
           53., 0.,
           60., 0.0321,
           68., 0.0321,
           74., 0.0366,
           81., 0.0333,
           88., 0.0363,
           95., 0.0342,
          102., 0.0310,
          110., 0.0286,
          116., 0.0221,
          119., 0.0221,
          361., 0.,
          366., 0.

NCNTH3 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.0362,
           74., 0.0362,
           81., 0.0371,
           88., 0.0373,
           95., 0.0363,
          102., 0.0307,
          110., 0.0309,
          116., 0.0244,
          119., 0.0244,
          361., 0.,
          366., 0.
```

```
* Nitrogen content of diseased leaf area (kg/kg).
NCNTD1 =    1., 0.,
           53., 0.,
           60., 0.0241,
           68., 0.0241,
           74., 0.0270,
           81., 0.0253,
           88., 0.0304,
           95., 0.0264,
          102., 0.0206,
          110., 0.0198,
          116., 0.0198,
          119., 0.0198,
          361., 0.,
          366., 0.

NCNTD2 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.0330,
           81., 0.0330,
           88., 0.0344,
           95., 0.0318,
          102., 0.0256,
          110., 0.0256,
          116., 0.0192,
          119., 0.0192,
          361., 0.,
          366., 0.

NCNTD3 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 0.0423,
           88., 0.0423,
           95., 0.0350,
          102., 0.0260,
          110., 0.0267,
          116., 0.0195,
          119., 0.0195,
          361., 0.,
          366., 0.
```

```
* Specific leaf weight of healthy leaf area (kg/ha).
SLWHL1 =    1., 300.00,
           53., 373.30,
           60., 386.50,
           68., 331.60,
           74., 476.80,
           81., 432.40,
           88., 567.20,
           95., 465.45,
          102., 495.05,
          110., 477.10,
          116., 490.40,
          119., 490.40,
          361., 300.00,
          366., 300.00

SLWHL2 =    1., 0.,
           53., 0.,
           60., 607.95,
           68., 607.95,
           74., 517.85,
           81., 417.20,
           88., 465.95,
           95., 440.05,
          102., 453.80,
          110., 438.25,
          116., 458.00,
          119., 458.00,
          361., 0.,
          366., 0.

SLWHL3 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 395.50,
           74., 395.50,
           81., 394.30,
           88., 472.95,
           95., 440.40,
          102., 483.75,
          110., 426.15,
          116., 396.05,
          119., 396.05,
          361., 0.,
          366., 0.
```

```
* Specific leaf weight of diseased leaf area (kg/ha).
SLWDS1 =    1., 0.,
           53., 0.,
           60., 377.85,
           68., 377.85,
           74., 444.60,
           81., 609.15,
           88., 551.50,
           95., 390.65,
          102., 537.15,
          110., 615.65,
          116., 455.15,
          119., 455.15,
          361., 0.,
          366., 0.

SLWDS2 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 540.90,
           81., 540.90,
           88., 706.70,
           95., 412.80,
          102., 568.70,
          110., 525.60,
          116., 605.95,
          119., 605.95,
          361., 0.,
          366., 0.

SLWDS3 =    1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 879.70,
           88., 879.70,
           95., 539.10,
          102., 431.95,
          110., 501.35,
          116., 591.65,
          119., 591.65,
          361., 0.,
          366., 0.
```

```
* Fraction healthy leaf area (-).
FHLL1 =     1., 1.,
           53., 1.,
           60., 1.,
           68., 0.89,
           74., 0.81,
           81., 0.71,
           88., 0.63,
           95., 0.59,
          102., 0.42,
          110., 0.35,
          116., 0.22,
          119., 0.22,
          361., 1.,
          366., 1.

FHLL2 =     1., 1.,
           53., 1.,
           60., 1.,
           68., 1.,
           74., 1.,
           81., 0.79,
           88., 0.52,
           95., 0.56,
          102., 0.62,
          110., 0.56,
          116., 0.68,
          119., 0.68,
          361., 1.,
          366., 1.

FHLL3 =     1., 1.,
           53., 1.,
           60., 1.,
           68., 1.,
           74., 1.,
           81., 1.,
           88., 0.71,
           95., 0.80,
          102., 0.57,
          110., 0.53,
          116., 0.55,
          119., 0.55,
          361., 1.,
          366., 1.
```

```
* Fraction diseased leaf area (-).
FDSL1 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.08,
           74., 0.16,
           81., 0.14,
           88., 0.20,
           95., 0.28,
          102., 0.40,
          110., 0.33,
          116., 0.18,
          119., 0.18,
          361., 0.,
          366., 0.

FDSL2 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 0.21,
           88., 0.48,
           95., 0.44,
          102., 0.38,
          110., 0.44,
          116., 0.32,
          119., 0.32,
          361., 0.,
          366., 0.

FDSL3 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 0.,
           88., 0.29,
           95., 0.20,
          102., 0.43,
          110., 0.47,
          116., 0.45,
          119., 0.45,
          361., 0.,
          366., 0.
```

```
* Disease severity of diseased leaf area (-).
SEVL1 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.10,
           74., 0.20,
           81., 0.22,
           88., 0.38,
           95., 0.34,
          102., 0.56,
          110., 0.80,
          116., 1.00,
          119., 1.00,
          361., 0.,
          366., 0.

SEVL2 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 0.05,
           88., 0.14,
           95., 0.13,
          102., 0.23,
          110., 0.28,
          116., 0.65,
          119., 0.65,
          361., 0.,
          366., 0.

SEVL3 =     1., 0.,
           53., 0.,
           60., 0.,
           68., 0.,
           74., 0.,
           81., 0.,
           88., 0.10,
           95., 0.20,
          102., 0.32,
          110., 0.45,
          116., 0.70,
          119., 0.70,
          361., 0.,
          366., 0.
```

```
* Disease severity of stem area (-).
SEVS1 = 0.,0., 366.,0.
SEVS2 = 0.,0., 366.,0.
SEVS3 = 0.,0., 366.,0.

*--------------------------------------*
* Parameters for sensitivity analyses. *
*--------------------------------------*

* Leaf nitrogen content.
SENS1 = 0.
* Fraction healthy leaf area.
SENS2 = 0.
* Fraction diseased leaf area.
SENS3 = 0.
* Disease severity of leaves.
SENS4 = 0.
* Disease severity of stems.
SENS5 = 0.
```

Appendix IIa. Listing of the SBORER model

SBORER.FOR

```
*-----------------------------------------------------------------------*
*                          SBORER - FSE                                 *
*                                                                       *
* A combination model for the growth of rice under the presence of      *
* Stem Borer: Scirpophaga incertulas Wlk.                               *
*             Scirpophaga innotata Wlk.                                 *
*             Chilo suppresalis Wlk.                                    *
*             Chilo polychrysus Mey.                                    *
*             Sesamia inferens Wlk.                                     *
*                                                                       *
* SBORER is based upon:                                                 *
* - ORYZA1: M.J. Kropff, H.H. van Laar & H.F.M. ten Berge (Eds.),       *
*           1993, ORYZA1, a basic model for irrigated lowland rice      *
*           production, IRRI, AB-DLO, TPE-WAU.                          *
* - L1DSTB: L. Bastiaans, May 1992.                                     *
*                                                                       *
* Authors: A. Elings,                                                   *
*            Research Institute for Agrobiology and Soil Fertility      *
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*            6700 AA Wageningen,                                        *
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*                                                                       *
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*            P.O. Box 933,                                              *
*            1099 Manila,                                               *
*            Philippines.                                               *
*                                                                       *
*            Philippine Rice Research Institute (PhilRice),             *
*            Munoz,                                                     *
*            Nueva Ecija,                                               *
*            Philippines.                                               *
*                                                                       *
* Version 1, October 1993: draft version                                *
* Version 2, March 1994:   first improvements                           *
*            October 1994: release version 2.0                          *
*                                                                       *
* Documentation:                                                        *
* A. Elings & E.G. Rubia, 1994. Models for the crop-pathosystems rice   *
* - bacterial leaf blight, sheat blight and stem. Manual for SARP       *
* Workshop, IRRI, April/May 1994.                                       *
*                                                                       *
* A. Elings & E.G. Rubia, 1994. Analysis of Damage Mechanisms by        *
* Pests and Diseases and their Effects on Rice Yield. SARP Research     *
* Proceedings.                                                          *
*                                                                       *
* The model is programmed in FORTRAN and runs in the FORTRAN            *
* Simulation Environment (FSE).                                         *
* See D.W.G. van Kraalingen, Simulation Reports CABO-TT no 23, 77       *
* pages, AB-DLO, P.O. Box 14, 6700 AA Wageningen, The Netherlands, and  *
* TPE-WAU, P.O. Box 430, 6700 AK Wageningen, The Netherlands.           *
*                                                                       *
* It is recommended to run the program under the SARP/COME-ON shell:    *
* J.J.M. van Riethoven, 1993. The SARP Shell, a crop growth simulation  *
* environment, AB-DLO, TPE-WAU, IRRI.                                   *
*                                                                       *
* External files needed:                                                *
* - TIMER.DAT                                                           *
* - RICE.DAT                                                            *
* - PEST.DAT                                                            *
* - weather file(s)                                                     *
* - RERUNS.DAT (if reruns are made)                                     *
*-----------------------------------------------------------------------*

*-----------------------------------------------------------------------*
*                                                                       *
*                                                                       *
*              FORTRAN Simulation Environment (FSE 2.0a)                *
*                          September, 1993                              *
*                                                                       *
*                                                                       *
*     FSE 2.0 is a simulation environment suited for simulation of      *
*     biological processes in time, such as crop and vegetation growth, *
*     insect population development etc.                                *
*                                                                       *
*     The MAIN program, subroutine FSE and subroutine MODELS are        *
*     programmed by D.W.G. van Kraalingen, DLO Centre for               *
*     Agrobiological Research, PO Box 14, 6700 AA, Wageningen, The      *
*     Netherlands (e-mail: d.w.g.van.kraalingen@cabo.agro.nl).          *
```

```
*                                                                      *
*     A manual of FSE 2.0 is in preparation.                           *
*                                                                      *
*     Version 1.0 of FSE is described in:                              *
*     Kraalingen, D.W.G. van 1991. The FSE system for crop simulation, *
*     Simulation Report CABO-TT No.23, Centre for Agrobiological       *
*     Research, Dept. of Theoretical Production Ecology, 77 pp.        *
*                                                                      *
*     Data files needed for FSE 2.0:                                   *
*          (excluding data files used by models called from MODELS):   *
*        - CONTROL.DAT (contains file names to be used),               *
*        - timer file whose name is specified in CONTROL.DAT,          *
*        - optionally, a rerun file whose name is specified in         *
*          CONTROL.DAT,                                                *
*        - weather data files as specified in timer file               *
*     Object libraries needed for FSE 2.0:                             *
*        - TTUTIL (at least version 3.2)                               *
*        - WEATHER (at least version from 17-Jan-1990)                 *
*----------------------------------------------------------------------*

      PROGRAM MAIN
      CALL FSE
      END

      SUBROUTINE FSE

      IMPLICIT REAL (A-Z)

*-----Standard declarations for simulation and output control

      INTEGER   ITASK   , INSETS, ISET  , IPFORM, IL, ILEN
      LOGICAL   OUTPUT  , TERMNL, RDINQR
      CHARACTER COPINF*1, DELTMP*1
      INTEGER   INPRS

      INTEGER   IMNPRS
      PARAMETER (IMNPRS=100)
      CHARACTER PRSEL(IMNPRS)*11

*-----Declarations for time control
      INTEGER   IDOY, IYEAR
      REAL      DELT, DOY, FINTIM, PRDEL, STTIME, TIME, YEAR

*-----Declarations for weather system
      INTEGER   IFLAG    , ISTAT1, ISTAT2 , ISTN
      REAL      ANGA     , ANGB  , ELEV   , LAT , LONG, RDD
      REAL      TMMN     , TMMX  , VP     , WN  , RAIN
      LOGICAL   WTRMES   , WTRTER
      CHARACTER WTRDIR*80, CNTR*7, WSTAT*6, DUMMY*1

*-----Declarations for file names and units
      INTEGER   IUNITR   , IUNITD   , IUNITO   , IUNITL   , IUNITC
      CHARACTER FILEON*80, FILEOL*80
      CHARACTER FILEIC*80, FILEIR*80, FILEIT*80
      CHARACTER FILEI1*80, FILEI2*80, FILEI3*80, FILEI4*80, FILEI5*80

*-----Declarations for observation data facility
      INTEGER   INOD , IOD

      INTEGER   IMNOD
      PARAMETER (IMNOD=100)
      INTEGER   IOBSD(IMNOD)

*-----Unit numbers for control file (C), data files (D),
*     output file (O), log file (L) and rerun file (R). File name for
*     control file and empty strings for input files 1-5.
*     WTRMES flags any messages from the weather system

      DATA IUNITC /10/, IUNITD /20/, IUNITO /30/
      DATA IUNITL /40/, IUNITR /50/
      DATA FILEIC /'CONTROL.DAT'/
      DATA FILEI1 /' '/, FILEI2 /' '/, FILEI3 /' '/
      DATA FILEI4 /' '/, FILEI5 /' '/
      DATA WTRMES /.FALSE./

*-----Open control file and read names of normal output file, log file
*     and rerun file (these files cannot be used in reruns)
      CALL RDINIT (IUNITC,0, FILEIC)
      CALL RDSCHA ('FILEON', FILEON)
      CALL RDSCHA ('FILEOL', FILEOL)
      CALL RDSCHA ('FILEIR', FILEIR)
      CLOSE (IUNITC)

*-----Open output file and possibly a log file
      CALL FOPENS  (IUNITO, FILEON, 'NEW', 'DEL')
      IF (FILEOL.NE.FILEON) THEN
         CALL FOPENS  (IUNITL, FILEOL, 'NEW', 'DEL')
      ELSE
         IUNITL = IUNITO
      END IF
```

```
*-----See if rerun file is present, and if so read the number of rerun
*     sets from rerun file

      CALL RDSETS (IUNITR, IUNITL, FILEIR, INSETS)

*=====================================================================*
*=====================================================================*
*                                                                     *
*                  Main loop and reruns begin here                    *
*                                                                     *
*=====================================================================*
*=====================================================================*



      DO 10 ISET=0,INSETS

      WRITE (*,'(A)') '   FSE 2.0a: Initialize model'

*-----Select data set
      CALL RDFROM (ISET, .TRUE.)


*=====================================================================*
*                                                                     *
*                        Initialization section                       *
*                                                                     *
*=====================================================================*

      ITASK  = 1
      TERMNL = .FALSE.
      WTRTER = .FALSE.

*-----Read names of timer file and input files 1-5 from control
*     file (these files can be used in reruns)
      CALL RDINIT (IUNITC,IUNITL,FILEIC)
      CALL RDSCHA ('FILEIT', FILEIT)
      IF (RDINQR ('FILEI1')) CALL RDSCHA ('FILEI1', FILEI1)
      IF (RDINQR ('FILEI2')) CALL RDSCHA ('FILEI2', FILEI2)
      IF (RDINQR ('FILEI3')) CALL RDSCHA ('FILEI3', FILEI3)
      IF (RDINQR ('FILEI4')) CALL RDSCHA ('FILEI4', FILEI4)
      IF (RDINQR ('FILEI5')) CALL RDSCHA ('FILEI5', FILEI5)
      CLOSE (IUNITC)

*-----Read time, control and weather variables from timer file
      CALL RDINIT (IUNITD  , IUNITL, FILEIT)
      CALL RDSREA ('STTIME', STTIME)
      CALL RDSREA ('FINTIM', FINTIM)
      CALL RDSREA ('PRDEL' , PRDEL )
      CALL RDSREA ('DELT'  , DELT  )
      CALL RDSINT ('IYEAR' , IYEAR )
      CALL RDSINT ('ISTN'  , ISTN  )
      CALL RDSINT ('IPFORM', IPFORM)
      CALL RDSCHA ('COPINF', COPINF)
      CALL RDSCHA ('DELTMP', DELTMP )
      CALL RDSCHA ('WTRDIR', WTRDIR)
      CALL RDSCHA ('CNTR'  , CNTR)
      CALL RDSINT ('IFLAG' , IFLAG)

*-----See if observation data variable exists, if so read it
      IF (RDINQR('IOBSD')) THEN
         CALL RDAINT ('IOBSD' , IOBSD, IMNOD, INOD)
         IF (IOBSD(1).EQ.0) INOD = 0
      ELSE
         INOD = 0
      END IF

*-----See if variable with print selection exists, if so read it
      IF (RDINQR('PRSEL')) THEN
         CALL RDACHA ('PRSEL',PRSEL,IMNPRS,INPRS)
      ELSE
         INPRS = 0
      END IF
      CLOSE (IUNITD)

*-----Initialize TIMER and OUTDAT routines
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      CALL OUTDAT (ITASK, IUNITO, 'TIME', TIME)

*-----Open weather file and read station information and return
*     weather data for start day of simulation.
*     Check status of weather system, WTRMES flags if warnings or errors
*     have occurred during the whole simulation. WTRTER flags if the run
*     should be terminated because of missing weather

      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY  , ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      WSTAT  = '444444'
```

```
      IF (ABS (ISTAT2).GE.111111) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE IF (ISTAT2.EQ.0) THEN
         WSTAT = '111111'
      END IF

*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)


*=====================================================================*
*                                                                     *
*                     Dynamic simulation section                      *
*                                                                     *
*=====================================================================*

      WRITE (*,'(A)') '   FSE 2.0a: DYNAMIC loop'

20    IF (.NOT.TERMNL) THEN

*---------------------------------------------------------------------*
*                     Integration of rates section                    *
*---------------------------------------------------------------------*

      IF (ITASK.EQ.2) THEN

*--------Carry out integration only when previous task was rate
*        calculation

         ITASK = 3

*--------Call routine that handles the different models
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*--------Turn on output when TERMNL logical is set to .TRUE.
         IF (TERMNL) OUTPUT = .TRUE.

