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Structure and validation of RICEPEST, a production situation-driven, crop growth model simulating rice yield response to multiple pest injuries for tropical Asia

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Abstract

RICEPEST, a model simulating yield losses due to several rice pests (sheath blight, brown spot, sheath rot, bacterial leaf blight, stem borers, brown plant hopper, defoliating insects, and weeds) under a range of specific production situations of tropical Asia was developed. The model was assessed, using: (1) combined data sets generated by a series of test-experiments conducted in different sites of the Philippines, India, and China; and (2) one additional, independent, validation-experiment where a wide range of production situations and injury profiles were manipulated at a single site. Model evaluation was based on the analysis of two output variables: grain yield and relative yield loss. The paper reports results of qualitative and quantitative methods used to assess RICEPEST. Qualitative evaluation involved visual examination of graphs where deviations (simulated minus observed) are plotted against simulated values, and displaying an area of acceptance. This method showed that, in general, RICEPEST accounted well for the yield reducing effects of rice pests. Two areas for potential improvement of RICEPEST were however, identified: the simulation of damage caused by dead hearts in water-stressed environments, and the simulation of damage caused by weeds. Quantitative evaluations made use of equivalence- and χ^2-tests. The equivalence tests rejected ($P \leq 0.05$) the hypothesis of difference between simulated and observed yield and relative yield loss larger than a preset tolerance in both test- and validation-experiments. Conversely, the χ^2-tests did not reject the hypothesis of difference in categorised simulated and observed yields and relative yield losses ($P \leq 0.05$) in both test- and validation-experiments. RICEPEST proved to simulate adequately yield losses and can be used as a

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tool to set research priorities for rice crop protection in tropical Asia.

Keywords: Simulation model; Model validation; Multiple-pest system; Damage mechanism; Yield loss; Rice diseases; Rice insect pests; Rice weeds

1. Introduction

The patterns of lowland rice cropping practices in tropical Asia, and the temporal profiles of injuries caused by rice pests—pathogens, insects, and weeds—have been shown to be strongly related in a recent study (Savary et al., 2000a). The diversity of pests to consider is so large (Teng et al., 1990), and the range of cropping practices is so wide (Greenland, 1997), that tools to explore the outcomes of this relationship, in terms of yield losses, are necessary.

Simulation modelling is one such tool, which allows to consider the dynamic interaction between crop growth and temporal injury profiles on yield and yield losses. Crop growth and development must however, reflect the combination of environmental factors, including the patterns of cropping practices, i.e. production situations where rice production takes place (De Wit and Penning de Vries, 1982; Savary, 1991; Rabbinge, 1993). A first step in this direction was made with the development of a preliminary yield loss simulation model (Willocquet et al., 1998, 2000). This model is a simple crop growth simulator, which can simulate attainable growth and yield in varying production situations. The model structure is also detailed enough to accommodate a number of injury mechanisms, representing a wide range of rice pests. Preliminary results on the model structure and performances (Willocquet et al., 2000) indicated adequate simulation of attainable growth and yield in selected production situations, and of yield losses caused by a few pests. The preliminary model was thus expanded to a more detailed version, in order to simulate yield losses caused by an array of pests in a wide range of lowland rice production situations.

The objectives of this article are threefold. First, the overall structure of an expanded, multiple-injury, production situation-flexible yield loss model for irrigated or rainfed lowland rice, called RICEPEST, is presented. Second, the damage mechanisms corresponding to eight types of injuries are presented, and their inclusion in the model are shown. These injury types are those caused by: (1) sheath blight (*Rhizoctonia solani*); (2) stem borers (*Scirpophaga incertulas*, *S. innotata*, *Chilo suppressalis*, *Sesamia inferens*); (3) weeds (either growing under the rice canopy, such as *Monochoria vaginalis* or outgrowing the rice crop, such as *Echinochloa* spp. and *Cyperus* spp.); (4) brown spot (*Cochliobolus miyabeanus*); (5) sheath rot (*Sarocladium oryzae*); (6) bacterial leaf blight (*Xanthomonas campestris* pv. *oryzae*); (7) brown plant happens (*Nilaparvata lugens*); and (8) defoliating insects (such as: *Cnaphalocrocis medinalis*, *Hydrellia philippina*). Third, this article reports a multi-site validation approach, using several techniques. Validation is an important step in the development of models addressing agricultural systems (Penning de Vries, 1977), including crop pest management aspects (Teng, 1981). Two experimental data sets were used to that aim. The performances of RICEPEST were first assessed by comparing its outputs with data from four independent field experiments (referred to as 'test-experiments') performed at different sites in tropical Asia (Laguna Province, Philippines; Zhejiang Province, China; and Uttar Pradesh, India; Willocquet et al., 1999a,b; Zhu et al., 2001). Second, RICEPEST was tested using an additional, independent field experiment (referred to as 'validation-experiment'), where a wide range of production situations and an array of injury profiles were artificially established in different experimental plots at the same location (Laguna Province, Philippines).

2. Materials and methods

2.1. RICEPEST structure

The system considered in the model is 1 m^2 of rice crop, with a 1 day time step. Time is scaled in DACE, that is, Day After Crop Establishment. Crop Establishment refers to transplanting in the case of transplanted rice, and to sowing in the case of direct-seeded rice. RICEPEST consists of two inter-connected sub-models. The first sub-model simulates the dynamics of the rice crop biomass, and the second simulates the dynamics of tiller population (Willocquet et al., 1998, 2000). Damage mechanisms for injuries due to eight different rice pests were included in the model. The overall structure of the model is shown in Fig. 1.

2.1.1. Crop growth

The biomass sub-model accounts for the daily accumulation and partitioning of assimilates towards roots, leaves, stems, and panicles. The amount of assimilates (POOL) is accumulated daily at a rate of growth, RG, which is written as:

$$\mathrm{RG}_t = \mathrm{RUE}_t \times \mathrm{RAD}_t \times (1 - \exp(-k \times \mathrm{LAI}_t)), \tag{1}$$

where RUE is the radiation use efficiency (Monteith (1977) was called *IRG* in Willocquet et al. (1998, 2000)), RAD is the daily radiation, $1 - \exp(-k \times \mathrm{LAI}_t)$ is the proportion of light intercepted by the crop, and k is the coefficient of light extinction.

The amounts of biomass partitioned daily to the leaves, the stems, the panicles, and the roots are named PARTL, PARTST, PARTP and PARTR, respectively. These amounts depend on coefficients of partitioning, which in turn depend on the development stage (van Keulen et al., 1982; Kropff et al., 1994).

After flowering, leaf senescence and translocation of starch from stems to panicles are also simulated. The dynamics of panicle weight is written as:

$$\mathrm{PANW}_{t+\Delta t} = \mathrm{PANW}_t + (\mathrm{PARTP}_t + \mathrm{RDIST})\,\Delta t, \tag{2}$$

where PANW is the dry weight of panicles, and RDIST is the daily flow of biomass redistributed from the stems to the panicles.

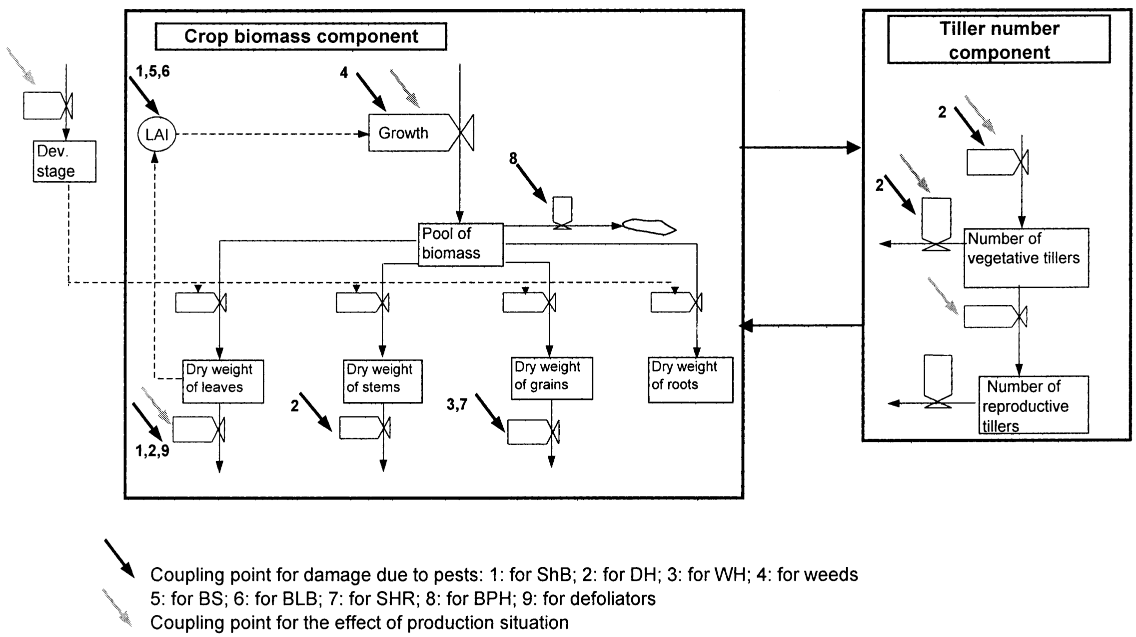

Fig. 1. Overall structure of the simulation model RICEPEST, including damage mechanisms of the different pests.

