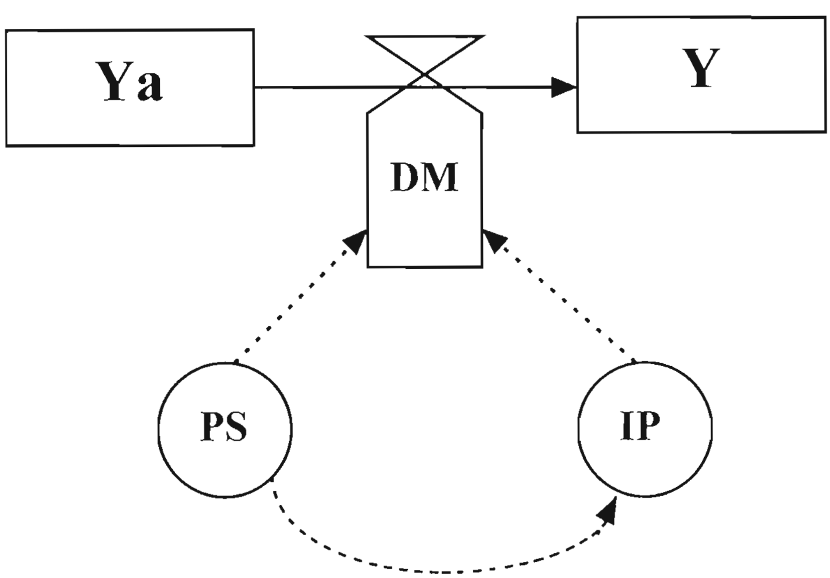
IRRI DISCUSSION PAPER SERIES NO. 34

Simulation of Yield Losses Caused by Rice Diseases, Insects, and Weeds in Tropical Asia

Laetitia Willocquet, Serge Savary, Luzviminda Fernandez,
Francisco Elazegui, and Paul Teng



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Simulation of Yield Losses Caused by Rice Diseases, Insects, and Weeds in Tropical Asia

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About the cover:
This sketch is a simplication of yield loss modeling. Yield loss modeling deals with two state variables: attainable yield (Ya) and actual yield (Y). Attainable yield translates into actual yield via a rate of reduction: damage mechanisms (DM). Damage mechanisms depend on the causal injury profiles (IP) which in turn depend on the production situation (PS). Production situations also directly affect the intensity of yield reduction for a given injury profile.

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Contents

Preface

Over the years, considerable efforts have been invested, at IRRI and elsewhere, in the quantification of yield losses. The topic of this discussion paper is an important one for at least two purposes: prioritizing research, and providing a rationale for integrated pest management or IPM. In the past, two types of approaches have been used: empirical (based on spontaneous or manipulated injuries due to disease, insects, and weeds) or conceptual (based on more, or less, complex simulation models). The work reported here bridges the two approaches, with the development of a simple, production situation-specific simulation model, which allows the exploration of scenarios that are derived from actual situations observed in farmers' fields.

Introduction

Decisions in plant protection may be categorized into two types (Zadoks 1985, Savary 1991): strategic (i.e., pertaining to large areas and relatively long periods of time) or tactical (i.e., addressing a particular crop within a growing season). Quantification and extrapolation of yield losses due to pests are necessary at both the strategic and tactical levels. They are needed at the strategic level because they allow research prioritization, and they are necessary at the tactical level because they provide information to implement action or improve pest management.

During the last decade, major advances have been achieved in this research area for rice, using different approaches and providing different outputs:

1. Empirical approach

This approach is field- or experimental plot-based, and makes use of an array of multivariate statistical methods:

- Characterization of production situations and injury profiles in Asia, and quantification of the interactions between these two components (e.g., Savary et al 1994, 1996a, Du et al 1997, Savary et al 1997b);
- Quantification of yield losses due to rice pests under a range of production situations (e.g., Savary et al 1996b, 1997a);

2. Mechanistic approach

This approach is process-based and makes use of simulation models to develop, test, and redesign hypotheses:

- Simulation of potential rice growth and yield (e.g., Graf et al 1990, Kropff et al 1994);
- Simulation of rice growth and yield limited by nitrogen and/or water (e.g., Graf & Hill 1992, Wopereis 1993, ten Berge et al 1994, Kropff et al 1994);
- Simulation of rice growth and yield reduced by pests (e.g., Graf & Hill 1992, Bastiaans 1993, Kropff & van Laar 1993, Rossing et al 1993, Elings & Rubia 1994, Pinnschmidt et al 1995).

Part of the simulation work mentioned above was done under the umbrella of the "Simulation and Systems Analysis for Rice Production" (SARP) project, a collaborative undertaking (1984-95) between IRRI, the Agricultural University of Wageningen, and several national agricultural research systems (NARS) in Asia.

The Project on Characterization of Rice Pests, a collaborative agreement (1991-98) between IRRI, the French Institute for Tropical Research (ORSTOM), and Asian NARS followed the empirical approach mentioned above with its two components, characterization of production situations and injury profiles, and experimental assessment of yield losses.

The empirical approach has shown that injury profiles and production situations are strongly linked, and that yield losses due to injuries depend on the production situation. Production situations were also shown to be shared between different sites in Asia. Thus, a "production situation" represents a useful concept to characterize the environment under which yield losses are quantified and estimated.

The mechanistic approach provided comprehensive simulation models that simulate potential, attainable, and actual rice growth and yield.

As part of the IRRI-ORSTOM Project on Rice Pest Characterization, modeling work was recently begun to simulate yield losses due to different rice pests under a range of production situations. The scope of this work is described in more detail below. Technically, this work builds on the outputs described above:

- The information obtained from the characterization of production situations and injury profiles done in Asia is used as a framework to define injury combinations and relevant production situations;
- The methodologies developed to experimentally quantify yield losses due to pests are used as templates to manipulate production situations and injuries in field experiments;
- The simulation models developed for potential, attainable, and actual rice growth and yield are used to generate a synthetic, simple crop growth model that is production situation-specific, and which includes damage mechanisms.

Concepts, objectives, and general approach

Scope

The work reported here represents the third component of the ORSTOM-IRRI Project on Characterization of Rice Pests. While the first two components aimed at describing and quantifying current yield losses caused by rice pests, this third component aims to extrapolate yield losses in a range of scenarios. Simulation modeling is the tool used for this purpose.

The IBSNAT and SARP projects generated models that could be examined for the same purpose. One main difference between the objective of the work reported here and the objectives of these projects is that emphasis was placed on combinations of injuries ("injury profiles"), a standpoint which the SARP-type models were not developed to address. Another difference is that in this study, we looked at a limited set of production situations corresponding to a range of attainable yields, and where those injuries occur and reduce yield to its actual level.

The simulation model reported here therefore is aimed at addressing a set of production situations. One main characteristic of this model is the crucial importance of the (net) rate of crop growth, which is made specific to production situations. This rate is defined and measured, following the very simple model of Johnson et al (1986). Another characteristic is the explicit consideration of the growth of rice tiller population. This was considered necessary at the onset of model development to adequately account for damage mechanisms that pertain to the tiller level. Some of the concepts used by Graf et al (1990) were employed for this purpose. While, therefore, this modeling work strongly draws upon previous modeling work on rice (Kropff et al 1994), it also builds on other modeling work to comply with its objectives.

Concepts for modeling attainable yield, damage mechanisms, and actual yields

Yield loss modeling is based on a set of concepts that were developed within the last two decades on production ecology and plant protection.

A crop grown in a field can be related to the *production situation* (PS) under which it is grown. This concept was originally defined by De Wit & Penning de Vries (1982) as "a set of factors—physical, biological, and socioeconomic—that determine agricultural production." Since the emphasis of this study is on pests, this component of the production situation was conceptually extracted from the set of components that constitute a production situation. Thus, in this report, a production situation represents the combination of environmental factors (biophysical—except pests— and socioeconomic) that defines the *attainable yield* (Ya). The attainable yield is the yield obtained in a field when free of *pests* and their resulting injuries (Rabbinge 1993). A pest is defined as any living organism that can reduce crop yield. In the case of rice (as in any crop), weeds, pathogens, and insects are considered as pests. The attainable yield can be reduced by the effect of factors such as pest *injuries*. An injury is a visible, measurable symptom caused by a harmful organism (Zadoks 1985). The resulting yield, obtained in a field injured by one or several pests, is defined as the *actual yield* (Y) (Rabbinge 1993): it is the yield actually harvested in a farmer's field. *Yield loss* (YL) or *damage* (Zadoks 1985) represents the difference between the attainable and the actual yield, that is, the yield losses caused by pest injuries. The relationships between these different concepts are summarized in Figs. 1 and 2.

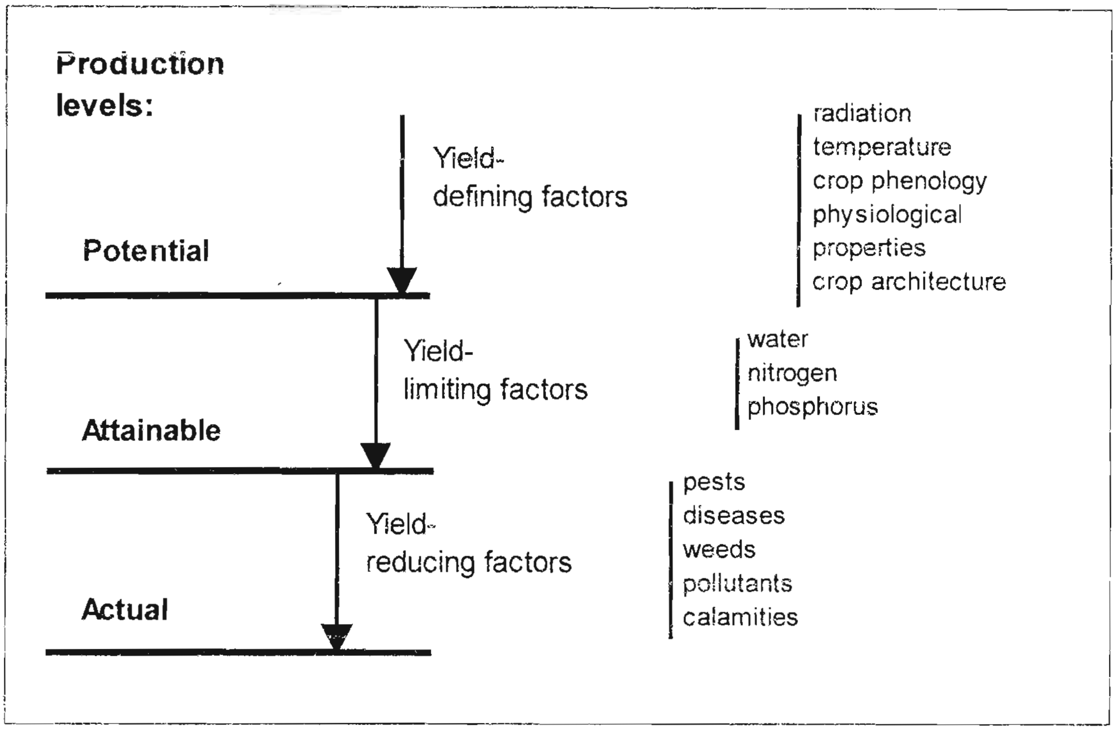

Fig. 1. Relationships among potential, attainable, and actual yields and yield-defining, yield-limiting, and yield-reducing factors (Rabbinge 1993).

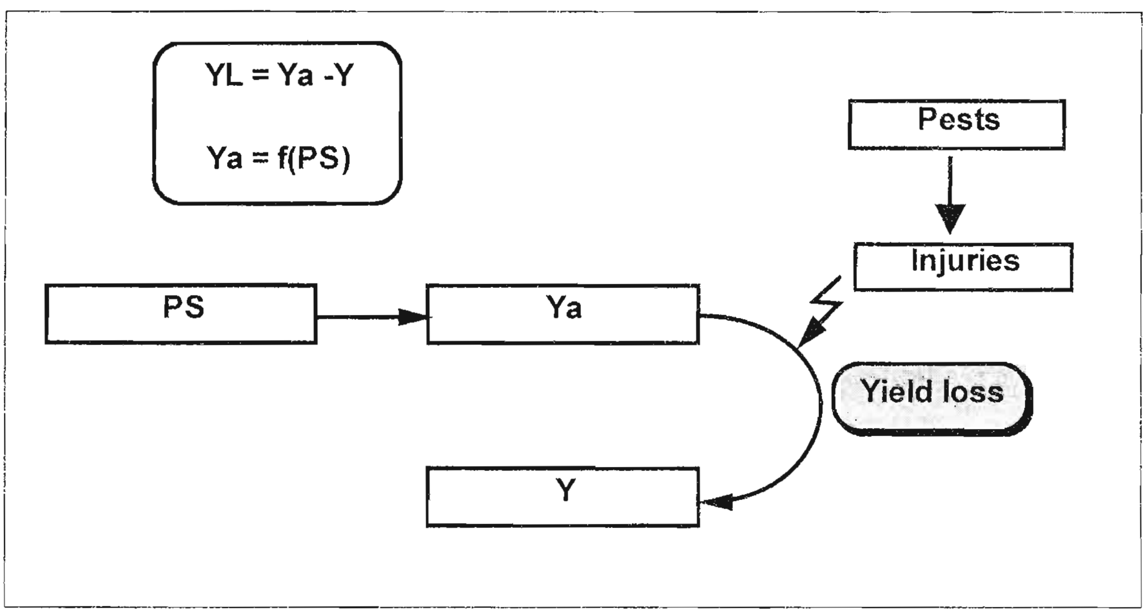

Fig. 2. Relationships between production situation, attainable yield, and actual yield. *PS: production situation; Y: actual yield; Ya: attainable yield; YL: yield loss.*

Damage functions, which quantify the relationships between injuries and yield losses (Zadoks 1985), can be determined empirically. They can also be defined from crop loss simulation models. In these models, the processes involved in plant growth are represented, as well as *damage mechanisms* (DM). A damage mechanism refers to the processes involved in crop growth that are affected by a harmful agent. Different mechanisms can be described (Rabbinge & Rijsdijk 1981, Boote et al 1983). Fig. 3 presents the main categories of damage mechanisms.

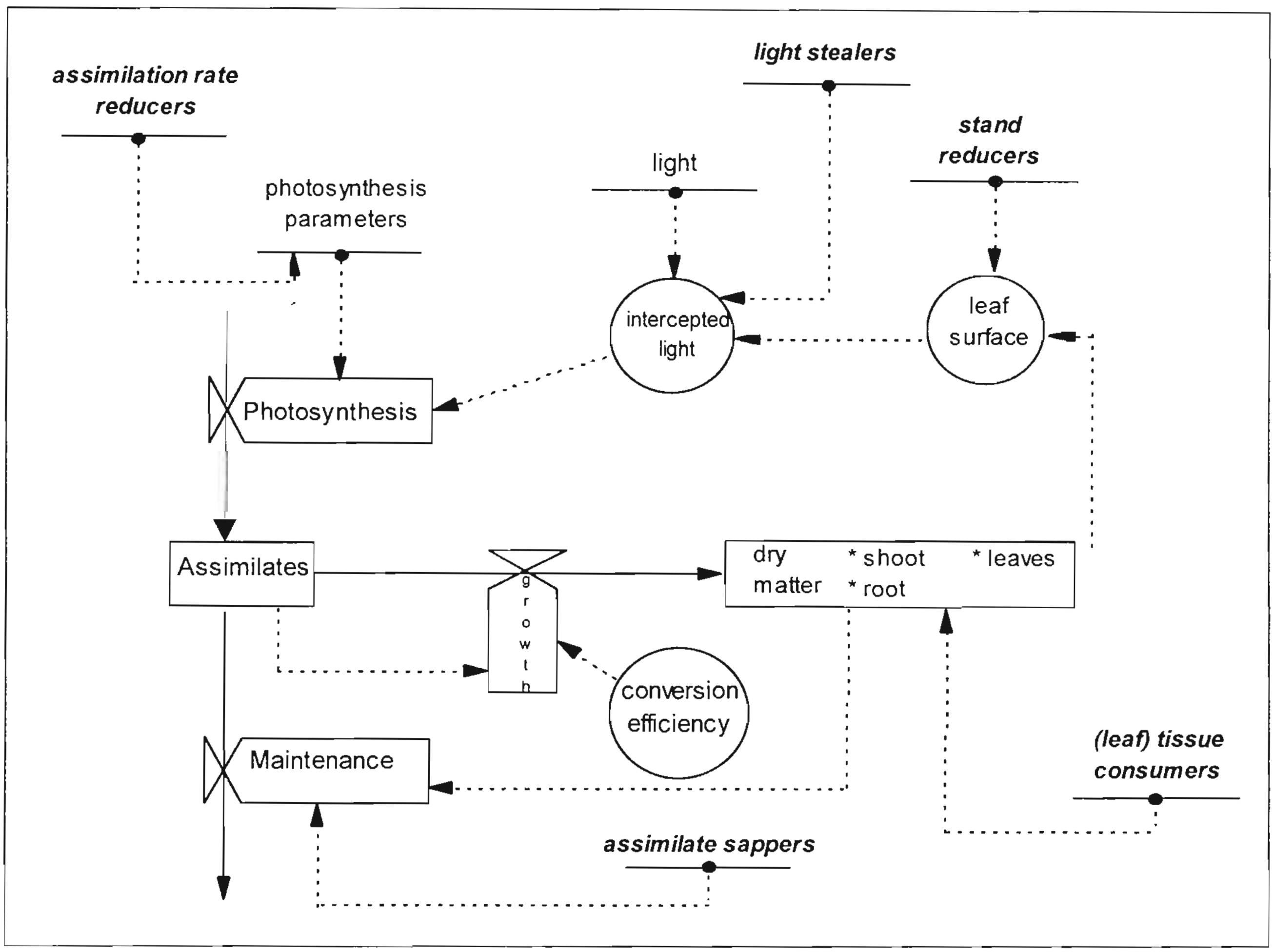

Fig. 3. Relational diagram of the model SUCROS87 indicating where the effects of various organisms are focused (Rabbinge & Bastiaans 1989).

Objectives

The objectives of this work are to better understand the mechanisms involved in the damage effects of pest injuries on rice, and to simulate rice yield losses due to single and multiple pests under a set of different, specific production situations. To meet these objectives, a simple crop growth model for rice, with coupling points to quantify damage effects due to pests, is developed. The ultimate aim is to provide background information that could be used for research prioritization and for improvement of pest management in farmers' fields.

Modeling yield losses in different production situations

A first, essential stage of this modeling work is to adequately account for production situations, i.e., simulate reasonably well attainable rice yields under a few sets of combinations of yield-limiting factors. A rice crop growth simulation model that simulates attainable yields under a range of production situations was thus developed. A second stage is to address a range of injuries that may prevail in these production situations. The model therefore has to have the capacity to simulate the mechanisms leading to yield losses due to several injuries under these production situations (see Fig. 4). The production situations and injuries addressed were defined on the basis of the characterization of injury profiles and production situations done in different sites in Asia (Savary et al 1994, 1996a, 1997b, Du et al 1997) (see Fig. 5).

The main steps taken, summarized in Fig. 6, and described in this paper, are as follows:

1. Definition of the structure of the crop growth model for rice (see next section, *Model description*);
2. Definition and parameterization of damage mechanism functions (from literature data) (see next section, *Model description*);
3. Designing field experiments to
   - calibrate the rice growth model simulating attainable yield under a set of specific production situations, and
   - test the simulation of yield loss due to pest injuries (see third section, *Field experiments to calibrate and test the model*).