      END IF

*---------------------------------------------------------------------*
*                Calculation of driving variables section             *
*---------------------------------------------------------------------*

      ITASK = 2

*-----Write time of output to screen and file
      IF (OUTPUT) THEN
         IF (ISET.EQ.0) THEN
            WRITE (*,'(13X,A,I5,A,F7.2)')
     &        'Default set, Year:', IYEAR, ', Day:', DOY
         ELSE
            WRITE (*,'(13X,A,I3,A,I5,A,F7.2)')
     &        'Rerun set:', ISET, ', Year:', IYEAR, ', Day:', DOY
         END IF
         IF (OUTPUT) CALL OUTDAT (2, 0, 'TIME', TIME)
         IF (OUTPUT) CALL OUTDAT (2, 0, 'DOY' , DOY)
      END IF

*-----Get weather data for new day and flag messages
      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY, ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      WSTAT  = '444444'
      IF (ABS (ISTAT2).GE.111111) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE IF (ISTAT2.EQ.0) THEN
         WSTAT = '111111'
      END IF

*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.
```

```
*-----------------------------------------------------------------------*
*              Calculation of rates and output section                  *
*-----------------------------------------------------------------------*

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

      IF (TERMNL.AND..NOT.OUTPUT.AND.PRDEL.GT.0.) THEN
*--------Call model routine again if TERMNL is switched on while
*        OUTPUT was off (this call is necessary to get output to file
*        when a finish condition was reached and output generation
*        was off)
         OUTPUT = .TRUE.
         CALL OUTDAT (2, 0, 'TIME', TIME)
         CALL OUTDAT (2, 0, 'DOY' , DOY)
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)
      END IF

*-----------------------------------------------------------------------*
*                            Time update                                *
*-----------------------------------------------------------------------*

*-----Check for FINTIM, OUTPUT and observation days
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      DO 30 IOD=1,INOD,2
         IF (IYEAR.EQ.IOBSD(IOD).AND.IDOY.EQ.IOBSD(IOD+1))
     &       OUTPUT = .TRUE.
30    CONTINUE

      GOTO 20
      END IF
```

```
*=======================================================================*
*                                                                       *
*                          Terminal section                             *
*                                                                       *
*=======================================================================*

      ITASK = 4

      WRITE (*,'(A)') '   PSE 2.0a: Terminate model'

      CALL OUTDAT (2, 0, 'TIME', TIME)

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*-----Generate output file dependent on option from timer file
      IF (IPFORM.GE.4) THEN
         IF (INPRS.EQ.0) THEN
            CALL OUTDAT (IPFORM, 0, 'Simulation results',0.)
         ELSE
*           Selection of output variables was in timer file
*           write tables according to output selection array PRSEL
            CALL OUTSEL (PRSEL,IMNPRS,INPRS,IPFORM,'Simulation results')
         END IF
      END IF

      IF (WTRTER) THEN
         WRITE (*,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
         WRITE (IUNITO,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
         IF (IUNITO.NE.IUNITL) WRITE (IUNITL,'(/,A,/,/,/)')
     &      ' The run was terminated due to missing weather'
      END IF

*-----Delete temporary output file dependent on switch from timer file
      IF (DELTMP.EQ.'Y'.OR.DELTMP.EQ.'y') CALL OUTDAT (99, 0, ' ', 0.)
```

```
10    CONTINUE

      IF (INSETS.GT.0) CLOSE (IUNITR)

*-----If input files should be copied to the output file,
*     copy rerun file (if present) and timer file and if there, input
*     files 1-5

      IF (COPINF.EQ.'Y'.OR.COPINF.EQ.'y') THEN
         IF (INSETS.GT.0) CALL COPFL2 (IUNITR, FILEIR, IUNITO, .TRUE.)
         CALL COPFL2 (IUNITD, FILEIT, IUNITO, .TRUE.)
         IF (FILEI1.NE.' ') CALL COPFL2 (IUNITD, FILEI1, IUNITO, .TRUE.)
         IF (FILEI2.NE.' ') CALL COPFL2 (IUNITD, FILEI2, IUNITO, .TRUE.)
         IF (FILEI3.NE.' ') CALL COPFL2 (IUNITD, FILEI3, IUNITO, .TRUE.)
         IF (FILEI4.NE.' ') CALL COPFL2 (IUNITD, FILEI4, IUNITO, .TRUE.)
         IF (FILEI5.NE.' ') CALL COPFL2 (IUNITD, FILEI5, IUNITO, .TRUE.)
      END IF

*-----Delete all .TMP files that were created by the RD* routines
*     during simulation
      CALL RDDTMP (IUNITD)

*-----Write to screen which files contain what
      IL = ILEN (FILEON)
      WRITE (*,'(/,3A)') ' File: ',FILEON(1:IL),
     &  ' contains simulation results'
      WRITE (*,'(2A)') ' File: WEATHER.LOG',
     &  ' contains messages from the weather system'
      IL = ILEN (FILEOL)
      WRITE (*,'(3A,/)') ' File: ',FILEOL(1:IL),
     &  ' contains messages from the rest of the model'

*-----Write message to screen and output file if warnings and/or errors
*     have occurred from the weather system, pause and wait for return
*     from user to make sure he has seen this message

      IF (WTRMES) THEN

         WRITE (*,'(/,A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
         WRITE (IUNITO,'(A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
         WRITE (*,'(A)') ' Press <Enter>'
         READ  (*,'(A)') DUMMY

      END IF

*-----Close output file and temporary file of OUTDAT
      CLOSE (IUNITO)
      CLOSE (IUNITO+1)

*-----Close log file (if used)
      IF (FILEOL.NE.FILEON) CLOSE (IUNITL)

*-----Close log file of weather system
      CLOSE (91)

      RETURN
      END

*-----------------------------------------------------------------------*
* SUBROUTINE MODELS                                                     *
* Authors: Daniel van Kraalingen                                        *
* Date   : 5-Jul-1993                                                   *
* Purpose: This subroutine is the interface routine between the FSE-    *
*          driver and the simulation models. This routine is called     *
*          by the FSE-driver at each new task at each time step. It     *
*          can be used by the user to specify calls to the different    *
*          models that have to be simulated                             *
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name   type meaning                                        units class *
* ----   ---- -------                                        ----- ----- *
* ITASK   I4  Task that subroutine should perform             -     I   *
* IUNITD  I4  Unit that can be used for input files           -     I   *
* IUNITO  I4  Unit used for output file                       -     I   *
* IUNITL  I4  Unit used for log  file                         -     I   *
* FILEI1  C*  Name of input file no. 1                        -     I   *
* FILEI2  C*  Name of input file no. 2                        -     I   *
* FILEI3  C*  Name of input file no. 3                        -     I   *
* FILEI4  C*  Name of input file no. 4                        -     I   *
* FILEI5  C*  Name of input file no. 5                        -     I   *
* OUTPUT  L4  Flag to indicate if output should be done       -     I   *
* TERMNL  L4  Flag to indicate if simulation is to stop       -     I/O *
* DOY     R4  Day number within year of simulation (REAL)     d     I   *
* IDOY    I4  Day number within year of simulation (INTEGER)  d     I   *
* YEAR    R4  Year of simulation (REAL)                       y     I   *
* IYEAR   I4  Year of simulation (INTEGER)                    y     I   *
```

```
* TIME    R4  Time of simulation                              d        I  *
* STTIME  R4  Start time of simulation                       d        I  *
* FINTIM  R4  Finish time of simulation                      d        I  *
* DELT    R4  Time step of integration                       d        I  *
* LAT     R4  Latitude of site                           dec.degr.    I  *
* WSTAT   C7  Status code from weather system                -        I  *
* WTRTER  L4  Flag whether weather can be used by model      -        O  *
* RDD     R4  Daily shortwave radiation                    J/m2/d     I  *
* TMMN    R4  Daily minimum temperature                  degrees C    I  *
* TMMX    R4  Daily maximum temperature                  degrees C    I  *
* VP      R4  Early morning vapour pressure                 kPa       I  *
* WN      R4  Average wind speed                            m/s       I  *
* RAIN    R4  Daily amount of rainfall                      mm/d      I  *
*                                                                        *
* Fatal error checks: none                                              *
* Warnings          : none                                              *
* Subprograms called: models as specified by the user                   *
* File usage        : none                                              *
*-----------------------------------------------------------------------*

      SUBROUTINE MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                   FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                   FILEIT, OUTPUT, TERMNL,
     &                   DOY   , IDOY  , YEAR  , IYEAR,
     &                   TIME  , STTIME, FINTIM, DELT ,
     &                   LAT   , WSTAT , WTRTER,
     &                   RDD   , TMMN  , TMMX  , VP   , WN, RAIN)
      IMPLICIT REAL (A-Z)

*     Formal parameters
      INTEGER   ITASK, IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      CHARACTER FILEI1*(*), FILEI2*(*), FILEI3*(*)
      CHARACTER FILEI4*(*), FILEI5*(*), FILEIT*(*)
      LOGICAL   OUTPUT, TERMNL, WTRTER
      CHARACTER WSTAT*(*)

*     Local variables
*     <none>
      SAVE

      CALL SBORER (ITASK, IUNITD, IUNITO, IUNITL ,
     &             FILEI1,FILEI3,FILEIT,
     &             OUTPUT,TERMNL, WSTAT, WTRTER,
     &             TIME,  STTIME, DOY,   IDOY, DELT, LAT,
     &             RDD,    TMMN,    TMMX,
     &             IYEAR)

      RETURN
      END

*=======================================================================*
* SUBROUTINE SBORER                                                     *
* Date    : March 1994                                                  *
* Version: 2                                                            *
* Author : A. Elings, AB-DLO & E.G. Rubia, IRRI                         *
* Purpose: This subroutine simulates growth of a rice species under     *
*          the presence of stem borer                                   *
*                                                                       *
* Fatal error checks: carbon balance, switches                          *
* Warnings          : partitioning tables                               *
* Subprograms called: INSECT, SBTILL, GRLAI, TOTASS, ASTRO, ASSIM       *
*                     TILPHO, ABSORB,SUBCD,SUBCBC                       *
* File usage        : none                                              *
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name   type meaning                                        units class *
* ----   ---- -------                                        ----- ----- *
* ITASK   I4  Task that subroutine should perform             -      I  *
* IUNITD  I4  Unit that can be used for input files           -      I  *
* IUNITO  I4  Unit used for output file                       -      I  *
* IUNITL  I4  Unit used for log  file                         -      I  *
* FILEI1  C*  Name of CROP FILE                               -      I  *
* FILEI3  C*  Name of PEST FILE                               -      I  *
* FILEIT  C*  Timer file                                      -      I  *
* OUTPUT  L4  Flag to indicate if output should be done       -      I  *
* TERMNL  L4  Flag to indicate if simulation is to stop       -     I/O *
* WSTAT   C7  Status code from weather system                 -      I  *
* WTRTER  L4  Flag whether weather can be used by model       -      O  *
* TIME    R4  Time of simulation                              d      I  *
* STTIME  R4  Start time of simulation                        d      I  *
* DOY     R4  Day number within year of simulation (REAL)     d      I  *
* IDOY    I4  Day number within year of simulation (INTEGER)  d      I  *
* DELT    R4  Time step of integration                        d      I  *
* LAT     R4  Latitude of site                            dec.degr.  I  *
* RDD     R4  Daily shortwave radiation (RDT)              J/m2/d    I  *
* TMN     R4  Daily minimum temperature                   degrees C  I  *
* TMX     R4  Daily maximum temperature                   degrees C  I  *
* IYEAR   I4  Year of simulation (INTEGER)                   y      I  *
*=======================================================================*
```

```
      SUBROUTINE SBORER (ITASK, IUNITD, IUNITO, IUNITL ,
     &                   FILEI1,FILEI3, FILEIT,
     &                   OUTPUT,TERMNL, WSTAT, WTRTER,
     &                   TIME,  STTIME, DOY,   IDOY, DELT, LAT,
     &                   RDT,    TMN,    TMX,
     &                   IYEAR)

      IMPLICIT REAL (A-Z)

*     Formal parameters

      INTEGER  ITASK , IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      LOGICAL  OUTPUT, TERMNL, WTRTER
      CHARACTER FILEI1*(*), FILEI3*(*), FILEIT*(*), WSTAT*7
      REAL RDT, TMN, TMX, TIME, DOY, DELT, LAT

*     Standard (FSE) local declarations

      INTEGER ITOLD, IMNP
      PARAMETER (IMNP=40)

*     standard model variables

      INTEGER IDOYS

*     local variables for SBORER

*     array declaration for SBIRTB, and possibly others
      INTEGER IMNP1
      PARAMETER (IMNP1=80)

      INTEGER SWICLI,SWILAI,SWINLV,SWITIL,LAISIM,OBS1,RDINF

      INTEGER ISBIRT
      REAL SBINFR,SBIRTB(IMNP1)

      INTEGER ILNCN
      REAL NCNLV,NCNLVT(IMNP)

*-----States
      REAL XWLVG, XWLVD,  XWST,  XWPA, XWTDM, XLAI, XNFLV
      REAL XWLGH, XWLDH, XWLGD, XWLDD, XWLGW, XWLDW
      REAL XNTI, XNDT, XNHL, XNDH, XNWH
      REAL WLVGI, WSTI,   WRTI
      REAL WLVG,  WLVD,    WSO, WST, WSTS, WSTR,  WRT
      REAL TS,    TSLV,   TSTR
      REAL WAG,    WRR
      REAL LAI,   LAIL, LAP0
      REAL DVS

*-----Species parameters and rates

      INTEGER ILREDF
      INTEGER ILEFF
      REAL AMAX
      REAL REDFT, REDFTT(IMNP)
      REAL EFF,   EFFTB(IMNP)

      INTEGER ILKDF
      REAL KDF,  KDFTB(IMNP), SCP
      REAL NFLV
      REAL NPLH, NH, NPLSB

      REAL DVR,   DVRV,   DVRR
      REAL TSHCKD,TSHCKL
      REAL SHCKD, SHCKL
      REAL TBD,   TBLV

      REAL HU,      HULV
      REAL DTGA,    DS0
      REAL MNDVS

      INTEGER ILFSH, ILFLV, ILLAI, ILFST,   ILFRT
      INTEGER ILFSO, ILSAI
      REAL FSH,     FSHTB(IMNP)
      REAL FLV,     FLVTB(IMNP)
      REAL FST,     FSTTB(IMNP)
      REAL FSTR
      REAL FRT,     FRTTB(IMNP)
      REAL FSO,     FSOTB(IMNP)
      REAL SAI, SSGA,  SSGATB(IMNP)

      REAL CRGCR, CRGLV, CRGST,   CRGRT, CRGSO, CRGSTR
      REAL FCLV,   FCST,  FCRT,   FCSO
      REAL CO2LV, CO2ST, CO2SO,  CO2RT
      REAL CHCIN, CHCFL, TNASS, CHCDIF
      REAL GCR,  GMAINT

      INTEGER ILDRLV
      REAL DRLVT(IMNP)
      REAL DRLV
```

```
      REAL LLV
      REAL GLV, GST, GSTR
      REAL GSO, GRT

      INTEGER ILNLV
      INTEGER ILXWLV, ILXWLD, ILXWST, ILXWPA, ILXWT, ILXNLV
      INTEGER ILXLGH, ILXLDH, ILXLGD, ILXLDD, ILXLGW, ILXLDW
      INTEGER ILXNHL,ILXNDH,ILXNWH,ILXNTI,ILXNDT
      INTEGER ILSLA

      REAL NFLVTB(IMNP)
      REAL XNFLVT(IMNP), XLAITB(IMNP)
      REAL XWLVGT(IMNP), XWLVDT(IMNP), XWSTTB(IMNP)
      REAL XWPATB(IMNP), XWTDMT(IMNP)
      REAL XWLGHT(IMNP), XWLDHT(IMNP)
      REAL XWLGDT(IMNP), XWLDDT(IMNP)
      REAL XWLGWT(IMNP), XWLDWT(IMNP)
      REAL XNTIT(IMNP),XNHLT(IMNP), XNDHT(IMNP),XNWHT(IMNP),XNDTT(IMNP)

      REAL SLA,  SLATB(IMNP)

      REAL RGRL

      INTEGER IWVAR
      CHARACTER WUSED*6

      SAVE

*     initial value of previous task
      DATA ITOLD /4/, WUSED /'UUU---'/

*     Check the new task against the old task, check the value
*     of DELT and check weather data
      CALL CHKTSK ('SBORER', IUNITO, ITOLD, ITASK)

      IF (DELT.LT.1.0) CALL ERROR
     &   ('SBORER','DELT too small for SBORER')

*     check weather data availability
      IF (ITASK.EQ.1.OR.ITASK.EQ.2.OR.ITASK.EQ.4) THEN
         DO 10 IWVAR=1,6
*        is there an error in the IWVAR-th variable ?
           IF (WUSED(IWVAR:IWVAR).EQ.'U'.AND.
     &         WSTAT(IWVAR:IWVAR).EQ.'4') THEN
               WTRTER = .TRUE.
               TERMNL = .TRUE.
               ITOLD  = ITASK
               RETURN
           END IF
10       CONTINUE
      END IF

      IF (ITASK.EQ.1) THEN

*        ----------------------
*        Initialization section
*        ----------------------

*        Send title(s) to output file

         CALL OUTCOM ('FSE-SBORER: Rice production under '
     &                //'stem borer presence')
         CALL OUTCOM ('Version March 1994')

*        Read timerfile for some time-related parameters

         CALL RDINIT (IUNITD  , IUNITL, FILEIT)

         CALL RDSREA ('DTRP'  , DTRP)

*        Read switches, and check their validity and range.
         CALL RDSINT ('SWILAI', SWILAI)
         CALL RDSINT ('SWINLV', SWINLV)
         CALL RDSINT ('SWICLI', SWICLI)
         CALL RDSINT ('SWITIL', SWITIL)

         IF ((SWITIL.EQ.1).AND.(SWILAI.EQ.0)) THEN
              WRITE (*,'(A)') ' Model termination'
              WRITE (*,'(A)') ' If SWITIL=1 then SWILAI must be 1'
              TERMNL = .TRUE.
         ENDIF
         IF (SWICLI.EQ.1) THEN
              WRITE (*,'(A)') ' This is a clipping experiment'
         ENDIF
         IF (((SWILAI.LT.0).OR.(SWILAI.GT.1)) .OR.
     &       ((SWINLV.LT.0).OR.(SWINLV.GT.2)) .OR.
     &       ((SWICLI.LT.0).OR.(SWICLI.GT.1)) .OR.
     &       ((SWITIL.LT.0).OR.(SWITIL.GT.1))) THEN
              WRITE (*,'(A)') ' Model termination'
              WRITE (*,'(A)') ' One or more switches out of range'
              TERMNL = .TRUE.
         ENDIF
```

```
      IDOYS = NINT(STTIME)

      CLOSE (IUNITD)

*     Read input file

      CALL RDINIT (IUNITD  , IUNITL, FILEI1)

*--------Oryza sativa initialization

      CALL OUTCOM ('Rice')

*     States

      CALL RDSREA ('WLVGI', WLVGI)
      CALL RDSREA ('WSTI',  WSTI)
      CALL RDSREA ('WRTI' , WRTI)

      DVS  = 0.
      LAI  = 0.
      SLA  = 0.
      TNASS= 0.
      TS   = 0.
      TSTR = 0.
      TSLV = 0.
      TSLVTR = 0.
      WLVEXP = 0.
      LAIEXP = 0.

      DAS  = 0.

      CKCIN = 0.
      CKCFL = 0.

*     For observed values

      XWLVG = 0.
      XWLVD = 0.
      XWST  = 0.
      XWPA  = 0.
      XWTDM = 0.
      XWCR  = 0.
      XNFLV = 0.
      XLAI  = 0.

*     Tillers densities.
      XNTI  = 0.
      XNHL  = 0.
      XNDH  = 0.
      XNWH  = 0.
      XNDT  = 0.

*     Leaf dry weights of each tiller class
      XWLGH  = 0.
      XWLDH  = 0.
      XWLGD  = 0.
      XWLDD  = 0.
      XWLGW  = 0.
      XWLDW  = 0.

*--------Rates

      DTGA   = 0.
      GCR    = 0.
      CRGCR  = 0.
      GSTR   = 0.
      LSTR   = 0.
      GMAINT = 0.
      DVR    = 0.
      AMAX   = 0.

*--------Other parameters

      CALL RDSREA ('NPLH'  , NPLH)
      CALL RDSREA ('NH'    , NH)
      CALL RDSREA ('NPLSB' , NPLSB)
      CALL RDSREA ('LAP0',   LAP0)
      CALL RDSREA ('FSTR',   FSTR)
      CALL RDSREA ('SCP',    SCP)
      CALL RDSREA ('TBD',    TBD)
      CALL RDSREA ('TBLV',   TBLV)
      CALL RDSREA ('CRGLV',  CRGLV)
      CALL RDSREA ('CRGST',  CRGST)
      CALL RDSREA ('CRGSTR', CRGSTR)
      CALL RDSREA ('CRGSO',  CRGSO)
      CALL RDSREA ('CRGRT',  CRGRT)
      CALL RDSREA ('FCLV',   FCLV)
      CALL RDSREA ('FCST',   FCST)
      CALL RDSREA ('FCSTR',  FCSTR)
      CALL RDSREA ('FSTR',   FSTR)
      CALL RDSREA ('FCRT',   FCRT)
```

```
      CALL RDSREA ('FCSO',    FCSO)
      CALL RDSREA ('TCLSTR',  TCLSTR)
      CALL RDSREA ('LRSTR',   LRSTR)
      CALL RDSREA ('DVRV',    DVRV)
      CALL RDSREA ('DVRR',    DVRR)
      CALL RDSREA ('SHCKD',   SHCKD)
      CALL RDSREA ('SHCKL',   SHCKL)

      CALL RDAREA ('EFFTB', EFFTB,  IMNP, ILEFF)
      CALL RDAREA ('KDFTB', KDFTB,  IMNP, ILKDF)
      CALL RDAREA ('REDFTT',REDFTT, IMNP, ILREDF)
      CALL RDAREA ('FSHTB', FSHTB,  IMNP, ILFSH)
      CALL RDAREA ('FRTTB', FRTTB,  IMNP, ILFRT)
      CALL RDAREA ('SSGATB',SSGATB, IMNP, ILSAI)

      RDINF = 1

      SBINFR = 0.
      ARTDH  = 0.
      DVSWH  = 0.
      TRLOSS = 0.
      FSH    = 0.
      FRT    = 0.
      FLV    = 0.
      FST    = 0.
      FST    = 0.
      FSO    = 0.
      DRLV   = 0.
      GSOM   = 0.