The rate of leaf senescence (RSENL) is made proportional to the dry weight of leaves, and to a relative RSENL depending on the development stage. The dynamics of leaf dry weight is written as:

$$\mathrm{LEAFW}_{t+\Delta t} = \mathrm{LEAFW}_t + (\mathrm{PARTL}_t - \mathrm{RSENL}_t)\,\Delta t. \quad (3)$$

2.1.2. Tiller dynamics

The second sub-model simulates the dynamics of tillers populations, i.e. tillering, tiller death due to competition, and maturation of vegetative tillers (VTIL), leading to the formation of reproductive tillers (REPTIL). Tillering is proportional to the dry matter allocated to stems and leaves, and decreases when the number of tillers approaches the maximum number of tillers (MAXTIL). Tiller death takes place during the later stage of the vegetative phase of the crop, and depends on the number of VTIL. Tiller maturation occurs at the booting stage, and is proportional to the relative rate of tiller maturity (RRMAT).

2.1.3. Damage mechanisms due to sheath blight

The simulated damage mechanisms due to sheath blight (SHB) are: (1) acceleration of leaf senescence due to SHB lesions on leaves and sheaths; and (2) decrease in green LAI due to the presence of lesions on the leaves. Based on field experiment data (Savary et al., 1995), the RSENL due to the first mechanism (RSHBL) is written as:

$$\mathrm{RSHBL}_t = 0.00076 \times \mathrm{SEVL}_t \times \mathrm{LEAFW}_t, \quad (4)$$

where SEVL is SHB severity (%) on leaves.

After integration of the first damage mechanism caused by SHB, Eq. (3) thus becomes:

$$\mathrm{LEAFW}_{t+\Delta t} = \mathrm{LEAFW}_t + (\mathrm{PARTL}_t - \mathrm{RSENL}_t - \mathrm{RSHBL}_t)\,\Delta t. \quad (5)$$

When the second damage mechanism is integrated in the model, LAI is computed as:

$$\mathrm{LAI}_t = \mathrm{SLA}_t \times \mathrm{LEAFW}_t \times (1 - (\mathrm{SEVL}_t/100)), \quad (6)$$

where SLA is the specific leaf area.

2.1.4. Damage mechanisms due to stem borers

The damage mechanism due to stem borer infestation in the vegetative phase of crop development is accounted for by subtracting dead tillers (dead hearts, DH) at a daily rate RDHTI from the number of tillers, and numerically linking this loss to the dry weights of stems and leaves. The dynamics of dry weights of stems and leaves is written as:

$$\mathrm{STEMW}_{t+\Delta t} = \mathrm{STEMW}_t + (\mathrm{PARTST}_t - \mathrm{RDIST}_t - \mathrm{RDHST}_t)\,\Delta t, \quad (7)$$

$$\mathrm{LEAFW}_{t+\Delta t} = \mathrm{LEAFW}_t + (\mathrm{PARTL}_t - \mathrm{RSENL}_t - \mathrm{RSHBL}_t - \mathrm{RDHL}_t)\,\Delta t, \quad (8)$$

with

$$\mathrm{RDHST}_t = \mathrm{STEMW}_t \times \mathrm{RDHTI}/\mathrm{VTIL}_t, \quad (9)$$

$$\mathrm{RDHL}_t = \mathrm{LEAFW}_t \times \mathrm{RDHTI}/\mathrm{VTIL}_t. \quad (10)$$

Stem borer infestation during the reproductive stage causes another type of damage, called white head (WH), where infested tillers bear panicles in which grain filling does not occur. This damage is reflected in RICEPEST by including an extra sink corresponding to larval feeding. Yield losses caused by WHs are made proportional to the fraction of injured panicles, and Eq. (2) becomes:

$$\mathrm{PANW}_{t+\Delta t} = \mathrm{PANW}_t + ((\mathrm{PARTP}_t + \mathrm{RDIST}) \times (1 - \mathrm{WHDM})) \times \Delta t, \quad (11)$$

where WHDM is the maximum proportion of WHs observed during the growing season.

2.1.5. Damage mechanisms due to weeds

Multiple damage mechanisms due to weed infestation (WEED), i.e. competition for light, water, and nutrients are synthesised into a reduction factor of the rate of crop growth (RFwd) which is a function of the weed dry weight. The rate of growth becomes:

$$\mathrm{RG}_t = \mathrm{RUE}_t \times \mathrm{RAD}_t \times (1 - \exp(-k \times \mathrm{LAI}_t)) \times (1 - \mathrm{RFwd}), \quad (12)$$

with

$$\mathrm{RFwd} = 1 - \exp(-0.003 \times \mathrm{WEEDDM}), \quad (13)$$

where WEEDDM is the total dry weight of weeds per square meter.

2.1.6. Damage mechanism for brown spot

Brown spot (BS) lesions produce toxins that decrease the photosynthetic activity of the leaf area surrounding the lesions (Ou, 1987). This can be translated by using the concept of virtual lesion size (Bastiaans, 1991). A virtual lesion corresponds to the area covered by the (visual) lesion, plus the area surrounding it, that cannot photosynthesise because of the effect of fungal toxins. If β is the ratio between the leaf area occupied by the virtual lesion and the leaf area occupied by the visual lesion, then P_x, the photosynthetic activity of an infected leaf with disease severity x ($0 \leq x \leq 1$) is related to P_0, the photosynthetic activity of a healthy leaf by the following equation (Bastiaans, 1991):

$$P_x / P_0 = (1 - x)^{\beta}. \quad (14)$$

As no data were available to quantify β for *C. miyabeanus*, the parameter β was estimated from Boote et al. (1980), who measured P_x of peanut leaves infected by peanut leafspot (caused by *Cercospora arachidicola).* An estimate of $\beta = 6.3$ was derived from a linear regression of $\ln(P_x/P_0)$ on $\ln(1 - x)$. To integrate this damage mechanism at the crop level, the LAI was multiplied by a reduction factor, $(1 - (\mathrm{BSDM}/100))^{\beta}$, where BSDM is the percent of leaf covered by (visual) lesions. The reduction factor corresponds to the fraction of LAI which is not photosynthetically active due to brown spot lesions (fraction of area covered by the visual and the virtual lesions). This coupling point is the same as the one used to account for the decrease in green LAI due to SHB lesions, and Eq. (6) becomes:

$$\mathrm{LAI}_t = \mathrm{SLA}_t \times \mathrm{LEAFW}_t \times (1 - (\mathrm{SEVL}_t/100)) \times (1 - (\mathrm{BSDM}_t/100))^{\beta}. \quad (15)$$

By multiplying, and not adding, the two reduction factors, the equation assumes that one pathogen cannot affect a leaf area that another has already damaged. Less-than-additive damage interactions between BS and SHB are thus modelled. The equation also assumes that BS and SHB lesions are randomly distributed both over the 1 m^2 area of the system, and within the crop canopy (i.e. successive canopy layers, differing in severities are not considered).

2.1.7. Damage mechanism for bacterial leaf blight

The main damage mechanism for bacterial leaf blight is a decrease in green LAI due to the presence of lesions on the leaves. The lesions consist of dead and water-soaked blade tissues (Ou, 1987; Elings et al., 1997). When this damage mechanism is included in RICEPEST, Eq. (15) becomes:

$$\mathrm{LAI}_t = \mathrm{SLA}_t \times \mathrm{LEAFW}_t \times (1 - (\mathrm{SEVL}_t/100)) \times (1 - (\mathrm{BSDM}_t/100))^{\beta} \times (1 - (\mathrm{BLBDM}_t/100)), \quad (16)$$

where BLBDM is the percent of leaf area covered by BLB lesions. Again, the equation assumes less-than-additive damage interactions between SHB, BS and BLB, and the three diseases are assumed to be randomly spatially distributed among the population of leaves, i.e. both over the 1 m^2 area of the system, and across layers of the canopy.

2.1.8. Damage mechanism for sheath rot

Sheath rot (SHR) lesions occur on the uppermost leaf sheaths enclosing the young panicles, which remain within the sheath (Ou, 1987), thus preventing grain filling of the damaged panicles. This is reflected in the model by decreasing the rate of increase in panicle dry weight (RPAN) with a ratio (SHRDM) corresponding to the fraction of panicles damaged by sheath rot. Eq. (11) becomes:

$$\mathrm{PANW}_{t+\Delta t} = \mathrm{PANW}_t + ((\mathrm{PARTP}_t + \mathrm{RDIST}_t) \times (1 - \mathrm{WHDM}) \times (1 - \mathrm{SHRDM})) \times \Delta t. \quad (17)$$

The same coupling point is used for damages caused by sheath rot and WHs. Again, a less-than-additive interaction between both damages is assumed, as well as their random distribution among the population of panicles considered in the system.