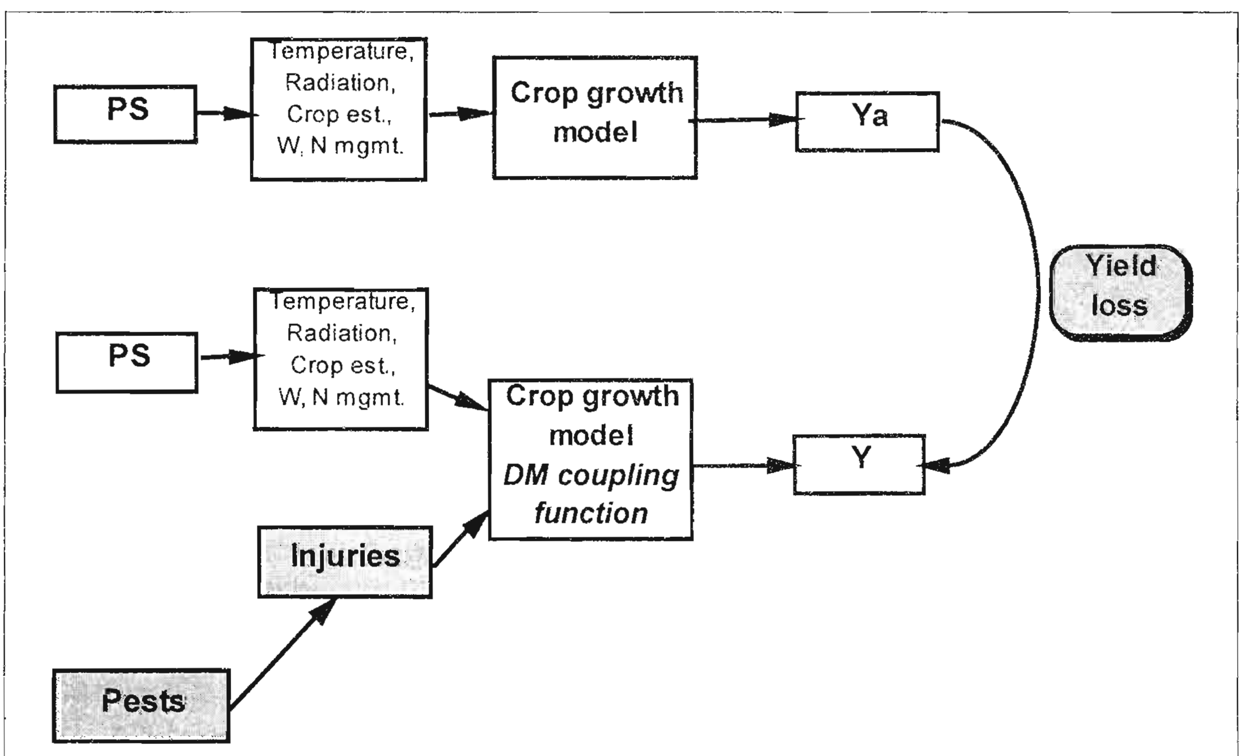

Fig. 4. Simulation of yield losses according to specific production situations using a crop growth model. *PS: production situation; Ya: attainable yield; Y: actual yield; DM: damage mechanism; W: water; N: nitrogen.*

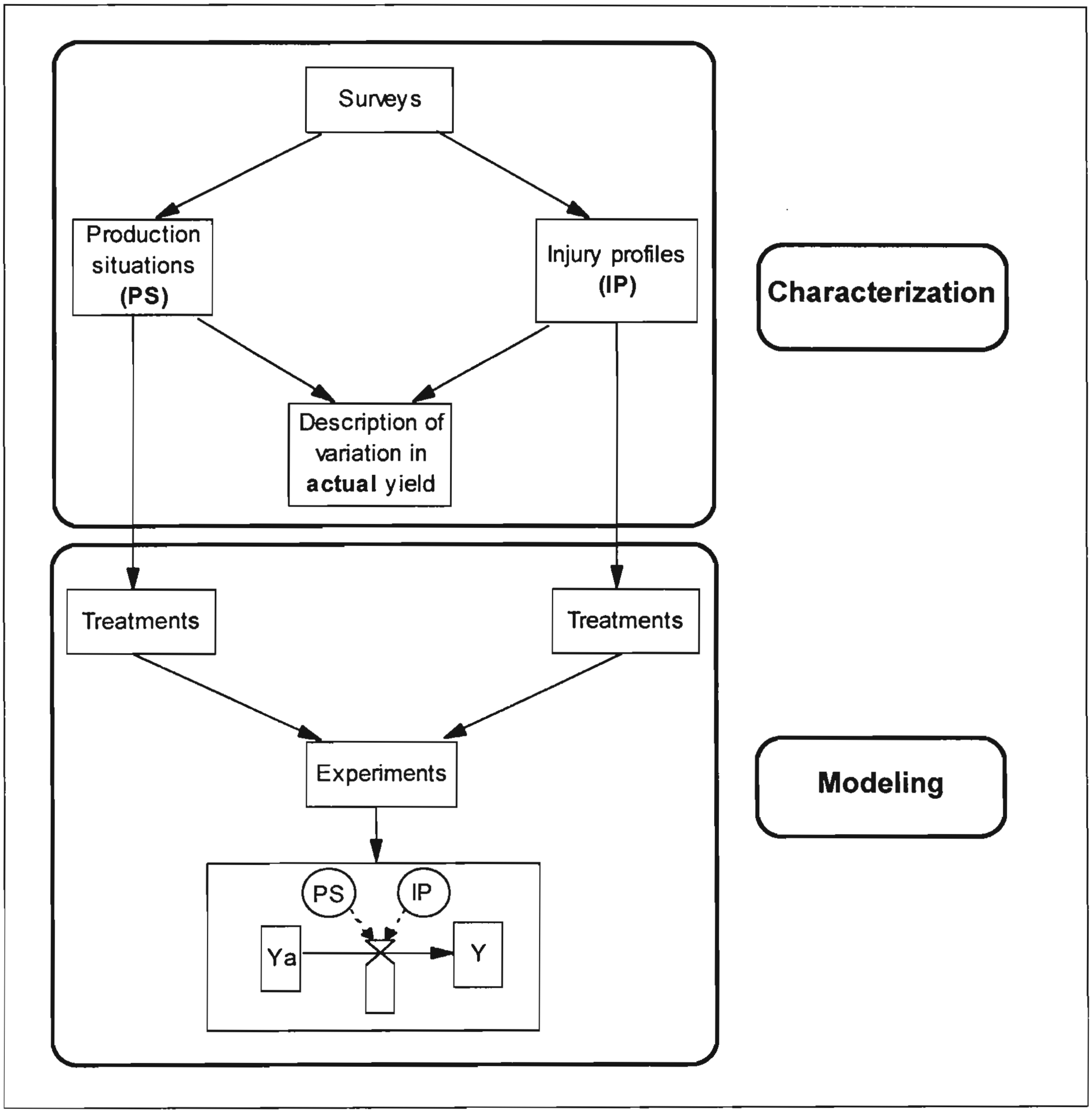

Fig. 5. Relationships between the characterization of variation in actual yield from surveys in farmers' fields (according to production situation and injury profile) and the framework for yield loss simulation.
Y = actual yield, Ya = attainable yield.

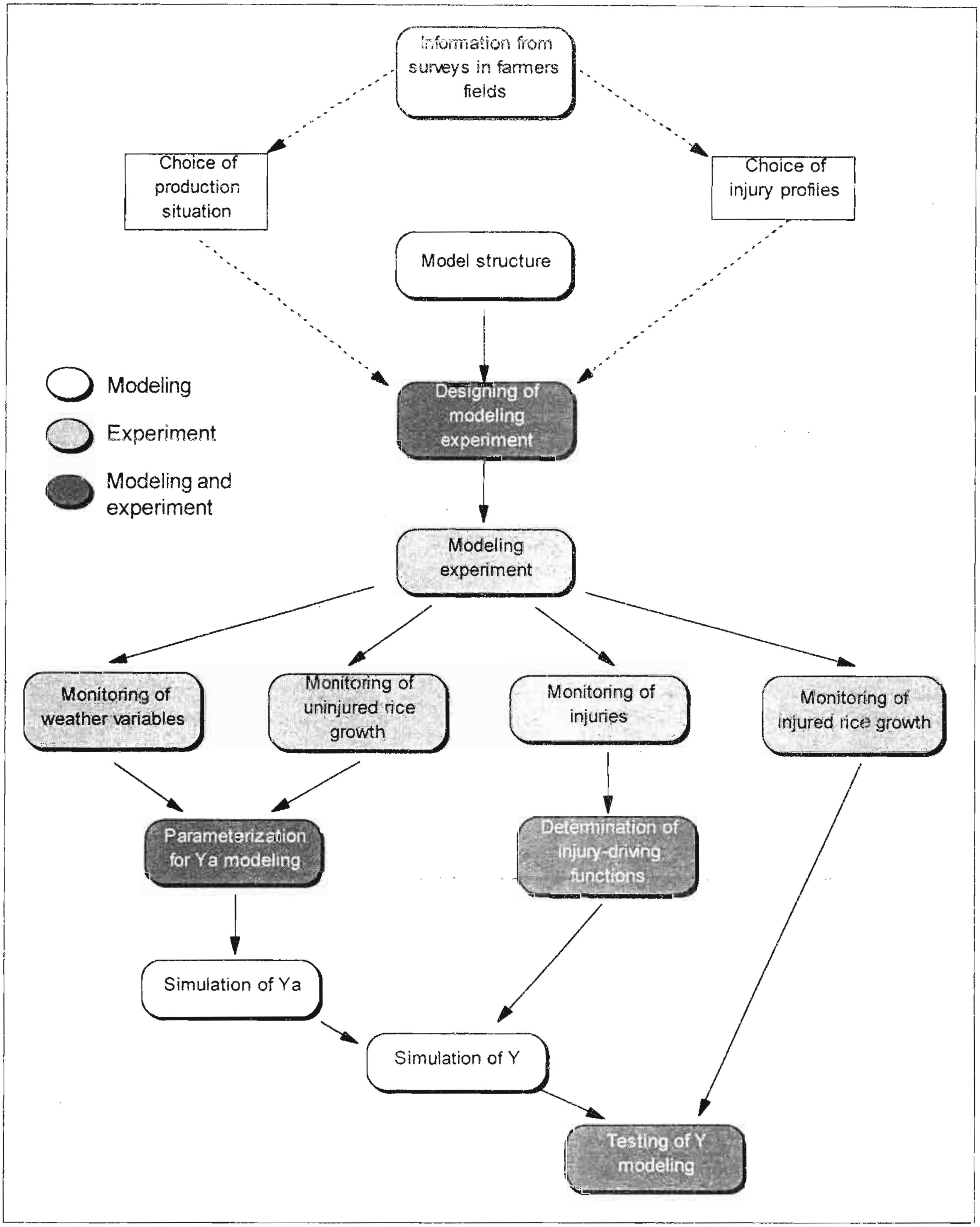

Fig. 6. Steps taken in modeling yield loss.
Y = actual yield, Ya = attainable yield.

Rice plots grown under different production situations are subject to different injuries, alone or in combination. Crop growth, crop yield, environmental factors, and pest injuries are monitored. Data from control plots (injury-free) are used to calibrate parameters for attainable yield simulation. Data from injured plots are used to test the simulation of yield losses due to pests;

4. Calibration of the simulation model for attainable growth (see fourth section, *Model parameterization – simulation of attainable yield*);

5. Validation of the model, and simulating attainable and actual yields, based on field experiments (see fifth section, *Model testing – simulation of actual yield*).

These steps represent the development and evaluation phases of the model, and are reported here. Further steps are foreseen, however, and are presented in the last section, *Final remarks*.

Model description

Rationale for developing a yield loss simulation model

The design criteria of the model are to allow:

- Simulation of growth and yield of a rice crop under selected production situations (defined by nitrogen and water management, crop establishment, and cultivar type);
- Simulation of damage effects of different rice pests (sheath blight, stem borers, and weeds) on rice growth and yield. For this, the dynamics of the number of tillers and of the dry weight of the different rice organs (panicles, roots, leaves, and stems) has to be simulated. This was done by representing the main processes involved in rice growth that are affected by the different rice pests addressed. Tillering, tiller mortality, biomass accumulation, partitioning, and leaf senescence are the main processes simulated in the model.
- Calibration, testing, and use by NARS. For this, the model needs to be as flexible as possible to address diverse production situations and injuries. It also has to be as simple as possible to make it transparent, calibrated at low cost of data, and easy to understand and use.

A simple crop growth simulation model for rice was developed based on crop growth models previously described (Johnson et al 1986, Graf et al 1990, Kropff et al 1994).

The time-step of the model is 1 d, and the system considered is 1 m^2 of rice crop. In the model, time is scaled in number of days after crop establishment (DACE). Crop establishment refers to sowing in the case of direct-seeded rice, and transplanting in the case of transplanted rice. The simulation starts at 14 DACE, which corresponds in our case to the timing of the first destructive sampling made to collect data on rice biomass (see below, "timing of operations"). These first data are used to define the initial state of the system (dry weight of organs and number of tillers) in the model. The simulation stops when the crop is ripe.

The model contains two interrelated subsystems: tiller number and crop biomass. State variables and simulated processes allow accounting for the effects of production situations and injuries on rice crop growth and yield (Fig. 7). For example, nutrient input level will affect the intrinsic rate of growth; sheath blight will affect leaf senescence; white head will affect the rate of partitioning towards the panicles. The simulation of these effects will be discussed in detail in this section.

The main processes of rice growth are simulated in the model as follows (Fig. 8): the daily accumulation of rice biomass is simulated in the model by a growth rate. This biomass is then distributed to the different rice organs (leaves, stems, roots, and panicles) according to partitioning coefficients, which vary over time, depending on the development stage of the crop. Tillering depends on the amount of biomass partitioned daily into the stems and leaves. At booting, most of the vegetative tillers become reproductive. These processes are described in detail in the next part of this section.

Damage mechanisms are simulated for sheath blight, stem borers, and weeds using data from the literature or from experiments. The definition of the coupling functions is presented later in this section.

The variables used in the model are listed in Appendix 1. The program of the model is written in FST (Fortran Simulation Translator; Rappoldt & van Kraalingen 1996) and is listed in Appendix 2.

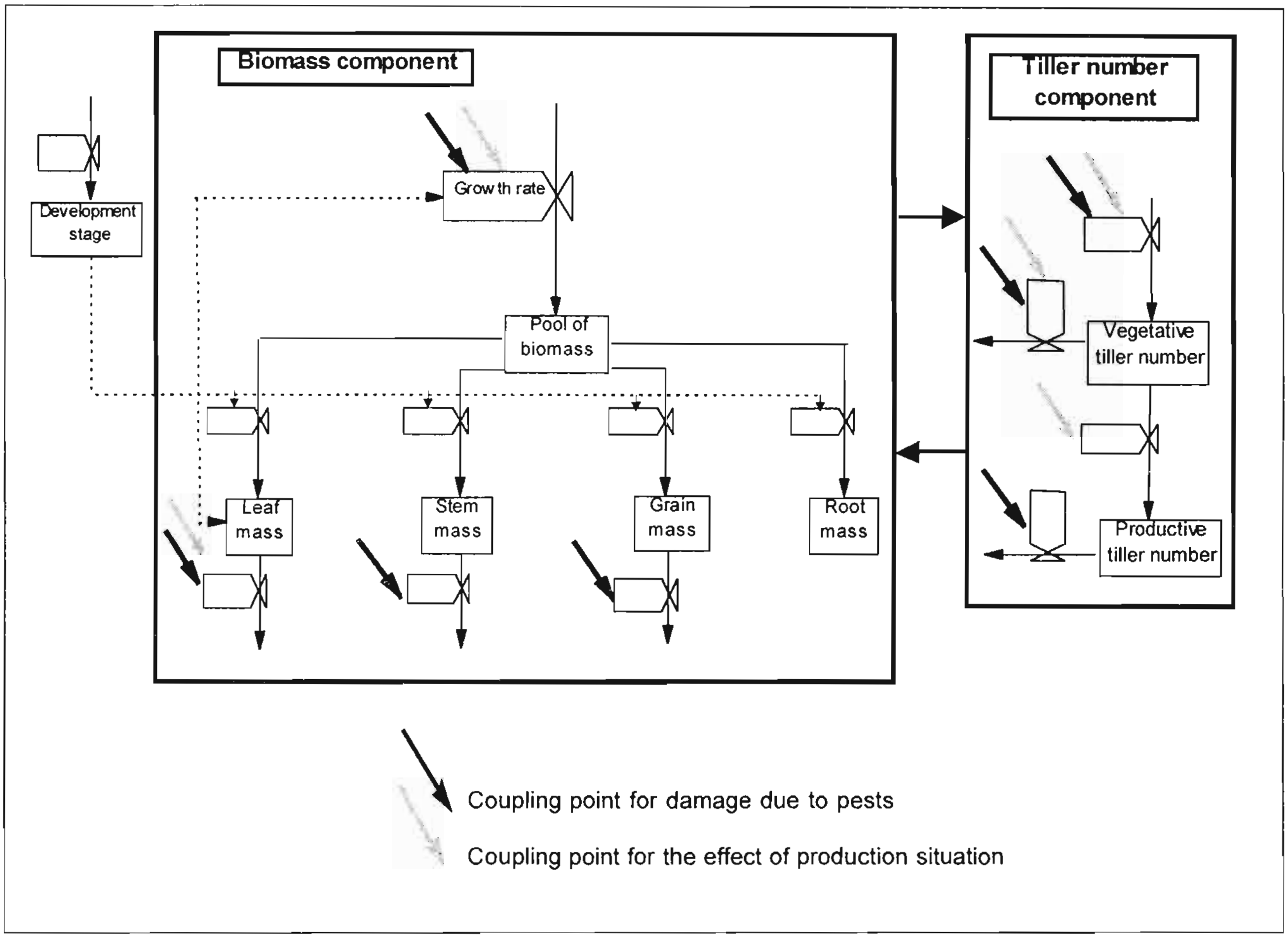

Fig. 7. Schematic representation of the rice crop growth model.

Modeling attainable growth and yield

Crop development

Crop development is measured by its successive stages (*DVS*). Development is operationally defined as the stage reached by the majority (more than 50%) of the plants at a given point in time. Development is scaled between 0 (at sowing) and 2 (at maturity). Development stage (at flowering) is 1.

Development is defined as a function of the sum of temperature (*SUMT*) above 8 °C. The minimum temperature threshold for rice cultivars (*TBASE*) is 8 °C (Gao et al 1992). The sum of temperature required for a crop to reach maturity depends on the variety type (short or long-duration). For a given variety, the rate of development may be altered by water stress (Puckridge & O'Toole 1981, Turner et al 1986, Inthapan & Fukai 1988, Wopereis et al 1996). Wopereis et al (1996) showed that the delay in flowering corresponded to the number of days between the date of zero leaf expansion and the recovery date. They suggested that if the water stress is high enough to stop the production of new leaves, the development of the crop also stops.

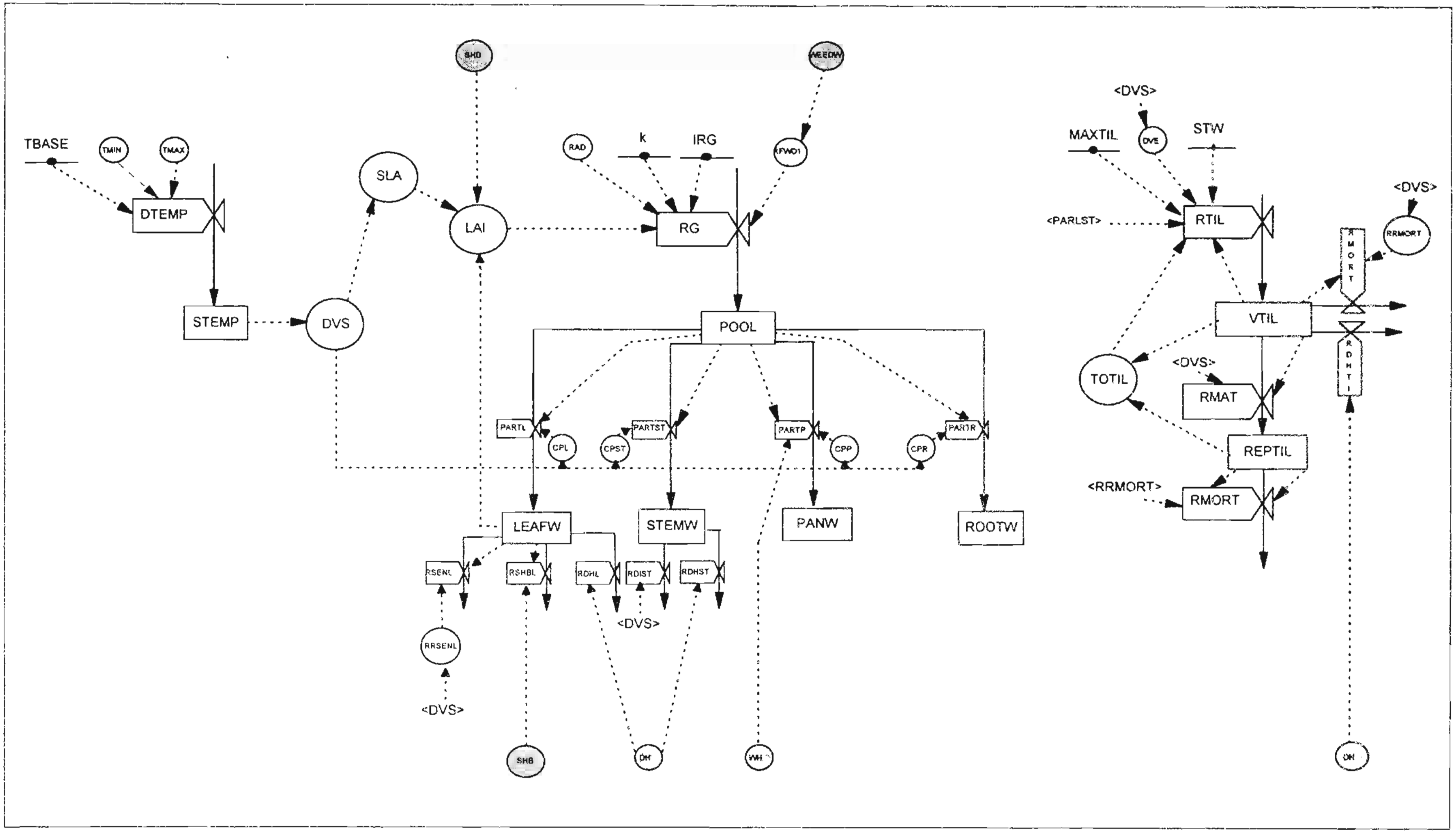

Fig. 8. Simplified relational diagram of the rice crop growth model, including damage mechanisms of different pests.

The temperature sum is computed as follows:

$$SUMT_{t+\Delta t} = SUMT_t + (DTEMP_t * \Delta t) \qquad (1)$$

with

$$DTEMP_t = max\,[0, ((TMAX_t + TMIN_t) / 2) - TBASE] \qquad (2)$$

where *TMIN* is the minimum daily temperature and *TMAX* is the maximum daily temperature.

In the case of direct-seeded rice, the initial value of *SUMT* corresponds to the sum of temperatures above *TBASE* between sowing and the day when simulation starts.

In the case of transplanted rice, the initial value of *SUMT* corresponds to the sum of temperatures above *TBASE* between sowing and the day when simulation begins, minus the sum of temperatures (*TSHOCK*) corresponding to the transplanting shock. The following equation is derived from Kropff et al (1994):

$$TSHOCK = 0.785 * STEMP(sdl) \qquad (3)$$

where *STEMP(sdl)* is the sum of temperatures above *TBASE* between sowing and transplanting of rice seedlings.

Crop growth

The amount of assimilates that are made available for plant growth (*POOL*) is accumulated daily at a rate of growth, *RG*:

$$POOL_{t+\Delta t} = POOL_t + (RG_t * \Delta t) \qquad (4)$$

The rate of growth, *RG*, is proportional to an intrinsic rate of growth (*IRG*), to the daily global solar radiation (*RAD*), and to the light intercepted by the crop canopy:

$$RG_t = IRG_t * RAD_t * [1 - exp(-k * LAI_t)] \qquad (5)$$

where $1 - exp(-k * LAI)$ is the proportion of light intercepted by the crop, following Beer's law, and k is the coefficient of light extinction. This has been estimated to be 0.6 for rice (Hayashi & Ito 1962), a value commonly used for most rice growth models.

LAI is proportional to the dry weight of leaves (*LEAFW*):

$$LAI_t = SLA_t * LEAFW_t \qquad (6)$$

where *SLA* is the specific leaf area (i.e., the leaf area per unit leaf dry weight, Appendix 1), and is a function of the crop development stage. Young leaves are thinner, and thus have a higher *SLA* than older leaves. It is therefore expected that *SLA* will decline over time. In short-duration, high-yielding varieties grown at 0 and 110 kg N ha^{-1}, the initial *SLA* was 0.035 $m^2\ g^{-1}$; it decreased linearly to 0.02 $m^2\ g^{-1}$ at flowering, and then decreased less sharply until maturity to 0.018 $m^2\ g^{-1}$ (Kropff et al 1994).