      CALL INSECT(ITASK,DELT,IDOY,IDOYS,RDINF,
     &            SBINFR,SWICLI,ARTDH,TCLSTR,LRSTR,DVSWH,
     &            TRLOSS,FCSTR,TEFF,MNDVS,
     &            FSH,FRT,FLV,FST,FSTR,FSO,
     &            CRGLV,CRGST,CRGSTR,CRGRT,CRGSO,
     &            WLVGI,WSTI,WRTI,DRLV,DVS,DTGA,GSOM,
     &            GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2,
     &            WLVGDH,WSTDH,WSTDDH,
     &            WLVGWH,WSTWH,WSOWH,
     &            WLVGHL,WSTHL,WSOHL,
     &            WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT,
     &            WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM,
     &            WLVTR,WSTSTR,WSTRTR,WRTTR,
     &            RMCR,CRGCR)

      CALL SBTILL(ITASK,DELT,RDINF,DAS,DTRP,DVS,DVR,NH,NPLH,DVSWH,
     &            SBINFR,ARTDH,TAV,TMX,GCRHL2,GSO,NCNLV,CRGCR,
     &            SWITIL,XNHL,XNDH,XNWH,XNTI,XNDT,
     &            GSOM,NHL,NDH,NWH,NTI,NDT,NGR,PROD,UNPROD)

      RDINF = 3

      CLOSE (IUNITD)

      CALL RDINIT (IUNITD  , IUNITL, FILEI3)

*     Observed values

      CALL RDAREA ('XWLVGT',XWLVGT,IMNP,ILXWLV)
      CALL RDAREA ('XWLVDT',XWLVDT,IMNP,ILXWLD)
      CALL RDAREA ('XWSTTB',XWSTTB,IMNP,ILXWST)
      CALL RDAREA ('XWPATB',XWPATB,IMNP,ILXWPA)
      CALL RDAREA ('XWTDMT',XWTDMT,IMNP,ILXWT)
      CALL RDAREA ('XNFLVT',XNFLVT,IMNP,ILXNLV)
      CALL RDAREA ('XLAITB',XLAITB,IMNP,ILLAI)
      CALL RDAREA ('XNTIT',XNTIT,IMNP,ILXNTI)
      CALL RDAREA ('XNHLT',XNHLT,IMNP,ILXNHL)
      CALL RDAREA ('XNDHT',XNDHT,IMNP,ILXNDH)
      CALL RDAREA ('XNWHT',XNWHT,IMNP,ILXNWH)
      CALL RDAREA ('XNDTT',XNDTT,IMNP,ILXNDT)
      CALL RDAREA ('XWLGHT',XWLGHT,IMNP,ILXLGH)
      CALL RDAREA ('XWLDHT',XWLDHT,IMNP,ILXLDH)
      CALL RDAREA ('XWLGDT',XWLGDT,IMNP,ILXLGD)
      CALL RDAREA ('XWLDDT',XWLDDT,IMNP,ILXLDD)
      CALL RDAREA ('XWLGWT',XWLGWT,IMNP,ILXLGW)
      CALL RDAREA ('XWLDWT',XWLDWT,IMNP,ILXLDW)

*     initialization pest input

      CALL RDSINT ('OBS1',   OBS1)
      CALL RDSREA ('RGRL',   RGRL)
      CALL RDSREA ('ARTDH',  ARTDH)
      CALL RDSREA ('DVSWH',  DVSWH)

      CALL RDSREA ('SENS1',  SENS1)

      CALL RDAREA ('SLATB', SLATB,  IMNP, ILSLA)
      CALL RDAREA ('NFLVTB',NFLVTB,IMNP, ILNLV)
      CALL RDAREA ('FLVTB', FLVTB,  IMNP, ILFLV)
      CALL RDAREA ('FSTTB', FSTTB,  IMNP, ILFST)
      CALL RDAREA ('FSOTB', FSOTB,  IMNP, ILFSO)
```

```
      CALL RDAREA ('DRLVT', DRLVT, IMNP, ILDRLV)
      CALL RDAREA ('SBIRTB',SBIRTB,IMNP, ISBIRT)
      CALL RDAREA ('NCNLVT',NCNLVT,IMNP, ILNCN)

      INCRDH = 0.
      INCRWH = 0.
      NDH1   = 0.
      NWH1   = 0.
      SBINFR = 0.
      TRLOSS = 0.
      LAISIM = 1

      FSH    = 0.
      FRT    = 0.
      FLV    = 0.
      FST    = 0.
      FSO    = 0.
      DRLV   = 0.
      GSOM   = 0.
      TEFF   = 0.
      MNDVS  = 1.
      DVR    = 0.

      CALL INSECT(ITASK,DELT,IDOY,IDOYS,RDINF,
     &                  SBINFR,SWICLI,ARTDH,TCLSTR,LRSTR,DVSWH,
     &                  TRLOSS,FCSTR,TEFF,MNDVS,
     &                  FSH,FRT,FLV,FST,FSTR,FSO,
     &                  CRGLV,CRGST,CRGSTR,CRGRT,CRGSO,
     &                  WLVGI,WSTI,WRTI,DRLV,DVS,DTGA,GSOM,
     &                  GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2,
     &                  WLVGDH,WSTDH,WSTDDH,
     &                  WLVGWH,WSTWH,WSOWH,
     &                  WLVGHL,WSTHL,WSOHL,
     &                  WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT,
     &                  WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM,
     &                  WLVTR,WSTSTR,WSTRTR,WRTTR,
     &                  RMCR,CRGCR)

      CALL SBTILL(ITASK,DELT,RDINF,DAS,DTRP,DVS,DVR,NH,NPLH,DVSWH,
     &                  SBINFR,ARTDH,TAV,TMX,GCRHL2,GSO,NCNLV,CRGCR,
     &                  SWITIL,XNHL,XNDH,XNWH,XNTI,XNDT,
     &                  GSOM,NHL,NDH,NWH,NTI,NDT,NGR,PROD,UNPROD)

      WAG    = WLVG + WST + WSO  + WLVD
      WCR    = WAG + WRT

      CLOSE (IUNITD)

      KDF    = LINT(KDFTB, ILKDF, DVS)

*     Use of subroutine ABSORB is optional.
      CALL ABSORB (ITASK,DELT,DAS,KDF,LAI,RDT,GCR,
     &                  ABS,CUMABS,CLUE,AVCLUE)

*     Initialize state variables

      ELSE IF (ITASK.EQ.2) THEN

*     ------------------------
*     Rate calculation section
*     ------------------------

************
*** 1. INPUT
************

      IF (SWITIL.EQ.1) THEN
          SBINFR = LINT(SBIRTB,ISBIRT,DOY)
      ELSEIF (SWITIL.EQ.0) THEN
          INCRDH = MAX(0.,NDH - NDH1)
          INCRWH = MAX(0.,NWH - NWH1)

          NDH1 = NDH
          NWH1 = NWH

          IF (NHL.GT.0) THEN
             SBINFR = (INCRDH+INCRWH)/NHL
          ELSE
             SBINFR = 0.
          ENDIF

      ENDIF

******************
*** 2. TEMPERATURE
******************

      TAV    = 0.5*(TMX + TMN)
      TAVD   = 0.5*(TAV + TMX)
```

```
******************
*** 3. DEVELOPMENT
******************

        HU    = MIN(30.-TBD, (MAX (0., TAV-TBD)))
        HULV  = MIN(26.-TBLV,(MAX (0., TAV-TBLV)))

        IF (DVS.LT.1.) THEN
           DVR = DVRV * HU
           IF (DAS.EQ.DTRP) TSTR = TS
           TSHCKD = SHCKD * TSTR
           IF (DAS.GT.DTRP .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.
        ELSE
           DVR = DVRR * HU
        ENDIF

*--------Cold days

        CALL SUBCD (DAS,DTRP,TAV,TIME,NCOLD)

********************
*** 4. LEAF NITROGEN
********************

           IF (SWINLV.EQ.0) THEN
               NFLV  = LINT(XNFLVT, ILXNLV, DOY)
               NCNLV = 10. * NFLV * SLA
           ELSEIF (SWINLV.EQ.1) THEN
               NFLV  = LINT(NFLVTB, ILNLV,  DVS)
               NCNLV = 10. * NFLV * SLA
           ELSE

*          (SWINLV=2)
               NCNLV = LINT(NCNLVT, ILNCN, DOY)
               IF (SLA.GT.0.) THEN
                   NFLV  = 0.1 * NCNLV / SLA
               ELSE
                   NFLV  = 0.
               ENDIF
            ENDIF

            IF (SENS1.NE.0.) THEN
                NCNLV = NCNLV + SENS1
                NCNLV = LIMIT(0.01,0.06,NCNLV)
                IF (SLA.GT.0.) THEN
                    NFLV  = 0.1 * NCNLV / SLA
                ELSE
                    NFLV  = 0.
                ENDIF
            ENDIF

******************
*** 5. ASSIMILATION
******************

        EFF   = LINT (EFFTB,  ILEFF, TAVD)
        REDFT = LINT (REDFTT, ILREDF,TAVD)
        KDF   = LINT (KDFTB, ILKDF, DVS)

        CALL TOTASS (DOY,  LAT , RDT, SCP, AMAX, EFF, KDF, LAI,
     &               REDFT,NFLV,
     &               DAYL, DTGA, DS0)

*****************************
*** 6. MAINTENANCE RESPIRATION
*****************************

        IF ((WLVG+WLVD).GT.0.) THEN
           MNDVS = WLVG/(WLVG+WLVD)
        ELSE
           MNDVS = 1.
        ENDIF

        Q10       = 2.
        TREF      = 25.
        TEFF      = Q10**((TAV-TREF)/10.)

*-------RMCR calculated in INSECT subroutine.

***********************************
*** 7. GROWTH AND LOSS OF DRY MATTER
***********************************

*--------Dry matter partitioning

        FSH  = LINT (FSHTB, ILFSH, DVS)
        FRT  = LINT (FRTTB, ILFRT, DVS)
        FLV  = LINT (FLVTB, ILFLV, DVS)
        FST  = LINT (FSTTB, ILFST, DVS)
        FSO  = LINT (FSOTB, ILFSO, DVS)

        FTOT = FRT+FSH*(FLV+FST+FSO)
```

```
      IF ((FTOT.LT.0.99).OR.(FTOT.GT.1.01)) THEN
          WRITE (*,'(A)') ' Warning'
          WRITE (*,'(A)') ' Sum of partioning fractions not 1'
      ENDIF

*--------Carbohydrate requirements
*       Calculated in INSECT subroutine

*--------Loss of crop weight due to transplantation

      IF ((DAS.EQ.DTRP).AND.(DAS.GT.0.)) THEN
          TRLOSS = (NPLSB-NPLH*NH)/NPLSB*(WAG+WRT)
      ELSE
          TRLOSS = 0.
      ENDIF

*--------Loss of green leaf weight

      DRLV   = LINT(DRLVT, ILDRLV, DVS)
      LLV    = WLVG * DRLV

*--------Loss of stem reserves.

      IF (DVS.LT.1.) THEN
         LSTR  = 0.
      ELSE
         LSTR  = WSTR / TCLSTR
      ENDIF

*--------Growth rates

      CALL INSECT(ITASK,DELT,IDOY,IDOYS,RDINF,
     &                  SBINFR,SWICLI,ARTDH,TCLSTR,LRSTR,DVSWH,
     &                  TRLOSS,FCSTR,TEFF,MNDVS,
     &                  FSH,FRT,FLV,FST,FSTR,FSO,
     &                  CRGLV,CRGST,CRGSTR,CRGRT,CRGSO,
     &                  WLVGI,WSTI,WRTI,DRLV,DVS,DTGA,GSOM,
     &                  GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2,
     &                  WLVGDH,WSTDH,WSTDDH,
     &                  WLVGWH,WSTWH,WSOWH,
     &                  WLVGHL,WSTHL,WSOHL,
     &                  WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT,
     &                  WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM,
     &                  WLVTR,WSTSTR,WSTRTR,WRTTR,
     &                  RMCR,CRGCR)

************************
*** 8. GROWTH MAINTENANCE
************************

      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)

      GMAINT = ((DTGA*30./44.)-RMCR)*44./30. -
     &          (GRT*CO2RT  +  GLV*CO2LV +
     &           GST*CO2ST  +  GSO*CO2SO +
     &           GSTR*CO2STR             +
     &          (1.-LRSTR)*LSTR*FCSTR*44./12.)

*****************************
*** 9. LEAF AREA DEVELOPMENT
*****************************

      SSGA   = LINT (SSGATB, ILSAI, DVS)
      SAI    = SSGA * WST

      SLA    = LINT(SLATB, ILSLA, DOY)

************************
** 9.1. SIMULATION OF LAI
************************

      IF (SWILAI.EQ.1) THEN

          CALL GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &               TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

****************************************
** 9.2. ANALYSIS OF EXPERIMENTS, LAI INPUT
****************************************

      ELSE

*--------       Simulation of leaf area before 1st observation is
available.

          IF (IDOY.EQ.OBS1) LAISIM = 0

          IF (LAISIM.EQ.0) THEN
```

```
            LAIL = LINT(XLAITB,ILLAI,DOY)
            LAI  = LAIL + 0.5 * SAI

         ELSE

            CALL GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &           TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

         ENDIF

      ENDIF

*********************************
*** 10. TILLER AND GRAIN DYNAMICS
*********************************

      CALL SBTILL(ITASK,DELT,RDINF,DAS,DTRP,DVS,DVR,NH,NPLH,DVSWH,
     &            SBINFR,ARTDH,TAV,TMX,GCRHL2,GSO,NCNLV,CRGCR,
     &            SWITIL,XNHL,XNDH,XNWH,XNTI,XNDT,
     &            GSOM,NHL,NDH,NWH,NTI,NDT,NGR,PROD,UNPROD)

*****************************
*** 10. OPTIONAL SUBROUTINES
*****************************

*--------Cumulative intercepted radiation
      CALL ABSORB (ITASK,DELT,DAS,KDF,LAI,RDT,GCR,
     &            ABS,CUMABS,CLUE,AVCLUE)

*******************
*** 11. DATA OUTPUT
*******************

      IF (OUTPUT) THEN
         CALL OUTDAT (2, 0, 'DAS',   DAS)
         CALL OUTDAT (2, 0, 'DVS',   DVS)
         CALL OUTDAT (2, 0, 'DTGA',  DTGA)
         CALL OUTDAT (2, 0, 'GCR',   GCR)
         CALL OUTDAT (2, 0, 'LAI',   LAI)
         CALL OUTDAT (2, 0, 'LAIL',  LAIL)
         CALL OUTDAT (2, 0, 'XLAI',  XLAI)
         CALL OUTDAT (2, 0, 'SAI',   SAI)
*        CALL OUTDAT (2, 0, 'XNFLV', XNFLV)
*         CALL OUTDAT (2, 0, 'NFLV',  NFLV)
*         CALL OUTDAT (2, 0, 'NCNLV', NCNLV)
         CALL OUTDAT (2, 0, 'XWLVG', XWLVG)
         CALL OUTDAT (2, 0, 'WLVG',  WLVG)
         CALL OUTDAT (2, 0, 'XWLVD', XWLVD)
         CALL OUTDAT (2, 0, 'WLVD',  WLVD)
         CALL OUTDAT (2, 0, 'XWST',  XWST)
         CALL OUTDAT (2, 0, 'WST',   WST)
         CALL OUTDAT (2, 0, 'XWPA',  XWPA)
         CALL OUTDAT (2, 0, 'WSO',   WSO)
         CALL OUTDAT (2, 0, 'XWTDM', XWTDM)
         CALL OUTDAT (2,0,  'XNTI',  XNTI)
         CALL OUTDAT (2,0,  'XNHL',  XNHL)
         CALL OUTDAT (2,0,  'XNDH',  XNDH)
         CALL OUTDAT (2,0,  'XNWH',  XNWH)
         CALL OUTDAT (2,0,  'XNDT',  XNDT)
         CALL OUTDAT (2, 0, 'WAG',   WAG)
         CALL OUTDAT (2, 0, 'WCR',   WCR)
         CALL OUTDAT (2, 0, 'XWCR',  XWCR)
         CALL OUTDAT (2, 0, 'AMAX',  AMAX)
         CALL OUTDAT (2, 0, 'EFF',   EFF)
         CALL OUTDAT (2, 0, 'CHCDIF',CHCDIF)
         CALL OUTDAT (2, 0, 'SBINFR',SBINFR)

         CALL OUTDAT (2, 0, 'NHL',   NHL)
         CALL OUTDAT (2, 0, 'NDH',   NDH)
         CALL OUTDAT (2, 0, 'NWH',   NWH)
         CALL OUTDAT (2, 0, 'NTI',   NTI)
         CALL OUTDAT (2, 0, 'NDT',   NDT)
         CALL OUTDAT (2, 0, 'NGR',   NGR)
         CALL OUTDAT (2, 0, 'PROD',  PROD)
         CALL OUTDAT (2, 0, 'UNPROD',UNPROD)

         CALL OUTDAT (2, 0, 'CUMABS',CUMABS)
         CALL OUTDAT (2, 0, 'AVCLUE',AVCLUE)
      END IF

   ELSE IF (ITASK.EQ.3) THEN

*        -------------------
*        Integration section
*        -------------------

*--------Days after sowing

         DAS = TIME - STTIME
```

```
*--------Development stage

        DVS  = INTGRL (DVS , DVR,          DELT)

*--------Plant organ weights

        CALL INSECT(ITASK,DELT,IDOY,IDOYS,RDINF,
     &                  SBINFR,SWICLI,ARTDH,TCLSTR,LRSTR,DVSWH,
     &                  TRLOSS,FCSTR,TEFF,MNDVS,
     &                  FSH,FRT,FLV,FST,FSTR,FSO,
     &                  CRGLV,CRGST,CRGSTR,CRGRT,CRGSO,
     &                  WLVGI,WSTI,WRTI,DRLV,DVS,DTGA,GSOM,
     &                  GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2,
     &                  WLVGDH,WSTDH,WSTDDH,
     &                  WLVGWH,WSTWH,WSOWH,
     &                  WLVGHL,WSTHL,WSOHL,
     &                  WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT,
     &                  WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM,
     &                  WLVTR,WSTSTR,WSTRTR,WRTTR,
     &                  RMCR,CRGCR)

        WST  = WSTS + WSTR
        WAG  = WLVG + WST  + WSO  + WLVD
        WCR  = WAG  + WRT
        XWCR = XWTDM + WRT
        WRR  = WSO * 0.90 / 0.86

*------Tiller dynamics.

        CALL SBTILL(ITASK,DELT,RDINF,DAS,DTRP,DVS,DVR,NH,NPLH,DVSWH,
     &                  SBINFR,ARTDH,TAV,TMX,GCRHL2,GSO,NCNLV,CRGCR,
     &                  SWITIL,XNHL,XNDH,XNWH,XNTI,XNDT,
     &                  GSOM,NHL,NDH,NWH,NTI,NDT,NGR,PROD,UNPROD)

*--------Temperature sums

        TS   = INTGRL (TS  , HU  ,         DELT)
        TSLV = INTGRL (TSLV, HULV ,        DELT)

*--------Cumulative intercepted radiation

        CALL ABSORB (ITASK,DELT,DAS,KDF,LAI,RDT,GCR,
     &                  ABS,CUMABS,CLUE,AVCLUE)

*--------Carbon balance check

        CALL SUBCBC (CKCIN,CKCFL,TIME,CBCHK)

        CHCIN  = (WLVG+WLVD  +WLVREM+WLVTR -WLVGI)*FCLV  +
     &           (WSTS+WSTDDH+WSTSRE+WSTSTR-WSTI) *FCST  +
     &           (WSTR       +WSTRRE+WSTRTR     ) *FCSTR +
     &           (WRT               +WRTTR -WRTI) *FCRT  +
     &           (WSO        +WSOREM            ) *FCSO
        TNASS  = INTGRL (TNASS, GMAINT, DELT)
        CHCFL  = TNASS * (12./44.)
        IF (CHCIN.LE.0.) CHCDIF = (CHCIN-CHCFL)/(1.+CHCIN)
        IF (CHCIN.GT.0.) CHCDIF = (CHCIN-CHCFL)/CHCIN

*--------Field observations

        XWLVG = LINT(XWLVGT, ILXWLV,  DOY)
        XWLVD = LINT(XWLVDT, ILXWLD,  DOY)
        XWST  = LINT(XWSTTB, ILXWST,  DOY)
        XWPA  = LINT(XWPATB, ILXWPA,  DOY)
        XWTDM = LINT(XWTDMT, ILXWT,   DOY)
        XLAI  = LINT(XLAITB, ILLAI,   DOY)
        XNTI  = LINT(XNTIT, ILXNTI,   DOY)
        XNHL  = LINT(XNHLT, ILXNHL,   DOY)
        XNDH  = LINT(XNDHT, ILXNDH,   DOY)
        XNWH  = LINT(XNWHT, ILXNWH,   DOY)
        XNDT  = LINT(XNDTT, ILXNDT,   DOY)
        XWLGH = LINT(XWLGHT, ILXLGH,  DOY)
        XWLDH = LINT(XWLDHT, ILXLDH,  DOY)
        XWLGD = LINT(XWLGDT, ILXLGD,  DOY)
        XWLDD = LINT(XWLDDT, ILXLDD,  DOY)
        XWLGW = LINT(XWLGWT, ILXLGW,  DOY)
        XWLDW = LINT(XWLDWT, ILXLDW,  DOY)

*--------Finish conditions of simulation.

        IF (DVS.GE.2.0)    TERMNL = .TRUE.