2.1.9. Damage mechanism for brown plant hopper

Brown plant hopper (BPH) infestation leads to four damage mechanisms (Sogawa, 1994): (1) assimilate sapping; (2) acceleration of leaf senescence of the lower leaves; (3) acceleration of leaf senescence of all the leaves (hopperburn); and (4) decrease in photosynthetic efficiency. BPH nymphs and adults sap assimilates at the base of rice plants by stylet feeding on the leaf sheath. BPH can thus be considered an extra-sink where assimilates transported in the phloem are diverted (Sogawa, 1992). Acceleration of leaf senescence is observed during the reproductive phase, and is characterised by leaf chlorosis on the lower leaves of the plant. Hopperburn is observed during the reproductive phase if BPH density exceeds 200 insects per hill (Watanabe, 1994). The last mechanism, decrease in photosynthetic efficiency, is due to N absorption by insects when they suck the phloem. In practice, damage mechanisms (1) and (2) only are considered in RICEPEST. Hopperburn is not considered, as it reflects a mis-management of insect pests, and is infrequent (Savary et al., 2000a). It is further assumed that the fourth damage mechanism is quantitatively less important than (1) and (2).

Damage mechanism (1) was quantified by Kenmore (1980), who separately measured the daily sucking rate per insect, and the dry weight per insect, according to the insect development stage. This allowed to quantify the relationship between insect dry weight and its sucking rate. The sucking rate was proportional to insect dry weight ($R^2 = 0.99$, $n = 6$, $P < 0.0001$), and was 5.91 mg mg^{-1} per day of dry weight of BPH. The first damage mechanism is included in the model by subtracting from the pool of assimilates (POOL) a sucking rate (RSUCK), corresponding to BPH consumption:

$$\mathrm{RSUCK} = 5.91 \times \mathrm{BPHDW}, \tag{18}$$

where BPHDW is the dry weight of BPH (g m^{-2}).

According to Sogawa (1994), an increase of 1 mg of BPH biomass corresponds to 6 mg of dead leaves. The second damage mechanism is thus included in the model by subtracting from the rate of increase of leaf dry weight a RSENL due to BPH:

$$\mathrm{RBPHL} = 6 \times \mathrm{DBPW}, \tag{19}$$

where DBPW is the daily increase in BPH dry weight. Eq. (8) becomes:

$$\begin{aligned}\mathrm{LEAFW}_{t+\Delta t} = \mathrm{LEAFW}_t &+ (\mathrm{PARTL}_t - \mathrm{RSENL}_t \\ &- \mathrm{RSHBL}_t - \mathrm{RDHL}_t - \mathrm{RBPHL}_t) \\ &\times \Delta t.\end{aligned} \tag{20}$$

2.1.10. Damage mechanism for defoliating insects

The most important damage mechanism incurred by defoliating insects is a decrease in rice leaf weight. This damage is included in RICEPEST as a rate of defoliation, RDEF, which corresponds to the amount of LEAFW which is removed daily by defoliating insects. Eq. (20) becomes:

$$\begin{aligned}\mathrm{LEAFW}_{t+\Delta t} = \mathrm{LEAFW}_t &+ (\mathrm{PARTL}_t - \mathrm{RSENL}_t \\ &- \mathrm{RSHBL}_t - \mathrm{RDHL}_t - \mathrm{RDEFL}_t) \\ &\times \Delta t.\end{aligned} \tag{21}$$

2.2. Selection of key production situations where rice growth is simulated

In a previous characterisation study, a series of six main patterns of rice cropping practices (PR) were identified across several sites of tropical Asia, and among a large population of farmers' fields (Savary et al., 2000a). These patterns range from PR1 (with medium to high fertiliser inputs; moderate pesticide inputs; long fallow periods; adequate water management; and sufficient labour availability), to PR3 (with low or no chemical inputs; medium fallow periods; very poor control of the water supply to the crop; and

Table 1
Crop management and patterns of cropping practices (PR) associated with the production situations addressed in the four test-experiments

Production situation	Cultivar	Crop establishment[a]	Crop density[b]	Fertiliser input[c]	Water management[d]	Corresponding pattern of cropping practices (based on Savary et al., 2000a)
PS1a[e]	IR72	TR1	T1	High	Full	PR1: predominantly (68%) transplanted rice crops with medium-high mineral fertilizer input in a rice–rice rotation. Moderate to low pesticide inputs and adequate availability of labour. Adequate and reliable water supply. Reflects reasonably reliable inputs (labour, chemicals) and infrastructure (irrigation) to rice production. Attainable yield: 5.9 t ha^{-1}
PS1b[f]	IR72	DS	D1	Medium 3	Full	
PS1c[g]	Jia Yu 293	DS	D2	Very high	Controlled	
PS2[f]	IR72	TR1	T1	Low	Full	PR2: resembles PR1, but with low (especially fertiliser) inputs, shortage of agricultural labour, and less reliable water supply. Attainable yield: 5.1 t ha^{-1}
PS3a[h]	IR64	TR1	T1	High	Constrained	PR3: predominantly (73%) transplanted rice crops in the Rice–Wheat system (very diverse crops preceding rice, including wheat). Very low inputs in the form of chemicals (fertilisers, pesticides). Large inputs in the form of labour. Poor to very poor control over the water supply. Attainable yield: 4.7 t ha^{-1}
PS3b[i]	Sita	TR2	T2	Medium 1	Constrained	
PS3c[i]	NDR80	DS	D1	Medium 2	Constrained	
PS4[g]	Fan 97	TR3	T2	Very high	Controlled	PR4: very intensive, transplanted rice production, with very short fallows. Very high fertiliser and pesticide inputs (e.g. insecticide application in excess of five, average N–P–K fertiliser: 260 kg ha^{-1}. Attainable yield: 7.7 t ha^{-1}

[a] TR1, transplanted with 10–12-day-old seedlings; TR2, transplanted with 25-day-old seedlings. Fifty kilograms Newton per hectare in seedbed, applied 20 DAS; TR3, transplanted with 28-day-old seedlings. One hundred kilograms Newton per hectare in seedbed, 50 at 10 days after sowing (DAS), and 50 at 20 DAS; DS, direct-seeded, by broadcasting of pregerminated seeds.

[b] T1, five seedlings per hill; hill spacing: 20×20 cm; T2, three seedlings per hill; hill spacing: 20×20 cm^2; D1, sowing density: 90 kg ha^{-1}; D2, sowing density: 37 kg ha^{-1}.

[c] Very high: N: 180 (70 at basal, 70 at tillering, and 40 at early booting) P: 15 at basal K: 35 at basal, 35 at tillering; High: N: 110 (30 at basal + 50 at tillering + 30 at early booting); Medium 1: N: 100 (50 at basal + 50 at early booting); Medium 2: N: 80 (40 at basal + 40 at early booting[(b)]); Medium 1: N: 60 (30 at basal + 30 at early booting); Low: N: 30 at basal.

[d] Full: full water supply, drained 2 weeks before harvest; controlled: full water supply, drained for 5–7 days at maximum tillering, and again 2 weeks before harvest; constrained: water supply stopped 15 days after crop establishment (rainfed).

[e] PS1a was called PS2 in Willocquet et al. (1998, 1999a,b, 2000) and in Zhu et al., submitted.

[f] PS1b and PS2 were called PS3 and PS1, respectively, in Willocquet et al. (1998, 2000).

[g] PS1c and PS4 were called PS6 and PS7, respectively, in Zhu et al., submitted.

[h] PS3a was called PS4 in Willocquet et al. (1999a).

[i] PS3b and PS3c were called PS8 and PS9, respectively, in Willocquet et al. (1999b).

Table 2
List of the experiments done to test and validate the rice yield loss simulation model

Experiment type	Site	Year	Season	Production situation	Injuries[a]
T1	Laguna, Philippines	1997	Rainy	PS1a, PS1b, PS2	DH, WH, SHB, WEED
T2	Laguna, Philippines	1998	Dry	PS1a, PS3a	DH, WH, WEED
T3	Zhejiang, Southern China	1998	Rainy	PS1a, PS1c, PS4	SHB, WEED
T4	Uttar Pradesh, Northern India	1998	Kharif	PS1a, PS3b, PS3c	DH, SHB, BS
V	Laguna, Philippines	1999	Rainy	PS1a, PS1b, PS1d, PS3d, PS4	Depend on PS (Table 3)

[a] In a given test-experiment, the same injury treatments were considered in all PSs. In all PSs, a non-injured, control treatment, and a treatment combining all injuries considered in the PS were included.

extensive availability of labour to tend the crops), and PR4 (with high to very high fertiliser, insecticide, herbicide, and fungicide inputs; very short fallow periods; adequate water management; and some labour availability for transplanting and hand-weeding). Other patterns reflect intermediate situations: in PR2, fertiliser, pesticide, and labour inputs are lower than in PR1; in PR5, fertiliser inputs are lower than in PR4 (but higher than in PR1), the fallow period is longer than in PR4, and direct seeding predominates. PR6 resembles PR5, but corresponds to higher constraints in terms of labour, and poorer control over the water supply to the crop. Broadly, these patterns represent an array of contexts, reflecting opportunities and constraints, under which rice production takes place in tropical Asia (Savary et al., 2000a). Estimated attainable yields corresponding to these patterns of cropping practices are listed in Table 1. PR1, for instance, represents a possible 'optimum' balance between resource use and productivity, and accounts for a very large proportion of surveyed fields (35.3%). PR3 corresponds to very strong environmental, especially climatic, infrastructural (lack of irrigation means), and economic constraints, that are partly compensated by labour; this pattern represents resource-poor farmers, and a large fraction of the sample too (33.4%). At the other extreme, PR4, which corresponds to the highest estimated attainable yield, and which is represented by a small fraction of the surveyed sample (2.6%), reflects an imbalance between resource use and productivity, where negative effects on environment may be expected (Savary et al., 2000a).