The intrinsic rate of growth, *IRG*, represents the overall efficiency of the crop to convert plant biomass from intercepted light. *IRG* thus embeds the efficiency of several processes: gross photosynthesis, respiration, transportation of photosynthates before on-site biosynthesis, and synthesis of complex molecules from photosynthates (proteins, lipids, polysaccharides, etc.). *IRG* may vary depending on:

- the efficiency of photosynthesis, which depends on the concentration of leaf N (e.g., Peng et al 1995) and on water availability (Penning de Vries et al 1989). The concentration of leaf N depends on the quantity of nutrient inputs and on crop establishment: a same level of N input corresponds to lower leaf N concentration in direct-seeded crops due to stronger N dilution in plant tissues (Schnier et al 1990a).
- the respective proportion of the different types of organic components synthesized from photosynthates. The energy required for the biosynthesis of a given compound depends on the type of organic group it belongs to (Penning de Vries et al 1989). For example, lipids require more energy (that is, more glucose) to be synthesized than carbohydrates, the proteins being in an intermediate position (Penning de Vries et al 1989). The proportion of compounds synthesized depends on the crop development stage.

Thus, *IRG* is expected to be dependent on nutrients and water management, on the establishment method (direct-seeding or transplanting), and on the development stage of a given crop.

IRG was estimated to be 1.4 g MJ^{-1} for a nonstressed rice crop (Sinclair & Horie 1989).

Partitioning of assimilates

The assimilates accumulated daily are partitioned to the different rice organs. The amounts of biomass partitioned daily to the leaves, panicles, stems, and roots are named *PARTL*, *PARTP*, *PARTST*, and *PARTR*, respectively. The amounts depend on coefficients of partitioning, which in turn depend on the development stage:

$$PARTL_t = POOL_t * CPL_{DVS_t} * (1 - CPR_{DVS_t}) \quad (7)$$

$$PARTP_t = POOL_t * CPP_{DVS_t} * (1 - CPR_{DVS_t}) \quad (8)$$

$$PARTST_t = POOL_t * CPST_{DVS_t} * (1 - CPR_{DVS_t}) \quad (9)$$

$$PARTR_t = POOL_t * CPR_{DVS_t} \quad (10)$$

where CPL_{DVS_t}, CPP_{DVS_t}, $CPST_{DVS_t}$, and CPR_{DVS_t} are the coefficients of partitioning of the assimilates to the leaves, panicles, stems, and roots, respectively, at the development stage at date *t*. *CPL*, *CPP*, and *CPST* represent the coefficients of partitioning relative to the biomass partitioned aboveground. *CPR* represents the coefficient of partitioning towards roots relative to the total rice biomass.

Thus, the increase in dry weight for the different rice organs is computed as follows:

$$LEAFW_{t+\Delta t} = LEAFW_t + PARTL_t * \Delta t \quad (11)$$

$$PANW_{t+\Delta t} = PANW_t + PARTP_t * \Delta t \quad (12)$$

$$STEMW_{t+\Delta t} = STEMW_t + PARTST_t * \Delta t \quad (13)$$

$$ROOTW_{t+\Delta t} = ROOTW_t + PARTR_t * \Delta t \quad (14)$$

The coefficients of partitioning vary with the development stage. In general, partitioning towards roots, stems, and leaves occurs until flowering. From this stage onwards, all the assimilates are partitioned towards the panicles for grain formation and grain filling. Partitioning towards the roots declines linearly from 50% to 0 between sowing and flowering. Partitioning towards leaves and stems is similar during the first stages, then partitioning towards stems is larger than that towards leaves (Penning de Vries et al 1989).

Coefficients of partitioning may be altered by:

1. water stress (Penning de Vries et al 1989): in this case, more assimilates are partitioned towards the roots;
2. nitrogen management and the type of crop establishment (Dingkuhn 1996).

Redistribution of reserves accumulated in the stems

Before flowering, when the growth rate of the crop is high, starch is accumulated in the stems. After flowering, starch is redistributed to the storage organs (i.e., to the grains). The fraction of stem dry weight at flowering that will be reallocated to panicles is approximately 25% in the case of rice (Penning de Vries et al 1989).

Equation (12) thus becomes:

$$PANW_{t+\Delta t} = PANW_t + (PARTP_t + RDIST_t) * \Delta t \qquad (15)$$

And equation (13) becomes:

$$STEMW_{t+\Delta t} = STEMW_t + (PARTST_t - RDIST_t) * \Delta t \qquad (16)$$

where *RDIST* is the daily flow of biomass redistributed from the stem reserves to the panicles.

Leaf senescence

In the model, a dead leaf is operationally defined as a leaf with at least 50% dead or infected area.

Leaf senescence also depends on the development stage. In the model, leaf senescence is made proportional to a relative rate of leaf senescence (*RRSENL*) and to the dry weight of leaves (*LEAFW*), with *RRSENL* depending on the development stage. Leaf senescence can be accelerated by water stress (Wopereis et al 1996) and reduced with higher leaf N content (Dingkuhn et al 1991). Since the leaf N content is diluted in the case of direct-seeded rice, leaf senescence is indirectly dependent on crop establishment.

$$RSENL_t = RRSENL_{DVS_t} * LEAFW_t \qquad (17)$$

Thus equation (11) becomes:

$$LEAFW_{t+\Delta t} = LEAFW_t + (PARTL_t - RSENL_t) * \Delta t \qquad (18)$$

Dynamics of tiller numbers

In the model, a tiller is operationally defined as a tiller with at least two fully expanded living leaves.

In a rice crop, the number of tillers increases until maximum tillering. The rate of tillering depends on cultivar type (with high or low tillering capacity), crop establishment method (Dingkuhn et al 1990, Schnier et al 1990a, 1990b), nitrogen management (Yoshida 1981, Schnier et al 1990a, 1990b), and water management. After maximum tillering, the youngest tillers die due to competition for light and nutrients (Ishizuka & Tanaka 1963). The rate of tiller mortality depends on crop establishment method (Dingkuhn et al 1990), nitrogen management, and water management. If no major stress occurs after flowering, the number of tillers will remain stable until maturity (Dingkuhn et al 1990).

Tillering

Two hypotheses (H) are forwarded to simulate tillering in the model:

H1. Tillering corresponds to the production of new leaves and stems. The tillering rate is assumed to be proportional to the rates of leaf and stem growth:

$$RTIL_t = (PARTL_t + PARTST_t) * STW \qquad (19)$$

where *RTIL* is the tillering rate, *PARTL* is the rate of leaf growth, *PARTST* is the rate of stem growth, and *STW* is the dry weight of one new tiller, i.e., a tiller with two fully expanded leaves.

H2. During tillering, leaf and stem growth contribute less and less to generating new tillers. Leaf and stem growth correspond progressively more to leaf production, leaf expansion, and stem elongation, and progressively less to new tiller production. Tiller production is therefore seen in the model to compete with tiller growth, with respect to assimilate allocation to stems, sheaths, and leaves. When the number of tillers reaches a maximum threshold, assimilates are no longer attributed to the formation of new tillers. This is reflected by introducing the factor *[1 - (VTIL/MAXTIL)]* in equation (19), where *VTIL* and *MAXTIL* represent the number of vegetative tillers and the maximum number of tillers, respectively. When the crop reaches the maximum tillering stage, assimilates are not allocated for tillering any more. This is reflected by a multiplicative term, *DVE*, which is made dependent on development stage. *DVE* equals 1 at the beginning of the simulation, then declines when *DVS* increases, and *DVE* equals 0 when *DVS* is larger than 0.8. Equation (19) thus becomes:

$$RTIL_t = (PARTL_t + PARTST_t) * STW * [1 - (VTIL_t / MAXTIL_t)] * DVE_t \qquad (20)$$

Tiller mortality

Between maximum tillering and flowering, some of the younger tillers die due to competition for light and nutrients (Ishizuka & Tanaka 1963).

$$RMORTV_t = RRMORT_{DVS_t} * VTIL_t \qquad (21)$$

$$RMORTR_t = RRMORT_{DVS_t} * REPTIL_t \qquad (22)$$

where $RRMORT_{DVS_t}$ is the relative rate of tiller mortality.

Tiller maturity

The shift from the vegetative phase to the reproductive phase of the crop is materialized and can be easily distinguished in the field by the booting stage. This is simulated in the model by the maturation of vegetative tillers, which become reproductive. A fraction of the vegetative tillers, *FST*, may remain vegetative and not produce any panicle. The dynamics of vegetative tillers and of reproductive tillers is described by equations (23) and (24), respectively:

$$VTIL_{t+\Delta t} = VTIL_t + (RTIL_t - RMORTV_t - RMAT_t) * \Delta t \quad (23)$$

$$REPTIL_{t+\Delta t} = REPTIL_t + (RMAT_t - RMORTR_t) * \Delta t \quad (24)$$

where *RMAT*, the maturity rate of the tillers, depends on the development stage.

If the development stage is larger than 0.8 and smaller than 1 (which corresponds to the booting stage), and if the fraction of vegetative tillers relative to the total number of tillers is larger than *FST*, equation (25) is applied. Otherwise, *RMAT* = 0.

$$RMAT_t = RRMAT * VTIL_t \quad (25)$$

with *RRMAT* = relative rate of maturity, set to 0.3.

Modeling attainable growth according to specific production situations

Following the above discussion, the effects of the different components that define a production situation on attainable rice growth can be accounted for in the model: this is made possible by calibrating parameters and driving functions used in the model according to the nature or quantity of the components corresponding to the production situation. This is summarized in the following table.

Parameters or driving functions	Components of a production situation			
	Cultivar type	Crop establishment	Nitrogen level	Water management
DVS = f(SUMT)	×	×		×
IRG = f(DVS)		×	×	×
CP_i = f(DVS)[a]		×	×	×
RSENL = f(DVS)		×	×	×
MAXTIL	×	×	×	×
RRMORT = f(DVS)		×	×	×

[a] CP_i refers to CPL, CPP, CPST, and CPR.

Considering that

- The quantification and understanding of these complex effects and interactions is partly documented,
- Simulating all these interactions would lead to a complex, nontransparent model, and
- Whereas in theory, a multitude of (cultivar type × crop establishment × nitrogen level × water management) combinations (that is, production situations) is possible, in practice, rice is actually grown under a few common production situations only (Savary et al 1998a, 1998b).

The calibration of the model for attainable growth simulation is made specific to a set of production situations, and not specific to inputs, which was the approach used in previous modeling efforts in the IBSNAT or SARP projects (see following sections). Thus, parameters and driving functions in our case are calibrated for a set of specific production situations, that is, a set of specific combinations of (cultivar type × crop establishment × nitrogen level × water management).

Modeling of damage mechanisms due to different rice pests

Sheath blight

Sheath blight lesions (caused by *Rhizoctonia solani*, AG1-1A) occur on the rice sheath and leaves. Different effects of sheath blight on rice crop physiology can be considered (Savary & Mew 1996):

1. Lesions on leaf cause leaf death
2. Lesions on sheath cause leaf death
3. Lesions on leaf cause a decrease in green LAI
4. Lesions on sheath cause a disturbance in assimilates, nutrients, and water transportation that may result in a decrease in the photosynthetic efficiency of the leaf blade
5. Lesions on leaf cause a decrease in the photosynthetic efficiency of the infected leaf.

It is hypothesized that the first three damage mechanisms are quantitatively much more important than the others.

Three damage mechanisms of sheath blight injury are thus considered in the model:

1. Lesions on leaf cause leaf death
2. Lesions on sheath cause leaf death
3. Lesions on leaf cause a decrease in green LAI

The rate of leaf senescence due to the first two mechanisms (*RSHBL*) can be written as:

$$RSHBL = RRSHBL * LEAFW \quad (26)$$

with

$$RRSHBL = (a * SEVL) + (b * SEVSH) + (c * SEVL * SEVSH) \quad (27)$$

where *SEVL* is sheath blight severity on leaves (%) and *SEVSH* is sheath blight severity on sheaths (%).

The parameters *a*, *b*, and *c* were derived from three field experiments where sheath blight foci were established (Savary et al 1995). In each experiment, four treatments were compared, where hills were inoculated (1) at the base with 5 g of rice grain hull (RGH) colonized by *Rhizoctonia solani* mycelium, (2) at the base with 15 g of colonized RGH, (3) in the upper part of the canopy with 5 g of colonized RGH, or (4) in the upper part of the canopy with 15 g of colonized RGH. Each treatment was represented by eight replicates. The severity on leaves, the severity on sheaths, the number of green leaves, and the number of dead leaves were recorded weekly on inoculated hills. The relative rate of leaf mortality was computed as:

$$RRSHBL = (NBG_{19} - NBG_{12} + NBD_{19}) / [((NBG_{12} + NBG_{19}) / 2) * 7] \quad (28)$$

where NBG_i and NBD_i are the number of green leaves per tiller and the number of dead leaves per tiller, respectively, *i* days after inoculation.

A multiple regression was done following equation (27) using *RRSHBL* values calculated from equation (28), and sheath blight severity observed 12 d after inoculation.

From this regression, only *a* was significantly related to *RRSHBL*, and the estimated value of *a* was 0.0007.

After integration of the two damage mechanisms involved in sheath blight injury, equation (18) thus becomes:

$$LEAFW_{t+\Delta t} = LEAFW_t + (PARTL_t - RSENL_t - RSHBL_t) * \Delta t \quad (29)$$

with

$$RSHBL_t = 0.0007 * SEVL_t * LEAFW_t \quad (30)$$

When the third damage mechanism (lesions on leaf cause a decrease in green LAI) is integrated in the model, equation (6) becomes:

$$LAI_t = SLA_t * LEAFW_t * (1 - (SEVL_t / 100)) \quad (31)$$

Dead hearts

Stem borer (e.g., *Scirpophaga incertulas*) larval feeding during the vegetative stage results in dead hearts. Rice plants may compensate for damage during early growth stages by producing new tillers (Rubia et al 1989).

The appearance of dead hearts is reflected in the model by subtracting the number of dead hearts from the number of vegetative tillers. The total number of dead hearts is distributed over a period of 20 d, which represents the residence time of dead hearts before they decay. The accumulated number of dead hearts over 20 d corresponds to the maximum number of dead hearts observed. In the model, the daily removal of vegetative tillers (*RDHTI*) is numerically linked to a corresponding loss in dry matter of leaves and sheaths, and equations (16) and (29) become, respectively:

$$STEMW_{t+\Delta t} = STEMW_t + (PARTST_t - RDIST_t - RDHST_t) * \Delta t \quad (32)$$

$$LEAFW_{t+\Delta t} = LEAFW_t + (PARTL_t - RSENL_t - RSHBL_t - RDHL_t) * \Delta t \quad (33)$$

with

$$RDHL_t = LWT_t * RDHTI_t \quad (34)$$

$$RDHST_t = STWT_t * RDHTI_t \quad (35)$$

$$LWT_t = LEAFW_t \;/\; VTIL_t \quad (36)$$

$$STWT_t = STEMW_t \;/\; VTIL_t \quad (37)$$

LWT and *STWT* are the dry weights of leaves and stems, respectively, per tiller.

White heads

Stem borer (e.g., *Scirpophaga incertulas*) larval feeding during the reproductive stage results in white heads. At low injury incidence (one or two panicles injured per hill or incidence lower than 10%), and for hills with high tillering capacity, compensation may occur between tillers of the same hill (Rubia et al 1989). In this case, the relative damage would be subproportional to white head incidence. It is not known, however, whether this mechanism would occur in the case of direct-seeded rice or transplanted rice with a small tillering capacity. In contrast, empirical field data suggest that when white head incidence is high (> 20%), the relative damage is overproportional to white head incidence (Rubia et al 1989, Savary et al unpublished data). In this case, other mechanisms may hide the compensation effect. One hypothesis would be that high white head incidence would correspond to early infestation by stem borers, primarily affecting panicles initiated in the early reproductive stage, which are usually the biggest panicles in a hill.

At the field scale, the estimated white head incidence is represented by the mean of observed incidences. At the hill level, incidences therefore vary about the mean, either below or above it. If, for example, the mean is relatively low (e.g., 10%), individual hill incidences below the mean may trigger compensation, whereas incidences above the mean correspond to overproportional damage. For simplicity, it is hypothesized that, at the field scale, the two processes cancel each other. As a result, the overall effect of white head corresponds to nonfilling of the injured panicles, without any compensation mechanism. The fraction of white head thus corresponds to the same fraction of yield loss, and equation (15) becomes:

$$PANW_{t+\Delta t} = PANW_t + \left[(PARTP_t + RDIST_t) * (1 - WH) \right] * \Delta t \qquad (38)$$

where *WH* is a parameter which is the maximum proportion of white heads recorded during the growing season.

Weeds

Weed infestation reduces crop growth by three damage mechanisms: competition for light, competition for water, and competition for nutrients (Spitters 1989). In the model, the overall effect is simulated by a reduction in rice crop growth, and equation (5) becomes:

$$RG_t = IRG_t * RAD_t * \left[(1 - exp(-k * LAI_t) \right] * (1 - RFwd) \qquad (39)$$

A function quantifying the relationships between *RFwd* and the weed biomass was derived from data reported by Kropff et al (1993) and Rao & Moody (1992):

$$RFwd = 1 - \exp(1 - 0.003 * WEED) \qquad (40)$$

where *WEED* represents the total dry weight of weeds per square meter.

Field experiments to calibrate and test the model

Objective and approach

The simulation of yield losses builds upon the use of damage coupling functions, which alter crop growth. It would thus be difficult to test a simulation model for yield losses which does not simulate with sufficient accuracy the growth of an injured crop. Furthermore, interactions are likely to occur between crop growth and injury mechanisms in a given production situation (which reflects an array of yield-limiting factors).

For these two major reasons, it is therefore critical to simulate well the attainable yield to test the simulation of yield losses. The following strategy was developed to simultaneously have an adequate simulation of the attainable yield, and test the simulation of yield losses under a given production situation (Fig. 9). It involves field experiments specifically designed with that aim, where, for a given production situation, rice plots free of pests and rice plots with pests (alone or in combination) are established.

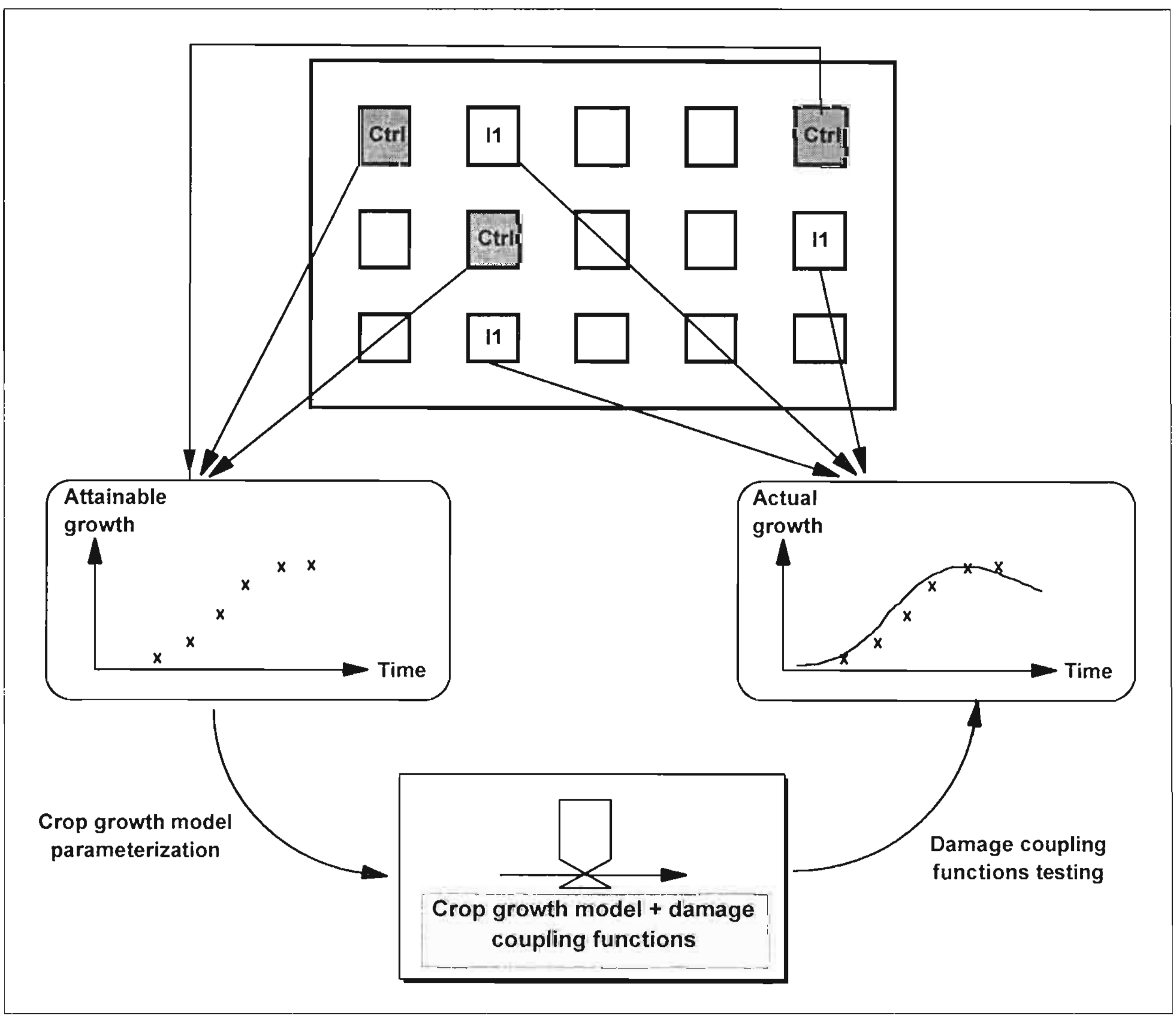

Fig. 9. Use of field data to parameterize and test the simulation model for yield losses due to rice pests.

