Research Priorities for Rice Pest Management in Tropical Asia: A Simulation Analysis of Yield Losses and Management Efficiencies

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Accepted for publication 12 March 2004.

ABSTRACT

Willocquet, L., Elazegui, F. A., Castilla, N., Fernandez, L., Fischer, K. S., Peng, S., Teng, P. S., Srivastava, R. K., Singh, H. M., Zhu, D., and Savary, S. 2004. Research priorities for rice pest management in tropical Asia: A simulation analysis of yield losses and management efficiencies. Phytopathology 94:672-682.

A simulation study was conducted to assess the current and prospective efficiency of rice pest management and develop research priorities for lowland production situations in tropical Asia. Simulation modeling with the RICEPEST model provided the flexibility required to address varying production situations and diverse pest profiles (bacterial leaf blight, sheath blight, brown spot, leaf blast, neck blast, sheath rot, white heads, dead hearts, brown plant-hoppers, insect defoliators, and weeds). Operational definitions for management efficacy (injury reduction) and management efficiency (yield gain) were developed. This approach enabled the modeling of scenarios pertaining to different pest management strategies within the agroecological contexts of rice production and their associated pest injuries. Rice pests could be classified into two broad research priority-setting categories with respect to simulated yield losses and management efficiencies. One group, including weeds, sheath blight, and brown spot, consists of pests for which effective pest management tools need to be developed. The second group consists of leaf blast, neck blast, bacterial leaf blight, and brown plant-hoppers, for which the efficiency of current management methods is to be maintained. Simulated yield losses in future production situations indicated that a new type of rice plant with high-harvest index and high-biomass production ("New Plant Type") was more vulnerable to pests than hybrid rice. Simulations also indicated that the impact of deployment of host resistance (e.g., through genetic engineering) was much larger when targeted against sheath blight than when targeted against stem borers. Simulated yield losses for combinations of production situations and injury profiles that dominate current lowland rice production in tropical Asia ranged from 140 to 230 g m^{-2}. For these combinations, the simulated efficiency of current pest management methods, expressed in terms of relative yield gains, ranged from 0.38 to 0.74. Overall, the analyses indicated that 120 to 200 × 10^6 tons of grain yield are lost yearly to pests over the 87 × 10^6 ha of lowland rice in tropical Asia. This also amounts to the potential gain that future pest management strategies could achieve, if deployed.

Additional keywords: *Chilo suppressalis*, *Cnaphalocrocis medinalis*, *Cochliobolus miyabeanus*, *Cyperus* spp., *Echinochloa* spp., *Hydrellia philippina*, *Monochoria vaginalis*, *Nilaparvata lugens*, *Oryza sativa*, *Pyricularia oryzae*, *Rhizoctonia solani*, *Sarocladium oryzae*, *Scirpophaga incertulas*, *Scirpophaga innotata*, *Sesamia inferens*, *Xanthomonas campestris* pv. *oryzae*.

Priority setting allows research organizations to specify relevant targets for their programs to achieve greater impact (14). Research that aims at improving crop pest management can be prioritized through assessing the current (68) and future importance of pests (pathogens, insects, and weeds) in terms of yield losses and efficiency of pest management methods (36). Advances in understanding the effect of injuries on crop physiology have allowed the integration of injury mechanisms through physiological coupling points (3,34,38) into simulation models (3,20,25,43,56,57). In turn, these models provide a better understanding of the interplay of mechanisms that determine yield losses (26,29,38,39,42,44). Only a few yield loss studies using this mechanistic approach have considered multiple pests (20,27, 34,69). While field experiments may generate estimates of losses caused by individual pests or pest profiles (e.g., for rice) (48), such studies are limited in their scope by the number of production situations that can be considered and the complexity of pest combinations and effects. Crop-growth simulators, on the other hand, provide the flexibility to assess yield reductions caused by individual pests within a pest profile, in current and projected (future) scenarios. Similarly, yield gains resulting from the removal, partial or complete, of a pest from a profile through pest management can be computed. A simulation approach, therefore, allows one to project estimates of (i) efficiencies, current or prospective, of certain pest management tools (yield gains); and (ii) impacts of research on crop or pest management to prioritize research efforts (19,37,39,57,68).

Rice (*Oryza sativa*), the staple crop of tropical Asia, is produced in a wide range of agroecological conditions (16). In a previous study based on surveys done in farmers' rice fields in the region (49), production situations (4,13,36,47) for lowland rice were shown to be strongly associated with injury profiles, i.e., specific combinations of injuries that affect a rice crop during the course of a cropping season. This information generated a frame-

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Publication no. P-2004-0505-01R

work to develop RICEPEST, a simulation model for yield losses due to multiple injuries with a range of different production situations (65,66). RICEPEST was validated for an array of production situations and injury profiles (65) using a multiple-site network of independent field experiments in the Philippines (Central Luzon) (62), China (Zhejiang Province) (71), and India (Uttar Pradesh) (64).

The objective of the work reported here was to use a simulation approach to assess (i) current losses caused by rice pests; (ii) yield gains, current or expected, associated with certain pest management practices; and (iii) changes in vulnerability due to new agronomic technologies; to derive research priorities for lowland rice pest management in tropical Asia.