We chose to consider some key patterns among this array of patterns of cropping practices, which are seen in this study as components of production situations (PS). PR1 was identified as a pivotal pattern; this pattern, however, is very broad, and may be subdivided into three production situations (PS1a, PS1b, and PS1c; Table 1) in our experiments, where PS1a is used as a reference production situation. PR2, which may be seen as a sub-optimal pattern relative to PR1, is represented here by PS2. PR3 is also very broad, and three variants, represented here by PS3a, PS3b, and PS3c were considered. PR4 was considered too, and is represented by PS4.

2.3. Field test experiments: multi-site model evaluation

RICEPEST was tested using data from four field experiments conducted in three different sites (referred to as test-experiments T1–T4, Table 2) where different production situations and injuries were considered (Table 2). The experimental details and results pertaining to these different test-experiments were separately reported (Willocquet et al., 1998, 1999a,b, 2000; Zhu et al., 2001). Two test-experiments (T1 and T2, Table 2) were conducted at the International Rice Research Institute (IRRI, Los Baños, Luzon, Philippines), during the rainy season 1997, and during the dry season 1998, one experiment (T3) was conducted at the China National Rice Research Institute (CNRRI, Hangzhou, Zhejiang Province, China), and one (T4) at the Narendra Deva University of Agriculture and Technology (NDUAT, Kumarganj, Uttar Pradesh, India). These experiments had identical designs, and consisted of main units, representing production situations, within which different injury treatments were applied. The reference production situation, PS1a, was used in all experiments. The other production situations considered were those selected as described above, and prevailing in the area where the experiment was conducted (Savary et al., 2000a). In each experiment, 3–5 injury treatments were applied in every production situation: 2–4 treatments involving pest injuries prevailing in the area where the experiment was established (Savary et al., 2000a), and a treatment where these injuries were combined. The injury treatments and a non-injured, control treatment were applied with three replications in individual plots randomly located within each production situation. Each individual plot was 2.8×2.8 m^2, and included four zones from the outer part of the plot towards its centre: one external border, one sampling zone, one buffer border, and a harvest area. Crop development, crop growth, environmental factors (daily temperature and radiation), and pest injuries were monitored throughout the growing season. Crop development and pest injuries were assessed weekly. Crop growth was measured from destructive samplings done every other week. The yield of the harvest area was measured at maturity.

2.4. Field validation experiment

2.4.1. General design

An additional field experiment referred to as 'validation-experiment', V (Table 2), was conducted at IRRI during the rainy season of 1998. In this fifth experiment, the widest possible range of production situations and injuries that can be dealt within a single trial were addressed to further evaluate RICEPEST. The experiment differed from the test-experiments by: (1) the larger number of (PS $\times$ injury) combinations considered; (2) the un-replication of injured treatments; and (3) the absence of destructive samplings in the injured treatments. The experiment involved five production situations: PS1a, PS1b, PS1d, PS3d, and PS4. These production situations were the same as in the test-experiments (Table 1), except for PS1d and PS3d, which slightly differed from PS1a and PS3b, respectively. In PS1d, the crop was grown under a rainfed environment, whereas in PS1a the rice crop was fully irrigated. PS1d thus resembles PS1a with a moderate water stress. In PS3d, the crop experienced a lower water stress than in PS3b, and involved Mashuri, an Indian cultivar different from that used in PS3b. Depending on the production situation, different injury treatments, alone or in combination, were applied (Table 3). The injury treatments were defined on the basis of the injury profiles determined by Savary et al. (2000a). All

Table 3
Injury treatments applied within each production situation in the validation experiment done in the Philippines (V) during the rainy season 1998

Injury[a]	PS1a[b]	PS1b	PS1d	PS3d	PS4
BLB	X			X	X
M	X	X		X	
SHR	X	X	X	X	
SHB				X	X
BPH	X				X
DH + WH + WEED	X	X	X	X	
DH + WH + SHB	X				X
SHB + BLB	X				X

[a] BLB, bacterial leaf blight; M, mechanical injury; SHR, sheath rot; SHB, sheath blight; BPH, brown plant hopper; DH, dead heart; WH, white head; WEED, weeds.

[b] Features of PSs are described in Table 1.

injury treatments were applied in PS1a, the reference production situation. Each production situation was represented by a main unit within which injury and control treatments were randomly distributed. The injury treatments consisted of unreplicated individual plots, whereas the non-injured control treatment was replicated in three plots. As in the test-experiments, all plots were 2.8×2.8 m^2. The control plots had the same design as in the test-experiments. The injured plots included a 20 cm-wide external border row, a 20 cm-wide assessment zone, and a central area. In the control plots, injury assessments and destructive samplings were done in the sampling zone. In the injured plots, visual assessments of pests were done in the assessment zone. Crop development and injuries were assessed weekly in all plots, and crop growth was measured from destructive samplings done in control plots every other week only, following Willocquet et al. (1998, 2000). Only the central area of the control plots was harvested, whereas both the assessment zone and the central area of the injured plots were harvested at crop maturity.

2.4.2. Manipulation of injuries

All pests were manipulated in order to obtain a spatially homogeneous distribution of injuries in the plots to be infested. The methodology used here is derived from techniques developed at IRRI to experimentally measure yield losses and develop an experimental yield loss database (Savary et al., 1997, 2000b).

SHB inoculation was done at maximum tillering. Five grams of inoculum was inserted at the base of each hill in transplanted rice plots, and 980 g of inoculum was broadcasted per plot in the case of direct seeded rice. The inoculum consisted of rice grain hull colonised by *R. solani* (Sharma and Teng, 1990).

BLB inoculation was done twice, at tillering and maximum tillering stages. Inoculation was done on all the second and third fully expanded leaves of hills per plants to be inoculated. At each inoculation, every other hill (20×20 cm^2 quadrat in direct-seeded crop) was inoculated. Leaves were inoculated by using the leaf clipping method (Kauffman et al., 1973; Savary et al., 1997), with a bacterial suspension at a concentration of 10^9 cells ml^{-1}. Leaves were cut at about 2 cm from the tip, using scissors previously dipped in the bacterial suspension. Scissors were dipped again after clipping every 3–5 leaves.

Sheath rot injury was achieved by inoculating three tillers per hill (for transplanted rice) or per plant (for direct-seeded rice) in 50 hills (or plants) per plot at booting stage. The inoculated hills (or plants) were located according to a diagonal pattern with a 28×56 cm^2 mesh. Following Estrada et al. (1979), inoculation was done by injecting a suspension of *S. oryzae* spores at the base of the boot, using a syringe. The concentration of the suspension was ca. 2×10^6 spores ml^{-1}, and 2 ml of suspension was injected in each boot. The suspension was prepared using a 10-day-old culture of *S. oryzae* grown on PDA.

In plots damaged by DH and WHs, rice leaf segments containing mature egg masses of the yellow stem borer, *S. incertulas*, were inserted between the stem and the sheath of a lower leaf, in a tiller belonging to a hill per plant to be infested. Twenty-five egg masses were inserted in each plot, in tillers located according to diagonal patterns with a 56×56 cm^2 mesh. Infestation took place at the tillering and booting stages for dead heart and WH damages, respectively.

In BPH plots, nine rice hills, grown in the greenhouse and infested by BPH, were transferred at maximum tillering stage. The infested hills formed a 3×3 grid, with one infested hill located in the centre of the plot. The infested hills were equidistant from each other, at 1 m intervals.

Mechanical injury (M), mimicking defoliating insects damage, was achieved by cutting all the leaves at their middle with scissors in half of the tillers of each hill of the plot. This was done in two stages, the first half of hills (spatially distributed according to diagonal patterns) being damaged at 20 DACE, and the second half at 30 DACE.

Weed injury was established by transplanting seedlings of *Echinochloa crus-galli* in the plots. *E. crus-galli* seedlings were grown in a nursery, and transplanted at a 20×20 cm^2 density, on diagonals between hills in the case of transplanted plots. The weed seedlings were transplanted at 11 DACE, and had the same age as the rice hills per plants to be infested.

2.4.3. Monitoring of injuries

Five assessment units (i.e. hills in transplanted stands, or 20×20 cm^2 quadrats in direct-seeded stands) were randomly chosen each week to assess SHB, bacterial leaf blight, sheath rot, DH, and WHs. Three tillers were randomly selected to assess SHB and bacterial leaf blight severity in each of the five assessment units. Percentages of leaf area covered by SHB lesions and percentages of leaf area covered bacterial leaf blight lesions were visually assessed for all the leaves using the following scale: 0, 1, 5, 10, 15%, and every 5% thereafter. The total number of tillers (including DH), the number of DH, the total number of panicles, the number of panicles damaged by sheath rot, and the number of WHs were counted in each of the five assessment units.