1. Data collection

   - Growth of pest-free rice crops is monitored with regular destructive samplings;
   - Growth of rice crops with pests, alone or in combination, is monitored with regular destructive samplings;
   - Different injuries are monitored;
   - Weather data are collected daily: maximum temperature, minimum temperature, radiation (or sunshine duration), and rainfall.

2. Model parameterization for the simulation of attainable yield (equations shown in the fourth section, *Model parameterization – simulation of attainable yield*):

   - Parameters needed to simulate attainable growth and yield are calibrated empirically from the observed growth and yield of the control, noninjured, treatments.

3. Model test for the simulation of actual yield (one example is given in the fifth section, *Model testing – simulation of actual yield*):

   - Driving functions reflecting the injury dynamic over time are derived from the observations of injuries;
   - Parameters calibrated for the control are used;
   - Simulations are done for the different treatments and compared to the observed values derived from the destructive samplings of the corresponding treatments.

Experimental design and management of a typical yield loss simulation experiment

Main units: production situations

The experiment involved main units representing different production situations (PS). Each of these main units should be seen as (statistically) independent entities. These main units represent production situations which are defined depending on the objective of the modeling work: they may represent current or future production situations existing (or foreseen) in a given region. In the work presented here, production situations were identified from surveys done in farmers' fields in several countries in tropical Asia (Savary et al 1994, 1997b, Du et al 1997, Zhu et al unpublished).

Subunits: injury treatments

In each main unit, one uninjured control and several injury treatments were considered. The determination of the injury treatments was done on the basis of

- representativeness of injuries in production situations considered,
- general representativeness of the damage mechanisms these injuries trigger, and
- ease of manipulation of injuries.

Injuries caused by weeds, stem borers, and sheath blight were addressed in this work since these are among the most common rice pests that cause yield losses (Savary et al 1998b).

Experiment layout

In each main unit, injury treatments were represented by 2.8 x 2.8-m plots, each with three replications. The plots were randomly distributed within each main unit.

The distance between each subunit (that is, between each plot in a main unit) must be carefully determined—at least 3 m—to minimize interplot interferences. This depends on the pests addressed and their ability to spread. In this study the distance was set to 3 m.

Within each main unit, the buffer area consists of transplanted rice, with the cultivar selected for the given PS. These buffer areas are subject to exactly the same management practices as the experimental plots, i.e., cultivar, fertilization, and water management (except for crop establishment, and of course injuries).

A sketch of a typical experimental layout is shown in Fig. 10.

Design of plot subunits

Each plot consists of 14 x 14 (= 196) units; each unit is 20 x 20 cm. Depending on the crop establishment, a unit may consist of a hill transplanted at its center (transplanted rice) or a number of direct-seeded plants (direct-seeded rice). Each plot is 2.8 x 2.8 m. It includes, from the outer part towards the center (see Fig. 11), the following zones:

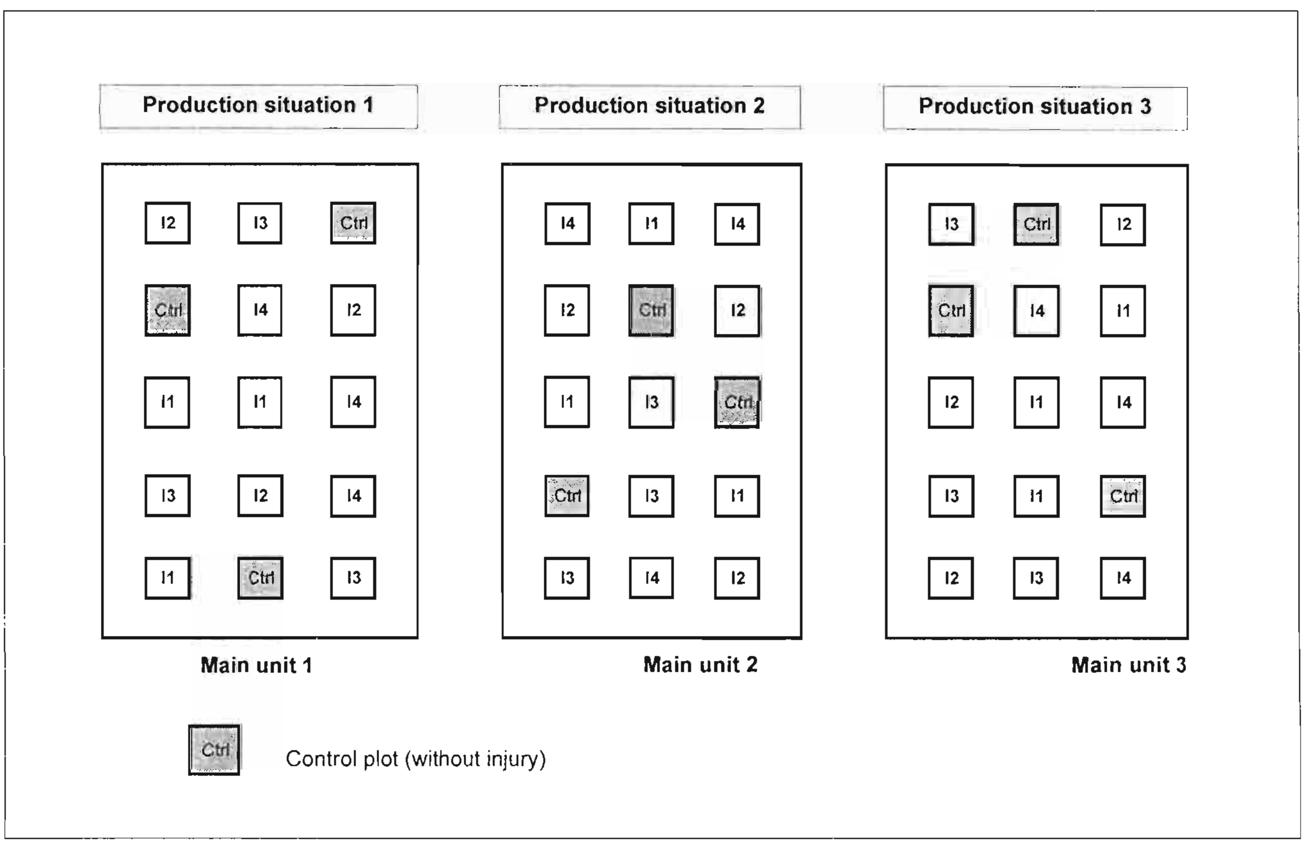

Fig. 10. Sketch of the layout of a typical yield loss modeling experiment.

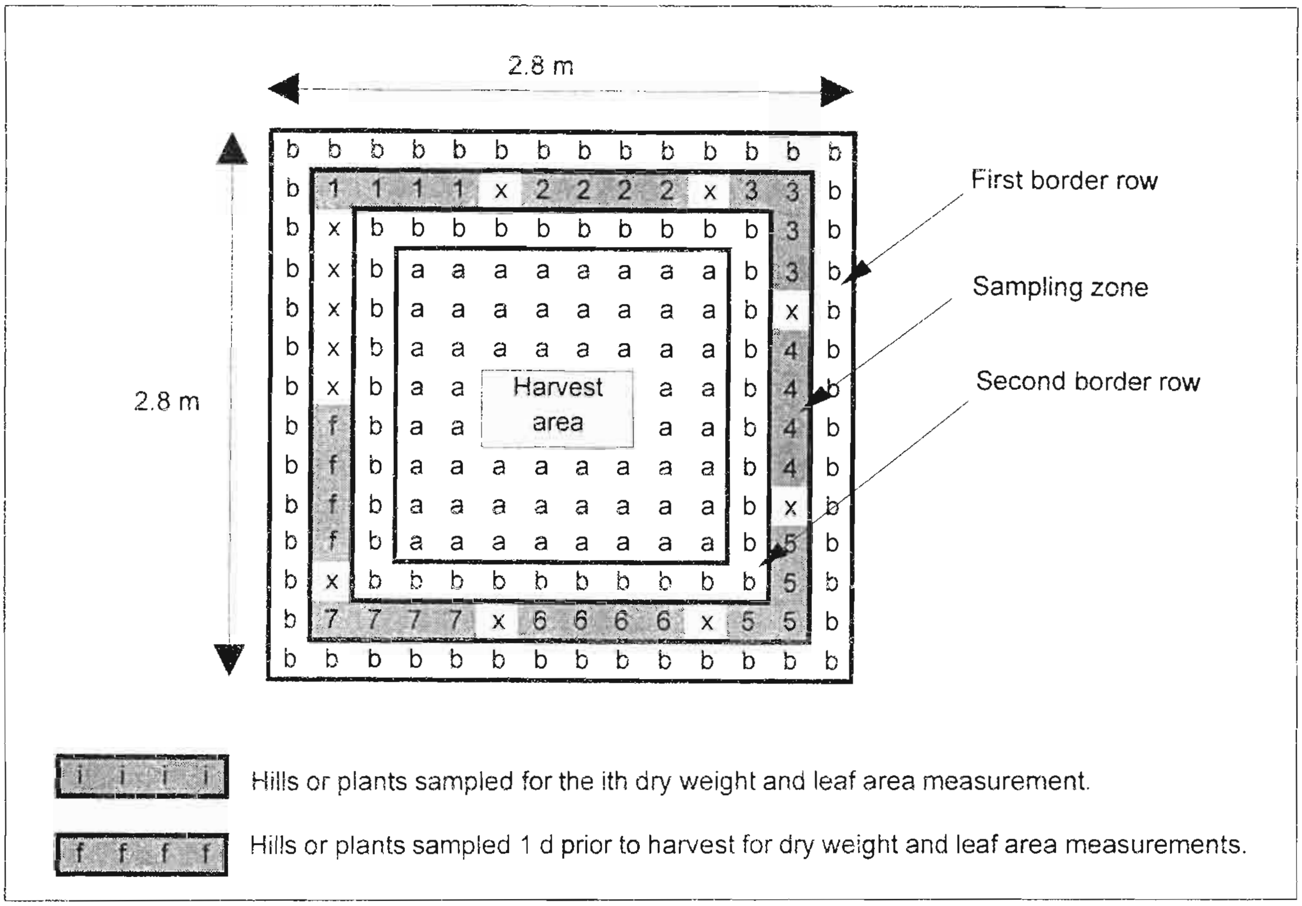

Fig. 11. Structure of an individual plot in a yield loss modeling experiment.

1. a first border row, 20 cm wide;
2. a sampling zone, where destructive samplings are done to monitor rice growth, and nondestructive pest assessments (visual observation) are done to monitor pests. The sampling zone is also 20 cm wide;
3. a second border row, 20 cm wide;
4. a harvest area at the center that is harvested at the end of the cropping season. The harvest area is 1.6 x 1.6 m.

The second border row serves as a "compensation" buffer, which the destructive sampling in the sampling zone makes necessary: when samples are taken away from the sampling zone, the neighboring units will inevitably have a tendency to grow more than the units that would be part of a homogeneous stand. This second border row therefore protects the harvest area from such an occurrence.

Timing of operations

A sketch summarizing a typical succession of the main experimental steps is given in Fig. 12.

- Crop establishment (transplanting for transplanted rice; sowing for direct-seeded rice; transplanting of buffer areas) in the field is done on the same day. Timing of subsequent operations is scaled with DACE (number of days after crop establishment).

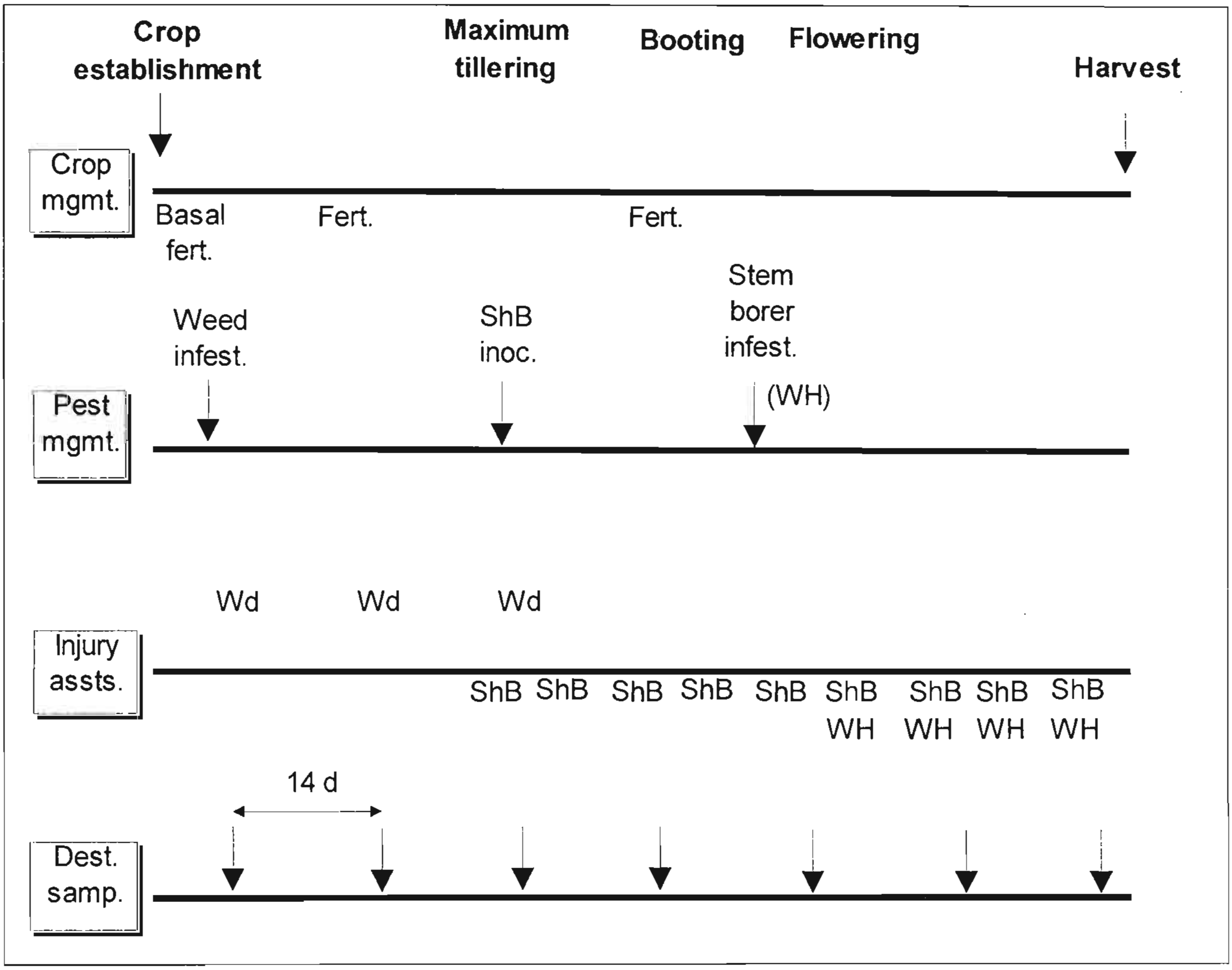

Fig. 12. Sketch of the timing of operations in a yield loss modeling experiment involving sheath blight (ShB), weeds (Wd), and white heads (WH).

This succession of operations is given as an example only. Each experiment has its own specific requirements, constraints, and problems. Even though many steps appear to be very much of a routine, they are not, in practice, so the experimenter has to adapt and adjust operations to achieve the objective of each experiment. One typical example is the timing of injury treatment establishment, which must coincide with some specific crop development stages that are specific to the injury considered.

- The timing of crop management operations (e.g., fertilizer application) and the timing of pest manipulations (e.g., infestation) are determined for each production situation based on the crop development stage. Experience shows that the development stage may vary very much with the production situation. It is therefore necessary to have a regular monitoring of the development stage, which in turn drives management operations.
- Destructive samplings are done every 14 d, starting 14 DACE until harvest.
- Pest assessment is done regularly throughout the growing season (see further details below).
- Harvest of the central area of each plot is done at crop maturity.

Examples of designs

A small network was developed with two other research institutions, CNRRI (China National Rice Research Institute) in China, and NDUAT (Narendra Deva University of Agriculture and Technology) in India, to test the model under a wide range of production situations and injury combinations. Yield loss experiments were or still are conducted at these different sites. The various production situations and injuries addressed in this network of experiments are outlined below. One common production situation (PS2) is included in all the experiments to test the performance of the model under different climatic and edaphic conditions. The other production situations and the injuries addressed are representative of what prevails in the different areas.

Experiment name, location, season, partner	Production situations addressed	Injuries addressed
IRRI VIII Los Baños, Philippines 1997 rainy season IRRI	PS2: short-duration, high-yielding cultivar; transplanted young rice seedlings; medium-high fertilization; fully irrigated crop. PS1: short-duration, high-yielding cultivar; transplanted young rice seedlings; low fertilization; fully irrigated crop. PS3: short-duration, high-yielding cultivar; direct-seeded rice; medium fertilization; fully irrigated crop.	Dead hearts Weeds Sheath blight White heads Dead hearts + weeds + sheath blight + white heads
IRRI IX Los Baños, Philippines 1998 dry season IRRI	PS2 PS4: short-duration, high-yielding cultivar; transplanted young rice seedlings; low fertilization; water-stressed from the tillering stage. PS5: short-duration, high-yielding cultivar; direct-seeded rice; medium fertilization; water-stressed from the tillering stage.	Dead hearts Weeds White heads Dead hearts + weeds + white heads
HGZ Hangzhou, China 1998 rainy season, "early rice" CNRRI	PS2 PS6: short-duration, high-yielding cultivar; direct-seeded rice; high fertilization; fully irrigated crop, drained for a few days at maximum tillering. PS7: short-duration, high-yielding cultivar; transplanted old rice seedlings; high fertilization; fully irrigated crop, drained for a few days at maximum tillering.	Weeds Sheath blight White heads Weeds + sheath blight + white heads
FAIZ Kumarganj, India 1998 kharif season NDUAT	PS2 PS8: short-duration, high-yielding cultivar; transplanted old rice seedlings; medium fertilization; rainfed from tillering stage. PS9: short-duration, high-yielding cultivar; direct-seeded rice; low fertilization; rainfed from tillering stage.	Dead hearts Sheath blight White heads Brown spot Dead hearts + sheath blight + white heads + brown spot

Manipulation of injuries: examples

For each plot to be infested/inoculated, it is necessary:

- to have the entire plot (2.8 × 2.8 m, each plot is considered an entity) infested;
- to have an infestation as homogeneous as possible.

Both points represent key experimental requirements because the destructive samplings are not taken at random (see Fig. 11). The spatial distribution of inoculated/infested hills or plants was carefully defined to provide a uniform distribution of disease in the whole plot, and more specifically for all the destructive sampling units.

In the following paragraphs, we provide additional details on the manipulation of a few injuries due to weeds, sheath blight, and stem borers. These specific details are given as examples only. They have to be adjusted depending on the location of the experiment, the production situations addressed, and the resources available. Nevertheless, modification of the procedures summarized below should aim at the objectives stated above.

Weeds

Weed control: a preemergence herbicide (pretilachlor) was applied in all the plots and in the buffer area at 3 DACE.

Weed infestation: 9-d-old seedlings of *Echinochloa crus-galli* produced in a nursery were transplanted in the plots at 20 x 20-cm density. The location layout of the transplanting of the weed seedlings is given in Fig. 13. The weed seedlings were transplanted at 7 DACE.

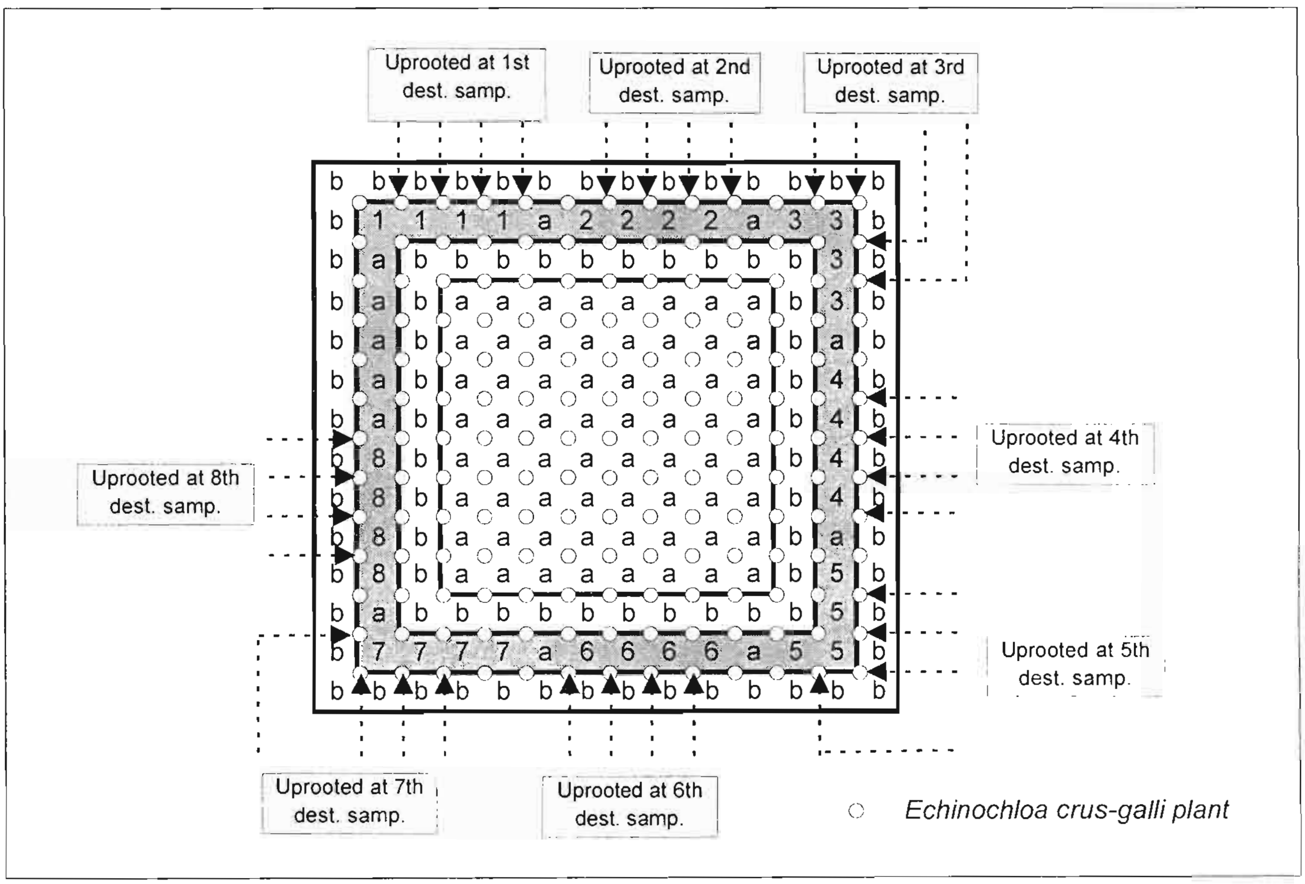

Fig. 13. Location of weeds to be transplanted and of weeds uprooted during the successive destructive samplings.