      ELSE IF (ITASK.EQ.4) THEN

*       ---------------
*       Terminal section
*       ---------------

*       Define graph for output
*       Use individual scale, small plot width for output
```

```
*         CALL OUTPLT (1,'WSO')
*         CALL OUTPLT (1,'TADRW')
*         CALL OUTPLT (6, 'Printplot of SBORER')

      END IF

      ITOLD = ITASK

      RETURN
      END

*-----------------------------------------------------------------------*
* SUBROUTINE SUBCBC                                                     *
*  Purpose: This function checks the Crop Carbon Balance                *
*           and stops the simulation if the difference between          *
*           CKCIN and CKCFL exceeds 0.1 %                               *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  CKCIN   R4  Accumulated C in the crop               kg C/ha  I       *
*  CKCFL   R4  Sum of integrated C fluxes              kg C/ha  I       *
*  TIME    R4  Time of simulation                         d     I       *
*  CKCHK   R4  Difference between in carbon balance       -     O       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE SUBCBC(CKCIN,CKCFL,TIME,CBCHK)
      IMPLICIT REAL (A-Z)

      CBCHK = 2.0*(CKCIN-CKCFL)/(CKCIN+CKCFL+1.E-10)

      IF (ABS(CBCHK).GT.0.001) THEN
        WRITE (*,10) CBCHK, CKCIN, CKCFL, TIME
 10     FORMAT (/,'* * *Error in Carbon Balance, please check* * *',/,
     &  ' CBCHK=',F8.3,', CKCIN=',F8.2,', CKCFL=',F8.2,' at TIME=',F6.1)
        STOP
      ENDIF

      RETURN
      END

*-----------------------------------------------------------------------*
* SUBROUTINE SUBCD                                                      *
*                                                                       *
*  Purpose: This subroutine determines the number of consecutive cold   *
*           days and terminates simulation if the number of days with   *
*           an average temperature below 12 oC exceeds 3                *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  DAS     R4  Number of days after sowing               -      I       *
*  DTRP    R4  Number of days between sowing and transpl.-      I       *
*  TAV     R4  Average daily temperature                 oC     I       *
*  TIME    R4  Time of simulation                        d      I       *
*  NCOLD   R4  Number of cold days                       -      O       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE SUBCD(DAS,DTRP,TAV,TIME,NCOLD)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      REAL TIME
      REAL TAV,NCOLD

      SAVE

      IF(DAS.EQ.DTRP) NCOLD=0.

      IF(TAV.LT.12.) THEN
         NCOLD = NCOLD + 1.
      ELSE
         NCOLD = 0.
      ENDIF

      IF (NCOLD.GT.3.) THEN

        WRITE (*,10) NCOLD, TIME
 10     FORMAT (/,'* * *Number of cold days (<12 C) exceeded 3* * *',/,
     &  ' NCOLD',F8.3, ' at TIME=',F6.1)
        STOP

      ENDIF

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE GRLAI                                                     *
*  Purpose: This subroutine calculates the total leaf area index        *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  SAI     R4  Stem area index                         ha/ha      I     *
*  SLA     R4  Specific leaf area                      ha/kg      I     *
*  DVS     R4  Development stage                         -        I     *
*  WLVG    R4  Weight of the green leaves              kg/ha      I     *
*  LAP0    R4  Plant leaf area at emergence              m2       I     *
*  DAS     R4  Number of days after sowing               -        I     *
*  DTRP    R4  Number of days between sowing and transpl.-        I     *
*  TSLV    R4  Temperature sum for leaf development      oC       I     *
*  RGRL    R4  Relative growth rate for leaf development 1/(oCd)  I     *
*  SHCKL   R4  Delay parameter in development          oCd/oCd    I     *
*  NPLSB   R4  Number of plants in seedbed             pl/m2      I     *
*  NH      R4  Number of hills                         hills/m2   I     *
*  NPLH    R4  Number of plants per hill               pl/hill    I     *
*  LAI     R4  Total leaf area index (including SAI)   ha/ha      O     *
*  LAIL    R4  Total leaf area index (excluding SAI)   ha/ha      O     *
*  TSHCKL  R4  Transplanting shock for phenological     oCd       O     *
*              development                                              *
*                                                                       *
*  FILE usage : none                                                    *
*                                                                       *
*-----------------------------------------------------------------------*

      SUBROUTINE GRLAI(SAI,SLA,DVS,WLVG,LAP0,DAS,DTRP,
     &                 TSLV,RGRL,SHCKL,NPLSB,NH,NPLH,LAI,LAIL,TSHCKL)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      REAL DAS,DTRP
      REAL TSLV,TSHCKL,SHCKL
      REAL LAI,LAIL,LAP0,SAI,SLA
      REAL RGRL,NPLSB,NPLH,NH
      REAL WLVG
      REAL DVS

*-----Local parameters
      REAL LAPI,LAII,LAIEXS,LAIEXP
      REAL TSLVTR,WLVEXS,WLVEXP

      SAVE

      LAIEXS = 0.
      WLVEXS = 0.

      IF (DAS.LT.DTRP)                                              THEN

         IF (LAI.LT.1.)                                             THEN
            LAPI   = LAP0 * (EXP(RGRL*TSLV))
            LAII   = LAPI * NPLSB
            LAI    = LAII
            WLVEXS = WLVG
            LAIEXS = LAI
          ELSE
            LAII  = 0.5*SAI + LAIEXS + SLA*(WLVG-WLVEXS)
            LAI   = LAII
          ENDIF

      ELSEIF (DAS.EQ.DTRP)                                          THEN
            LAI    = LAII * NPLH*NH/NPLSB
            TSLVTR = TSLV
            TSHCKL = SHCKL * TSLVTR

      ELSE

         IF (TSLV.LT.(TSLVTR+TSHCKL))                               THEN
            LAI    = LAII * NPLH*NH/NPLSB
         ELSE
            IF ((LAI.LT.1.).AND.(DVS.LT.0.6))                       THEN
               LAI    = LAII * NPLH*NH/NPLSB *
     &                        (EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
               WLVEXP= WLVG
               LAIEXP= LAI
            ELSE
               LAI    = 0.5*SAI + LAIEXP +  SLA*(WLVG-WLVEXP)
            ENDIF
          ENDIF
      ENDIF

      LAIL = LAI - 0.5*SAI

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                     *
*  Purpose: This subroutine calculates astronomic daylength,            *
*           diurnal radiation characteristics such as the daily         *
*           integral of sine of solar elevation and solar constant.     *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                  units  class    *
*  ----   ---- -------                                  -----  -----    *
*  DOY     R4  Daynumber (Jan 1st = 1)                    -      I      *
*  LAT     R4  Latitude of the site                    degrees   I      *
*  SC      R4  Solar constant                          J m-2 s-1 O      *
*  DS0     R4  Daily extraterrestrial radiation        J m-2 d-1 O      *
*  SINLD   R4  Seasonal offset of sine of solar height    -      O      *
*  COSLD   R4  Amplitude of sine of solar height          -      O      *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)    h      O      *
*  DSINB   R4  Daily total of sine of solar height        s      O      *
*  DSINBE  R4  Daily total of effective solar height      s      O      *
*                                                                       *
*  FATAL ERROR CHECKS (execution terminated, message)                   *
*  condition: LAT > 67, LAT < -67                                       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE ASTRO (DOY, LAT,
     &                  SC , DS0, SINLD, COSLD, DAYL, DSINB, DSINBE)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      REAL DOY,LAT,SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE

*-----Local parameters
      REAL PI,RAD
      PARAMETER (PI=3.141592654)

      SAVE

      RAD   = PI/180.

*-----check on input range of parameters
      IF (LAT.GT.67.)  STOP 'ERROR IN ASTRO: LAT> 67'
      IF (LAT.LT.-67.) STOP 'ERROR IN ASTRO: LAT>-67'

*-----declination of the sun as function of daynumber (DOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+10.)/365.))

*-----SINLD, COSLD and AOB are intermediate variables

      SINLD = SIN (RAD*LAT)*SIN (DEC)
      COSLD = COS (RAD*LAT)*COS (DEC)
      AOB   = SINLD/COSLD

*-----daylength (DAYL)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)

      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE = 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &         12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT (1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                    *
*  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      *
```

```
*  REDFT    R4  Temperature reduction on AMAX                -       I  *
*  NFLV     R4  Nitrogen fraction leaves                   g/m2      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, ASSIM                      *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE TOTASS (DOY,  LAT , DTR, SCP, AMAX, EFF, KDF, LAI,
     &                   REDFT,NFLV,
     &                   DAYL, DTGA, DS0)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      REAL DOY,LAT,DTR,SCP,KDF,DAYL,DTGA,DS0
      REAL AMAX,EFF,LAI,REDFT,NFLV

*-----Local parameters
      REAL XGAUSS(3), WGAUSS(3)
      REAL PI
      INTEGER I1, IGAUSS

      PARAMETER (PI = 3.141592654)

      SAVE

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

      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 ASSIM (SCP,AMAX,EFF,KDF,LAI,SINB,PARDR,PARDF,REDFT,NFLV,
     &              FGROS)

*--------integration of assimilation rate to a daily total (DTGA)
        DTGA = DTGA+FGROS*WGAUSS(I1)

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                     *
*  Purpose: This subroutine performs a Gaussian integration over        *
*           depth of canopy by selecting three different LAI's and      *
*           computing assimilation at these LAI levels. The             *
*           integrated variable is FGROS.                               *
*                                                                       *
*  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  *
*  REDFT    R4  Temperature reduction on AMAX               -         I  *
*  NFLV     R4  Nitrogen fraction leaves                    g/m2      I  *
*  FGROS    R4  Instantaneous assimilation rate of          kg CO2/   O  *
*               whole canopy                               ha soil/h     *
*                                                                        *
*  SUBROUTINES and FUNCTIONS called : none                               *
*  FILE usage : none                                                     *
*-----------------------------------------------------------------------*

      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  REDFT,NFLV,
     &                  FGROS)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      REAL SCP,KDF,SINB,PARDR,PARDF,FGROS
      REAL AMAX,EFF,LAI,REDFT,NFLV

*-----Local parameters

      REAL XGAUSS(3), WGAUSS(3)
      REAL KN
      INTEGER I1, I2, IGAUSS

      PARAMETER (KN = 0.4)

      SAVE

*-----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.

      DO 10 I1=1,IGAUSS
         LAIC = LAI * XGAUSS(I1)

*--------calculate leaf nitrogen for each layer, based on exponential
*        distribution.
         IF ((LAI.GT.0.01).AND.(KN.GT.0.)) THEN
            SLNI = NFLV * LAI * KN * EXP(-KN*LAIC)/(1.-EXP(-KN*LAI))
         ELSE
            SLNI = NFLV
         ENDIF

*--------calculate actual maximum photosynthesis rate from N and temp.
         AMAX  = MIN(60.,(-6.5+32.4*SLNI)*REDFT)

*--------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
         IF (AMAX.GT.0.) THEN
            FGRSH  = AMAX * (1.-EXP(-VISSHD*EFF/AMAX))
         ELSE
            FGRSH = 0.
         END IF
```

```
*--------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)
           IF (AMAX.GT.0.) THEN
              FGRS = AMAX * (1.-EXP(-VISSUN*EFF/AMAX))
           ELSE
              FGRS = 0.
           END IF
           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)
        FGROS = FGROS + FGL * WGAUSS(I1)

10    CONTINUE
      FGROS = FGROS * LAI

      RETURN
      END

*=====================================================================*
* SUBROUTINE SBTILL                                                   *
* Date    : January 1994                                              *
* Author  : A. Elings                                                 *
* Purpose: This subroutine simulates the interaction between stem     *
*          borers and tiller dynamics, and computes grain density.    *
*                                                                     *
* Based upon subroutine SINK (July, 1993 by J.J.M. Riethoven &        *
* H. Drenth), which was based upon the MACROS TIL module (1989), and  *
* tiller subroutine in SWHEAT model by van Keulen & Seligman, 1987.   *
* Further based upon sburoutine SUBGRN of ORYZA_1.                    *
*                                                                     *
* Fatal error checks: none                                            *
* Warnings          : none                                            *
* Subprograms called: none                                            *
* File usage        : none                                            *
*                                                                     *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
* name   type meaning                                  units  class   *
* ----   ---- -------                                  -----  -----   *
* ITASK   I4  Task that subroutine should perform        -      I     *
* DELT    R4  Time step of integration                   d      I     *
* RDINF   I4  Variable determining whether data are      -      I     *
*             read from CROP.DAT or PEST.DAT                         *
* DVS     R4  Development stage                          -      I     *
* DVR     R4  Development rate                         d-1      I     *
* NH      R4  Number of hills                        hills/m2   I     *
* NPLH    R4  Number of plants per hill              pl/hill    I     *
* DVSWH   R4  DVS after which white heads are formed     -      I     *
* SBINFR  R4  Stem borer infection rate           till/till/d   I     *
* ARTDH   R4  Average residence time for a dead heart    d-1     I     *
* TAV     R4  Average temperature                        oC      I     *
* GCRHL2  R4  Growth of healthy tillers, not adjusted  kg/ha/d   I     *
*             for carbohydrate requirements                          *
* NCNLV   R4  Nitrogen content leaves                 g N/g DM   I     *
* GSOM    R4  Maximum grain filling rate              kg/ha/d    O     *
* NHL     R4  Healthy tiller density                  till/ha    O     *
* NDH     R4  Dead heart density                      till/ha    O     *
* NWH     R4  White head density                      till/ha    O     *
* NTI     R4  Total tiller density                    till/ha    O     *
* NGR     R4  Grain density                          kernels/ha  O     *
*=====================================================================*

      SUBROUTINE SBTILL(ITASK,DELT,RDINF,DAS,DTRP,DVS,DVR,NH,NPLH,DVSWH,
     &                  SBINFR,ARTDH,TAV,TMX,GCRHL2,GSO,NCNLV,CRGCR,
     &                  SWITIL,XNHL,XNDH,XNWH,XNTI,XNDT,
     &                  GSOM,NHL,NDH,NWH,NTI,NDT,NGR,PROD,UNPROD)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,RDINF,SWITIL
      REAL DAS,DTRP
      REAL DVS,DVR,DVSWH,TAV,TMX
      REAL NH,NPLH,NHL,NDH,NWH,NTI,NDT,NGR
      REAL XNHL,XNDH,XNWH,XNTI,XNDT
      REAL SBINFR,ARTDH
      REAL GCRHL2,GSO,NCNLV,CRGCR,GSOM
```

```
*-----Local parameters

      INTEGER IMNP
      PARAMETER (IMNP=40)

      INTEGER IGGRT
      REAL GGR,GGRT(IMNP)

      INTEGER ITILN
      REAL TILN,TILNTB(IMNP)

      INTEGER ILRTIL
      REAL RTILT(IMNP)

      REAL DVST1,DVST2,DVST3,DVST4,DVST5,DVSTF,DVSTD
      REAL DVSG1,DVSG2
      REAL DVSF1,DVSF2
      REAL NTII,TILMX
      REAL NHLPH,NDHPH,NWHPH,NTIPH,NDTPH
      REAL NHLM2,NDHM2,NWHM2,NTIM2,NDTM2
      REAL FRDH,FRWH
      REAL GNTI,LNTI,LNTISB,LNTIDH,LNTIWH
      REAL TCFT,TCDT
      REAL GGRMN,GGRMX,WGRMX,GFP,TEFG
      REAL GNGR,LNGR
      REAL GNFL,NFL,SPGF,SPFERT,TFERT
      REAL CTT,COLDTT,SF1,SF2
      REAL PROD,UNPROD

      LOGICAL GRAINS

      SAVE

      IF (ITASK.EQ.1) THEN
***** INITIALIZATION

*     Read input from CROP.DAT and PEST.DAT, respectively.
      IF (RDINF.EQ.1) THEN
          CALL RDSREA ('DVST1',  DVST1)
          CALL RDSREA ('DVST2',  DVST2)
          CALL RDSREA ('DVST3',  DVST3)
          CALL RDSREA ('DVST4',  DVST4)
          CALL RDSREA ('DVST5',  DVST5)
          CALL RDSREA ('DVSG1',  DVSG1)
          CALL RDSREA ('DVSG2',  DVSG2)
          CALL RDSREA ('DVSF1',  DVSF1)
          CALL RDSREA ('DVSF2',  DVSF2)
          CALL RDSREA ('TCFT',   TCFT)
          CALL RDSREA ('TCDT',   TCDT)
          CALL RDSREA ('TCFG',   TCFG)
          CALL RDSREA ('WGRMX',  WGRMX)
          CALL RDSREA ('TILMX',  TILMX)
          CALL RDSREA ('SPGF',   SPGF)
          CALL RDAREA ('TILNTB', TILNTB,IMNP,ITILN)
          CALL RDAREA ('RTILT',  RTILT, IMNP,ILRTIL)
          CALL RDAREA ('GGRT',   GGRT,  IMNP,IGGRT)
          CALL RDSREA ('NGRT',   NGRT)
      ELSEIF (RDINF.EQ.3) THEN
          CONTINUE
      ENDIF


*     Initial number of tillers
*     Remark: this figure is only valid at transplanting, and it is
*             assumed that tillering starts after transplanting.
      NTII  = NH * NPLH * 10000.

      NHL    = NTII
      NDH    = 0.
      NWH    = 0.
      NTI    = 0.
      NDT    = 0.
      NFL    = 0.
      NGR    = 0.
      GGR    = 0.
      PROD   = NHL
      UNPROD = 0.

      ELSEIF (ITASK.EQ.2) THEN
***** RATE CALCULATION SECTION

*-----TILLERS

      IF (SWITIL.EQ.0) THEN

*     Loss rate of healthy tillers due to stem borer infestation (/ha/d)
        LNTISB = NHL*SBINFR

      ELSEIF (SWITIL.EQ.1) THEN
```

```
*       Development stages for formation and death of tillers.
        IF ((DVST1-DVS.LE.0.).AND.(DVS-DVST2.LE.0.).AND.
     &                          (DAS.GT.DTRP).AND.(DVR.GT.0.)) THEN
            DVSTF = 1.
        ELSE
            DVSTF = 0.
        ENDIF

        IF ((DVST3-DVS.LE.0.).AND.(DVS-DVST4.LE.0.).AND.
     &                                          (DAS.GT.DTRP)) THEN
            DVSTD = 1.
        ELSE
            DVSTD = 0.
        ENDIF

*       Growth and loss rates of number of tillers (/ha/d).
        IF (NHL.LT.TILMX*NH*10000.) THEN
            TILN = LINT(TILNTB,ITILN,NCNLV)
            GNTI = DVSTF * MAX(0.,TILN)
        ELSE
            GNTI = 0.
        ENDIF

        IF (NCNLV.LT.0.03) THEN
            LNTI = DVSTD*AMAX1(0.,1.E5)
        ELSE
            LNTI = 0.
        ENDIF

*     Loss rate of healthy tillers due to stem borer infestation (/ha/d)
        LNTISB = NHL*SBINFR

*       Loss rate of dead hearst due to disappearance (/ha/d).
        LNTIDH = NDH/ARTDH

*       Loss rate of white heads due to crop condition.
        LNTIWH = LNTI * NWH/NHL

*        Calculation of rates of change in productive and unproductive
*        tillers.

         IF (DVS.LT.DVST5) THEN
             CPROD  = GNTI-LNTI-LNTISB
             CUNPRO = 0.
         ELSE
             IF (UNPROD.GE.-(GNTI-LNTI-LNTISB)) THEN
                 CPROD = 0.
             ELSE
                 CPROD = GNTI-LNTI-LNTISB+UNPROD
             ENDIF

             IF (UNPROD.GE.-(GNTI-LNTI-LNTISB)) THEN
                 CUNPRO = GNTI-LNTI-LNTISB
             ELSE
                 CUNPRO = MAX(GNTI-LNTI-LNTISB,-UNPROD)
             ENDIF
          ENDIF

        ENDIF

*-----GRAINS

*-----Grain filling rate.

*       Grain filling period (days).
        IF (DVS.GE.DVSG1) THEN
            GFP   = 1./(1.33*DVR)
        ELSE
            GFP = 0.
        ENDIF

*       Minimum and maximum growth rate of one grain (kg/d).
        IF (GFP.GT.0.) THEN
            GGRMN = WGRMX/GFP
        ELSE
            GGRMN = 0.
        ENDIF
            GGRMX = AMIN1(GGRMN*2.,1.E-6)

*       Temperature effect on grain filling.
        TEFG   = LINT(GGRT,  IGGRT, TAV)

*       Maximum growth rate of storage organs.
        GSOM   = NGR*GGRMX*TEFG

*-----Grain formation.

        IF (GSO.LT.0.001) GRAINS=.FALSE.