BPH dry weight was measured weekly by sampling BPH on six hills per plot using the conventional tapping method (Elazegui et al., 1990). A stratified sampling scheme was used. Three categories of hills were determined, depending whether hills were placed 14, 42 or 71 cm apart from the nearest infested hill. Two hills of each category were sampled. The sampled BPH were oven-dried and weighed. The dry weight of BPH per square meter was computed accounting for the relative frequency of the different categories of hills sampled.

Weed infestation was measured as the dry matter of weeds at successive destructive samplings done every other week. Weeds located in consecutive 20×80 cm^2 areas of the assessment zone were uprooted, gently washed with tap water to remove soil particles, oven-dried, and weighed.

The means of SHB severity, bacterial leaf blight severity, sheath rot incidence, WH incidence, number of DH per square meter, BPH dry weight per square meter, and weed dry weight per square meter were calculated at all assessment dates.

2.5. Approaches used to evaluate the RICEPEST model

The evaluation of RICEPEST thus builds upon a set of five complementary field experiments. The model was first tested in the four test-experiments (T1–T4) conducted in the Philippines, in China, and in India in 1997 and 1998. In each of these experiments, the parameters required to simulate attainable growth and yield in a given production situation were calibrated using crop growth and crop development data from the control (injury free) treatment. In a given production situation, the calibrated model was then used to simulate the actual growth and yield corresponding to the different injured treatments. Data derived from the measurements of injuries monitored throughout the cropping season were included in the model as driving functions. Observed growth and yield data of the injury treatments were then used to test the simulations of yield losses caused by the corresponding pests.

RICEPEST was further evaluated using an independent field validation-experiment (V) conducted at IRRI during the rainy season 1998 (Table 2). In this fifth experiment, parameters used to simulate attainable growth and yield for PS1a (the reference production situation) were derived from those determined for this production situation in the test-experiments previously conducted in the Philippines, in China, and in India. RICEPEST was calibrated for PS1b using parameters determined in experiment T1 (Table 2) conducted at IRRI during the rainy season 1997. PS1d had the same features as PS1a (Table 2) except for water management. The validation-experiment was conducted during the rainy season, and rainfalls occurred regularly. Water supply was thus assumed to be similar in PS1d and PS1a, and the parameters used to simulate the attainable growth and yield for PS1d were thus the same as those used for PS1a. The parameters used in PS4 were derived from parameters determined for this PS in experiment T3 conducted in China (Table 2). A low water stress was observed in PS3d during the validation experiment, whereas PS3b suffered of high water stress in the experiment done in India. PS3d was thus different from all the production situations considered in the different test-experiments. RICEPEST was therefore, calibrated for PS3d using data from the control plots of the validation-experiment. As in the test-experiments, RICEPEST was run to simulate crop growth and yield corresponding to the different injury treatments considered. Comparison of observed and simulated grain yield allowed to assess the performances of the different damage coupling functions, and their interactions.

2.6. Qualitative and quantitative model validation

Four complementary graphical and statistical approaches were used to assess the model performance, both from qualitative and quantitative standpoints.

The first approach consists in visually comparing the dynamics of simulations to real world data (Penning de Vries, 1977). Observed and simulated values of key variables of the system are plotted over time for visual examination and qualitative assessment of the model performances. The second approach consists in a visual examination of the difference between observed and simulated values. Deviations, i.e. simulated minus observed values, are plotted against the corresponding simulated values, and a predetermined envelope of acceptance is displayed on the graph (Mitchell, 1997). The envelope of acceptance defines an area within which dots representing deviations are considered acceptable model performances. The envelope of acceptance can be determined on the basis of the precision of measurements of model input(s) and/or model output(s), and/or by considering the model purpose. In the third approach, the performance of the model is statistically evaluated by an equivalence test (Garrett, 1997). The equivalence test allows to test the null hypothesis: 'the difference between two means is greater than a specified tolerance range defined by a researcher prior to experimentation'. Rejection of the null hypothesis leads to the conclusion that the two means are equivalent within a reasonable tolerance range (Garrett, 1997). The equivalence test is applied here to compare simulated outputs to observed data, and the null hypothesis tested is: 'the mean of deviations is greater than the predefined tolerance range'. In practice, the null hypothesis is rejected with a type I error of 5% when the 95% confidence interval of the mean of deviations falls within the tolerance range (Garrett, 1997). The tolerance range is a predetermined interval within which the mean of deviations is considered acceptable. In our case, it corresponds to the envelope of acceptable area. In the fourth approach, the χ^2-test of goodness-of-fit (Teng, 1981) is used to compare categorised observed and simulated outputs. This last approach allows to test whether the model outputs fall into the same preset categories as observed values.

The first approach (visual comparison of simulated and observed variables over time) was used to assess the model capacity to simulate the attainable (non-injured) growth and yield of rice stands in the different production situations considered in the validation-experiment. The dry weights of leaves, stems, roots, and panicles, and the total dry weight of organs were displayed.

The three other approaches were applied to assess the model performances in simulating yield losses. In these approaches, the variables pertaining to the different (PS × injury) treatments applied in the four test-experiments were combined to provide a first data set. A second data set was built from the variables pertaining to the different (PS × injury) treatments applied in the validation-experiment. Two variables were selected to test the overall performance of RICEPEST: the grain yield (Y, in g m^{-2}) and the relative grain yield loss (RYL, expressed as a percentage). Grain yield is one output of the modelled system, that integrates over time the accumulation of (injury × environment) interactions determining crop growth. It is also economically the most important simulation output variable of the considered system. The relative yield loss (i.e. the percentage of grain yield loss relative to the corresponding attainable grain yield) represents the overall damage effects caused by a given injury, or combined injuries, on the final yield.

In the second approach (examination of the deviations), deviations of grain yield (DY), and of relative grain yield loss (DRYL) were considered. The area of acceptance for DY was set to $\pm 10\%$ of the grain yield. The assessment of yield in general (Poate, 1988), and of a rice crop, in particular, is subject to an experimental error which can be estimated to at least 10% (Savary et al., 1994). The area of acceptance for DRYL was thus set to $\pm 10\%$. A deviation of $\pm 10\%$ in estimated relative yield loss is consistent with the intended model main use, which is to define re-

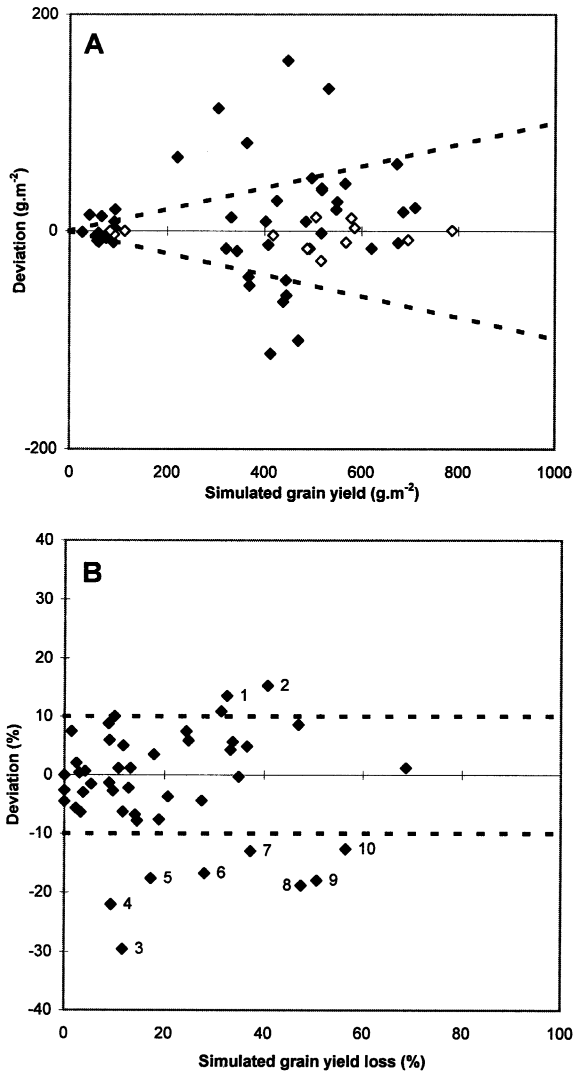

Fig. 2. Deviation (simulated–observed) versus simulated grain yield (A) and simulated relative grain yield loss (B) corresponding to the different (PS × injury) treatments applied in the four test-experiments. The dotted lines enclose the acceptable area. Close symbols represent the injury treatments tested in the four test-experiments (T1: Philippines, rainy season 1997; T2: Philippines, dry season 1998; T3: Southern China, 1998; and T4: Northern India, 1998). Open symbols represent control treatments, that is un-injured rice crop, addressed in these experiments. (1) Experiment T2, PS1a, WEED; (2) experiment T2, PS1a, DH + WH + WEED; (3) experiment T1, PS2, WEED; (4) experiment T4, PS1a, DH; (5) experiment T4, PS3c, DH; (6) experiment T2, PS3a, DH + WH + WEED; (7) experiment T1, PS1a, WH; (8) experiment T1, PS1a, DH + WH + WEED; (9) experiment T4, PS3b, DH; (10) experiment T1, PS2, DH + WH + WEED.

search priorities for rice protection against its pests in tropical Asia.