Sheath blight

Inoculum: it consisted of 1:4 rice grain hull substrate. The substrate had been inoculated 10-14 d earlier with *Rhizoctonia* AGI-1A, using 3-d-old cultures grown on potato dextrose agar (PDA).

Inoculation: all the hills of transplanted plots were inoculated by inserting 5 g of inoculum at the base of the hill. Direct-seeded plots were inoculated by broadcasting 980 g of inoculum on each plot, so that the same quantity of inoculum was applied in transplanted and direct-seeded plots. Inoculation was done at the maximum tillering stage and was repeated 1 wk later if the disease had not established well after the first inoculation.

Dead hearts and white heads

Production of egg masses: moths of stem borers collected in bushes surrounding rice fields were placed in a nylon cage on a rice plant for 3-4 d. When egg masses were mature (6-8 d after moth collection), i.e., at the "black-head" stage, when a dark dot was observed at the tip of the eggs), leaf segments (about 5 cm long) containing the mature egg masses were cut. These leaf segments were inserted between the stem and the sheath of a lower leaf, in a tiller belonging to a hill/plant to be infested. On the average, one moth produces one egg mass.

Infestation: the location of the tillers to be inoculated is mapped in Fig. 14. This represents a total of 51 egg masses to be inserted in each plot. When the total amount of egg masses needed could not be produced from moths collected in 1 d, successive moth collections (every 2-3 d; the interval should be as short as possible) were done until the required number of moths was reached. Egg mass infestation was thus done in successive batches. For each batch, infestation of all plots was done with the same fraction of egg masses, so that infestation conditions were similar for all the plots. Infestation took place at the tillering and booting stages for dead heart and white head damage, respectively.

b	**b**	b	b	b	**b**	b	b	b	**b**	b	b	b	**b**
b	1	1	1	**1**	x	2	2	**2**	2	x	3	**3**	b
b	x	b	**b**	b	b	b	**b**	b	b	b	**b**	3	b
b	x	**b**	a	a	a	**a**	a	a	a	**a**	b	3	b
b	**x**	b	a	a	**a**	a	a	a	**a**	a	b	x	**b**
b	x	b	a	**a**	a	a	a	**a**	a	a	b	**4**	b
b	x	b	**a**	a	a	a	**a**	a	a	a	**b**	4	b
b	f	**b**	a	a	a	**a**	a	a	a	**a**	b	4	b
b	**f**	b	a	a	**a**	a	a	a	**a**	a	b	4	**b**
b	f	b	a	**a**	a	a	a	**a**	a	a	b	**x**	b
b	f	b	**a**	a	a	a	**a**	a	a	a	**b**	5	b
b	x	**b**	b	b	b	**b**	b	b	b	**b**	b	5	**b**
b	**7**	7	7	7	**x**	6	6	6	**6**	x	5	**5**	b
b	b	b	b	**b**	b	b	b	**b**	b	b	**b**	b	b

Fig. 14. Location of tillers to be infested by stem borer egg masses.
In bold: plants/hills where one tiller is to be infested.

Weather monitoring

The following daily weather data throughout the growing season are required to run the model:

- minimum temperature;
- maximum temperature;
- global radiation (or sunshine duration, when global radiation is not available).

These data were monitored by local weather stations (such as at IRRI) or by weather stations belonging to the national weather bureaus.

Measurement of crop growth, and assessment of injuries, crop development, and water status

The following operational definitions were used in all experiments:

- Development stage: stage of development that has been reached by the majority (more than 50%) of the plants in a given plot.
- Tiller: tiller that has at least two fully expanded living leaves.
- Reproductive tiller: tiller that is booting or has passed booting stage.
- Vegetative tiller: tiller that has not yet booted; tiller without panicle.
- Leaf (or living leaf): leaf with at least 50% green area.
- Dead leaf: leaf with at least 50% dead or infected area.

Destructive sampling to measure rice growth

The sampling zone contained successive destructive sampling areas, 20 x 80 cm each (i.e., four units at each sampling date).

Destructive sampling was done every 14 d, starting at 14 DACE. The last crop growth assessment (i.e., 7th, 8th, or 9th, depending on the rice growth duration) was done 1 d before harvest.

Variables pertaining to crop growth were measured by destructive sampling. In each plot, rice plants (and weeds) in the destructive sampling area to be sampled were uprooted.

Uprooting of rice plants

At each destructive sampling, rice plants were uprooted in each plot. Four hills were uprooted in the case of transplanted plots. For direct-seeded plots, a rectangular frame made of hard wire measuring 20 x 80 cm was used to delimit the area to be sampled. Uprooted plants were placed in one bag. The bags were kept in a cooler with ice cubes for transportation. The sampled plants were then brought to the laboratory for processing. First, all the samples were gently washed in tap water to remove the soil particles, especially on the roots. Samples were kept in coolers or transferred to a cold room until processing (this period should not exceed 2 d).

Processing of sampled rice plants

The dry weights of leaves, stems, roots, and panicles were obtained separately. Rice leaf area was measured as well.

The following procedure was applied for each sample (i.e., the bulk of four units) obtained from one individual plot:

1. The total number of vegetative tillers (excluding dead hearts and dead tillers), the total number of dead hearts, the total number of reproductive tillers (i.e., at the booting stage or carrying a panicle), and the total number of white heads were recorded.
2. The second topmost tiller was selected for leaf area assessment: only living leaves, i.e., with green area larger than 50%, were assessed for leaf area.

   The total leaf area per tiller (LA2T) was measured by using a leaf area meter (LI-COR, USA) (total over all the leaves; individual leaf data were not needed).
3. All the living leaves from the second topmost tiller were placed in a paper bag for oven drying (sample LW2T).
4. Dead leaves (dead area of the leaf is more than 50%), dead tillers (tillers with dead leaves), and dead hearts were discarded.
5. Leaf blades, stem + sheath, panicles, and roots were separated and placed in a paper bag for oven drying (samples LW, SW, PW, and RW, respectively).
6. All the samples were oven-dried for 5-7 d at 60 °C until dry.
7. All the samples were weighed separately.

The total leaf area per sample (TLA) was computed following Yoshida et al (1976):

$$TLA = LA2T * TLW/LW2T$$

where $TLW = LW2T + LW$.

Assessment of injuries in the plots

Weed infestation

Weed infestation was measured by the dry matter weight of weeds at successive destructive samplings. These were done at the same time as the destructive sampling of rice.

Weeds located near the sample rice plants, at the side of the external border, were uprooted. Four *Echinochloa crus-galli* plants were uprooted in each plot (see Fig. 13).

For each weed sample, weeds were gently washed in tap water to remove soil particles, especially on the roots. Weeds were placed in a paper bag, oven-dried, and weighed.

Other injuries

Five units were randomly chosen for assessment. At the beginning of the growing season, units were chosen only from within the sampling zone. Later on, when more than four destructive samplings had been taken, units from those remaining in the sampling zone and also from the external border of the central area beside the zone where units have been sampled were assessed (see Fig. 15).

Sheath blight injuries For each of the five units assessed, the total number of tillers and the number of infected tillers were counted. For each unit assessed, three tillers were randomly selected for severity assessment: the percent of sheath area covered by sheath blight lesions

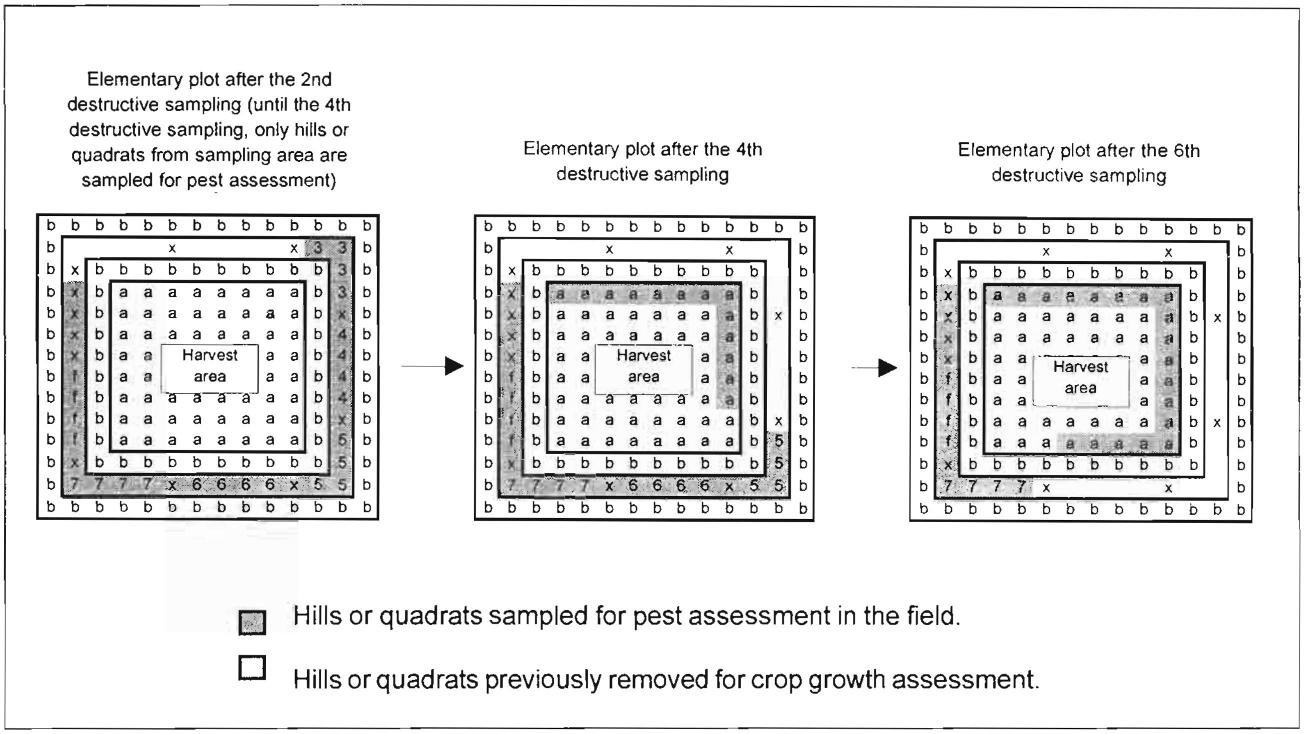

Fig. 15. Sampling design for pest assessment in the field.

(relative to the total area of the leaf, i.e., green + dead tissues) was visually measured, and the percent of leaf area covered by sheath blight lesions for all the leaves was computed. The percent of dead leaf was also recorded. For severity assessment on the leaf, the following percentage scale was used: 0, 1, 5, 10, 15, and every 5% thereafter. For severity assessment on the stem (sheath), the following percentage scale was used: 0, 1, 3, 5, 7, 10, 15, and every 5% thereafter. Sheath blight assessment was done weekly in all the plots, starting 1 wk before sheath blight inoculation to harvest.

Dead heart injuries For each of the five units assessed, the total number of tillers (including dead hearts) and the number of dead hearts were counted. Dead heart assessment was made weekly in all the plots, starting before infestation until flowering. The number of dead hearts was also recorded on the units sampled every 2 wk.

White head injuries For each of the five units assessed, the total number of panicles (counted when more than 50% of the panicle has emerged) and the number of damaged panicles were counted. White head assessment was made weekly in all the plots, starting at panicle exsertion, until harvest. The number of white heads in the sample units was also recorded every 2 wk.

Assessment of the water status of the soil

The water status of the soil needs to be assessed, especially in production situations where water stress is imposed. These data may be used to characterize semiquantitatively the water stress experienced over time by the crop and to characterize the PS itself.

For each plot, the water status of the soil was assessed weekly during the whole growing season, according to the scale described by Savary et al (1996a):

Soil hard: no foot imprint is left when tramping on the soil
Soil soft: faint imprint appears when tramping on the soil
Soil dry: the soil moisture is far below capacity (some cracks are visible)
Soil moist: the soil does not have any crack and appears visually damp
Soil wet: the soil has passed its water-holding capacity; water oozes under a foot step

Without standing water

1 soil dry and hard
2 soil moist and hard
3 soil moist and soft
4 soil wet and hard
5 soil wet and soft

With little standing water (water level lower than 5 cm)

6 soil hard
7 soil soft

With adequate standing water (water level between 5 and 15 cm)

8 soil hard
9 soil soft

With too much water (water level higher than 15 cm)

10 soil hard
11 soil soft

Monitoring of the crop development stage

For each plot, the development stage is assessed weekly during the whole growing season according to the key described by Savary et al (1996a):

10: seedling
20: tillering
30: stem elongation/panicle initiation
40: booting
50: heading
60: flowering
70: milk
80: dough
90: ripening
100: fully mature

Assessment of lodging

By the end of the growing season, plots may lodge. In this case, from the start of lodging to harvest, all the plots were assessed weekly for lodging according to the scale presented in Savary et al (1997a). Two variables were recorded:

1. Incidence was determined by estimating the percent of lodged hills (plants).
2. The degree of lodging was recorded using the following scale as a guide:

Lodging severity scale:

0: no lodging

1: 5 to 25°

2: 25 to 45°

3: over 45°

Auxiliary data

Unexpected injuries (e.g., rats, birds, etc.) were documented similarly.

Collection of yield data

The final yield of each individual plot was measured in two steps:

1. Ten units were carefully chosen to represent as best as possible the status of the plot at harvest.

   For each unit, the following steps were done:

   a. All the panicles were collected and placed in one bag;

   b. The panicles were brought to the laboratory and dried;

   c. The panicles were threshed, and the filled grains were separated from rachis and unfilled grains;

   d. The filled grains and rachis + unfilled grains were weighed separately, and moisture content of grains was measured.

2. The central area of each individual plot was then harvested, the harvest was threshed and dried (14% moisture content), and the yield was determined.

Model parameterization—simulation of attainable yield

Some parameters required to simulate attainable growth are not specific to a production situation and are constant values that remain unchanged across the different production situations addressed.

Other parameters, and the driving functions, are production situation-specific (see p. 17). They are derived from measurements on a noninjured rice crop grown under the corresponding production situation (using the procedure indicated in the third section, *Field experiments to calibrate and test the model*).

The determination of parameter values and of driving functions used in the model is described in the following section.

Initial values

The initial values of the pool of assimilates, the dry weight of panicles, and the number of reproductive tillers are set at 0.

For each injury treatment (including the control), initial values of the dry weight of leaves, stems, and roots, and of the number of vegetative tillers, are computed from measurements done during the first destructive sampling in the plots corresponding to the treatment to be simulated.

Parameters

- The coefficient of light extinction (*k*) is set at 0.6 (Hayashi & Ito 1962).
- The maximum number of tillers (*MAXTIL*) is computed from the destructive sampling done in the control plots: it is the maximum value of the number of vegetative tillers, derived by averaging all the values for maximum number of tillers in the control plots.
- The number of vegetative tillers produced per unit of biomass partitioned to the leaves and stems (*STW*) is set at 20, based on measurements taken in a farmer's field planted with IR72 in Laguna, Philippines (Willocquet & Fernandez unpublished). This value represents the average biomass of a newly formed tiller (excluding root biomass), estimated by weighing 100 newly formed tillers, i.e., secondary tillers with two fully expanded leaves.
- The relative rate of tiller maturity (*RRMAT*) is set at 0.3.
- The fraction of sterile (vegetative) tillers remaining after booting (*FST*) is computed from measurements done during the destructive sampling of the control plots.
- The minimum threshold for rice growth (*TBASE*) is set at 8 °C (Gao et al 1992).
- The day of crop establishment (*DOYCE*) is the Julian day of crop establishment.
- The daily rate of redistribution of starch from stems to panicles (*RDIST*) equals 0 when the development stage is smaller than 1 (that is, before flowering). After flowering, it is equal to *DDIST*:

$$DDIST = (STEMW_{DVS=1} - STEMW_{DVS=2}) \,/\, (DACE_{DVS=2} - DACE_{DVS=1}) \qquad (41)$$

Driving functions

- The daily minimum temperature, maximum temperature, and global radiation are used. When only the number of sunshine hours is available, the global radiation is derived from Angstrom's formula (1924):

$$RAD = RAD_a * [\, a + b * (SSD \,/\, DAYL) \,] \tag{42}$$

where RAD_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}), SSD is the duration of bright sunshine (h), and $DAYL$ is the daylength (h). Values of a and b are set at 0.29 and 0.42, respectively. These values correspond to estimates done by Frere and Popov (1979) for tropical humid areas.

- The development stage (DVS) is made dependent on the temperature sum above the temperature threshold, using observations done on the control plots: the sum of temperature at flowering and maturity, corresponding to DVS=1 and 2, respectively, is used to build the corresponding driving function in the model.

- The intrinsic rate of growth between the destructive samplings i and $i+1$ is computed from measurements done in the control plots:

$$IRG_{(i+i-1)/2} = \frac{(TOTW_i - TOTW_{i-1}) \,/\, (DACE_i - DACE_{i-1})}{RAD_{i-1,i} * \left(1 - \exp\left[-k * (LAI_{i-1} + LAI_i) \,/\, 2\,\right]\right)} \tag{43}$$

where i = destructive sampling number;

$TOTW_i$ = total dry weight at destructive sampling i;

$DACE_i$ = number of days after crop establishment at destructive sampling i;

$RAD_{i-1,i}$ = average radiation between destructive sampling $i-1$ and destructive sampling i;

LAI_i = LAI at destructive sampling i;

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and a driving function relating the $IRG_{(i+i-1)/2}$ to the corresponding development stage is built.

- The coefficients of partitioning to roots (CPR_i) (partitioning relative to total dry matter) are computed from measurements done during the destructive sampling of the control plots.

$$CPR_{(i+i-1)/2} = \frac{ROOTW_i - ROOTW_{i-1}}{TOTW_i - ROOTW_{i-1}} \,/\, (DACE_i - DACE_{i-1}) \tag{44}$$

where i = destructive sampling number;

$TOTW_i$ = total dry weight at destructive sampling i;

$ROOTW_i$ = root dry weight at destructive sampling i;

$DACE_i$ = number of days after crop establishment at destructive sampling i.

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and a driving function relating the $CPR_{(i+i-1)/2}$ to the corresponding development stage is built.

- The coefficients of partitioning to panicles (*CPP*) and leaves (*CPL*) (partitioning relative to the aboveground dry matter) are computed from measurements done during the destructive sampling of the control plots.

$$CPP_{(i+i-1)/2} = \frac{PANW_i - PANW_{i-1}}{(TOTW_i - ROOTW_i) - (TOTW_{i-1} - ROOTW_{i-1})} \; / \; (DACE_i - DACE_{i-1}) \qquad (45)$$

$$CPL_{(i+i-1)/2} = \frac{LEAFW_i - LEAFW_{i-1}}{(TOTW_i - ROOTW_i) - (TOTW_{i-1} - ROOTW_{i-1})} \; / \; (DACE_i - DACE_{i-1}) \qquad (46)$$

where i = destructive sampling number;

$TOTW_i$ = total dry weight at destructive sampling i;

$LEAFW_i$ = leaf dry weight at destructive sampling i;

$ROOTW_i$ = root dry weight at destructive sampling i;

$PANW_i$ = panicle dry weight at destructive sampling i;

$DACE_i$ = number of days after crop establishment at destructive sampling i.

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and driving functions relating the $CPP_{(i+i-1)/2}$ and $CPL_{(i+i-1)/2}$ to their corresponding development stages are built.

- The coefficient of partitioning to stems (*CPS*) (partitioning relative to the aboveground dry matter) is computed as:

$$CPS_i = 1 - CPP_i - CPL_i \qquad (47)$$

- The specific leaf area (*SLA*) is related to the development stage from measurements done during the destructive sampling of the control plots.

$$SLA_i = LAI_i \,/\, LEAFW_i \qquad (48)$$

where i = destructive sampling number;

$LEAFW_i$ = leaf dry weight at destructive sampling i;

LAI_i = leaf area index at destructive sampling i.

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and a driving function relating the SLA_i to its corresponding development stage is built.

- The relative rate of leaf senescence (*RRSENL*) is related to the development stage from measurements done during the destructive sampling of the control plots.

$$RRSENL_{(i+i-1)/2} = \frac{LEAFW_{i-1} - LEAFW_i}{LEAFW_{i-1}} \; / \, (DACE_i - DACE_{i-1}) \qquad (49)$$

where i = destructive sampling number;

$LEAFW_i$ = total number of tillers at destructive sampling i;

$DACE_i$ = number of days after crop establishment at destructive sampling i.

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and the driving function relating the $RRSENL_{(i+i-1)/2}$ to the corresponding development stage is built.

- The fraction of assimilates allocated for the development of new tillers (DVE) depends on the development stage:

  $DVE = 1$ if $DVS \leq 0.4$

  DVE declines linearly from 1 to 0 for $0.4 < DVS \leq 0.8$

  $DVE = 0$ if $DVS > 0.8$

- The relative rate of mortality of the tillers ($RRMORT$) is computed from measurements done during the destructive sampling of the control plots.

$$RRMORT_{(i+i-1)/2} = \frac{TOTIL_{i-1} - TOTIL_i}{TOTIL_{i-1}} \; / \, (DACE_i - DACE_{i-1}) \qquad (50)$$

where i = destructive sampling number;

$TOTIL_i$ = total number of tillers at destructive sampling i;

$DACE_i$ = number of days after crop establishment at destructive sampling i.

The development stage corresponding to $DACE_{(i+i-1)/2}$ is determined, and the driving function relating the $RRMORT_{(i+i-1)/2}$ to the corresponding development stage is built.

Model testing—simulation of actual yield

An example is given in this section, where the model was tested for three production situations in an experiment conducted at IRRI during the 1997 rainy season.