        IF (DAS.EQ.DTRP) THEN
            COLDTT = 0.
            TFERT  = 0.
```

```
          NTFERT = 0.
       ENDIF

*      Floret formation.
       IF ((DVS.GE.DVSF1).AND.(DVS.LE.DVSF2).AND.(CRGCR.GT.0.)) THEN
          GNFL = GCRHL2/CRGCR * SPGF
       ELSE
          GNFL = 0.
       ENDIF

*      Effect of cold days on fertility.
       IF ((DVS.GE.0.75) .AND. (DVS.LE.1.2)) THEN
          CTT    = MAX(0., 22.-TAV)
          COLDTT = COLDTT + CTT
       ENDIF

       IF ((DVS.GE.0.96) .AND. (DVS.LE.1.2)) THEN
          TFERT  = TFERT  + TMX
          NTFERT = NTFERT + 1.
       ENDIF

*      Growth of number of grains.
       IF ((DVS.GE.1.0) .AND.(.NOT. GRAINS)) THEN
          GRAINS = .TRUE.
          SF1    = 1. - (4.6+0.054*COLDTT**1.56)/100.
          SF1    = MIN(1., MAX(0.,SF1))
          TFERT  = TFERT/(NTFERT)
          SF2    = 1./(1.+EXP(0.853*(TFERT-36.6)))
          SF2    = MIN(1., MAX(0.,SF2))
          SPFERT = MIN(SF1, SF2)

*      Growth of number of grains limited by organ formation.
          GNGR1  = NFL*SPFERT

*     Growth of number of grains limited by number of productive panicles
          NGRMX = PROD*NGRT
          GNGR2 = (NGRMX-NGR)/TCFG

          GNGR  = MAX(0.,MIN(GNGR1,GNGR2))

       ELSE
          GNGR   = 0.
       ENDIF

*      Loss of number of grains, mainly due to stem borer infestation.
       IF ((DVS.GT.DVST5).AND.(UNPROD.LT.-(GNTI-LNTI-LNTISB)).AND.
      &                                              (PROD.GT.0.)) THEN
            LNGR   = (GNTI-LNTI-LNTISB+UNPROD)/PROD * NGR
       ELSE
            LNGR   = 0.
       ENDIF

       ELSEIF (ITASK.EQ.3) THEN
***** INTEGRATION SECTION

*-----TILLERS
*      Number of healthy, non-infested tillers (/ha).
*      Number of deadhearts and whiteheads (/ha).
*      Total number of tillers (/ha).

       IF (SWITIL.EQ.0) THEN

          NHL = XNHL
          NDH = XNDH
          NWH = XNWH
          NDT = XNDT
          NTI = XNTI

*         Calculation of number of productive and unproductive tillers.

          IF (DVS.LT.DVST5) THEN
              PROD   = NHL
              UNPROD = 0.
          ELSE
              IF (PROD.LT.NHL) THEN
                  PROD   = PROD
               ELSE
                  PROD   = NHL
               ENDIF

               UNPROD = NTI-PROD-NDT

          ENDIF

       ELSEIF (SWITIL.EQ.1) THEN

          NHL   = INTGRL(NHL,(GNTI-LNTI-LNTISB),                DELT)
          NDT   = INTGRL(NDT,(LNTI+LNTIWH),                     DELT)
          NDH   = INTGRL(NDH,INSW(DVS-DVSWH,LNTISB,0.)-LNTIDH,  DELT)
          NWH   = INTGRL(NWH,INSW(DVS-DVSWH,0.,LNTISB)-LNTIWH,  DELT)
          NTI   = NHL+NDH+NWH+NDT
```

```
*       Calculation of number of productive and unproductive tillers.

        PROD   = INTGRL(PROD  ,CPROD ,DELT)
        UNPROD = INTGRL(UNPROD,CUNPRO,DELT)

      ENDIF

*     Number of healthy tillers, deadhearts, whiteheads, and total
*     number of tillers per hill, and per m2.
      NHLPH  = NHL/NH
      NDTPH  = NDT/NH
      NDHPH  = NDH/NH
      NWHPH  = NWH/NH
      NTIPH  = NHLPH + NDHPH + NWHPH

      NHLM2  = NHL/10000.
      NDTM2  = NDT/10000.
      NDHM2  = NDH/10000.
      NWHM2  = NWH/10000.
      NTIM2  = NHLM2+NDHM2+NWHM2+NDTM2

*     Fraction deadhearts and whiteheads.
      IF (NTIM2.GT.0.) THEN
          FRDH   = NDHM2/NTIM2
          FRWH   = NWHM2/NTIM2
      ELSE
          FRDH   = 0.
          FRWH   = 0.
      ENDIF

*-----GRAINS.

*    Total number of florets and grains on healthy, non-infested tillers
      NFL = INTGRL(NFL, GNFL     , DELT)
      NGR = INTGRL(NGR, GNGR-LNGR, DELT)

      ENDIF

      RETURN
      END

*=======================================================================*
* SUBROUTINE INSECT                                                     *
* Date    : January 1994                                                *
* Author  : A. Elings                                                   *
* Purpose: This subroutine simulates loss rates, growth rates and       *
*          weights of all plant organs of healthy tillers, dead hearts  *
*          and white heads.                                             *
*                                                                       *
* Fatal error checks: none                                              *
* Warnings          : none                                              *
* Subprograms called: TILPHO                                            *
* File usage        : none                                              *
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name   type meaning                                       units  class *
* ----   ---- -------                                       -----  ----- *
* ITASK   I4  Task that subroutine should perform             -       I  *
* DELT    R4  Time step of integration                        d       I  *
* RDINF   I4  Variable determining whether data are           -       I  *
*             read from CROP.DAT or PEST.DAT                           *
* IDOY    R4  Integer value of day of year                    d       I  *
* IDOYS   R4  Integer value of day of sowing                  d       I  *
* SBINFR  R4  Stem borer infection rate                 till/till/d   I  *
* SWICLI  R4  Switch to indicate clipping experiment          -       I  *
* ARTDH   R4  Average residence time for a dead heart       d-1       I  *
* TCLSTR  R4  Time coefficient for loss of stem reserves    d-1       I  *
* LRSTR   R4  Loss rate stem reserves                     kg/ha/d     I  *
* DVSWH   R4  DVS after which white heads are formed          -       I  *
* TRLOSS  R4  Weight loss due to transplanting            kg/ha/d     I  *
* FCSTR   R4  Mass fraction carbon in stem reserves         kg/kg     I  *
* TEFF    R4  Temperature effect on maintenance               -       I  *
* MNDVS   R4  Effect of DVS on maintenance                    -       I  *
* GSOM    R4  Maximum grain filling rate                    kg/ha/d   I  *
* DTGA    R4  Daily total gross assimilation                kg/ha/d   I  *
* DVS     R4  Development stage                               -       I  *
* GCRHL2  R4  Growth of healthy tillers, not adjusted       kg/ha/d   O  *
*             for carbohydrate requirements                            *
* RMCR    R4  Maintenace respiration rate of crop     kg CH2O/ha/d  I/O  *
*                                                                       *
* OTHER ABBREVIATIONS USED:                                             *
* xxxxSB: (due to) stem borer infestation, or clipping                  *
* xxxxREM: removed from crop by clipping (or xxxxRE)                    *
* xxxxTR: 'lost' at transplanting                                       *
* xxxxHL: healthy, i.e. not infested tillers                            *
* xxxxDH: dead hearts, caused by stem borer infestation in veg. phase   *
* xxxxWH: white heads, caused by stem borer infestation in gen. phase   *
* xCRxx:  crop                                                          *
* xLVxx:  leaves                                                        *
* xSTSxx: structural stem material                                      *
* xSTRxx: stem reserves (or xSRxx)                                      *
* xSOxx:  storage organs                                                *
```

```
* xSHxx:  shoot                                                        *
* xRTxx:  roots                                                        *
* xAGxx:  above ground                                                 *
* Fxxx:   fraction                                                     *
* Lxxxx:  loss                                                         *
* xxxGxx: green                                                        *
* xxxDxx: dead (healhty tillers and white heads)                       *
*         or disappeared (dead hearts)                                 *
* Gxxxx:  growth                                                       *
* Wxxxx:  weight                                                       *
* Rxxxx:  maintenance respiration                                      *
* MAINxx: maintenance respiration, intermediate variables              *
* CRxxxx: carbohydrate requirements                                    *
*                                                                      *
* Subroutines used: TILPHO                                             *
*======================================================================*

      SUBROUTINE INSECT(ITASK,DELT,IDOY,IDOYS,RDINF,
     &                  SBINFR,SWICLI,ARTDH,TCLSTR,LRSTR,DVSWH,
     &                  TRLOSS,FCSTR,TEFF,MNDVS,
     &                  FSH,FRT,FLV,FST,FSTR,FSO,
     &                  CRGLV,CRGST,CRGSTR,CRGRT,CRGSO,
     &                  WLVGI,WSTI,WRTI,DRLV,DVS,DTGA,GSOM,
     &                  GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2,
     &                  WLVGDH,WSTDH,WSTDDH,
     &                  WLVGWH,WSTWH,WSOWH,
     &                  WLVGHL,WSTHL,WSOHL,
     &                  WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT,
     &                  WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM,
     &                  WLVTR,WSTSTR,WSTRTR,WRTTR,
     &                  RMCR,CRGCR)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,IDOY,IDOYS,SWICLI,RDINF
      REAL SBINFR,ARTDH
      REAL TCLSTR,LRSTR
      REAL DVS,DVSWH
      REAL TRLOSS,FCSTR,TEFF,MNDVS,DRLV,DTGA,RMCR,CRGCR
      REAL FSH,FRT,FLV,FST,FSTR,FSO
      REAL CRGLV,CRGST,CRGSTR,CRGRT,CRGSO
      REAL WLVGI,WSTI,WRTI
      REAL GSOM,GCR,GLV,GST,GSTR,GRT,GSO,GCRHL2
      REAL WLVGDH,WSTDH,WSTDDH
      REAL WLVGWH,WSTWH,WSOWH
      REAL WLVGHL,WSTHL,WSOHL
      REAL WLVG,WLVD,WSTS,WSTR,WST,WSO,WRT
      REAL WLVREM,WSTSRE,WSTRRE,WSOREM,WAGREM

*-----Local parameters

      REAL FTRWH, FTRDH
      REAL LLVSB, LSTSSB,LSTRSB,LSOSB
      REAL LVREM, STSREM,STRREM,SOREM, GLVSB, GSTSSB,GSTRSB,GSOSB
      REAL LLVHL, LLVDH, LSTSDH,LLVWH, LSTRHL,LSTRDH,LSTRWH
      REAL WLVDHL,WSTSHL,WSTRHL,WRTHL
      REAL WLVDDH,WSTSDH,WSTRDH,WRTDH
      REAL WLVDWH,WSTSWH,WSTRWH,WRTWH
      REAL TRLLV,TRLSTS,TRLSTR,TRLRT
      REAL WLVTR,WSTSTR,WSTRTR,WRTTR
      REAL DTGAHL,DTGADH,DTGAWH
      REAL RMCRHL,RMCRDH,RMCRWH
      REAL GCRHL1,GCRDH1,GCRWH1,GCRWH2
      REAL GLVHL, GSTSHL,GSTRHL,GLVWH, GSTSWH,GSTRWH,GSOHL
      REAL GSOX,  DIFF

      SAVE

      IF (ITASK.EQ.1) THEN
******INITIALIZATION

*     Read input from CROP.DAT and PEST.DAT, respectively.
          IF (RDINF.EQ.1) THEN
              CONTINUE
          ELSEIF (RDINF.EQ.3) THEN
              CALL RDSREA ('FTRDH',  FTRDH)
              CALL RDSREA ('FTRWH',  FTRWH)
          ENDIF

          WLVGHL = WLVGI
          WLVDHL = 0.
          WSTSHL = WSTI
          WSTRHL = 0.
          WSTHL  = 0.
          WSOHL  = 0.
          WRTHL  = 0.

          WLVGDH = 0.
          WLVDDH = 0.
          WSTSDH = 0.
          WSTRDH = 0.
```

```
      WSTDDH = 0.
      WSTDH  = 0.
      WRTDH  = 0.

      WLVGWH = 0.
      WLVDWH = 0.
      WSTSWH = 0.
      WSTRWH = 0.
      WSTWH  = 0.
      WRTWH  = 0.
      WSOWH  = 0.

      WLVREM = 0.
      WSTSRE = 0.
      WSTRRE = 0.
      WSOREM = 0.
      WAGREM = 0.

      WLVTR  = 0.
      WSTSTR = 0.
      WSTRTR = 0.
      WRTTR  = 0.

      WLVG   = WLVGHL + WLVGDH + WLVGWH
      WLVD   = WLVDHL + WLVDDH + WLVDWH
      WSTS   = WSTSHL + WSTSDH + WSTSWH
      WSTR   = WSTRHL + WSTRDH + WSTRWH
      WST    = WSTS + WSTR
      WSO    = WSOHL + WSOWH
      WRT    = WRTI

      GCRHL2 = 0.
      GCRDH2 = 0.
      GCRWH2 = 0.
      GCR    = 0.

      CALL TILPHO(ITASK,RDINF,IDOY,IDOYS,DTGA,TEFF,MNDVS,
     &                WLVG,WLVGHL,WLVGDH,WLVGWH,
     &                WST ,WSTHL ,WSTDH ,WSTWH,
     &                WSO ,WSOHL        ,WSOWH,
     &                WRT ,WRTHL ,WRTDH ,WRTWH,
     &                DTGAHL,DTGADH,DTGAWH,RMCR,RMCRHL,RMCRDH,RMCRWH)

      ELSEIF (ITASK.EQ.2) THEN
******RATE CALCULATIONS

* Calculation of photosynthesis and maintenance of tiller classes.
      CALL TILPHO(ITASK,RDINF,IDOY,IDOYS,DTGA,TEFF,MNDVS,
     &                WLVG,WLVGHL,WLVGDH,WLVGWH,
     &                WST ,WSTHL ,WSTDH ,WSTWH,
     &                WSO ,WSOHL        ,WSOWH,
     &                WRT ,WRTHL ,WRTDH ,WRTWH,
     &                DTGAHL,DTGADH,DTGAWH,RMCR,RMCRHL,RMCRDH,RMCRWH)

* Loss rates of weights of healthy plant organs due to infestation or
* clipping (kg/ha/d). No root loss is assumed.
      LLVSB  = WLVGHL*SBINFR
      LSTSSB = WSTSHL*SBINFR
      LSTRSB = WSTRHL*SBINFR
      LSOSB  = WSOHL *SBINFR

* In case of a clipping experiment (SWICLI=1), plant material is removed
* In case of a deadheart/whitehead experiment (SWICLI=0), there is an
* increase in plant organ weight classified to infested tillers.
      LVREM  = LLVSB  * SWICLI
      STSREM = LSTSSB * SWICLI
      STRREM = LSTRSB * SWICLI
      SOREM  = LSOSB  * SWICLI
      GLVSB  = LLVSB  * (1.-SWICLI)
      GSTSSB = LSTSSB * (1.-SWICLI)
      GSTRSB = LSTRSB * (1.-SWICLI)
      GSOSB  = LSOSB  * (1.-SWICLI)

* Loss rate of leaf weight of healthy tillers due to senescence
* (kg/ha/d)
      LLVHL  = WLVGHL * DRLV

* Loss rates of plant organ weight of deadhearts, due to disappearance
* (kg/ha/d). Natural sensescense is included.
      LLVDH  = WLVGDH/ARTDH
      LSTSDH = WSTSDH/ARTDH
      LSTRDH = WSTRDH/ARTDH

* Loss rate of leaf weight due to senescence of whiteheads is similar to
* healthy leaves (kg/ha/d). No disappearance.
      LLVWH  = WLVGWH*DRLV

* Loss rates of stem reserves due to translocation (kg/ha/d).
      LSTRHL = INSW(DVS-1., 0., WSTRHL / TCLSTR)
      LSTRWH = INSW(DVS-1., 0., WSTRWH / TCLSTR)
```

```
* Growth rates.
* carbohydrate requirements for organ dry matter production are directly
* used in the calculation of actual organ growth rates.
* CRGCR, the carbohydrate requirement for total dry matter production
* is calculated afterwards.
* GCRxx is the carbohydrates need for growth for the different tiller
* classes
* Translocation included (1=before, 2 = after translocation).

        GCRHL1 = (DTGAHL*30./44.)-RMCRHL+(LSTRHL*LRSTR*FCSTR*30./12.)
        GCRDH1 = (DTGADH*30./44.)-RMCRDH
        GCRWH1 = (DTGAWH*30./44.)-RMCRWH+(LSTRWH*LRSTR*FCSTR*30./12.)

* Part of the dead heart and white head assimilates are translocated to
* healthy tillers.

        GCRHL2 = GCRHL1 + FTRDH*GCRDH1 + FTRWH*GCRWH1
        GCRDH2 = (1.-FTRDH) * GCRDH1
        GCRWH2 = (1.-FTRWH) * GCRWH1

* GSOHL is limited by the supply from the source (GSOX), and the maximum
* growth
* rate (GSOM). The difference is added to the stem reserves.
        GSOX   = GCRHL2 * FSH * FSO
        GSOHL  = AMIN1(GSOM*CRGSO,GSOX)              /CRGSO
        DIFF   = AMAX1(0.,GSOX-GSOM*CRGSO)

* Growth rate of stem reserves of healthy tillers is increased by
* carbohydrates that can not be absorbed by the grains.
        GLVHL  = GCRHL2 * FSH * FLV                  /CRGLV
        GSTSHL = GCRHL2 * FSH * FST * (1.-FSTR)      /CRGST
        GSTRHL = (GCRHL2 * FSH * FST * FSTR + DIFF) /CRGSTR

* For simplicity, assimilates formed by dead hearts and white heads and
* not translocated to healthy tillers, are equally distributed over
* stems and leaves.
        GLVDH  = GCRDH2 * 0.5                        /CRGLV
        GSTSDH = GCRDH2 * 0.5 * (1.-FSTR)            /CRGST
        GSTRDH = GCRDH2 * 0.5 * FSTR                 /CRGSTR

        GLVWH  = GCRWH2 * 0.5                        /CRGLV
        GSTSWH = GCRWH2 * 0.5 * (1.-FSTR)            /CRGST
        GSTRWH = GCRWH2 * 0.5 * FSTR                 /CRGSTR

* Overall growth rates.
* Any root growth is supported by or through the healthy tillers.
        GLV    = GLVHL  + GLVWH  + GLVDH
        GST    = GSTSHL + GSTSWH + GSTSDH
        GSTR   = GSTRWH + GSTRWH + GSTRDH
        GSO    = GSOHL
        GRT    = GCRHL2 * FRT                        /CRGRT
        GCR    = GLV + GST + GSTR + GSO + GRT

* Carbohydrate requirements for dry matter production.
        IF (GCR.GT.0.) THEN
           CRGCR = (GLV*CRGLV + GST*CRGST + GSTR*CRGSTR + GSO*CRGSO
     &              + GRT*CRGRT)/GCR
        ELSE
           CRGCR = 0.
        ENDIF

* Loss rates due to transplanting. It is assumed that not stem borer
* infestation has occured yet, so only healthy tillers are affected.
        TRLLV  = TRLOSS * FSH * FLV
        TRLSTS = TRLOSS * FSH * FST * (1.-FSTR)
        TRLSTR = TRLOSS * FSH * FST * FSTR
        TRLRT  = TRLOSS * FRT

     ELSEIF (ITASK.EQ.3) THEN
******INTEGRATIONS

* Weights of plant organs of healthy tillers (kg/ha).
        WLVGHL = INTGRL(WLVGHL,GLVHL-LLVHL-LLVSB-TRLLV,          DELT)
        WLVDHL = INTGRL(WLVDHL,LLVHL,                            DELT)
        WSTSHL = INTGRL(WSTSHL,GSTSHL-LSTSSB-TRLSTS,             DELT)
        WSTRHL = INTGRL(WSTRHL,GSTRHL-LSTRHL-LSTRSB-TRLSTR,      DELT)
        WSTHL  = WSTSHL+WSTRHL
        WSOHL  = INTGRL(WSOHL,GSOHL-LSOSB,                       DELT)

* Weights of plant organs of dead hearts (kg/ha).
        WLVGDH = INTGRL(WLVGDH,INSW(DVS-DVSWH,GLVSB,0.)+GLVDH-LLVDH,
     &                                                           DELT)
        WLVDDH = INTGRL(WLVDDH,LLVDH,                            DELT)
        WSTSDH =INTGRL(WSTSDH,INSW(DVS-DVSWH,GSTSSB,0.)+GSTSDH-LSTSDH,
     &                                                           DELT)
        WSTRDH =INTGRL(WSTRDH,INSW(DVS-DVSWH,GSTRSB,0.)+GSTRDH-LSTRDH,
     &                                                           DELT)
        WSTDH  = WSTSDH+WSTRDH
        WSTDDH = INTGRL(WSTDDH,LSTSDH+LSTRDH                    ,DELT)
```