In the third approach (equivalence test), the null hypotheses tested were: 'the means of DY and DRYL are greater than the predetermined tolerance ranges'. Ninety-five percent confidence intervals for DY and DRYL (excluding data pertaining to un-injured crop stands) were computed. The tolerance range was set to ± 36 g m^{-2} for DY in the test-experiments (i.e. $\pm 10\%$ of the mean of grain yield over the 45 data points), to ± 42 g m^{-2} for DY in the validation-experiment (i.e. $\pm 10\%$ of the mean of grain yield over the 23 data points), and to $\pm 10\%$ for DRYL.

In the fourth approach (χ^2-test), preset numerical boundaries were defined so as to generate meaningful categories, i.e. to obtain a class filling large enough to perform valid χ^2-tests (Dagnélie, 1975). Four and five categories (total strength is 45) were thus defined for Y and RYL, respectively, when the combined data from test-experiments were considered (data pertaining to un-injured crop stands were excluded from the analysis). The boundaries defining categories for Y were 0, 200, 400, 600 and 800 g m^{-2}. The boundaries defining categories for RYL were 0, 10, 20, 30, 50 and 100%. Three and four categories (total strength is 23) were defined for Y and RYL, respectively, when the validation-experiment was considered. The boundaries defining categories for Y were 0, 400, 500 and 600 g m^{-2}. The boundaries defining categories for RYL were 0, 5, 10, 20 and 100%.

3. Results

3.1. Test-experiments: model performances under various environments

In the four experiments conducted in three sites, simulated yields ranged from 50 to 800 g m^{-2} (i.e. 0.5–8 t ha^{-1}). When outputs from these experiments were considered, 30 out of 45 deviations of grain yield (un-injured treatments not included) fell within the acceptance area, using the second approach for model evaluation (Fig. 2A). Seven deviations (out of which five were above, and two were below the acceptance area) were larger than $\pm 20\%$ of the simulated grain yield. The open symbols in Fig. 2A represent un-injured rice stands in the different production situations. These data show that a wide range of attainable yields (100–800 g m^{-2}) was achieved in these test-experiments. Simulated relative yield losses ranged from 0 to 70% (Fig. 2B). Except for the WEED treatment in PS2 of the experiment T1, conducted in the Philippines during the rainy season 1997 (dot 3 in Fig. 2B), all deviations were smaller than 30%, and one deviation only was between 20 and 30%. Ten yield loss deviations only were outside the acceptance area. Eight out of these 10 outliers were below the acceptance area, i.e. represented underestimations of yield losses by the model. Most of the 10 outliers corresponded either to DH injury in the Indian experiment (under-estimation of yield losses), or to treatments including weed injury (under-estimation of yield losses in four cases, over-estimation of yield losses in two cases).

When applying the equivalence test, the 95% confidence intervals for DY (simulated minus observed yield) and DRYL (simulated minus observed relative yield loss) were within the tolerance range (Table 4). The hypotheses of deviation means for yield (DY) and relative yield loss (DRYL) being greater than the tolerance ranges were thus rejected ($P \leq 5\%$) for both variables. The confidence interval for DRYL was much narrower than the tolerance range. As many outliers detected in Fig. 2B corresponded to crops injured by weeds, statistics and confidence intervals for DY and DRYL were computed considering the sub-set of data involving weed injury, either alone or in combination. The average of DY was lower than the average computed when considering all injury treatments (-3.5 vs -2.0). Underestimation of damage by the model was thus in general more pronounced for weeds than for other injuries. This was reflected by the right-side of the confidence interval of DY as well, which was larger than the right-side of the tolerance range. The null hypothesis of the mean of yield deviation greater than the tolerance ranges was thus not rejected in the case of this sub-set of data. The confidence interval of DRYL was within the tolerance, but the left-side of the confidence interval of DRYL was very close to the left-side of the tolerance (-9.96 vs -10).

Following the fourth approach, the χ^2 value obtained when comparing categorised, observed and simulated yields was 0.26, corresponding to $P = 0.97$. A χ^2 value of 1.84 was obtained when relative yield loss was considered, corresponding to $P = 0.77$. In both cases, the null hypothesis ‘observed and simulated distributions of variables are drawn from the same distribution’ was not rejected, and large probability values were associated to the tests.

3.2. Field validation experiment

The parameters used to simulate attainable growth in the various production situations (except PS3d) of the validation experiment were derived from the test-experiments. A few recalibrations were however, necessary in two specific cases (radiation use efficiency decreased and rela-

Table 4
Statistics, confidence interval and tolerance range for deviation of yield and relative yield loss, computed from the pool of data pertaining to the different (PS × injury) treatments applied in the four field test-experiments (T1–T4) done in the Philippines, Southern China, and Northern India

Variable name[a]	Mean	Standard deviation	95% confidence interval		Tolerance
DY	7.86	51.7	−7.66	+23.38	−36+36
DRYL	−2.01	9.81	−4.96	+0.94	−10+10
DY[b]	10.59	71.44	−27.47	+48.65	−36+36
DRYL[b]	−3.54	12.05	−9.96	+2.88	−10+10

[a] DY, deviation in yield; DRYL, deviation in relative yield loss.
[b] Only treatments injured by weeds, alone or in combination, were accounted for in the computations.

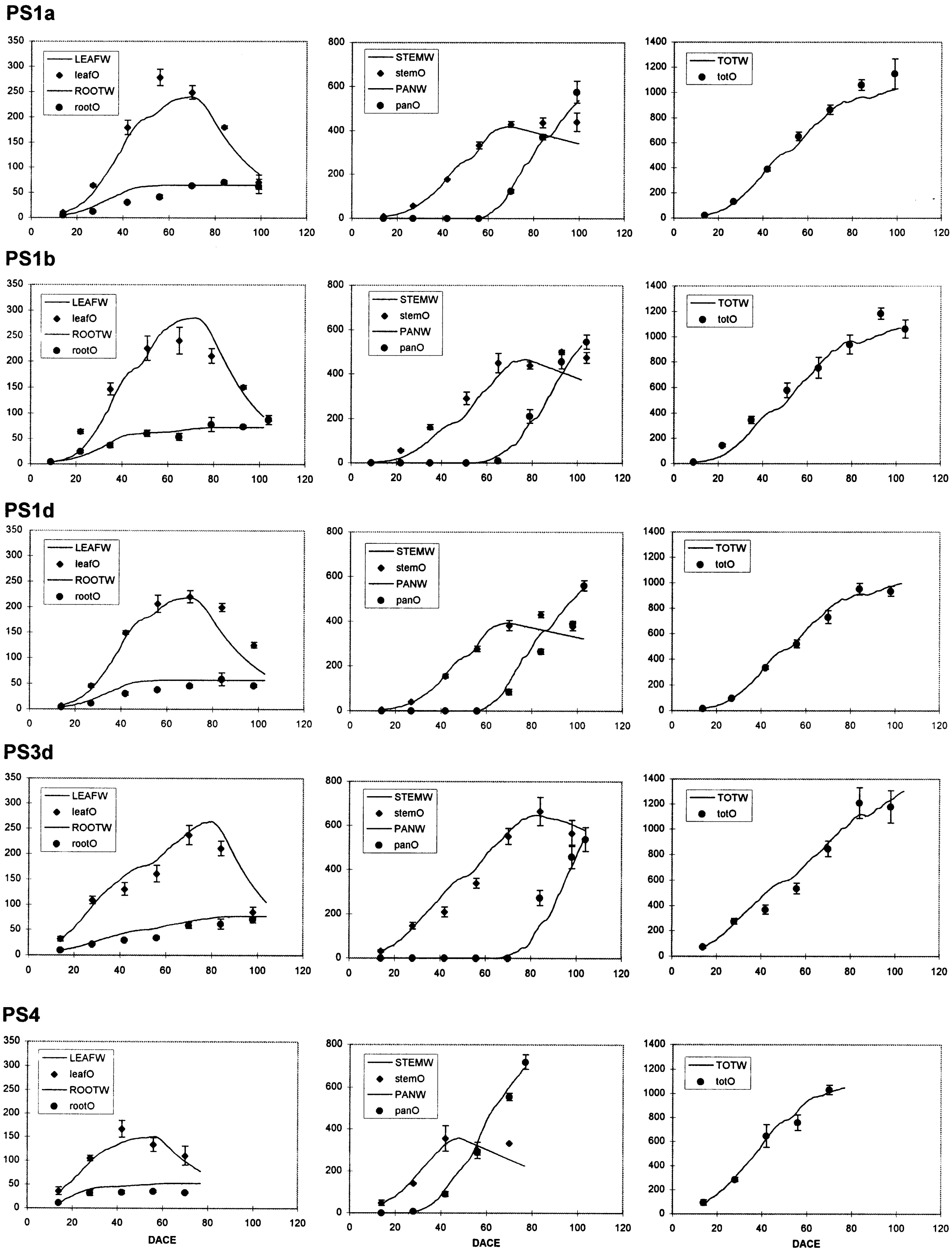

Fig. 3. Observed (●,◆) ± SEM, and simulated (plain line) attainable rice growth in the five production situations considered in the validation field experiment (V) conducted in the Philippines during the rainy season, 1998. The different variables shown are: dry weight (g m^{-2}) of roots (ROOTW), leaves (LEAFW), stems (STEMW), panicles (PANW), and total dry weight (TOTW).