The observed values corresponding to the most meaningful variables (that is, organ weight and tiller number) are plotted as time series, together with the simulated values. Interpretation of the plots allows a first evaluation of the model by visually comparing observed and simulated data (Penning de Vries et al 1989).

Characteristics of the experimental example

Crop establishment was done on 4 July 1997. PS1 and PS2 plots were harvested on 9 October, and PS3 plots were harvested on 13 October. Weather data were collected by the lowland IRRI weather station located 500 m from the experimental site. The weather conditions prevailing during the experiment are given in Fig. 16. The minimum temperature varied between 22 and 24 °C most of the time. The maximum temperature ranged from 29 to 33 °C. Variations between 2 consecutive d could be as high as 5 °C. These variations were similar to those observed for the daily global radiation. Most of the daily radiation ranged from 10 to 25 MJ m^{-2} d^{-1}, with lower radiation corresponding to rainy days. Two periods (1-9 Aug and 26 Aug-17 Sep) were relatively dry, with rainfall lower than 5 mm occurring every 4-5 d. Except for these two periods, rainfall occurred nearly every day.

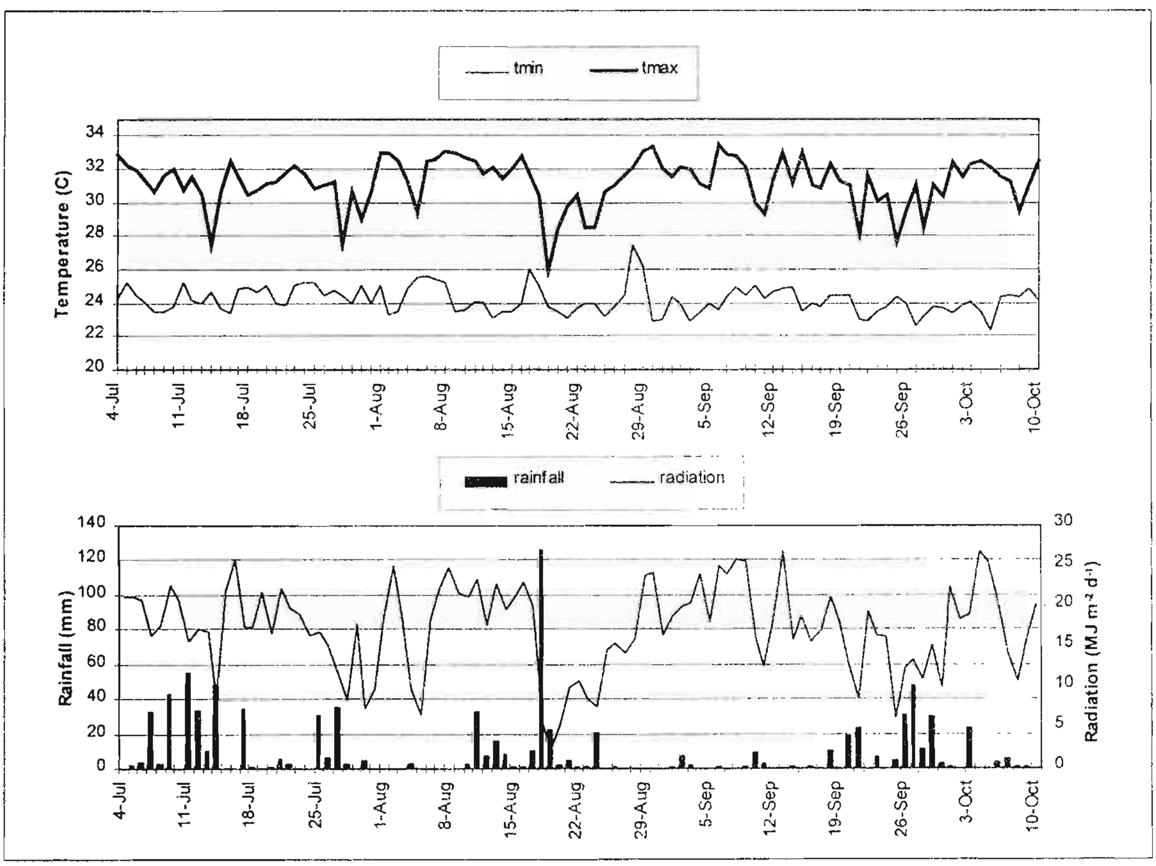

Fig. 16. Weather patterns during the experiment done at IRRI in 1997 to calibrate and test the rice yield loss simulation model.

The cropping practices associated with the three production situations considered are as follows:

Production situation	Components				
	Variety	Crop establishment	Crop density	Fertilization[a]	Water management
PS1	IR72 (short cycle, high-yielding cultivar)	Transplanted with 14-d-old seedlings	5 seedlings $hill^{-1}$ Hill spacing: 20 x 20 cm	N: 30 (at basal)	Full water supply, drained 2 wk before harvest
PS2	IR72 (short cycle, high-yielding cultivar)	Transplanted with 14-d-old seedlings	5 seedlings $hill^{-1}$ Hill spacing: 20 x 20 cm	N:110 (30 at basal) + 50 at early booting +30 at flowering)	Full water supply, drained 2 wk before harvest
PS3	IR72 (short cycle, high-yielding cultivar)	Direct-seeded	Sowing density: 90 kg ha^{-1}	N: 60 (30 at basal + 30 at early booting)	Full water supply, drained 2 wk before harvest

[a]K and P were amply supplied by irrigation water of volcanic origin used at the IRRI farm.

The following injury treatments were considered within each production situation:

DH: dead hearts

WH: white heads

SHB: sheath blight

WD: weeds

COMBI: dead hearts + white heads + sheath blight + weeds

CTRL: uninjured control (attainable yield corresponding to each production situation)

Simulation of attainable yield

For each production situation, the different parameters and driving functions needed to simulate attainable growth were derived from the data collected from the control plots. The simulations of attainable growth and yield were close to the observed ones (Fig. 17).

In PS1 (Fig. 17A), leaf weight increased up to 200 g m^{-2} and then declined after flowering due to leaf senescence. Root weight increased until flowering and then remained stable. Stem weight increased regularly until flowering, and then decreased due to the translocation of stored starch from the stem to the panicles. Panicle weight increased regularly from flowering to maturity. The observed and simulated attainable panicle yields for that production situation were 556 and 569 g m^{-2}, respectively. The LAI followed a pattern similar to that of the dry weight of leaves, reaching a maximum of 4 (simulated) and 4.5 (observed). Tillering occurred until 40 DACE (maximum tillering stage), when 800 vegetative tillers m^{-2} were produced. This number then declined in a first stage due to tiller death, and in a second stage due to the maturity of tillers. At maturity, 450 reproductive tillers m^{-2} remained.

Similar patterns were found in PS2 (Fig. 17B), but with higher attainable tillering, growth, and yield. This may be due to the higher amount of fertilizer applied in this production situation.

Faster tillering and higher maximum LAI were observed and simulated in PS3 (Fig. 17C) due to the direct-seeded crop establishment.

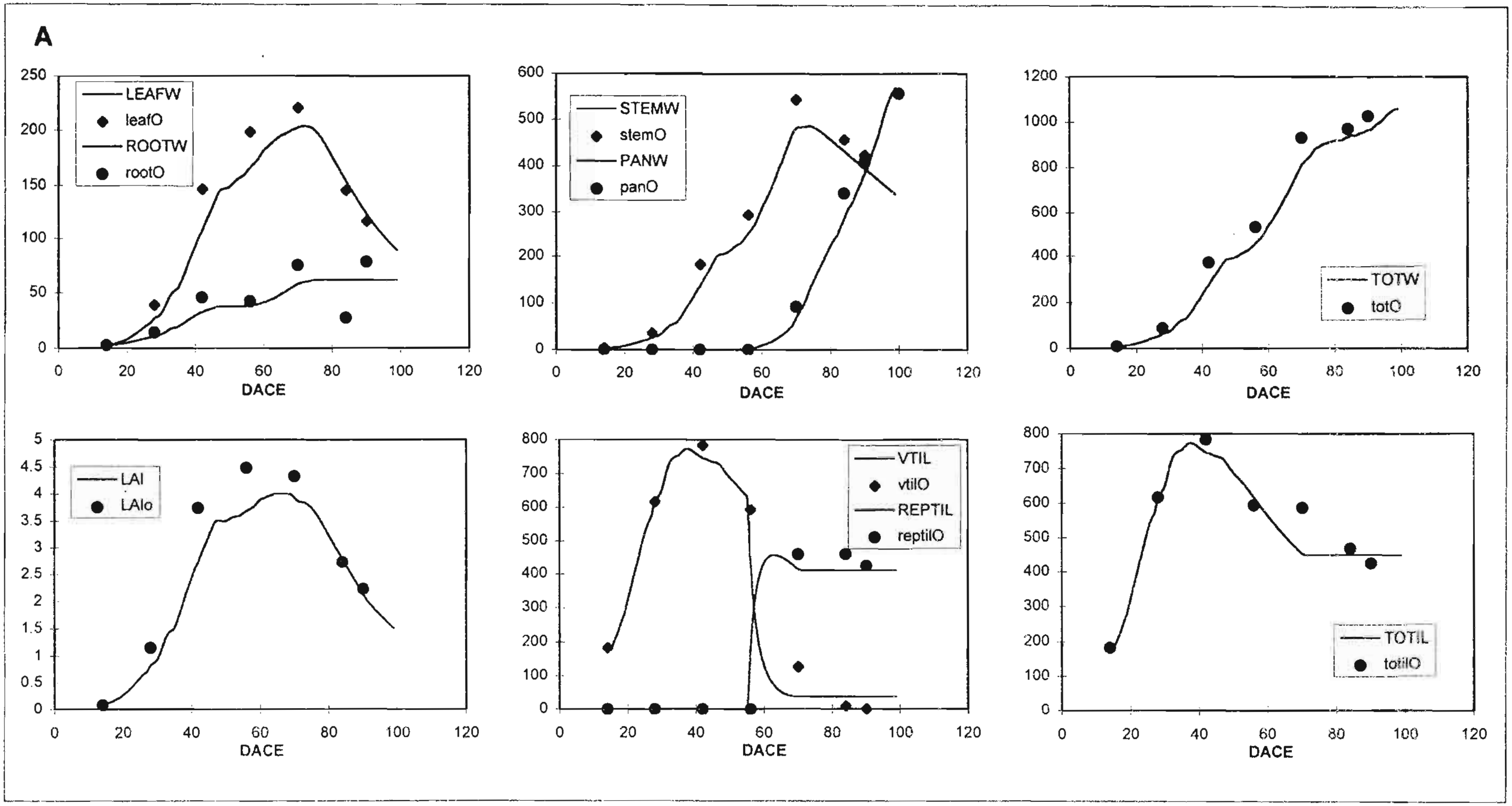

Fig. 17. Attainable rice growth in three PS: observed (•,•) and simulated (-) dry weight (g m^{-2}) of roots (ROOTW), leaves (LEAFW), stems (STEMW), panicles (PANW), and total dry weight (TOTW); LAI (LAI); number (m^{-2}) of vegetative tillers (VTIL), of reproductive tillers (REPTIL), and total number of tillers (TOTIL).

Observed data were collected from the experiment done at IRRI in 1997 in the control plots (see text for details). A: PS1; B: PS2; C: PS3.

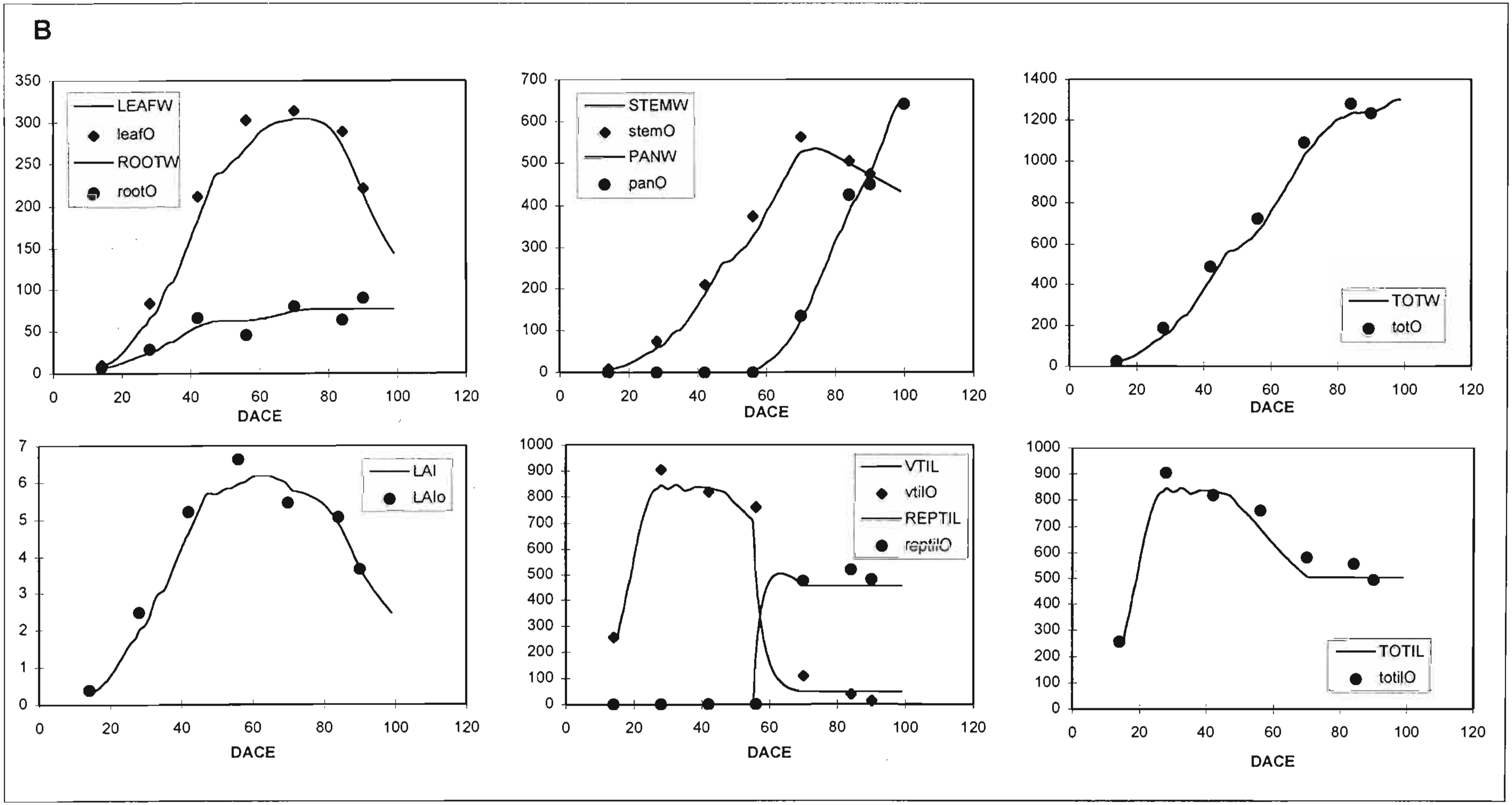

Fig. 17. Attainable rice growth in three PS...continued

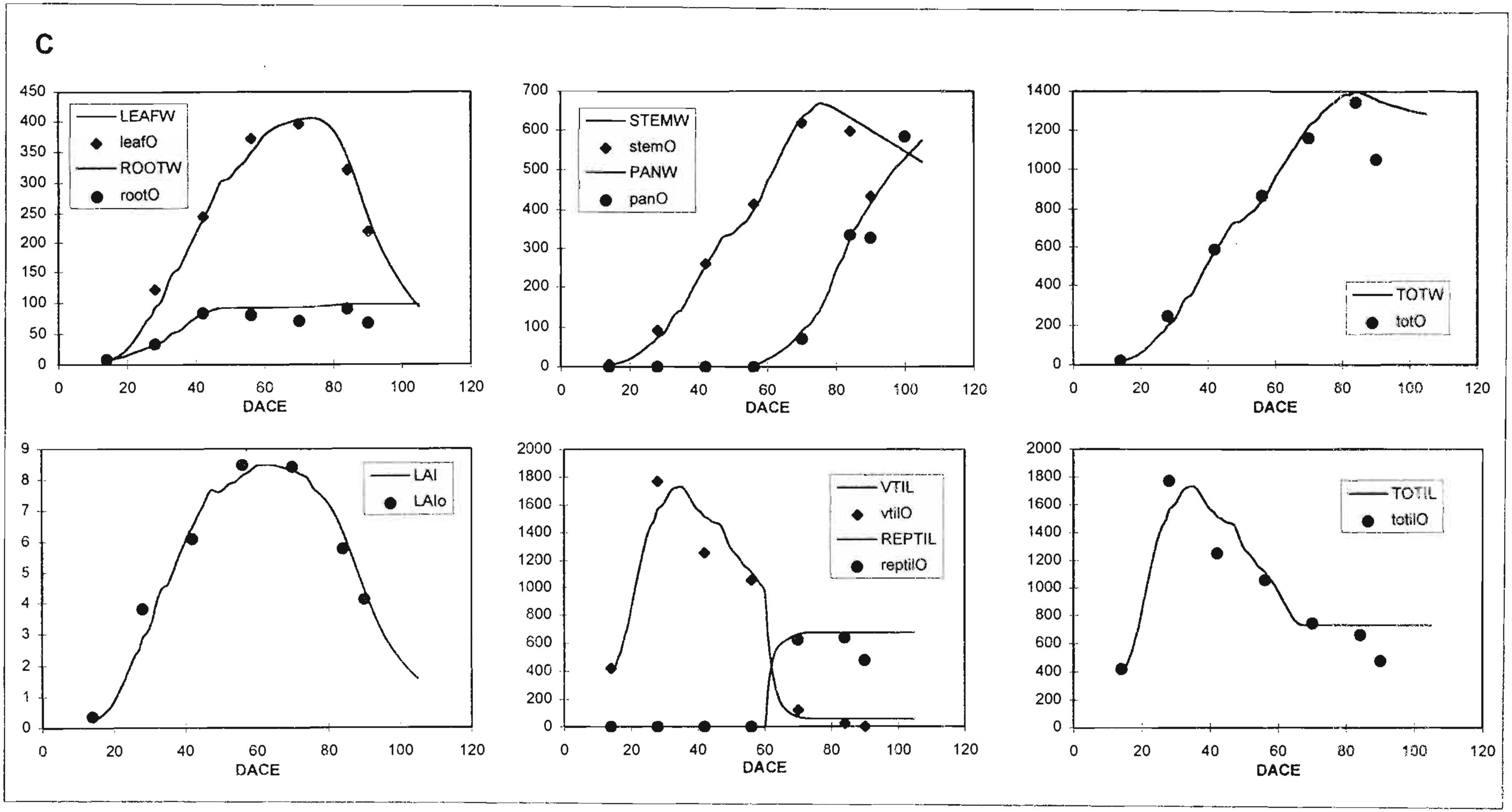

Fig. 17. Attainable rice growth in three PS...continued

Simulation of yield loss

In each (PS x injury) combination, the parameters and driving functions that were determined from the controls of the corresponding production situation and that simulated attainable growth and yield were used. The driving functions and parameters corresponding to the injury to be simulated were derived from pest monitoring.

Dead hearts

Dead heart incidence was 15%, 13%, and 22% at 40 DACE for PS1, PS2, and PS3, respectively. The incidence then decreased linearly until 80 DACE. At this date, no dead heart could be observed anymore.

In the three production situations, the effect of dead hearts on tiller death, the subsequent loss of dry weight of leaves and stems, and the compensation mechanisms were well reflected by the model, as well as the resulting yields (Fig. 18).

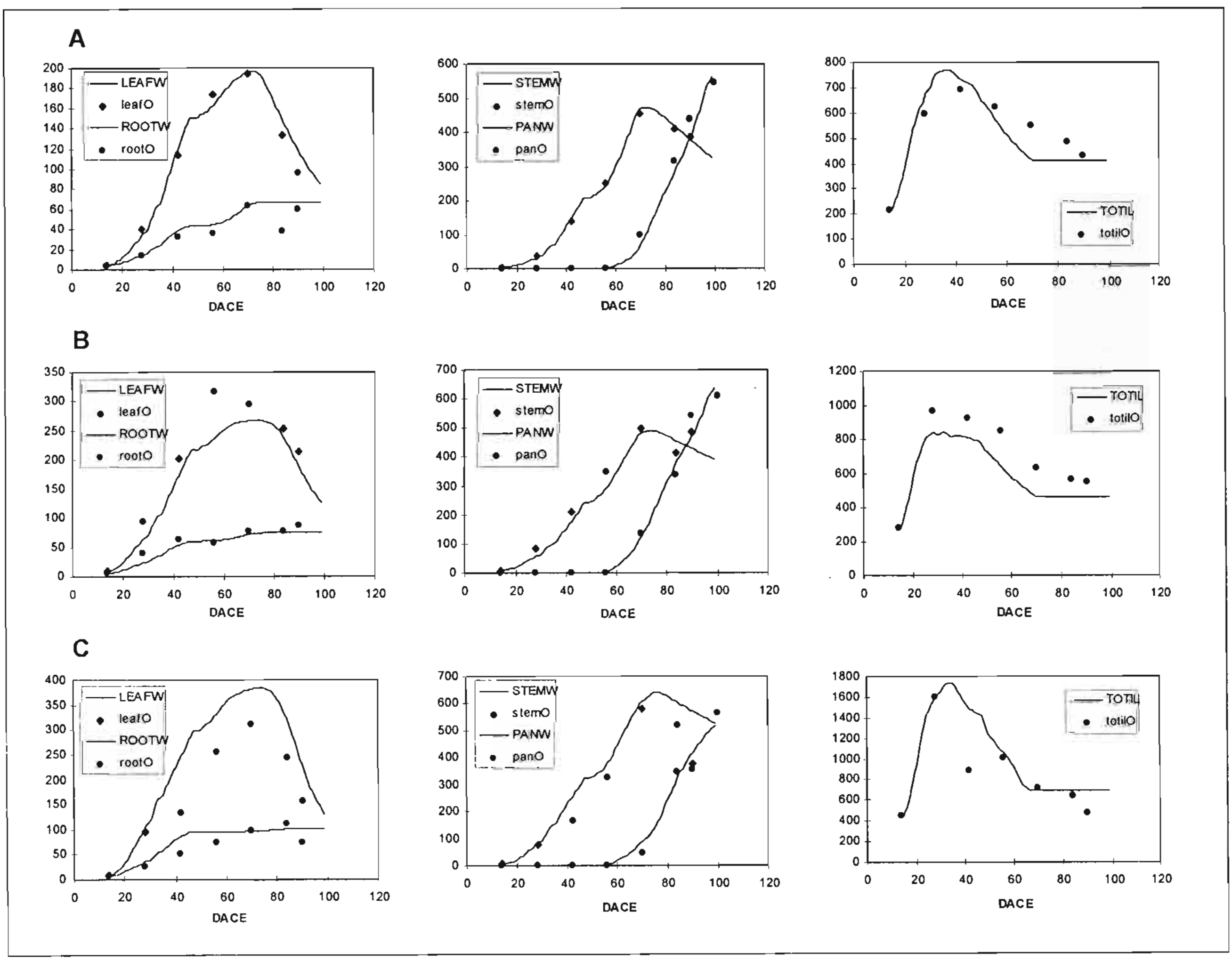

Fig. 18. Rice growth damaged by dead hearts in three PS: observed (•,•) and simulated (-) dry weight of rice organs, and tiller number.
Observed data were collected from the experiment done at IRRI in 1997, DH plots (see text for details). A: PS1; B: PS2; C: PS3.