```
* Weights of plant organs of white heads (kg/ha).
      WLVGWH = INTGRL(WLVGWH,INSW(DVS-DVSWH,0.,GLVSB)+GLVWH-LLVWH,
     &                                                        DELT)
      WLVDWH = INTGRL(WLVDWH,LLVWH,                           DELT)
      WSTSWH = INTGRL(WSTSWH,INSW(DVS-DVSWH,0.,GSTSSB)+GSTSWH, DELT)
      WSTRWH =INTGRL(WSTRWH,INSW(DVS-DVSWH,0.,GSTRSB)+GSTRWH-LSTRWH,
     &                                                        DELT)
      WSTWH  = WSTSWH+WSTRWH
      WSOWH  = INTGRL(WSOWH,GSOSB,                            DELT)

* Weights of plant organs of all tillers (kg/ha).
      WLVG   = WLVGHL + WLVGDH + WLVGWH
      WLVD   = WLVDHL + WLVDDH + WLVDWH
      WSTS   = WSTSHL + WSTSDH + WSTSWH
      WSTR   = WSTRHL + WSTRDH + WSTRWH
      WST    = WSTS + WSTR
      WSO    = WSOHL           + WSOWH

* Weight of removed material in clipping experiment (kg/ha).
      WLVREM = INTGRL (WLVREM, LVREM,                         DELT)
      WSTSRE = INTGRL (WSTSRE, STSREM,                        DELT)
      WSTRRE = INTGRL (WSTRRE, STRREM,                        DELT)
      WSOREM = INTGRL (WSOREM, SOREM,                         DELT)
      WAGREM = WLVREM + WSTSRE + WSTRRE + WSOREM

* Weight of material 'lost' at transplanting (kg/ha)
      WLVTR  = INTGRL (WLVTR, TRLLV,                          DELT)
      WSTSTR = INTGRL (WSTSTR, TRLSTS,                        DELT)
      WSTRTR = INTGRL (WSTRTR, TRLSTR,                        DELT)
      WRTTR  = INTGRL (WRTTR, TRLRT,                          DELT)

* The root system is divided over the tiller classes on the basis of
leaf
* weights.
      WRT    = INTGRL (WRT,GRT-TRLRT,                         DELT)
      IF (WLVG.GT.0.) THEN
          WRTHL  = WRT * WLVGHL/WLVG
          WRTDH  = WRT * WLVGDH/WLVG
          WRTWH  = WRT * WLVGWH/WLVG
      ELSE
          WRTHL  = 0.
          WRTDH  = 0.
          WRTWH  = 0.
      ENDIF

   ENDIF

   RETURN
   END
```

```
*=====================================================================*
* SUBROUTINE TILPHO                                                   *
* Date   : January 1994                                               *
* Author : A. Elings                                                  *
* Purpose: This subroutine simulates photosynthesis and maintenance   *
*          respiration rates of healthy tillers, dead hearts  and     *
*          white heads.                                               *
*                                                                     *
* Fatal error checks: none                                            *
* Warnings          : none                                            *
* Subprograms called: none                                            *
* File usage        : none                                            *
*                                                                     *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
* name   type meaning                                    units  class *
* ----   ---- -------                                    -----  ----- *
* ITASK   I4  Task that subroutine should perform          -       I  *
* RDINF   I4  Variable determining whether data are        -       I  *
*             read from CROP.DAT or PEST.DAT                         *
* IDOY    R4  Integer value of day of year                 d       I  *
* IDOYS   R4  Integer value of day of sowing               d       I  *
* DTGA    R4  Daily total gross assimilation            kg/ha/d    I  *
* TEFF    R4  Temperature effect on maintenance            -       I  *
* MNDVS   R4  Effect of DVS on maintenance                 -       I  *
* RMCR    R4  Maintenace respiration rate of crop     kg CH2O/ha/d I/O *
*                                                                     *
* OTHER ABBREVIATIONS USED:                                           *
* xxxxHL: healthy, i.e. not infested tillers                          *
* xxxxDH: dead hearts, caused by stem borer infestation in veg. phase *
* xxxxWH: white heads, caused by stem borer infestation in gen. pahse *
* Wxxxx:  weight                                                      *
* xCRxx:  crop                                                        *
* xLVxx:  leaves                                                      *
* xSTxx:  stem                                                        *
* xSOxx:  storage organs                                              *
* xSHxx:  shoot                                                       *
* xRTxx:  roots                                                       *
*=====================================================================*

   SUBROUTINE TILPHO(ITASK,RDINF,IDOY,IDOYS,DTGA,TEFF,MNDVS,
  &                  WLVG,WLVGHL,WLVGDH,WLVGWH,
  &                  WST ,WSTHL ,WSTDH ,WSTWH,
  &                  WSO ,WSOHL        ,WSOWH,
```

```
     &                    WRT ,WRTHL ,WRTDH ,WRTWH,
     &                    DTGAHL,DTGADH,DTGAWH,RMCR,RMCRHL,RMCRDH,RMCRWH)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER ITASK,IDOY,IDOYS,RDINF
      REAL DTGA,DTGAHL,DTGADH,DTGAWH
      REAL TEFF,MNDVS
      REAL WLVG,WLVGHL,WLVGDH,WLVGWH
      REAL WST ,WSTHL ,WSTDH ,WSTWH
      REAL WSO ,WSOHL       ,WSOWH
      REAL WRT ,WRTHL ,WRTDH ,WRTWH
      REAL RMCR,RMCRHL,RMCRDH,RMCRWH

*-----Local parameters

      REAL MAIN,MAINHL,MAINDH,MAINWH
      REAL MAINLV,MAINST,MAINSO,MAINRT

      SAVE

      IF (ITASK.EQ.1) THEN
******INITIALIZATION

*     Read input from CROP.DAT and PEST.DAT, respectively.
          IF (RDINF.EQ.1) THEN
              CALL RDSREA ('MAINLV', MAINLV)
              CALL RDSREA ('MAINST', MAINST)
              CALL RDSREA ('MAINSO', MAINSO)
              CALL RDSREA ('MAINRT', MAINRT)
          ELSEIF (RDINF.EQ.3) THEN
              CONTINUE
          ENDIF

          RMCR   = 0.

      ELSEIF (ITASK.EQ.2) THEN
******RATE CALCULATIONS

* Total gross assimilation of tillers.
* It is assumed that leaf+stem area, on which photosynthesis
* calculations are based, has the same distribution as leaf weight over
* the tiller classes.
          IF (IDOY.EQ.IDOYS) THEN
                  DTGAHL = DTGA
                  DTGADH = 0.
                  DTGAWH = 0.
          ELSEIF (WLVG.GT.0.) THEN
                  DTGAHL = DTGA * WLVGHL/WLVG
                  DTGADH = DTGA * WLVGDH/WLVG
                  DTGAWH = DTGA * WLVGWH/WLVG
          ELSE
                  DTGAHL = 0.
                  DTGADH = 0.
                  DTGAWH = 0.
          ENDIF

* Maintenance respiration.
* First some intermediate variables are calculated (MAINxx), then actual
* maintenace respiration for each tiller class.
          MAIN   = WLVG  *MAINLV+WST  *MAINST+WSO  *MAINSO+WRT  *MAINRT
          MAINHL = WLVGHL*MAINLV+WSTHL*MAINST+WSOHL*MAINSO+WRTHL*MAINRT
          MAINDH = WLVGDH*MAINLV+WSTDH*MAINST              +WRTDH*MAINRT
          MAINWH = WLVGWH*MAINLV+WSTWH*MAINST+WSOWH*MAINSO+WRTWH*MAINRT

          RMCR   = (WLVG*MAINLV + WST*MAINST +
     &              WSO*MAINSO  + WRT*MAINRT) * TEFF * MNDVS

          IF (MAIN.GT.0.) THEN
              RMCRHL = MAINHL/MAIN * RMCR
              RMCRDH = MAINDH/MAIN * RMCR
              RMCRWH = MAINWH/MAIN * RMCR
          ELSE
              RMCRHL = 0.
              RMCRDH = 0.
              RMCRWH = 0.
          ENDIF

      ENDIF

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE ABSORB                                                    *
*  Purpose: This subroutine calculates absorbed photosynthetic active   *
*           radiation for more than one leaf layer, and crop light use  *
*           efficiency                                                  *
*  A. Elings, March 1994                                                *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
```

```
*  name    type meaning                                    units  class *
*  ----    ---- -------                                    -----  ----- *
*  ITASK    I4  Task that subroutine should perform          -      I   *
*  DELT     R4  Time step of integration                     d      I   *
*  DAS      R4  Number of days after sowing                  -      I   *
*  KDF      R4  Extinction coefficient for diffuse light                I   *
*  LAITL    R4  Total leaf + stem area index, per layer     ha/ha   I   *
*  LAIG     R4  Total green leaf area index (excl. stem)    ha/ha   I   *
*  RDT      R4  Daily total of global radiation            J/m2/d   I   *
*  GCR      R4  Daily crop growth                           kg/ha   I   *
*  ABS      R4  Daily absorbed PAR                          J/m2    O   *
*  CUMABS   R4  Cumulative absorbed PAR                     J/m2    O   *
*  CLUE     R4  Crop light use efficiency                   kg/J    O   *
*  AVCLUE   R4  Average crop light use efficiency over      kg/J    O   *
*               last 10 days                                           *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : none                             *
*  FILE usage : none                                                   *
*                                                                      *
*----------------------------------------------------------------------*

      SUBROUTINE ABSORB (ITASK,DELT,DAS,KDF,LAI,RDT,GCR,
     &                   ABS,CUMABS,CLUE,AVCLUE)

      IMPLICIT REAL(A-Z)

*-----Formal parameters
      INTEGER ITASK
      REAL DAS
      REAL KDF,RDT
      REAL LAI
      REAL GCR
      REAL ABS,CUMABS,CLUE,AVCLUE

*-----Local parameters
      INTEGER N,M
      REAL CLUEC,TOCLUE
      REAL PARTR

      PARAMETER (M=10)
      DIMENSION CLUEC(M)

      SAVE

      IF (ITASK.EQ.1) THEN
******INITIALIZATION
      CUMABS = 0.

      DO 10 N = M,1,-1
      CLUEC(N) = 0.
10    CONTINUE
      TOCLUE = 0.

      ELSEIF (ITASK.EQ.2) THEN
******RATE CALCUATIONS

*-----PAR transmitted by higher leaf layers
      PARTR  = 0.5 * RDT

*-----Absorbed photosynthetically active radiation
      IF (LAI.GT.0.) THEN
          ABS = (1.-0.08) * PARTR * (1.-EXP(-KDF*LAI))
      ELSE
          ABS = 0.
      ENDIF

*-----Crop light use efficiency
*     = slope of relation cumabs, wag/xwtdm
      IF ((GCR.GT.0.).AND.(ABS.GT.0.)) THEN
          CLUE = GCR/ABS
      ELSE
          CLUE = 0.
      ENDIF

*-----Average crop light use efficiency over last 10 days

      TOCLUE    = 0.
      DO 30 N = 10,2,-1
      CLUEC(N)  = CLUEC(N-1)
      TOCLUE    = TOCLUE+CLUEC(N)
30    CONTINUE
      CLUEC(1)  = CLUE
      TOCLUE    = TOCLUE+CLUEC(1)
      IF (DAS.LT.10.) THEN
          AVCLUE = 0.
      ELSE
          AVCLUE = TOCLUE/10.
      ENDIF

      ELSEIF (ITASK.EQ.3) THEN
******INTEGRATIONS
```

```
*-----Cumulative absorbed radiation
      CUMABS = INTGRL (CUMABS, ABS, DELT)

      ELSE IF (ITASK.EQ.4) THEN
      CONTINUE
      ENDIF

      RETURN
      END
```

Appendix IIb. SBORER input files

CONTROL.DAT

```
* CONTROL.DAT created by COME-ON 0.2b
FILEON='RESULTS.OUT'
FILEIR='RERUNS.DAT'
FILEIT='TIMER.DAT'
FILEI1='CROP.DAT'
FILEI3='PEST.DAT'
FILEOL='RESULTS.LOG'
```

TIMER.DAT

```
*****************************************************************
*  RUNCONTROL FILE for COME-ON                                  *
*****************************************************************

* Weather data specification
WTRDIR = 'C:\WEATHER\'
CNTR   = 'PHIL'
ISTN   = 1          ! Station number of weather data
IFLAG = 1101        ! Indicates where weather error and warnings go
                    ! (1100 means errors and warnings only to log file,
                    ! see FSE manual)

* Time variables
IYEAR  = 1992       ! Year of weather data
DELT   = 1.         ! Time step of integration

* Output options
COPINF = 'N'        ! Swich variable denoting what to be done with
                    ! inputfiles:
                    !    'N' = do not copy inputfiles into outputfile
                    !    'Y' = copy inputfiles into outputfile

PRDEL  = 5.         ! Time between consecutive outputs to file,
                    ! (when PRDEL=0, no output is generated, when PRDEL is
                    ! very large (i.e. 10000) only initial and terminal
                    ! output is generated).
IPFORM = 4          ! (0 = no output table, 4 = normal table,

                    !  5 = tab-delimited (for Excel), 6=TTPLOT format)
DELTMP  = 'N'       ! Switch variable what should be done with the
                    ! temporary output file:
                    !    ('N' = do not delete,
                    !     'Y' = delete)

*PRSEL = 'WSO','TADRW','<TABLE>','DVS','<TABLE>'
*IOBSD = 1992,183
                    ! list of data for which output is required

*****************************************************************
*  DEFTIMER for use with COME-ON                                *
*****************************************************************

ANGA   = 0.25       ! Angstrom parameters: dry tropical A=0.25 B=0.45
ANGB   = 0.45       !                      humid tropical A=0.29 B=0.42
                    !                 cold and temperate A=0.18 B=0.55

* Time variables
STTIME = 361.       ! Sowing date ; Start day of simulation
FINTIM = 500.       ! Finish time of simulation

DTRP = 21.          ! Days between sowing and transplanting

**********
* SWTICHES
**********

SWILAI = 1    ! 0 = LAI input, analysis of experiments
              ! 1 = LAI simulated, scenario studies
SWINLV = 2    ! 0 = Reading observations: XNFLVT, g/m2
              ! 1 = 'Simulating'         : NFLVTB, g/m2
              ! 2 = Reading observations: NCNLVT, g/g
SWICLI = 0    ! 0 = Stem borer experiment
              ! 1 = Clipping experiment
SWITIL = 1    ! 0 = Tiller densities input
              ! 1 = Tiller densities simulated
```

CROP.DAT

```
************************************************************
* CROP.DAT file                                            *
*                                                          *
* STEM BORER EXPERIMENTS                                   *
*                                                          *
* STATION:   IRRI                                          *
* YEAR & SEASON: Dry Season, 1993                          *
* VARIETY:  IR64                                           *
* TREATMENT:   DEADHEARTS, WHITEHEADS                      *
* PLOT:   325, 326, 327,     328                           *
* AUTHOR: E.G. RUBIA                                       *
************************************************************

*-------------------------------------------*
* General functions and parameters for rice. *
*-------------------------------------------*

SHCKL  = 0.25
SHCKD  = 0.4

EFFTB  = 10., 0.54,
         40., 0.36

KDFTB  = 0. , 0.4,
         0.2, 0.4,
         0.6, 0.6,
         2.1, 0.6,
         3.0, 0.6

SCP    = 0.2

REDFTT = -10., 0.,
          10., 0.,
          20., 1.,
          37., 1.,
          43., 0.

SSGATB = 0. , 0.0003,
         0.9, 0.0003,
         2.1, 0.,
         3.0, 0.

TBD    = 8.
TBLV   = 8.

MAINLV = 0.02
MAINST = 0.015
MAINSO = 0.003
MAINRT = 0.01

CRGLV  = 1.326
CRGST  = 1.326
CRGSO  = 1.462
CRGRT  = 1.326
CRGSTR = 1.111

FCSTR  = 0.444
FCLV   = 0.419
FCST   = 0.431
FCRT   = 0.431
FCSO   = 0.487

LRSTR  = 0.947
TCLSTR = 10.

FSHTB  = 0.0,  0.50,
         0.43, 0.75,
         1.0,  1.0,
         2.1,  1.,
         3.0,  1.

FRTTB  = 0.0,  0.50,
         0.43, 0.25,
         1.0,  0.0,
         2.1,  0.,
         3.0,  0.

LAPO   = 0.0001

WLVGI  = 1.
WSTI   = 0.
WRTI   = 1.

FSTR   = 0.23
```

```
*-----------------------------------------------------------------*
* Parameters and functions specific for var. IR64 in all treatments. *
*-----------------------------------------------------------------*

NPLH   = 8.

NH     = 25.
NPLSB  = 1000.

DVRV   = 0.000834
DVRR   = 0.001387

*------------------------*
* Tiller characteristics *
*------------------------*

* Development stages indicating beginning and end of potential tiller
* formation.
DVST1 = 0.43
DVST2 = 0.84

* Development stages indicating beginning and end of potential tiller
* death.
DVST3 = 0.43
DVST4 = 1.44

* Development stage indicating end of formation of productive tillers.
DVST5 = 0.75

* Time coefficients for formation and death of tillers.
TCFT = 15.
TCDT = 10.

* Tiller formation rate in relation to leaf nitrogen content.
* (Makarim, 1994).
TILNTB = 0.    , 0.,
         0.0189, 0.,
         0.028 , 0.,
         0.0293, 104167.,
         0.0350, 416667.,
         0.06  , 500000.

*Average tiller death rate
TILDTH = 1.0E+5

* Maximum number of tillers per hill.
TILMX = 40.

*-----------------------*
* Grain characteristics *
*-----------------------*

* Development stages indicating beginning and end of floret formation.
DVSF1 = 0.65
DVSF2 = 1.00

*Spikelet growth factor.
SPGF  = 64900.

* Development stages indicating beginning and end of grain formation.
DVSG1 = 0.95
DVSG2 = 1.15

* Time coefficients for formation of grains.
TCFG = 3.

*Relation of temperature to growth rate of grains.
GGRT  = 10., 0.0,
        15., 0.0,
        18., 0.75,
        23., 1.0,
        27., 0.9,
        40., 0.0

* Maximum number of grains per productive tiller.
NGRT = 60.

* Maximum weight of one kernel (kg)
WGRMX = 25.5E-6
```

PEST.DAT

```
*****************************************************************
* PEST.DAT file                                                 *
*                                                               *
* STEM BORER EXPERIMENTS                                        *
*                                                               *
* STATION:       IRRI                                           *
* YEAR & SEASON: Dry Season, 1993                               *
* VARIETY:       IR64                                           *
* TREATMENT:     WHITEHEADS                                     *
* PLOT:          325, 326, 327, 328                             *
* AUTHOR:        E.G. RUBIA                                     *
*****************************************************************

*---------------------------------------------------------------*
* Parameters and functions specific for var. IR64 in all treatments. *
*---------------------------------------------------------------*

RGRL = 0.006
OBS1 = 15

*---------------------------------------------------------------*
* Parameters and functions for var. IR64 in specific treatment. *
*---------------------------------------------------------------*

SLATB   =      0.,  0.00363,
              15.,  0.00363,
              21.,  0.00538,
              27.,  0.00377,
              34.,  0.00346,
              48.,  0.00256,
              62.,  0.00195,
              76.,  0.00213,
              90.,  0.00172,
             104.,  0.00124,
             112.,  0.00124,
             240.,  0.,
             360.,  0.00300,
             366.,  0.00300

DRLVT   =       0.,     0.,
                0.33,   0.,
                0.39,   0.,
                0.49,   0.,
                1.26,   0.02,
                1.63,   0.03,
                1.93,   0.04,
                2.01,   0.04,
                3.    , 0.

FSTTB   =       0.0 ,  0.40,
                0.26,  0.59,
                0.31,  0.50,
                0.39,  0.67,
                0.53,  0.59,
                0.74,  0.58,
                0.96,  0.56,
                1.26,  0.44,
                1.63,  0.,
                1.92,  0.,
                2.01,  0.,
                3.   ,  0.

FLVTB   =       0.0 ,  0.60,
                0.26,  0.41,
                0.31,  0.50,
                0.39,  0.33,
                0.53,  0.41,
                0.74,  0.42,
                0.96,  0.24,
                1.26,  0.06,
                1.63,  0.,
                1.92,  0.,
                2.01,  0.,
                3.   ,  0.

FSOTB   =       0.0 ,  0.,
                0.26,  0.,
                0.31,  0.,
                0.39,  0.,
                0.53,  0.,
                0.74,  0.,
                0.96,  0.2,
                1.26,  0.50,
                1.63,  1.0,
                1.92,  1.0,
                2.01,  1.0,
                3.   ,  0.
```

```
XWLVGT =      1.,     0.,
             15.,    22.,
             21.,    29.,
             27.,    53.,
             34.,    81.,
             48.,   359.,
             62.,  1068.,
             76.,  1863.,
             90.,  1781.,
            104.,  1021.,
            112.,   697.,
            366.,     0.

XWSTTB =      1.,     0.,
             15.,    23.,
             21.,    34.,
             27.,    58.,
             34.,   113.,
             48.,   516.,
             62.,  1542.,
             76.,  3698.,
             90.,  5030.,
            104.,  4262.,
            112.,  3818.,
            366.,     0.