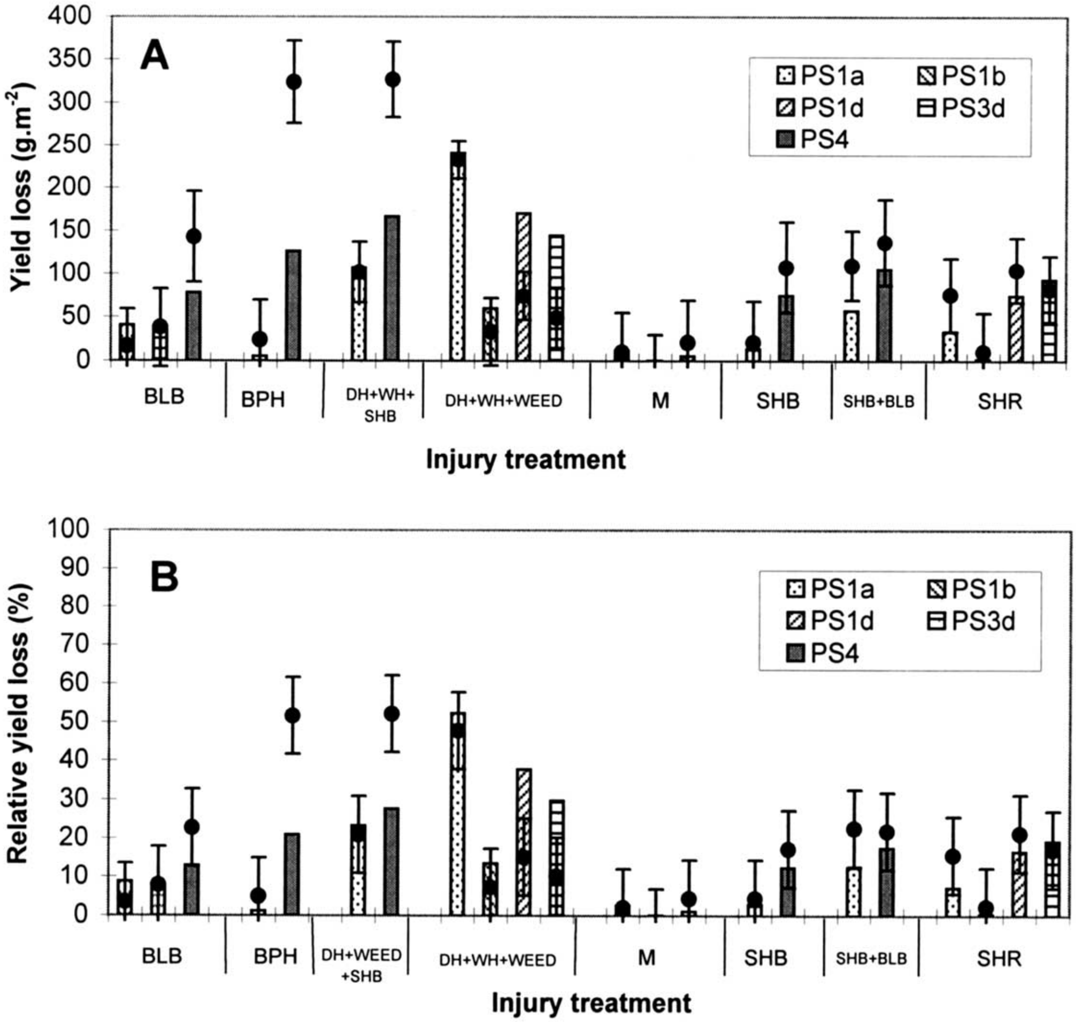

Fig. 4. Observed (dots and error bars) and simulated (solid bars) yield loss (A) and relative yield loss (B) in the validation experiment (V) conducted in the Philippines during the rainy season 1998. Error bars represent $\pm 10\%$ of the corresponding actual yield.

tive RSENL increased in PS1b; flowering and maturity development stages delayed in PS4).

The observed and simulated dry weights of organs in un-injured rice crops are displayed in Fig. 3. The dynamics of organ dry weights was similar in the five PSs. The dry weight of leaves increased until flowering, then decreased due to leaf senescence. The dry weight of roots increased until flowering, and then remained stable. The dry weight of stems increased until flowering, and then declined, due to translocation of starch from stems to panicles. The dry weight of panicles increased near-linearly from flowering to maturity. The total dry weight of organs increased strongly at the beginning of the growing season, then increased linearly, and its progression progressively slowed down as maturity was approaching. Crop cycles were around 100 days except in PS4, where crop maturity was reached within 80 days. The maximum dry weight of stems was the highest in PS3d, and the lowest in PS4. The maximum dry weight of leaves was much lower in PS4 than in the other production situations. The final panicle dry weight was however, the largest in PS4 (720 g m^{-2}), followed by PS1a and PS1d (572 and 560 g m^{-2}), and PS1b and PS3d (546 and 537 g m^{-2}). The final total dry weight of organs ranged from 1000 to 1200 g m^{-2}. The simulated and observed growth values were close in all production situations.

Simulated and observed yield losses and relative yield losses in the different (injury treatment × production situation) combinations are displayed in Fig. 4A and B. Observed yield losses ranged between 0 and 330 g m^{-2}, and simulated yield losses ranged between 0 and 245 g m^{-2} (Fig. 4A). The largest yield losses occurred in the combined injury treatments (DH + WH + SHB, and DH + WH + WEED), and were the lowest in the mechanical injury treatment. In general, simulated yield loss was within the range of observed yield ± 10%. Yield loss was strongly under-estimated in PS4 (treatments BPH and DH + WH + SHB), and strongly over-estimated in treatment DH + WH + WEED in PS1d and PS3d. Similar trends were observed when relative yield losses were displayed (Fig. 4B). Observed relative yield losses ranged between 0 and 70%, and simulated relative yield losses ranged between 0 and 55%.

Simulated yields ranged between 200 and 600 g m^{-2}, and attainable yields ranged between 450 and 600 g m^{-2} in the validation experiment (Fig. 5A). Most deviations in grain yield were within the acceptance area, with only two over-estimated, and three under-estimated yield simulations. Most simulated relative yield losses were within 0–30% (Fig. 5B). Two deviations were over (DH + WH + WEED in PS1d and PS3d), and two were below (PS4, BPH and DH + WH + SHB) the acceptance area.

The 95% confidence intervals of both DY and DRYL were within the corresponding tolerance ranges (Table 5). Again, the hypotheses of mean of deviations greater than the tolerance ranges were rejected for both Y and RYL.

The χ^2 value obtained when comparing categorised observed and simulated yield was 0.00, corresponding to $P = 1$. A χ^2 value of 1.53 was obtained when relative yield loss was considered, corresponding to $P = 0.68$. In both cases, the null hypothesis of equal distributions was not rejected, and very large probability values were obtained.

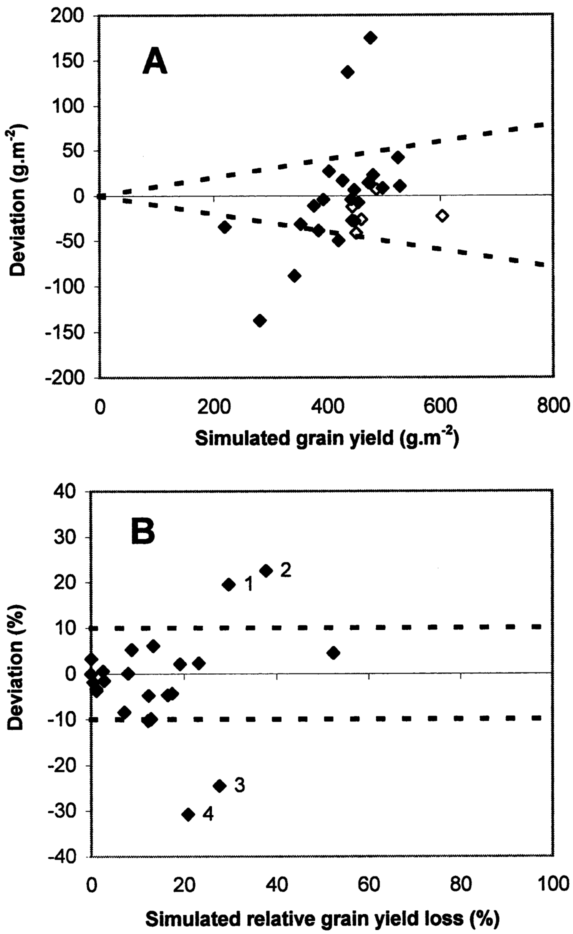

Fig. 5. Deviation (simulated–observed) versus simulated grain yield (A) and simulated relative grain yield loss (B) corresponding to the different (PS × injury) treatments applied in the validation field experiment (V) conducted in the Philippines during the rainy season, 1998. The dotted lines enclose the acceptable area. Plain symbols represent injury treatments, and open symbols represent control treatments, that is un-injured rice crop. (1) PS3d, DH + WH + WEED; (2) PS1d, DH + WH + WEED; (3) PS4, DH + WH + SHB; (4) PS4, BPH.