Sheath blight

In PS1 and PS2, sheath blight severity increased up to 55 DACE, reaching 4.5%, remained at this level for 2 wk, and then declined sharply (Fig. 19). The disease was less intensive in PS3. In PS1 and PS2, the effect of sheath blight on leaf senescence was well reflected by the model, as well as the resulting yield (Fig. 20). In PS3, leaf senescence was slightly underestimated, but the resulting simulated yield was very close to the observed one.

Weeds

The dry weight of weeds increased linearly up to 350, 170, and 130 g m^{-2} at 42 DACE for PS1, PS2, and PS3, respectively (Fig. 21). Since a further increase in weed infestation would not have represented any more realistic conditions, hand-weeding was done 46 DACE in all the weedy plots.

In PS1, the effect of weeds was slightly underestimated by the model (Fig. 22). This may reflect the fact that under a production situation which is not optimum for rice growth, the effect of weeds may be higher. Two hypotheses can be forwarded to explain this: (1) under these conditions, weeds are more competitive than rice; (2) after weed infestation, the availability of nutrients in the soil is reduced, and since no fertilizer application was done after the basal one, the rice crop could not reach the same growth rate as a rice crop free of weeds grown under the same fertilizer management. The dry matter of weeds plus rice at 47 DACE (at the time of hand-weeding) was 550 g m^{-2}, whereas the rice dry matter at the same time in the control was 450 g m^{-2}. Thus, it can be assumed that more nutrients were absorbed in the weedy plots than in the control plots.

In PS2, the effect of weeds was slightly overestimated by the model. This may reflect the fact that under a production situation favorable for rice growth, the effect of weeds may be less than expected.

In PS3, the simulated crop growth was close to the observed one.

The coupling function used to reflect the effect of weeds on rice growth was parameterized from data where rice was grown under conditions similar to that in PS3 (irrigated rice, with medium fertilization). We may expect the model to underestimate the weed damage under worse production situations, and to overestimate the weed damage under better production situations.

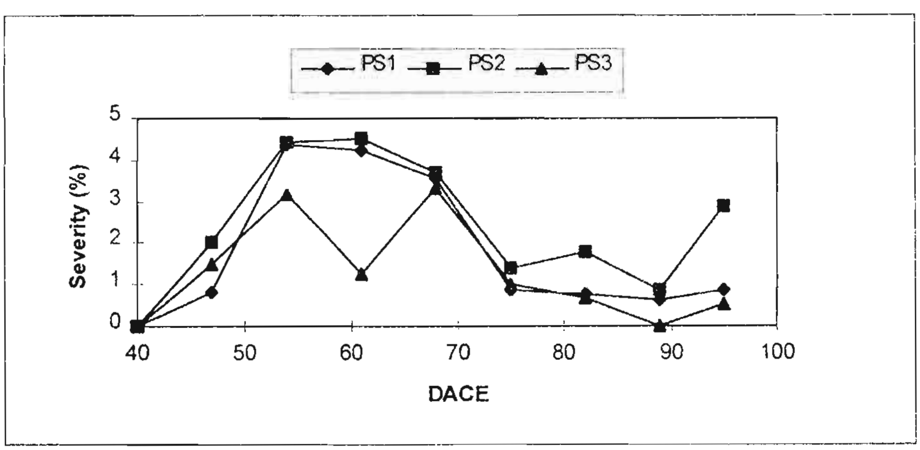

Fig. 19. Sheath blight severity on leaves in plots damaged by sheath blight (ShB treatment) in the experiment done at IRRI during the 1997 rainy season.

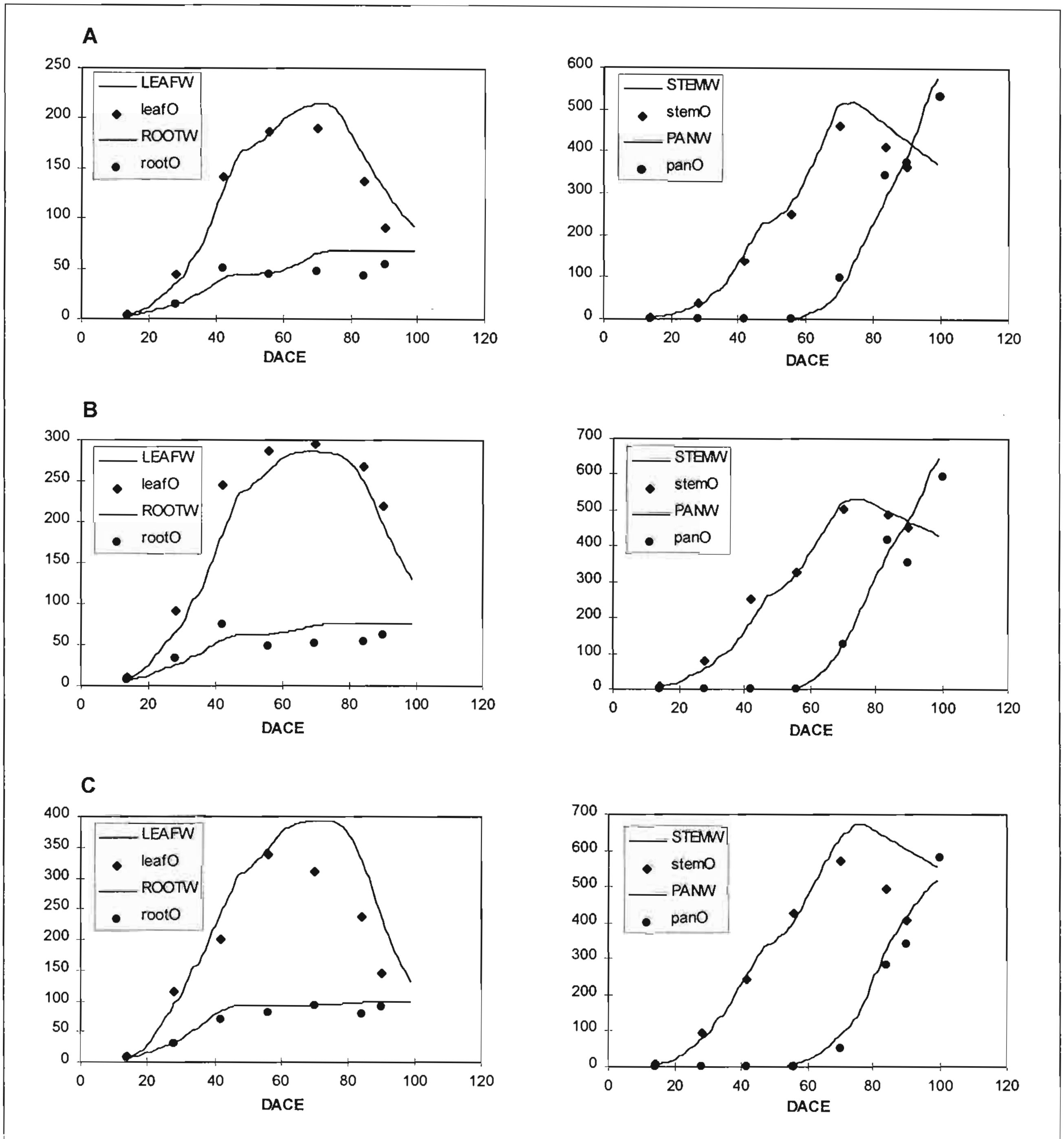

Fig. 20. Rice growth damaged by sheath blight in three PS: observed (•,⬩) and simulated (-) dry weight of rice organs.
Observed data were collected from the experiment done at IRRI in 1997, ShB plots (see text for details).
A: PS1; B: PS2; C: PS3.

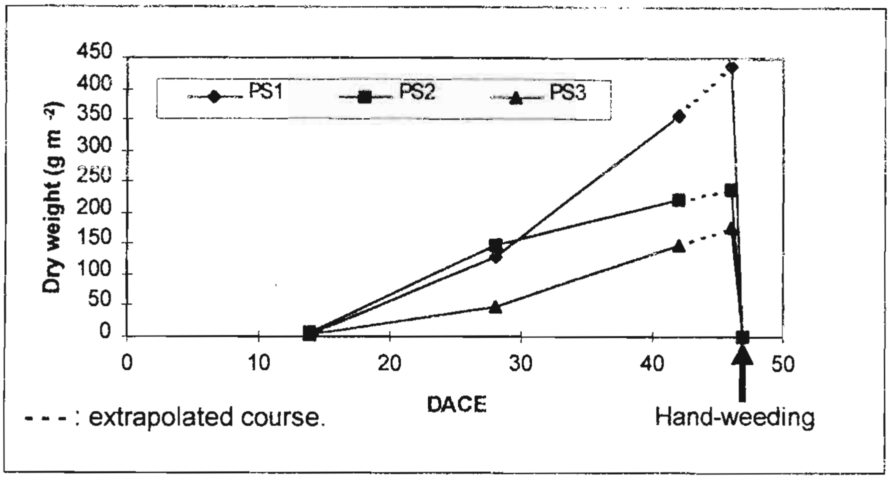

Fig. 21. Dry weight of weeds in WEED treatment.

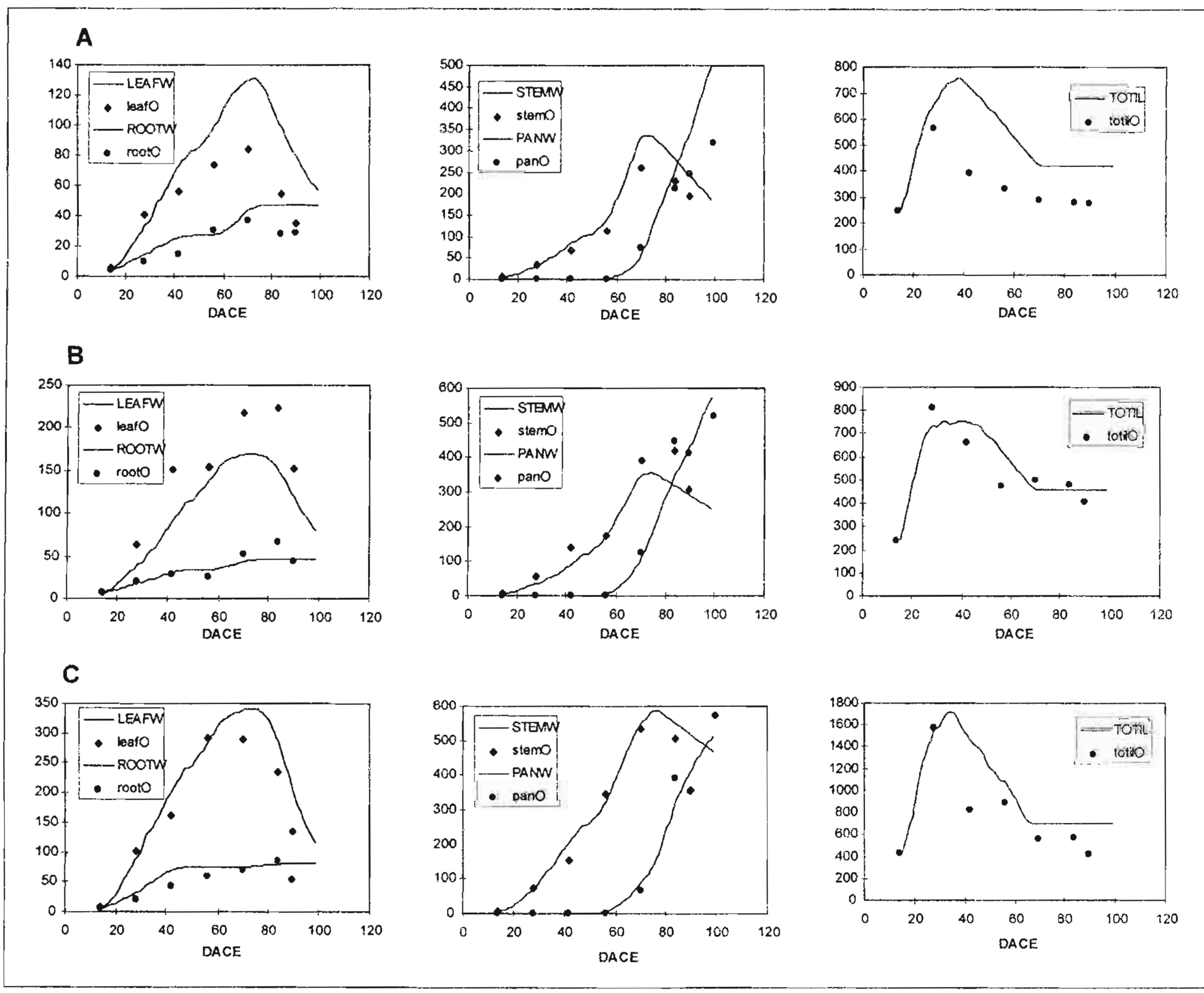

Fig. 22. Rice growth damaged by weeds in three PS: observed (•,•) and simulated (-) dry weight of rice organs, and tiller number.
Observed data were collected from the experiment done at IRRI in 1997, WD plots (see text for details).
A: PS1; B: PS2; C: PS3.

White heads

White heads represented 35%, 32%, and 12% of the panicle population in PS1, PS2, and PS3, respectively. In PS1 and PS3, the damage due to white heads was well simulated, and the simulated yields were very close to the observed ones (Fig. 23). In PS2, the simulated panicle yield was 437 g m^{-2} and the observed yield was 341 g m^{-2}. This difference may be due to two reasons: (1) some panicles may have been damaged by stem borers, but did not show the white head symptom, and nonvisible injuries may have reduced their dry weight; (2) the biggest panicles may have been injured by stem borers, thus leading to an overproportional yield loss.

Combined injuries

In this treatment, dead hearts, sheath blight, weeds, and white head injuries were combined. Dead heart incidence was 22%, 15%, and 26% at 40 DACE for PS1, PS2, and PS3, respectively. The incidence then decreased linearly until 80 DACE. At this date, no dead heart was observed anymore. Sheath blight severity increased linearly until 54 DACE, reaching 3%, 5%, and 3% in PS1, PS2, and PS3, respectively. Then, it decreased progressively and was below 1.5% after 75 DACE. The dry weight of weeds increased linearly until 42 DACE and reached 300, 260, and 250 g m^{-2} for PS1, PS2, and PS3, respectively. Hand-weeding was done at 46 DACE. White heads represented 40%, 20%, and 10% of the panicle population in PS1, PS2, and PS3, respectively.

In PS1, crop growth was overestimated by the model, leading to a final panicle yield of 285 g m^{-2}, whereas the panicle yield estimated from harvest data was 174 g m^{-2} (Fig. 24A). The simulation of damage due to weeds may be the cause of this overestimation: among all the injuries tested alone, injury due to weed was underestimated by the model in this production situation, whereas the other damages were fairly well simulated by the model.

In PS2, the simulated growth of leaves, stems, and roots, and the tiller number dynamics were close to the observed ones (Fig. 24B). Nevertheless, panicle growth was overestimated by the model, leading to a final panicle yield of 419 g m^{-2}, whereas the panicle yield estimated from harvest data was 250 g m^{-2}. The simulation of damage due to white heads may be the cause of

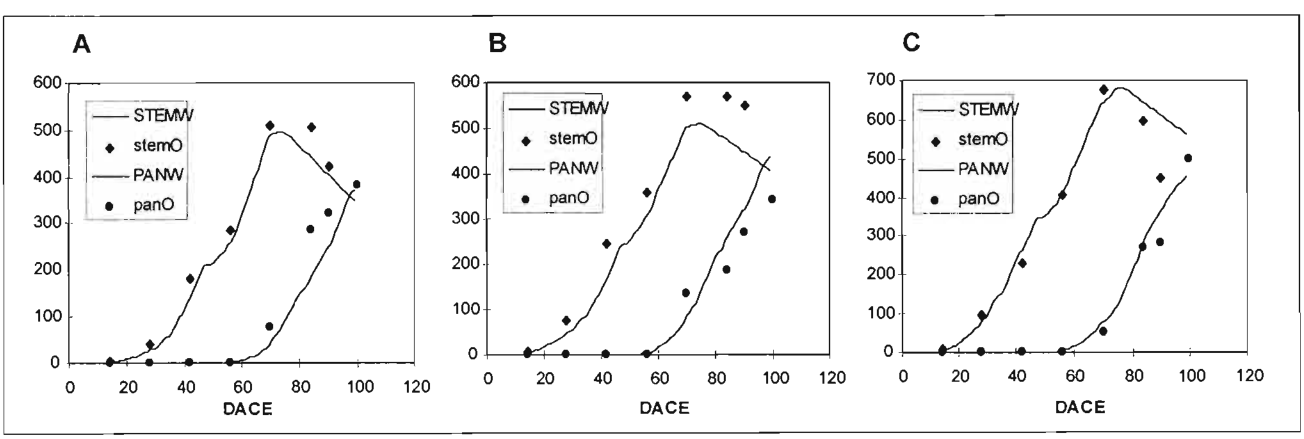

Fig. 23. Rice growth damaged by white heads in three PS: observed (•,◆) and simulated (-) dry weight of rice stems and panicles.
Observed data were collected from the experiment done at IRRI in 1997, WH plots (see text for details).
A: PS1; B: PS2; C: PS3.

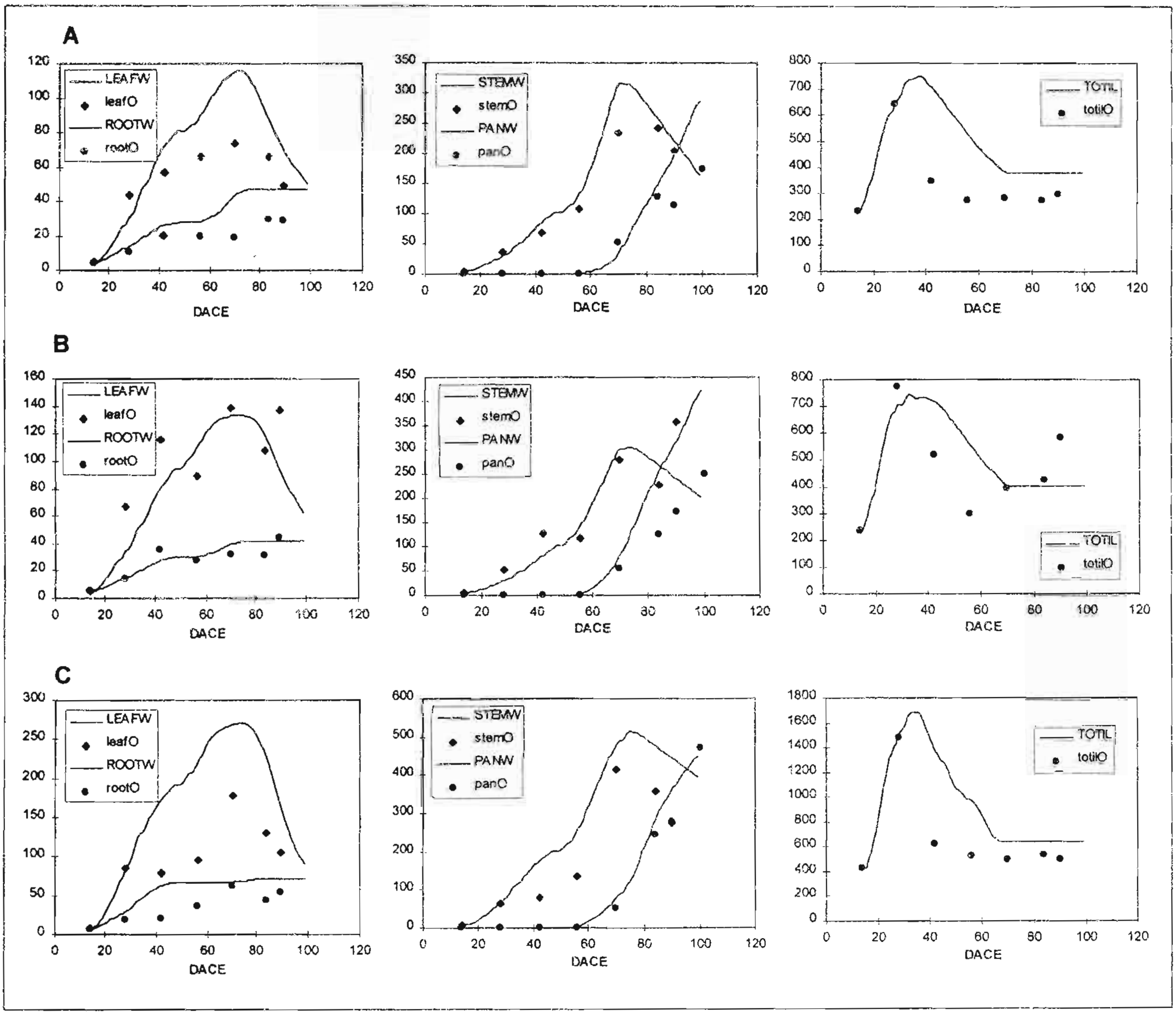

Fig. 24. Rice growth damaged by dead hearts, white heads, sheath blight, and weeds in three PS: observed (•,•) and simulated (-) dry weight of rice organs, and tiller number.
Observed data were collected from the experiment done at IRRI in 1997, COMBI plots (see text for details). A: PS1; B: PS2; C: PS3.

this overestimation: among all the injuries tested alone, injury due to white heads was underestimated by the model, whereas the other damages were fairly well simulated by the model. Also, dead hearts, sheath blight, and weeds affect leaf growth, and this seems to have been correctly simulated in the model.