XWPATB =      0.,     0.,
             15.,     0.,
             21.,     0.,
             27.,     0.,
             34.,     0.,
             48.,     0.,
             62.,     0.,
             76.,   348.,
             90.,  1870.,
            104.,  6500.,
            112.,  5550.,
            366.,     0.

XWLVDT =      0.,     0.,
             15.,     0.,
             21.,     0.,
             27.,     0.,
             34.,     0.,
             48.,     8.,
             62.,    40.,
             76.,    66.,
             90.,   289.,
            104.,   896.,
            112.,   785.,
            366.,     0.

XWTDMT =      0.,     0.,
             15.,    45.,
             21.,    62.,
             27.,   111.,
             34.,   195.,
             48.,   883.,
             62.,  2649.,
             76.,  5947.,
             90.,  8970.,
            104., 12679.,
            112., 10850.,
            366.,     0.

XLAITB =      0.,   0.,
             15.,   0.078,
             21.,   0.155,
             27.,   0.201,
             34.,   0.281,
             48.,   0.938,
             62.,   2.16,
             76.,   4.11,
             90.,   3.73,
            104.,   2.42,
            112.,   1.53,
            366.,   0.

*number of healthy tillers
XNHLT =              0.,   0.,
                    14.,   0.,
                    15.,   2.0E+6,
                    21.,   1.94E+6,
                    27.,   2.03E+6,
                    34.,   2.36E+6,
```

```
                    48.,   5.83E+6,
                    62.,   9.81E+6,
                    76.,   9.58E+6,
                    90.,   9.36E+6,
                   104.,   9.58E+6,
                   112.,   8.60E+6,
                   113.,   0.,
                   366.,   0.

*number of dead tillers
XNDTT  =             0.,  0.,
                    15.,  0.,
                    21.,  0.,
                    27.,  0.,
                    34.,  0.,
                    35.,  0.,
                    48.,  0.,
                    62.,  0.,
                    76.,  0.,
                    90.,  843750.,
                   104.,  703125.,
                   112.,  541700.,
                   113.,  0.,
                   366.,  0.

* Total number of tillers (healthy + dh + wh + dead)
XNTIT =        0.,  0.,
              14.,  0.,
              15.,  2000000.,
              21.,  1942708.,
              27.,  2026042.,
              34.,  2359375.,
              48.,  5843800.,
              62., 10156200.,
              76., 10218700.,
              90., 11125000.,
             104.,  11375000.,
             112.,  10031200.,
             113.,  0.,
             366.,  0.

* Number of deadhearts
XNDHT =       0., 0.,
             47., 0.,
             48., 0.,
             76., 0.,
             90., 640600.,
            104., 203100.,
            112., 31200.,
            113., 0.,
            366., 0.

* Number of whiteheads
XNWHT =       0., 0.,
             89., 0.,
             90., 281250.,
            104., 890600.,
            112., 854200.,
            113., 0.,
            366., 0.

* Weight of green leaves of healthy tillers
XWLGHT =      1.,      0.,
             15.,     22.,
             21.,     29.,
             27.,     53.,
             34.,     81.,
             48.,    359.,
             62.,   1060.,
             76.,   1814.,
             90.,   1694.,
            104.,   934.,
            112.,    652.,
            366.,      0.

* Weight of dead leaves of healthy tillers
XWLDHT  =     1.,      0.,
             15.,      0.,
             21.,      0.,
             27.,      0.,
             34.,      0.,
             48.,      8.,
             62.,     40.,
             76.,     64.,
             90.,    232.,
            104.,    704.,
            112.,    660.,
            366.,      0.
```

```
* Weight of geen leaves of whiteheads
XWLGWT =      0., 0.,
             34., 0.,
             48., 0.,
             62., 0.,
             76., 0.,
             90., 87.,
            104., 86.,
            112., 45.,
            113., 0.,
            366., 0.

* Weight of dead leaves of whiteheads
XWLDWT =      0., 0.,
             34., 0.,
             48., 0.,
             62., 0.,
             76., 0.,
             90., 20.,
            104., 69.,
            112., 76.,
            113., 0.,
            366., 0.

* Weight of stems of whiteheads
XWSTWT =      0., 0.,
             15., 0.,
             27., 0.,
             34., 0.,
             47., 0.,
             48., 0.,
             62., 0.,
             76., 0.,
             90., 182.,
            104., 303.,
            112., 216.,
            113., 0.,
            366., 0.

* Weight of geen leaves of deadhearts
XWLGDT =   0., 0.,
         366., 0.

* Weight of dead leaves of deadhearts
XWLDDT =   0., 0.,
         366., 0.

* Weight of stems of deadhearts
XWSTDT =   0., 0.,
         366., 0.

* DUMMY!!!
XNFLVT  =    0., 0.,
           366., 0.

* DUMMY!!!!!
NFLVTB =  0.,  2.,
          1.,  1.5,
          2.1, 1.0

NCNLVT  =     0.,   0.0330,
             62.,   0.0329,
             76.,   0.0306,
             90.,   0.0274,
            104.,   0.0210,
            112.,   0.0200,
            360.,   0.0330,
            366.,   0.0330

*------------*
* Stem borer *
*------------*

* Stem borer infestation rate, related to day of the year.
SBIRTB = 0., 0.,
         77., 0.,
         78., 0.,
         79., 0.,
         81., 0.0048,
         85., 0.0062,
         88., 0.0072,
         91., 0.0083,
         92., 0.0091,
         93., 0.039,
         95., 0.0046,
        105., 0.0045,
        106., 0.,
        366., 0.
```

```
* Development stage after which stem borers cause whiteheads, not
* deadhearts.
DVSWH = 1.3

* Average residence time of deadhearts (d).
ARTDH = 14.

* Fraction assimilates produced in healthy leaf area of white heads
* and dead hearts, translocated to non-enfested tillers.
FTRWH = 0.2
FTRDH = 0.5

****************************************
** PARAMETERS FOR SENSITIVITY ANALYSIS **
****************************************