4. Discussion

4.1. Representativeness of the experimental framework

The various (production situation × injury profile) combinations addressed in the different

Table 5
Statistics, confidence interval and tolerance range for deviation of yield and relative yield loss, computed from the pool of data pertaining to the different (PS × injury) treatments applied in the validation experiment (V) done in the Philippines during the rainy season 1998

Variable name[a]	Mean	Standard deviation	95% confidence interval		Tolerance
DY	−0.23	64.6	−29.60	+29.17	−42+42
DRYL	−1.90	11.62	−7.19	+3.39	−10+10

[a] DY, deviation in yield; DRYL, deviation in relative yield loss.

field experiments provided quantitative information on crop growth and injury dynamics throughout the crop cycle. The choice of the combinations was based on a characterisation study conducted in tropical Asia (Savary et al., 2000a). This basis for selection of production situations and of the associated injuries warrants the representativeness of this simulation study with respect of current and emerging production situations and their biotic constraints. The different experiments generated data sets with wide variations in attainable yield (from 83 to 787 g m^{-2}) and yield loss (from 0 to 69%). This allowed to test the flexibility of the model, and its ability to simulate rice growth under a wide array of environmental (abiotic and biotic) conditions.

4.2. Methods used to assess the model performance

Many approaches have been proposed for model validation in agricultural systems (Teng, 1981; Rossing, 1991), but the reliability of most of these approaches have been questioned (Thornton and Hansen, 1996; Mitchell, 1997; Analla, 1998). According to Rykiel (1996), no standard method for validation of ecological models is currently available. This may be explained by the nature of the hypothesis to be tested during the process of model validation. The general null hypothesis to be tested is: 'the simulated output(s) is (are) different from observed value(s)'.

Statistical tools typically test the opposite null hypothesis, that of equality between two entities. Only a few tests are available that allow to test the null hypothesis of difference between variables (Garrett, 1997). Another reason for the lack of standardised validation methods is the complexity of systems modelled, and the number of model outputs.

We therefore, used a combination of qualitative and quantitative validation methods. First, qualitative methods involved the examination of plots. Dynamic plots displayed simulated and observed $\pm$SEM data over time (Penning de Vries, 1977). Static plots displayed deviations that are plotted against the corresponding simulated data (Mitchell, 1997). Second, we used quantitative methods, i.e. equivalence tests (Garrett, 1997) and χ^2-tests. This set of complementary methods were considered to provide sufficient information to assess the model performance.

4.3. Simulation of attainable yield

The adequate simulation of attainable growth and yield in the four test-experiments and in the validation-experiment indicates that the structure of the model is flexible enough to account for a number of production situations prevailing in tropical Asia. The parameterisation for attainable growth in PS1a, PS1b, and PS4 in the validation-experiment, using parameters determined in previous, independent test-experiments allowed to test the model ability to simulate adequately the growth of a crop in a given production situation, in different sites or/and in different years. In this respect, RICEPEST behaved in a satisfactory way, given its simplicity and the relatively small number of parameters used. The model did simulate well attainable growth in PS1a, and only minor changes were required to adequately simulate attainable growth in PS1b and PS4.

4.4. Simulation of yield losses

The second approach (plots of deviations) showed that 78 and 83% of deviations in relative yield loss were within the envelope area of acceptance in test-experiments and in the final validation-experiment, respectively. This approach however, pointed at two areas for model improvement with respect to specific injuries. First, RICEPEST tends to under-estimate yield losses due to weeds (Table 4, Fig. 2B). Improvement in model accuracy would thus be desirable based on specific experiments which should address the yield-reducing effect of prevailing weed species in different production environments. The second area for model improvement concerns the simulation of yield losses caused by DH in water-stressed environments, which RICEPEST under-estimates (Fig. 2B). Detailed experiments should be conducted on this injury in this widespread type of rice-growing environment. In studies on yield losses due to DH, emphasis has been placed on compensation mechanisms that occur in transplanted rice crops where there is an ample supply of water and nutrients (Rubia et al., 1996). However, compensation may not occur at a similar intensity when the production situation is poorer, i.e. when compensation is constrained. More generally, these two remarks point at the need to consider a diversity of production situations when quantifying damage mechanisms.

In the test-experiments and in the final validation-experiment, deviation in yield and relative yield loss fell within the predetermined tolerance range (equivalence test). Conversely, χ^2-tests did not lead to rejection of the null hypothesis that observed and simulated yields have the same distribution. The same hypothesis for relative yield

Table 6
Models developed to simulate the effects of rice pests on crop growth and yield

Aim of model		Model development			Model use[f]	References
Scope[a]	Pest or injury[b]	Parms[c]	Validation[d]	Simplicity[e]		
SP	BLB	E	++	++	IL, N	Elings et al. (1997)
SP	BPH	E	+	++	IL	Kenmore (1980)
		E	−	++	IL	Watanabe (1994)
SP	DEF	E	+	++	IL	Graf et al. (1992)
SP	LB	E	+	++	IL	Bastiaans (1993)
		E	+	+	IL	Luo et al. (1997)
SP	SHB	E	++	+	IL	Fan et al. (1992)
SP	Stem borers (DH and WH)	E	+	++	IL	Rubia and Penning de Vries (1990)
SP	WD	E, EG	+	++	IL	Graf et al. (1990)
		E	+	++	IL, CE	Kropff et al. (1993)
		E, EG	++	++	IL, W	Caton et al. (1999)
MP	DEF, LB, SHB, WD and generic pests	EG, E	+	+	IL	Pinnschmidt et al. (1995)
MP	BLB, BPH, BS, DEF, DH, SHB, SHR, WD, WH	E	++	+++	IL, PS	Willocquet et al. (this paper)

[a] SP, single-pest; MP, multiple-pest.

[b] BLB, bacterial leaf blight; BPH, brown plant hopper; DEF, defoliators; LB, leaf blast; SHB, sheath blight; DH, dead hearts; WH, white heads; WD, weeds; SHR, sheath rot.

[c] E, parameters quantified experimentally; EG, parameters derived from educated guesses.

[d] −, no validation; +, validation with partial calibration from field input data, or with a limited number of datasets; ++, validation with a large number of independent datasets.

[e] Model simplicity, from very complex (+), to complex (++), to simple (+++).

[f] Environmental factors (injury, cropping practices) that were varied in model simulations: IL, injury level; N, nitrogen input; CE, crop establishment method; W, water management; PS, production situation.

loss was not rejected either. Results obtained following the third and fourth approaches thus showed that the model adequately accounted for damage mechanisms incurred by rice pests, when considered collectively.

4.5. Potential uses of the RICEPEST model

Several simulation models have been developed to better understand and predict the effects of pest injuries on rice growth and yield (Table 6). These models vary greatly in complexity, some having a relatively simple structure, others being derived from detailed preexisting agrophysiological models, and being quite complex. These models also differ in their degree of validation. Most of these models concentrate on the effects of an individual rice pest. Also, most of these models do not specifically consider variation in rice cropping practices, and when it is the case, only one varying component of the rice crop management is considered. The novelty of RICEPEST consists in the combination of four characteristics: (1) the structure of the model is simple, so as to enable easy model verification, validation (Penning de Vries, 1977), and use for hypotheses testing; (2) RICEPEST is heavily field-documented and -validated, using a large, regional database of specific rice yield loss experiments in a range of tropical environments; (3) the model includes a large number of injury mechanisms, thus allowing to consider the main pests of rice, from pathogens to insects, and weeds; and (4) the design of RICEPEST is such that the impact of rice pests in differing production situations, or the consequences of changes in pests' impact with changes in rice production situations, can explicitly be studied.

Few attempts have been made to integrate the damage mechanisms due to several injuries in a crop growth simulation model. Two well-documented examples, in the case of potato (Johnson, 1992) and rice (Pinnschmidt et al., 1995), illustrate the potential uses of such models: (1) to better understand the underlying mechanisms of interactions between injuries; (2) to improve pest management within a multiple-pest system. RICEPEST can be used for these two purposes; it however, can also be used for a third one, research prioritisation, as outlined below.

The robustness of RICEPEST is illustrated by its capacity to generate reliable simulations over different climatic seasons and sites. RICEPEST also allows to address a wide range of production situations (and their multiple effects on crop growth). Generic driving functions (e.g. RUE) and parameters (e.g. MAXTIL) for the simulation of attainable growth and yield can thus be determined in order to address current production situations. Future production situations can be explored as well by modifying the generic driving functions and parameters, according to specific hypotheses. These hypotheses refer to the attainable yield, and pertain to new, or changing, technologies, such as the use of new rice plant types with low tillering capacity, or cropping practices involving optimised nutrient supply (Hossain and Fischer, 1995).

RICEPEST can also reliably simulate the damage caused by an array of rice pests, considered alone or simultaneously. Additional hypotheses which refer to the actual yield, and pertain to current, or likely, injury profiles, can therefore, be forwarded and tested with the model. The emergence of new pest problems (Mew, 1992) can also be considered.

The model reported in this paper appears robust and reliable enough as a strategic tool to analyse yield loss trends where various production situations and multiple injuries are considered. It is therefore, possible to use RICEPEST as a tool to address current, and explore future scenarios of cropping practices and injury profiles, and thus help in setting research priorities for rice pest management.

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