In PS3, except for leaf growth, the growth of the different rice organs and the tiller number dynamics were well simulated (Fig. 24C). Overestimated leaf growth may be due to an underestimation of the effect of sheath blight, as was observed in the ShB treatment. It nevertheless did not affect the prediction of panicle yield.

General assessment of model performance

The simulated grain yield was computed as the simulated panicle yield minus the observed weight of unfilled grains, axes, and rachis. The simulated grain yields were plotted against the actual yields for the 18 (PS x injury) combinations addressed in this experiment (Fig. 25). An area covering plus or minus 10% of the observed yield was defined as an area within which yield estimations from the simulation models were acceptable: the assessment of the yield of a rice crop itself is subject to an experimental error which can be estimated to be 10% (Poate 1988). Even if the model could predict yield with an accuracy lower than 10% of the yield, this would probably not be proven.

The model failed to simulate yields within the acceptable area in four cases: PS1, WD and COMBI; PS2, WH and COMBI. The inability of the model to simulate well damages due to weeds in PS1 and due to white heads in PS2 was also reflected in the respective COMBI treatments. Further testing of the model is needed, but this first evaluation shows the potential usefulness of the model and the areas to be addressed more thoroughly to improve it.

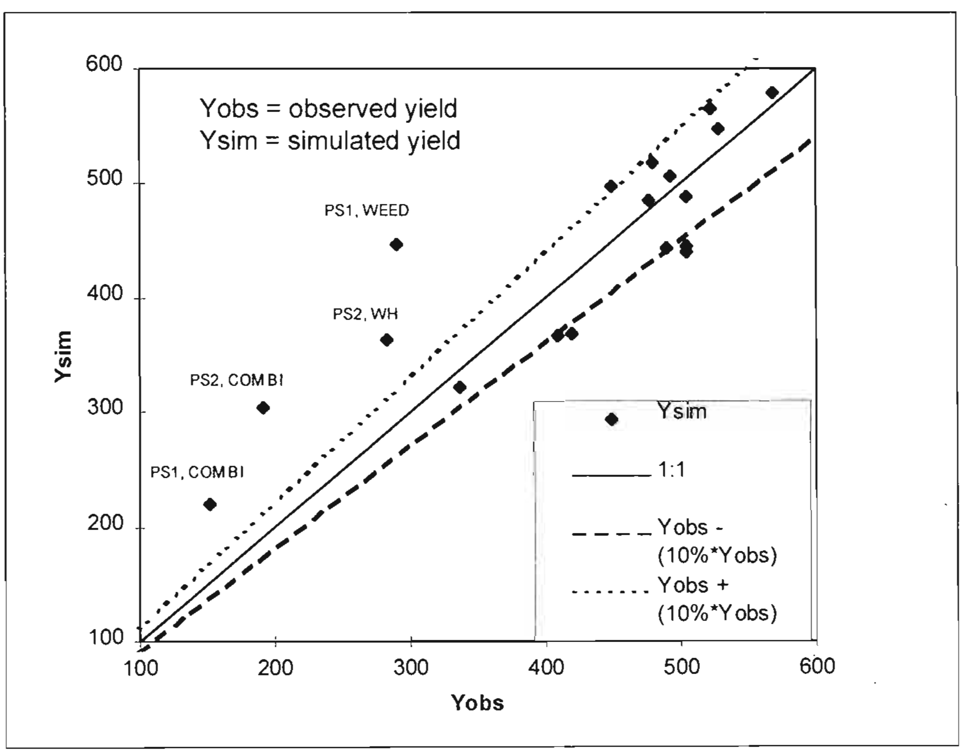

Fig. 25. Simulated versus observed yield in the experiment done at IRRI in 1997. *Each dot represents one treatment within one production situation, including the control treatment.*

Final remarks

The first evaluation of the model suggests that:

- The approach used to calibrate the model allows simulations of attainable growth and attainable yield that are close to the observed values under a set of production situations;
- This approach thus enables simulation of damage mechanisms, and of the resulting actual growth and yield to be tested;
- The model is flexible enough to account for diverse production situations and various injury mechanisms;
- In most cases, simulations of actual growth and yield are close to those observed, and lead to simulated actual yield that is within the acceptance range (that is, observed yield $\pm$ 10%);
- When simulations are not close to observations, the model could be improved further.
  - Simulation of damage mechanisms due to weed infestation could be improved by calibrating the damage function for different production situations;
  - Simulation of damage mechanisms due to white head infestation could be improved by making use of additional data from detailed studies on damage mechanisms involved in this injury.

The model structure, and the approach used to calibrate and test it, can be used by different research teams to address specific (production situation × injuries) combinations based on the methodology presented in this paper. The model is flexible enough to address other injuries, such as those due to brown planthopper, bacterial leaf blight, or defoliators.

Currently, the model is being tested in field experiments in India, China, and the Philippines, to cover a wide array of both production and injury profiles.

Two main potential uses of this model are:

1. Extrapolation to different levels of injuries: as opposed to fixed regression models, this model is based on mechanisms leading to yield losses. These mechanisms prevail at any level of injury, and departure from the range of injuries observed in the experiments may be considered. This property of simulation models allows extrapolations. Extrapolation of injury levels beyond those observed enables us to address a range of injury scenarios, and then provides management tools that would establish the expected yield losses for a series of temporal injury patterns in given production situations. Simple rules could then be derived that would determine when protection actions are necessary.
2. Extrapolation to other (current or future) production situations: conversely, the simulation model makes use of intrinsic rates of growth (IRG) that correspond to given production situations. If these were to change, the IRG would too, and the effects of pests could thus be assessed under these production situations. This would then provide tools to help define the pest risk associated with different or new production situations.

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Appendix 1
Variables used in the rice yield loss simulation model

Acronym	Unit	Meaning
CPL	-	Coefficient of partitioning in leaves [= f(DVS)]
CPP	-	Coefficient of partitioning in panicles [= f(DVS)]
CPR	-	Coefficient of partitioning in roots [= f(DVS)]
CPST	-	Coefficient of partitioning in stems [= f(DVS)]
DH	Ntil	Number of dead hearts
DTEMP	C day^{-1}	Daily rate of increase in temperature sum above threshold
DVE	-	Fraction of assimilates used to generate new tillers [= f(DVS)]
DVS	-	Development stage [= f(STEMP)]
IRG	g MJ^{-1}	Intrinsic rate of growth
K	-	Coefficient of light extinction
LAI	m^2 m^{-2}	Leaf area index
LEAFW	g	Dry weight of green leaves
MAXTIL	Ntil	Maximum number of tillers
PANW	g	Dry weight of panicles
PARTL	g d^{-1}	Daily rate of increase in leaf weight
PARTP	g d^{-1}	Daily rate of increase in panicle weight
PARTR	g d^{-1}	Daily rate of increase in root weight
PARTST	g d^{-1}	Daily rate of increase in stem weight
POOL	g	Biomass produced
RAD	MJ m^{-2} d^{-1}	Daily radiation
RDH	Ntil d^{-1}	Daily rate of increase in number of dead hearts
RDIST	g d^{-1}	Daily rate of starch translocated from stem to panicles
REPTIL	Ntil	Number of reproductive tillers
RG	g d^{-1}	Daily rate of increase in rice biomass
RRMAT	Ntil $Ntil^{-1}$ d^{-1}	Relative rate of tiller maturity
RMORT	g d^{-1}	Daily rate of tiller mortality
ROOTW	g	Dry weight of roots
RRMORT	Ntil $Ntil^{-1}$ d^{-1}	Relative rate of tiller mortality [= f(DVS)]
RRSENL	g g^{-1} d^{-1}	Relative rate of leaf senescence [= f(DVS)]
RSENL	g d^{-1}	Daily rate of leaf senescence
RSHBL	g d^{-1}	Daily rate of leaf senescence due to lesions of ShB on leaves
RTIL	Ntil d^{-1}	Daily rate of tillering
SEVL	-	Severity of sheath blight on leaves
SLA	m^2 g^{-1}	Specific leaf area [= f(DVS)]
STEMP	C	Sum of temperatures above the threshold for rice growth
STEMW	g	Dry weight of stems (sheath + culm)
STW	g $Ntil^{-1}$	Number of young tillers produced per unit of biomass
TBASE	C	Temperature threshold for rice growth
TMAX	C	Daily maximum temperature
TMIN	C	Daily minimum temperature
VTIL	Ntil	Number of vegetative tillers
WEED	g	Weed dry weight
WH	-	Fraction of white heads relative to the total number of panicles

Appendix 2

Listing of the FST program for the rice yield loss simulation model

```
*Crop growth model for rice with coupling functions for damage
mechanisms
*for sheath blight, dead hearts, white heads, and weeds
*System: population of tillers in 1 m² of rice field
*Time step: 1 d
*Simulation of the dynamics of:
*1. Development stage
*2. Biomass in the different organs of the plant
*3. Number of tillers
*The simulation starts at the time of first destructive sampling
*(14 DACE): days after crop establishment (sowing for DS,
*transplanting for TR)
*run0: simulation of attainable growth
*runs 1 to 5: simulation of damages due to various injuries
```

```
DEFINE_CALL TILMAT(INPUT,INPUT,INPUT,INPUT,INPUT,OUTPUT)

TITLE YLMPS2

MODEL

INITIAL

*1.switchers
*switcher for daily weather data, actual (-1), or parameter(+1)
PARAM SWIWTH   =-1.

*2.state variables, initial values
*biomass produced (incon=0)                                   g
INCON POOLI    =0.
*dry weight of roots (incon from first measurements,          g
*                      corresponding trt.)
INCON ROOTWI   =6.9
*dry weight of green leaves (incon from first measurements,
*                             corresponding trt.)             g
INCON LEAFWI   =9.9
*dry weight of stems (sheath + culm)(incon from first measurements,
*                                      corresponding trt.)    g
INCON STEMWI   =8.3
*dry weight of panicles (incon=0)                             g
INCON PANWI    =0.
*number of vegetative tillers (incon from first measurements,
*                               corresponding trt.)        Ntil
INCON VTILI    =256.
```

```
*number of reproductive tillers (incon=0)                          Ntil
INCON RPTILI   =0.
*total number of dead hearts
INCON SDHI     =0.

*sum of temperatures above the threshold for rice growth             C
*between sowing and first destructive sampling
*-transplanting shock in case of transplanted rice
INCON STEMPI   =358.


*3.parameters
*coefficient of light extinction (=0.6, Hayashi & Ito 1962)          -
PARAM K        =0.6
*Maximum number of tillers at maximum tillering                    Ntil
PARAM MAXTIL  =904.
*Number of vegetative tillers produced/unit of biomass         Ntil g-1
PARAM STW      =20.
*Relative rate of tiller maturation                                 d-1
PARAM RRMAT    =0.3
*Fraction of sterile tillers after booting                            -
PARAM FST      =0.05
*Daily redistribution of starch from stem to panicle              g d-1
PARAM DDIST    =4.42
*Temperature threshold for rice growth (=8, Kropff et al 1994)       C
PARAM TBASE    =8.
*day of crop establishment (Julian day)
PARAM DOYCE    =184.
*parameter used in simulating leaf senescence due to sheath blight
PARAM A=0.0007

*the simulation stops at maturity, when DVS=2
FINISH DVS > 2.

PRINT DACE,LEAFW,ROOTW,STEMW,PANW,TOTW,LAI,VTIL,REPTIL,TOTIL
PRINT DVS,DACE,CPP,CPL,CPR,CPST
PRINT DVS,DACE,TMIN,TMAX,RAD,DTEMP,STEMP,DOY,PARLST
PRINT ABGRW,RMORTV,RMORTR,IRG,RG
PRINT SEVL,RSHBL,SDH

*STTIME = day of first destructive sampling (Julian day)
TIMER STTIME = 198., FINTIM = 365., PRDEL=1.,DELT=1.

TRANSLATION_GENERAL DRIVER='EUDRIV'

DYNAMIC

*0.driving  functions
```

```
*development stage relative to the temperature sum above threshold
*for rice growth
FUNCTION DVST =0., 0., 1446.,1., 2030.,2., 2130.,2.1
*intrinsic rate of growth relative to DVS
FUNCTION IRGT  =0.,1.58, 0.34,1.58, 0.54,1.31,...
                  0.73,1.37, 0.92,1.26, 1.27,0.96,1.6,0.56,...
                2.1,0.56
*coefficient of partitioning in panicles relative to DVS
FUNCTION CPPT  =0.,0., 0.75,0., 0.95,0.4, 1.3,1., 2.1,1.
*coefficient of partitioning in leaves relative to DVS
FUNCTION CPLT  =0.,0.54, 0.13,0.54, 0.35,0.53, 0.55,0.49, ...
                  0.74,0.36, 0.95,0.03, 1.3,0., 2.1,0.
*coefficient of partitioning in roots relative to DVS
FUNCTION CPRT  =0.,0.27, 0.13,0.27, 0.35,0.14, 0.55,0.12, 0.74,0., ...
                  0.95,0.04, 1.3,0., 2.1,0.

*Specific leaf area (m^2 g^-1) relative to DVS
FUNCTION SLAT  =0.07,0.036, 0.26,0.033, 0.45,0.030, 0.65,0.025,...
                  0.83,0.022, 1.07,0.019, 1.53,0.018, 1.73,0.017,...
                2.1,0.017
*fraction of assimilates used to generate new tillers, relative to DVS
FUNCTION DVET  =0.,1., 0.4,1., 0.8,0., 2.,0., 2.1, 0.
*relative rate of tiller mortality, relative to DVS
FUNCTION RMTT =0.,0., 0.4,0.0, ...
                 0.45,0.022, 1.,0.022, 1.05,0., 2.1,0.0
*relative rate of leaf mortality, relative to DVS
FUNCTION RRSENT =0.,0., 1.07,0., 1.3,0.006, 1.63,0.044, 2.1,0.044

*pest levels (=0 for run0: simulation of attainable growth)
*number of dead hearts driving function, relative to DACE
FUNCTION RDHTIT=0.,0., 120.,0.
*fraction of white heads driving function, relative to DACE
FUNCTION WHT=0.,0., 120.,0.
*weed dry weight (g m^-2) driving function, relative to DACE
FUNCTION WEEDT =0.,0., 120.,0.
*sheath blight severity driving function, relative to DACE
FUNCTION SEVLT =0.,0., 120.,0.

*1.weather data and timing variables
*RDD is expressed in KJ m^-2 d^-1 in the input file
*it is then entered in the model in J m^-2 d^-1
*RDD is thus divided by 1 000 000 to compute RAD,
*and RAD is then expressed in MJ m^-2 d^-1

WEATHER WTRDIR='C:\SYS\WEATHER\', CNTR='PHIL', ISTN=1, IYEAR=1997
XRDD=20.
XTMMX=32.
XTMMN=25.
```

```
TMAX     =INSW(SWIWTH,TMMX,XTMMX)
TMIN     =INSW(SWIWTH,TMMN,XTMMN)
RAD      =INSW(SWIWTH,RDD/1000000.,XRDD)

DACE     =MAX(0.,DOY-DOYCE)

*2.computation of degree days above the thermal threshold

STEMP    =INTGRL(STEMPI,DTEMP)
DTEMP    =MAX(0.,((TMAX+TMIN)/2.)-TBASE)

*3.computation of development stage

DVS      =AFGEN(DVST,STEMP)

*4.daily accumulation of biomass, and partitioning
*in roots, leaves, stems, and panicles; mortality of leaves and stems

POOL     =INTGRL(POOLI,RPOOL)
RPOOL    =RG-PARTR-PARTP-PARTST-PARTL
RG       =IRG*(1.-EXP(-K*LAI))*RAD*(1.-RFWD1)
IRG      =AFGEN(IRGT,DVS)
LAI      =SLA*LEAFW*(1.-(SEV/100.))
SLA      =AFGEN(SLAT,DVS)
RFWD1    =1.-EXP(-0.003*WEED)
WEED     =AFGEN(WEEDT,DACE)

ROOTW    =INTGRL(ROOTWI,PARTR)
PARTR    =CPR*POOL
CPR      =AFGEN(CPRT,DVS)
PANW     =INTGRL(PANWI,RPANW)
RPANW    =(PARTP+RDIST)*(1.-WH)
PARTP    =CPP*(1.-CPR)*POOL
RDIST    =INSW(DVS-1.,0.,DDIST)
CPP      =AFGEN(CPPT,DVS)
WH       =AFGEN(WHT,DACE)
STEMW    =INTGRL(STEMWI,RSTW)
RSTW     =PARTST-RDHST-RDIST
PARTST   =CPST*(1.-CPR)*POOL
CPST     =1.-CPL-CPP
RDHST    =STWT*RDHTI
STWT     =STEMW/VTIL
LEAFW    =INTGRL(LEAFWI,RLEAFW)
RLEAFW   =PARTL-RSENL-RDHL-RSHBL
PARTL    =CPL*(1.-CPR)*POOL
CPL      =AFGEN(CPLT,DVS)
RSENL    =RRSENL*LEAFW
RRSENL   =AFGEN(RRSENT,DVS)
```

```
RDHL     =LWT*RDHTI
LWT      =LEAFW/VTIL
RSHBL    =A*SEV*LEAFW
SEVL    =AFGEN(SEVLT,DACE)
ABGRW   =LEAFW+STEMW+PANW
TOTW    =LEAFW+STEMW+PANW+ROOTW

*6.tillering, tiller maturity, and tiller mortality

CALL TILMAT(DVS,FST,VTIL,TOTIL,RRMAT,RMAT)

TOTIL   =VTIL+REPTIL
VTIL    =INTGRL(VTILI,FLVTIL)
FLVTIL  =RTIL-RMORTV-RDHTI-RMAT
RTIL    =PARLST*STW*(1.-(VTIL/MAXTIL))*DVE
PARLST  =PARTL+PARTST
DVE     =AFGEN(DVET,DVS)
RMORTV  =RRMORT*VTIL
RRMORT  =AFGEN(RMTT,DVS)
RDHTI   =AFGEN(RDHTIT,DACE)
REPTIL  =INTGRL(RPTILI,FLRTIL)
FLRTIL  =RMAT-RMORTR
RMORTR =RRMORT*REPTIL
SDH     =INTGRL(SDHI,RDHTI)
END

*run1: damage due to dead heart injury
*initial dry weights and tiller number
INCON ROOTWI   =5.7
INCON LEAFWI   =9.5
INCON STEMWI   =8.4
INCON VTILI    =281.
*number of dead hearts, relative to DACE
FUNCTION RDHTIT=0.,0., 20.,0., 30.,0., 40.,8., ...
                50.,5., 60.,0., 120.,0.
END

*run2: damage due to white head injury
*initial dry weights and tiller number
INCON ROOTWI   =4.6
INCON LEAFWI   =7.4
INCON STEMWI   =6.4
INCON VTILI    =227.
*fraction of white heads, relative to DACE
FUNCTION WHT=0.,.32, 120.,.32
FUNCTION RDHTIT=0.,0., 120.,0.
END
```

```
*run3: damage due to weed injury
*initial dry weights and tiller number
INCON ROOTWI   =6.6
INCON LEAFWI   =6.8
INCON STEMWI   =5.8
INCON VTILI    =242.
*weed dry weight (g m-2), relative to DACE
FUNCTION WEEDT =0.,0.,14.,5., 28.,147., 42.,221., 46.,242.,...
                47.,0., 120.,0.
FUNCTION WHT   =0.,0., 120.,0.
END

*run4: damage due to sheath blight injury
*initial dry weights and tiller number
INCON ROOTWI   =6.9
INCON LEAFWI   =9.8
INCON STEMWI   =8.1
INCON VTILI    =269.
*sheath blight severity, relative to DACE
FUNCTION SEVLT =0.,0.,40.,0., 47.,2., 54.,4.4, 61.,4.5,...
                 68.,3.7, 75.,1.4, 82.,1.8, 89.,.9, 95.,2.9,...
                110.,2.9
FUNCTION WEEDT =0.,0., 120.,0.
END

*run5: combined damages due to dead hearts, white heads,
*weeds, and sheath blight
*initial dry weights and tiller number
INCON ROOTWI   =5.1
INCON LEAFWI   =5.2
INCON STEMWI   =4.6
INCON VTILI    =233.
* number of dead hearts, relative to DACE
FUNCTION RDHTIT=0.,0., 20.,0., 30.,0., 40.,5., ...
                50.,5., 60.,0., 120.,0.
*fraction of white heads, relative to DACE
FUNCTION WHT   =0.,.2, 120.,.2
*weed dry weight (g m-2), relative to DACE
FUNCTION WEEDT =0.,0.,14.,4.6, 28.,94., 42.,266., 46.,315.,...
                 47.,0., 120.,0.
*sheath blight severity, relative to DACE
FUNCTION SEVLT =0.,0.,40.,0., 47.,2.05, 54.,5.3, 61.,2.5,...
                68.,1.4, 75.,0.5, 82.,0.3, 89.,0.4, 95.,1.2,...
               110.,1.2
END

STOP
```

```
*subroutine to compute tiller maturity
```

```
      SUBROUTINE  TILMAT(DVS,FST,VTIL,TOTIL,RRMAT,RMAT)
      IMPLICIT REAL (A-Z)

      IF  ((DVS.LT.0.8).OR.(DVS.GE.1.))  THEN
      RMAT=0.
      ELSE
      IF(VTIL.LT.(FST*TOTIL))THEN
      RMAT=0.
      ELSE
      RMAT=VTIL*RRMAT
      ENDIF
      ENDIF
      RETURN
      END
```

ERRATUM

p. 35: Equation (44) should be changed to:

$$CPR_{(i+i-1)/2} = \frac{ROOTW_i - ROOTW_{i-1}}{TOTW_i - TOTW_{i-1}} \quad / (DACE_i - DACE_{i-1})$$