* Leaf nitrogen content (kg/kg)
SENS1 = 0.
```

Appendix III. Acronyms used in the BLIGHT and SBORER models

Acronym	Explanation	Dimension
ABS	Daily absorbed photsynthetic active radiation	J m^{-2} d^{-1}
ADDL(x)	Dead leaf area for canopy layer x (intermediate variable)	ha ha^{-1}
ADSL(x)	Diseased leaf area for canopy layer x (intermediate variable)	ha ha^{-1}
AHLL(x)	Healthy leaf area for canopy layer x (intermediate variable)	ha ha^{-1}
AMAX	Actual CO_2 assimilation rate at light saturation for individual leaves at a specific height in the canopy (Subroutine ASSIMP)	kg CO_2 ha^{-1} leaf h^{-1}
AMAXD(x)	AMAX of diseased leaf area in canopy layer x	kg CO_2 ha^{-1} h^{-1}
AMAXDC(x)	Correction factor on AMAX due to disease presence in canopy layer x	-
AMAXDT	Function relating correction factor on AMAX due to disease presence to disease severity	-
AMAXH(x)	AMAX of healthy leaf area in canopy layer x	kg CO_2 ha^{-1} leaf h^{-1}
AOB	Intermediate variable	-
ARTDH	Average residence time of dead hearts	d
ASEV(x)	Average disease severity of leaves and stems in canopy layer x	-
ASEVL	Average disease severity of diseased leaf area	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
ATMTR	Atmospheric transmission coefficient	-
AVCLUE	Average crop light use efficiency over the last 10 days	kg J^{-1}
CBCHK	Difference between carbon added to the crop since initialization and the net total of integrated carbon fluxes, relative to their sum	-
CKCIN	Carbon in the crop accumulated since simulation started	kg C ha^{-1}
CKCFI	Sum of integrated carbon fluxes into and out of the crop	kg C ha^{-1}
CLUE	Daily crop light use efficiency	kg J^{-1}
CLUEC	Intermediate variable in calucation AVCLUE	kg J^{-1}
CLUSTF	Cluster factor	-
CNTI	Carbohydrate requirements for initiation and maintenance of one tiller	kg CH_2O ha^{-1} ground d^{-1}
CNTIT	Function relating carbohydrate requirements for initiation and maintenance of one tiller to crop development stage	

COLDTT	Accumulated cold degree-days	^{o}C d
COS	Cosine function (intrinsic FORTRAN function)	-
COSLD	Intermediate variable in calculating solar height	-
CO2LV	CO_2 production factor for growth of leaves	kg CO_2 kg^{-1} DM
CO2RT	CO_2 production factor for growth of roots	kg CO_2 kg^{-1} DM
CO2SO	CO_2 production factor for growth of storage organs	kg CO_2 kg^{-1} DM
CO2ST	CO_2 production factor for growth of stems	kg CO_2 kg^{-1} DM
CO2STR	CO_2 production factor for growth of stem reserves	kg CO_2 kg^{-1} DM
CPROD	Change in number of productive tillers	number d^{-1}
CRGCR	Carbohydrate (CH_2O) requirement for dry matter production	kg CH_2O kg^{-1} DM
CRGLV	Carbohydrate requirement for leaf dry matter production	kg CH_2O kg^{-1} DM leaf
CRGRT	Carbohydrate requirement for root dry matter production	kg CH_2O kg^{-1} DM root
CRGSO	Carbohydrate requirement for stor. organ dry matter production	kg CH_2O kg^{-1} DM st.organ
CRGST	Carbohydrate requirement for stem dry matter production	kg CH_2O kg^{-1} DM stem
CRGSTR	Carbohydrate requirement for stem reserves production	kg CH_2O kg^{-1} DM
CUMABS	Cumulative absorbed photosynthetic active radiation	J m^{-2} ground
CUNPROD	Change in number of unproductive tillers	number d^{-1}
DAS	Number of days after sowing	d
DAYL	Daylength	h
DEC	Declination of the sun	radians
DELT	Time interval of integration (reserved name)	d
DIFF	Difference between sink-limited and source-limited growth rate of the storage organs	kg DM ha^{-1} ground d^{-1}
DOY	Daynumber since 1 January (day of year) (reserved variable name)	-
DOYS	Seeding date, daynumber of year	-
DOYTR	Transplanting date, daynumber of year	-
DRLVT	Table for leaf death coefficient as function of DVS	d^{-1}, -
DS0	Daily extra-terrestrial radiation	J m^{-2} d^{-1}
DSINB	Integral of SINB over the day	s d^{-1}
DSINBE	As DSINB, but with a correction for lower atmospheric transmission at lower solar elevations	s d^{-1}
DTGA	Daily total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1} ground d^{-1}
DTGADH	Daily total gross assimilation of dead hearts	kg CO_2 ha^{-1} ground d^{-1}
DTGAHL	Daily total gross assimilation of healthy tillers	kg CO_2 ha^{-1} ground d^{-1}
DTGAWH	Daily total gross assimilation of white heads	kg CO_2 ha^{-1} ground d^{-1}
DTR	Daily total global radiation	J m^{-2} d^{-1}
DTRP	Number of days after transplanting	-
DVR	Development rate of the crop	d^{-1}
DVRV	Development rate in the vegetative phase (pre-anthesis)	(^{o}C d)$^{-1}$

DVRR	Development rate in the reproductive phase (post-anthesis)	$(^{o}C\ d)^{-1}$
DVS	Development stage of the crop	-
DVSI	Initial value of development stage of the crop	-
DVSF1	Development stage at beginning of floret formation	-
DVSF2	Development stage at end of floret formation	-
DVSG1	Development stage at beginning of grain formation	-
DVSG2	Development stage at end of grain formation	-
DVSTD	Variable with value 1 during tiller death	-
DVSTF	Variable with value 1 during tiller formation	-
DVST1	Development stage at beginning of tiller formation	-
DVST2	Development stage at end of tiller formation	-
DVST3	Development stage at beginning of tiller death	-
DVST4	Development stage at end of tiller death	-
DVST5	Development stage at which productive tiller density is determined	-
DVSWH	Development stage before which dead hearts, and after which white heads are formed	-
EFF	Initial light use efficiency for individual leaves	kg CO_2 ha^{-1} leaf h^{-1} (J m^{-2} leaf $s^{-1})^{-1}$
EFFD(x)	EFF of diseased leaf area in layer x	kg CO_2 ha^{-1} leaf h^{-1}
EFFDC(x)	Correction factor on EFF due to disease presence in canopy layer x	-
EFFDT	Function relating correction factor on EFF due to disease presence to disease severity	
EFFH(x)	EFF of healthy leaf area in canopy layer x	kg CO_2 ha^{-1} leaf h^{-1}
EFFTB	Table of EFF as a function of temperature	EFF, ^{o}C
FCLV	Mass fraction carbon in the leaves	kg C kg^{-1} DM
FCRT	Mass fraction carbon in the roots	kg C kg^{-1} DM
FCSO	Mass fraction carbon in the storage organs	kg C kg^{-1} DM
FCST	Mass fraction carbon in the stems	kg C kg^{-1} DM
FCSTR	Mass fraction carbon in the stem reserves	kg C kg^{-1} DM
FDDL(x)	Fraction dead leaf area in canopy layer x	-
FDDT(x)	Fraction dead leaf plus stem area in canopy layer x	-
FDSL(x)	Fraction diseased leaf area of canopy layer x	-
FDSLx	Function relating fraction diseased leaf area of canopy layer x to time	
FDDLA	Total fraction dead leaf plus stem area	-
FDSLA	Total fraction diseased leaf plus stem area	-
FDSLW	Weight fraction of total diseased leaf area	-
FDST(x)	Fraction diseased leaf plus stem area in canopy layer x	-
FGL	CO_2 assimilation rate at a specific depth in the canopy (SBORER model)	kg CO_2 ha^{-1} leaf h^{-1}

FGL	CO_2 assimilation rate at a specific depth in a canopy layer (BLIGHT model)	kg CO_2 ha^{-1} leaf h^{-1}
FGROS	Instantaneous canopy CO_2 assimilation (SBORER model)	kg CO_2 ha^{-1} ground h^{-1}
FGROS	Instantaneous canopy CO_2 assimilation rate (BLIGHT model)	kg CO_2 ha^{-1} ground h^{-1}
FGROSL	Instantaneous canopy layer CO_2 assimilation rate (BLIGHT model)	kg CO_2 ha^{-1} ground h^{-1}
FGRS	Intermediate variable for calculation of assimilation of sunlit leaves	-
FGRSD	Intermediate variable for calculation of assimilation of sunlit leaves, accounting for diseased leaf area	-
FGRSH	CO_2 assimilation rate at one depth in the canopy for shaded leaves (SBORER model)	kg CO_2 ha^{-1} leaf h^{-1}
FGRSH	CO_2 assimilation rate at one depth in a canopy layer for shaded leaves (BLIGHT model)	kg CO_2 ha^{-1} leaf h^{-1}
FGRSHD	Intermediate varialbe for calculation of assimilation of shaded leaves, accounting for diseased leaves	-
FGRSHH	Intermediate variable for calculation of assimilation of sunlit leaves, accounting for healthy leaves	-
FGRSHL	Intermediate variable for calculation of assimilation of sunlit leaves, accounting for healthy leaves	-
FGRSUN	CO_2 assimilation rate at one depth in the canopy for sunlit leaves (SBORER model)	kg CO_2 ha^{-1} leaf h^{-1}
FGRSUN	CO_2 assimilation rate at one depth in a canopy layer for sunlit leaves (BLIGHT model)	kg CO_2 ha^{-1} leaf h^{-1}
FHLL(x)	Fraction healthy leaf area of canopy layer x	-
FHLLx	Function relating fraction healthy leaf area of canopy layer x to time	
FHLLA	Total fraction total healthy leaf plus stem area	-
FHLLW	Weight fraction of total healthy leaf area	-
FHLT(x)	Fraction healthy leaf plus stem area in canopy layer x	-
FINTIM	Finish time, period of simulation (reserved name)	d
FLV	Fraction of shoot dry matter allocated to leaves	-
FLVTB	Table of FLV as function of DVS	-, -
FRDF	Fraction diffuse in incoming radiation	-
FRT	Fraction of total dry matter allocated to roots	-
FRTTB	Table of FRT as function of DVS	-, -
FSH	Fraction of total dry matter allocated to shoots	-
FSHTB	Table of FSH as function of DVS	-, -
FSLLA	Fraction of sunlit leaf area	-
FSO	Fraction of shoot dry matter allocated to storage organs	-
FSOTB	Table of FSO as function of DVS	-, -

FST	Fraction of shoot dry matter allocated to stems	-
FSTTB	Table of FST as function of DVS	-, -
FTOT	Sum of factions of partitioning tables	-
FSTR	Fraction carbohydrates allocated to the stems, that is stored as reserves	-
FTRDH	Fraction carbohydrates formed by dead hearts translocated to healthy tillers	-
FTRWH	Fraction carbohydrates formed by white heads translocated to healthy tillers	-
GCR	Gross growth rate of crop dry matter, including translocation	kg DM ha^{-1} ground d^{-1}
GCRDH1	Potential amount of carbohydrates used for growth of dead hearts	kg CH_2O ha^{-1} d^{-1}
GCRDH2	Actual amount of carbohydrates used for growth of dead hearts	kg CH_2O ha^{-1} d^{-1}
GCRHL1	Potential amount of carbohydrates used for growth of healthy tillers	kg CH_2O ha^{-1} d^{-1}
GCRHL2	Actual amount of carbohydrates used for growth of healthy tillers	kg CH_2O ha^{-1} d^{-1}
GCRWH1	Potential amount of carbohydrates used for growth of white heads	kg CH_2O ha^{-1} d^{-1}
GCRWH2	Actual amount of carbohydrates used for growth of white heads	kg CH_2O ha^{-1} d^{-1}
GFP	Grain filling period	d
GGR	Rate of increase in grain weight	kg DM ha^{-1} ground d^{-1}
GGRMN	Minimum growth rate of one grain	kg DM d^{-1}
GGRMX	Maximum growth rate of one grain	kg DM d^{-1}
GGRT	Function relating growth rate of one grain to temperature	
GLAI	Green leaf plus stem area index	ha leaf ha^{-1} ground
GLV	Dry matter growth rate of leaves	kg DM ha^{-1} ground d^{-1}
GLVHL	Dry matter growth of healthy tillers	kg DM ha^{-1} ground d^{-1}
GLVSB	Dry matter growth of leaves of infested tillers, or loss of healthy tillers, due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
GLVWH	Dry matter growth of white heads	kg DM ha^{-1} ground d^{-1}
GNGR	Daily increment in grain number	number ha^{-1} ground d^{-1}
GNTI	Daily increment in number of healthy tillers	number ha^{-1} ground d^{-1}
GRAINS	Fortran logical function whether grains are formed	Boolean
GRT	Dry matter growth rate of roots	kg DM ha^{-1} ground d^{-1}
GSO	Dry matter growth rate of storage organs	kg DM ha^{-1} ground d^{-1}
GSOHL	Dry matter growth of storage organs of healthy tillers	kg DM ha^{-1} ground d^{-1}
GSOM	Maximum, sink-limited dry matter growth of storage organs of healthy tillers	kg DM ha^{-1} ground d^{-1}

GSOSB	Dry matter growth of storage organs of infested tillers, or loss of healthy tillers, due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
GSOX	Intermediate variable in growth calculation	-
GST	Dry matter growth rate of stems	kg DM ha^{-1} ground d^{-1}
GSTR	Dry matter growth rate of the stem reserves	kg DM ha^{-1} ground d^{-1}
GSTRHL	Dry matter growth of stem reserves of healthy tillers	kg DM ha^{-1} ground d^{-1}
GSTRSB	Dry matter growth of stem reserves of infested tillers, or loss of healthy tillers, due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
GSTRWH	Dry matter growth of stem reserves of white heads	kg DM ha^{-1} ground d^{-1}
GSTSHL	Dry matter growth of structural stem material of healthy tillers	kg DM ha^{-1} ground d^{-1}
GSTSWH	Dry matter growth of structural stem material of white heads	kg DM ha^{-1} ground d^{-1}
HOUR	Selected hour during the day	h
HU	Daily heat units effective for phenological development	(^oC d) d^{-1}
HULV	Daily heat units effective for leaf area development	(^oC d) d^{-1}
I1	Do-loop counter	-
I2	Do-loop counter	-
IDAS	Integer value of days after sowing	d
IGAUSS	Do-loop counter	-
IN	Number of canopy layers	-
IYEAR	Integer value of year of sowing	-
KBL	Extinction coefficient for direct component of direct PAR flux	ha ground ha^{-1} leaf
KDF	Extinction coefficient for leaves	ha ground ha^{-1} leaf
KDFTB	Table of KDF as function of development stage (DVS)	-, -
KDRT	Extinction coefficient for total direct PAR flux	ha ground ha^{-1} leaf
LAPI	Leaf area per plant in seedbed	m^2 $plant^{-1}$
LAI	Total area index (leaves + stems)	ha leaf ha^{-1} ground
LAIA(x)	Leaf area index above selected canopy layer in assimilation calculation	ha leaf ha^{-1} ground
LAIC	Leaf area index above selected height in canopy	ha leaf ha^{-1} ground
LAIDD	Total dead leaf area	ha leaf ha^{-1} ground
LAIDS	Total diseased leaf area	ha leaf ha^{-1} ground
LAIEXP	Leaf area index at end of exponential leaf area growth phase	ha leaf ha^{-1} ground
LAIEXS	Leaf area index at end of exponential leaf area growth phase in seedbed	ha leaf ha^{-1} ground
LAIG(x)	Green leaf plus stem area for canopy layer x	ha leaf ha^{-1} ground
LAIHL	Total healthy leaf area	ha leaf ha^{-1} ground
LAII	Initial leaf area index at tranplanting	ha leaf ha^{-1} ground
LAIL	Total leaf area	ha leaf ha^{-1} ground

LAILLx	Function relating leaf area of canopy layer 1 to time	
LAILL(x)	Leaf area of canopy layer x	ha leaf ha^{-1} ground
LAITL(x)	Leaf plus stem area in canopy layer x	ha leaf ha^{-1} ground
LAIX	Total leaf area (intermediate variable)	ha leaf ha^{-1} ground
LAT	Latitude of the weather station (reserved variable name from WEATHER)	degrees
LLV	Loss of leaves	kg leaf ha^{-1} d^{-1}
LLVDH	Dry matter loss of leaves of dead hearts due to senescence	kg DM ha^{-1} ground d^{-1}
LLVHL	Dry matter loss of leaves of healthy tillers due to disappearance	kg DM ha^{-1} ground d^{-1}
LLVSB	Dry matter loss of leaves of healthy tillers due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
LLVWH	Dry matter loss of leaves of white heads due to senescence	kg DM ha^{-1} ground d^{-1}
LNGR	Daily decrease in grain number	number ha^{-1} ground d^{-1}
LNTI	Daily decrease in number of healthy tillers due to crop conditions	number ha^{-1} ground d^{-1}
LNTIDH	Daily decrease in number of dead hearts due todisappearance	number ha^{-1} ground d^{-1}
LNTISB	Daily decrease in number of healthy tillers due to stem borer infestation	number ha^{-1} ground d^{-1}
LNTIWH	Daily decrease in number of white heads due to crop conditions	number ha^{-1} ground d^{-1}
LRSTR	Fraction (1 - 5.3%) of allocated stem reserves that is available for growth (5.3% loss due to membrane passages)	-
LSTR	Loss rate of stem reserves	kg stem res. ha^{-1} d^{-1}
LSTRDH	Dry matter loss of stem reserves of dead hearts due to disappearance	kg DM ha^{-1} ground d^{-1}
LSTRHL	Dry matter loss of stem reserves of healthy tillers due to senescence	kg DM ha^{-1} ground d^{-1}
LSTRWH	Dry matter loss of stem reserves of white heads due tosenescence	kg DM ha^{-1} ground d^{-1}
LSTSDH	Dry matter loss of structural stem material of dead hearts due to disappearance	kg DM ha^{-1} ground d^{-1}
LSOSB	Dry matter loss of storage organs of healthy tillers due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
LSTRSB	Dry matter loss of stem reserves of healthy tillers due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
LSTSSB	Dry matter loss of structural stem material of healthy tillers due to stem borer infestation	kg DM ha^{-1} ground d^{-1}
LVREM	Dry matter loss of leaves of healthy tillers due to clipping	kg DM ha^{-1} ground d^{-1}
MAINDH	Intermediate variable in calculation of maintenance respiration of dead hearts	-

MAINDT	Function relating respiration rate to disease severity	
MAINHL	Intermediate variable in calculation of maintenance respiration of healthy tillers	-
MAINLV	Maintenance respiration coefficient of leaves	kg CH_2O kg^{-1} DM d^{-1}
MAINRT	Maintenance respiration coefficient of roots	kg CH_2O kg^{-1} DM d^{-1}
MAINSO	Maintenance respiration coefficient of storage organs	kg CH_2O kg^{-1} DM d^{-1}
MAINST	Maintenance respiration coefficient of stems	kg CH_2O kg^{-1} DM d^{-1}
MAINWH	Intermediate variable in calculation of maintenance respiration of white heads	-
MNDVS	Factor accounting for effect of DVS on maintenance respiration	-
NCDALL	Intermediate variable in calculation of average leaf nitrogen content of diseased leaf area	
NCDAV	Average leaf nitrogen content of diseased leaf area	kg N kg^{-1} DM
NCHALL	Intermediate variable in calculation of average leaf nitrogen content of healthy leaf area	
NCHAV	Average leaf nitrogen content of healthy leaf area	kg N kg^{-1} DM
NCNLV	Nitrogen content in the leaves	kg N kg^{-1} leaves
NCNLVT	Function relating leaf nitrogen content to time	-
NCNTD(x)	N content of diseased leaf area in canopy layer x	kg N kg^{-1} DM
NCNTDx	Function relating N content of diseased leaf area in canopy layer x to time	
NCNTHx	Function relating N content of healthy leaf area in canopy layer x to time	
NCNTH(x)	N content of healthy leaf area in canopy layer x	kg N kg^{-1} DM
NCOLD	Number of cold days	d
NDH	Dead heart density	number ha^{-1}
NDHPH	Number of dead hearts per hill	number $hill^{-1}$
NFLV	Nitrogen fraction in the leaves	g N m^{-2} leaf
NFLVD(x)	Nitrogen fraction of diseased leaf area in canopy layer x	g m^{-2}
NFLVH(x)	Nitrogen fraction of healthy leaf area in canopy layer x	g m^{-2}
NFLVTB	Table of NFLV as function of development stage (DVS)	-
NGR	Grain density	number ha^{-1}
NGRT	Maximum number of grains per productive tiller	number $tiller^{-1}$
NH	Number of hills	hills m^{-2}
NHL	Healthy tiller density	number ha^{-1}
NHLPH	Number of healthy tillers per hill	number $hill^{-1}$
NPLH	Number of plants per hill	plants $hill^{-1}$
NPLSB	Number of plants in seedbed	plants m^{-2}
NTFERT	Number of days for TFERT	d
NTI	Total tiller density	number ha^{-1}
NTII	Initial total tiller density	number ha^{-1}

NTIPH	Total number of tillers per hill	number $hill^{-1}$
NTIP	Potential tiller density	number ha^{-1}
NWH	White head density	number ha^{-1}
NWHPH	Number of white heads per hill	number $hill^{-1}$
OBS1	Day of the year that first observation was taken	d
PAR	Instantaneous flux of photosynthetically active radiation	J m^{-2} ground s^{-1}
PARABS(x)	Absorbed photosynthetic active radiation by canopy layer x	J m^{-2} d^{-1}
PARDF	Instantaneous diffuse flux of incoming PAR	J m^{-2} ground s^{-1}
PARDR	Instantaneous direct flux of incoming PAR	J m^{-2} ground s^{-1}
PARTR	Photosynthetic active radiation transmitted by upper canopy layer	J m^{-2} d^{-1}
PI	Ratio of circumference to diameter of circle	-
PRDEL	Time interval for tabular printed output (reserved name)	d
PROD	Productive tiller density	number ha^{-1}
Q10	Factor accounting for increase of maintenance respiration with a 10 °C rise temperature	-
RAD	Factor to convert degrees to radians	radians $degree^{-1}$
RAIN	Precipitation (reserved weather variable name)	mm
RDD	Daily global radiation (reserved weather variable name)	J m^{-2} d^{-1}
RDINF	Parameter determining whether data are read from the PEST.DAT or CROP.DAT input file	-
REDFT	Factor accounting for effect of temperature on AMAX	-
REDFTT	Table of REDFT as function of temperature	-, °C
REFH	Reflection coefficient for diffuse PAR	-
REFS	Reflection coefficient for direct PAR	-
RGCR	Growth respiration rate of the crop	kg CO_2 ha^{-1} d^{-1}
RGRL	Relative growth rate of leaf area during exponential growth	$(°C\ d)^{-1}$
RMAIN	Ratio between respiration of diseased and healthy leaf area	-
RMCR	Maintenance respiration rate of the crop	kg CH_2O ha^{-1} d^{-1}
RMCRDH	Growth respiration rate of dead heart fraction of crop	kg CH_2O ha^{-1} d^{-1}
RMCRHL	Growth respiration rate of healthy tiller fraction of crop	kg CH_2O ha^{-1} d^{-1}
RMCRWH	Growth respiration rate of white head fraction of crop	kg CH_2O ha^{-1} d^{-1}
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}
RTILT	Funtion relating maximum tiller density to leaf nitrogen content	-
SAI	Stem area index	ha ha^{-1}
SAIL(x)	Stem area in canopy layer x	ha leaf ha^{-1} ground
SBINFR	Relative stem borer infection rate	d^{-1}
SBIRTB	Function relating relative stem borer infection rate to time	-

SC	Solar constant, corrected for varying distances between sun and earth	J m^{-2} s^{-1}
SCP	Scattering coefficient of leaves for PAR	-
SENS1	Parameter to simply enable variation in leaf N content	-
SENS2	Parameter to simply enable variation in FHLL	-
SENS3	Parameter to simply enable variation in FDSL	-
SENS4	Parameter to simply enable variation in SEVL	-
SENS5	Parameter to simply enable variation in SEVS	-
SEVL(x)	Disease severity of diseased leaf area in canopy layer x	-
SEVLx	Function relating disease severity of diseased leaf area in canopy layer x to time	-
SEVS(x)	Disease severity of diseased stem area in canopy layer x	-
SEVSx	Function relating disease severity of diseased stem area in canopy layer x to time	-
SF1	Spikelet fertility due to low temperatures	-
SF2	Spikelet fertility due to high temperatures	-
SHCKD	Parameter indicating relation between seedling age and delay in phenological development	^{o}C d (^{o}C d)$^{-1}$
SHCKL	Parameter indicating relation between seedling age and delay in leaf area development	^{o}C d (^{o}C d)$^{-1}$
SIN	Sine function (intrinsic FORTRAN function)	-
SINB	Sine of solar elevation	-
SINLD	Intermediate variable in calculating solar declination	-
SLA	Specific leaf area	ha leaf kg^{-1} leaf
SLATB	Table of SLA as function of DVS	-
SLWDAL	Intermediate variable in calculation of average specific leaf weight of diseased leaf area	-
SLWDS(x)	SLW of diseased leaf area in canopy layer x	kg leaf ha^{-1} leaf
SLWDSx	Function relating SLW of diseased leaf area in canopy layer x to time	-
SLWHAL	Intermediate variable in calculation of average specific leaf weight of healthy leaf area	-
SLWHL(x)	SLW of healthy leaf area in canopy layer x	kg leaf ha^{-1} lea
SLWHLx	Function relating SLW of healthy leaf area in canopy layer x to time	-
SNLI	Specific Leaf N at the top of the canopy	kg N ha^{-1} leaf
SOREM	Dry matter loss of storage organs of healthy tillers due to clipping	kg DM ha^{-1} ground d^{-1}
SPFERT	Spikelet fertility	-
SPGF	Spikelet growth factor	number kg^{-1}
SQV	Intermediate variable in calculation of reflection coefficient	-

SSGA	Specific green stem area	ha kg^{-1} stem
SSGATB	Table of SSGA as function of DVS	-, -
STRREM	Dry matter loss of stem reserves of healthy tillers due to clipping	kg DM ha^{-1} ground d^{-1}
STSREM	Dry matter loss of structural stem material of healthy tillers due to clipping	kg DM ha^{-1} ground d^{-1}
STTIME	Start time of simulation (reserved variable name)	d
SWICLI	Switch to simulate clipping (1) or stem borer (0) experiment	-
SWILAI	Switch to use as input in the model measured (0) or simulated (1) LAI	-
SWINLV	Switch to use as input in the model NFLV vs. DVS (1), or vs. DOY (0), or NCNLV vs. DOY (2)	-
SWISEN	Switch to enable (1) or disable (0) sensitivity analysis	-
SWITIL	Swith to use measured tiller density as model input, or to simulate tiller dynamics	-
TAV	Daily average temperature	^oC
TAVD	Daily average daytime temperature	^oC
TBD	Base temperature for development	^oC
TBLV	Base temperature for juvenile leaf area growth	^oC
TCDT	Time coefficient for death of tillers	d^{-1}
TCFG	Time coefficient for formation of grains	d^{-1}
TCFT	Time coefficient for formation of tillers	d^{-1}
TCLSTR	Time coefficient for loss of stem reserves	d^{-1}
TEFF	Factor accounting for effect of temperature on maintenance respiration	-
TEFG	Temperature effect on grain filling rate	-
TFERT	Accumulated temperature for high temperature effect on spikelet fertility	^oC
TILMX	Maximum number of tillers per hill	number $hill^{-1}$
TILDTH	Tiller death rate	number d^{-1}
TILN	Tiller formation rate in relation to leaf N content	number d^{-1}
TILNTB	Table of TILN as function of leaf N content	-
TIME	Time in simulationreserved variable name)	d
TMAX	Daily maximum temperature	^oC
TMAXT	Table daily maxx temperature as function of day of the year	^oC, d
TMD	Maximum temperature for development	^oC
TMIN	Daily minimum temperature	^oC
TMINT	Table daily min. temperature as function of day of the year	^oC, d
TMMN	Daily minimum temperature (reserved weather variable name)	^oC

TMMX	Daily maximum temperature (reserved weather variable name	^{o}C
TNASS	Total net CO_2 assimilation	kg CO_2 ha^{-1}
TOCLUE	Intermediate variable in calculation AVCLUE	kg J^{-1}
TREF	Reference temperature	^{o}C
TRLLV	Rate of green leaf weight loss due to transplanting	kg ha^{-1} d^{-1}
TRLOSS	Loss of total dry matter at transplanting	kg DM ha^{-1} ground d^{-1}
TRLSTR	Rate of structural stem weight loss due to transplanting	kg ha^{-1} d^{-1}
TRLSTS	Rate of stem reserves loss due to transplanting	kg ha^{-1} d^{-1}
TRLRT	Rate of root weight loss due to transplanting	kg ha^{-1} d^{-1}
TS	Temperature sum for phenological development	^{o}C d
TSEVL	Total leaf area occupied by disease (total severity)	ha leaf ha^{-1} leaf
TSEVS	Total stem area occupied by disease (total severity)	ha leaf ha^{-1} leaf
TSHCKD	Transplanting shock for phenological development	^{o}C d
TSHCKL	Transplanting shock for leaf area development	^{o}C d
TSLV	Temperature sum for leaf area development	^{o}C d
TSLVTR	Temperature sum for leaf area development at tranplanting	^{o}C d
TSTR	Temperature sum for phenological development at tran-planting	^{o}C d
UNPROD	Productive tiller density	number ha^{-1}
VISD	Obsorbed direct component of direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISDF	Absorbed diffuse flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISPP	Absorbed light flux by leaves perpendicular on direct beam	J m^{-2} leaf s^{-1}
VISSHD	Total absorbed flux for shaded leaves per unit leaf area(at depth LAIC)	J m^{-2} leaf s^{-1}
VISSUN	Total absorbed flux for sunlit leaves in one of three Gauss point classes	J m^{-2} leaf s^{-1}
VIST	Absorbed total direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VP	Vapour pressure (reserved weather variable name)	kPa
WAG	Total above-ground dry matter	kg DM ha^{-1}
WAGREM	Total dry matter loss of healthy tillers due to clipping	kg DM ha^{-1} ground d^{-1}
WCR	Total biomass (crop)	kg DM ha^{-1}
WEATHER	Routine from TTUTIL library, call to read external weather data files	-
WGAUSS	Array containing weights to be assigned to Gauss points	-
WGRMX	Maximum individual grain weight	kg $grain^{-1}$
WLVD	Dry weight of dead leaves	kg ha^{-1}
WLVDS	Weight of diseased leaf area	kg ha^{-1}
WLVHL	Weight of healthy leaf area	kg ha^{-1}

WLVEXP	Weight of leaves at end of exponential leaf growth phase	kg ha^{-1}
WLVEXS	Weight of leaves at end of exponential leaf growth phase in seedbed	kg ha^{-1}
WLVDDH	Weight of dead leaves of dead hearts	kg ha^{-1}
WLVDHL	Weight of dead leaves of healthy tillers	kg ha^{-1}
WLVDWH	Weight of dead leaves of white heads	kg ha^{-1}
WLVG	Dry weight of green leaves	kg ha^{-1}
WLVGDH	Weight of green leaves of dead hearts	kg ha^{-1}
WLVGHL	Weight of green leaves of healthy tillers	kg ha^{-1}
WLVGI	Initial dry weight of the leaves	kg ha^{-1}
WLVGWH	Weight of green leaves of white heads	kg ha^{-1}
WLVREM	Weight of removed leaves of healthy tillers	kg ha^{-1}
WLVTR	Green leaf weight loss due to transplanting	kg ha^{-1}
WN	Wind speed (reserved weather variable name)	m s^{-1}
WRR	Dry weight rough rice (final yield)	kg ha^{-1}
WRT	Dry weight of the roots	kg ha^{-1}
WRTDH	Weight of roots of dead hearts	kg ha^{-1}
WRTHL	Weight of roots of healthy tillers	kg ha^{-1}
WRTI	Initial dry weight of the roots	kg ha^{-1}
WRTWH	Weight of roots of white heads	kg ha^{-1}
WSO	Dry weight of storage organs	kg ha^{-1}
WSOHL	Weight of storage organs of healthy tillers	kg ha^{-1}
WSOI	Initial dry weight of storage organs	kg ha^{-1}
WSOREM	Weight of removed storage organs of healthy tillers	kg ha^{-1}
WSOWH	Weight of storage organs of white heads	kg ha^{-1}
WST	Dry weight of the stems	kg ha^{-1}
WSTDDH	Weight of dead stem material of dead hearts	kg ha^{-1}
WSTDH	Weight of structural stem material plus stem reserves of dead hearts	kg ha^{-1}
WSTHL	Weight of structural stem material plus stem reserves of healthy tillers	kg ha^{-1}
WSTI	Initial dry weight of the stems	kg ha^{-1}
WSTWH	Weight of structural stem material plus stem reserves of white heads	kg ha^{-1}
WSTR	Dry weight of stems reserves	kg ha^{-1}
WSTRDH	Weight of stem reserves of dead hearts	kg ha^{-1}
WSTSRE	Weight of removed stem reserves of healthy tillers	kg ha^{-1}
WSTRHL	Weight of stem reserves of healthy tillers	kg ha^{-1}
WSTRWH	Weight of stem reserves of white heads	kg ha^{-1}
WSTRRE	Weight of removed stem reserves of healthy tillers	kg ha^{-1}
WSTRTR	Stem reserves loss due to transplanting	kg ha^{-1}
WSTS	Dry weight of structural stems	kg ha^{-1}

WSTSDH	Weight of structural stem material of dead hearts	kg ha^{-1}
WSTSHL	Weight of structural stem material of healthy tillers	kg ha^{-1}
WSTSWH	Weight of structural stem material of white heads	kg ha^{-1}
WSTSTR	Structural stem weight loss due to transplanting	kg ha^{-1}
WRTTR	Root weight loss due to transplanting	kg ha^{-1}
XGAUSS	Array containing Gauss points	-
XLAI	Observed values of LAI	ha ha^{-1}
XLAITB	Table of XLAI as function of day of year	-
XNDH	Observed dead heart density	number ha^{-1}
XNDTT	Table of XNDH as day of year	-
XNDT	Observed dead tiller density	number ha^{-1}
XNDTT	Table of XNDT as day of year	-
XNFLV	Observed values of NFLV	g N m^{-2} leaf
XNFLVT	Table of XNFLV as function of day of year	-
XNHL	Observed healthy tiller density	number ha^{-1}
XNHLT	Table of XNHL as function of day of year	-
XNWH	Observed white head density	number ha^{-1}
XNWHT	Table of XNWH as function of day of year	-
XNTI	Observed total tiller density	number ha^{-1}
XNTIT	Table of XNTI as function of day of year	-
XSLA	Observed values of specific leaf area	ha leaf kg^{-1} leaf
XSLATB	Table of XSLA as function of day of year	-
XWLVD	Observed values of WLVD	kg ha^{-1}
XWLVDT	Table of XWLVD as function of day of year	-
XWLVG	Observed values of WLVG	kg ha^{-1}
XWLVGT	Table of XWLVG as function of day of year	-
XWPA	Observed values of WSO	kg ha^{-1}
XWPATB	Table of XWPA af function of day of year	-
XWST	Observed values of WST	kg ha^{-1}
XWSTTB	Table of XWST as function of day of year	-
XWTDM	Observed values of WAG	kg ha^{-1}
XWTDMT	Table of XWTDM as function of day of year	-