MATERIALS AND METHODS

RICEPEST. Simulations were performed with RICEPEST, a crop growth model that accounts for the effects of production situations on crop growth and the growth-reducing effects of pest injuries (65,66). The time step of the model is 1 day, and the system considered is 1 m^2 of a rice crop. The model consists of two linked components, one that simulates the dynamics of the rice crop biomass, and the other that simulates the dynamics of the population of rice tillers. The model incorporates injury mechanisms (3,38) from a series of pests that are important in tropical lowland rice production (2,17,18,30–32,48,49,52,55): *Xanthomonas campestris* pv. *oryzae* (bacterial leaf blight [BLB]); *Rhizoctonia solani* (sheath blight [SHB]); *Cochliobolus miyabeanus* (brown spot [BS]); *Sarocladium oryzae* (sheath rot [SHR]); *Pyricularia oryzae* (leaf blast [LB] and neck blast [NB]); several stem borers (*Scirpophaga incertulas*, *S. innotata*, *Chilo suppressalis*, and *Sesamia inferens* causing white heads [WH] and dead hearts [DH]); *Nilaparvata lugens* (brown plant-hoppers [BPH]); various leaf-feeding insects (e.g., *Cnaphalocrocis medinalis* and *Hydrellia philippina*); and a range of weeds (WEED) growing under the rice crop canopy (such as *Monochoria vaginalis*) or above it (such as *Echinochloa* spp. or *Cyperus* spp.). RICEPEST was validated in a multi-site network of field experiments encompassing major production situations of lowland rice in tropical Asia, and the main injury profiles that occur in these environments were manipulated. Rice plots corresponding to production situation by injury profile combinations were monitored over the course of the season with respect to crop growth (dry weight of organs) and development and dynamics of injuries. This allowed comparisons of observed and simulated outputs for model validation (62,64–66,71).

Production situations and injury profiles. We define a driver as a set of parameters and functional relationships used as simulation inputs. The following two types of drivers were used: crop drivers that were defined for each generic production situation (GPS) and injury drivers that were defined for each injury profile (IN).

Crop drivers consisted of initial values of state variables (e.g., initial dry weight of stems), crop parameters (e.g., maximum number of tillers), and driving functions (e.g., radiation use efficiency as a function of development stage). Crop drivers were determined for six GPSs that corresponded to six major patterns of cropping practices for lowland rice in tropical Asia (49). GPSs included crop establishment method, cultivar type, and nutrient and water management (Table 1). Parameters and driving functions for each crop driver associated with the six GPSs (Fig. 1) had been determined in field experiments reported elsewhere (65,66).

Injury drivers were defined into two broad groups to mimic the typical dynamics of injuries. The first group included injuries that generally appear in the vegetative stage and progressively increase as the crop develops (e.g., BLB and BPH) and they were entered in the model as driving functions over time (i.e., crop development). The second group included injuries occurring in the reproductive stage of the crop to rapidly achieve a maximum level (e.g., SHR and NB). These injuries were entered into the injury driver as a maximum injury level only. Similarly to crop drivers, each injury driver included driving functions over crop development as well as a set of fixed parameters. Three injury drivers (Fig. 2) corresponding to three major injury profiles (49) were defined as follows: IN1 = high levels of SHB and medium levels of BPH, DH, WH, defoliators, and weeds; IN2 = high levels of BLB, BS, BPH, defoliators, and weeds and medium levels of SHR, DH, and WH; and IN3 = high levels of SHR, NB, WH, SHB, BS, LB, and DH and medium levels of weeds.

Simulation of attainable yield, actual yield, and yield losses. In all simulation analyses, yield losses were simulated in three steps. The attainable (noninjured) yield was first simulated for a given production situation using the corresponding crop driver as input, setting all injuries to zero. Then with the same crop driver, the injury driver corresponding to the considered injury profile (see below) was entered in the model to simulate the actual (injured crop) yield. Yield losses caused by individual injuries were also simulated in a third step. The injury level was left at its default level in the injury profile, while other injuries were set to zero. Yield losses caused by single pests or pest combinations (injury profiles) were computed as the differences between the simulated attainable yield and simulated actual yields.

TABLE 1. Experimental generic production situations (GPS) of lowland rice production in tropical Asia, and weather data used for simulations with the RICEPEST simulation model

Generic production situation[a]	Ya[b]	Weather data used for simulations
GPS1: Transplanted rice with young seedlings; short cycle, high yielding, high tillering capacity cultivar; good water management; N fertilization of 110 kg/ha.	5.2 (rainy season) 6.9 (dry season)	Rainy and dry seasons during 1998, Los Baños, Laguna Province, Philippines (14°12′N, 121°18′E)
GPS2: Transplanted rice with young seedlings; short cycle, high yielding, high tillering capacity cultivar; good water management; N fertilization of 60 kg/ha.	4.5	Rainy season during 1998 at Los Baños
GPS3: Transplanted rice with old seedlings; long cycle cultivar; poor water management with medium water stress; N fertilization of 90 kg/ha.	4.7	Rainy (kharif) season during 1998 at Faizabad, Uttar Pradesh, India (26°39′N, 82°9′E)
GPS4: Transplanted rice with old seedlings; short cycle cultivar; good water management; N fertilization of 180 kg/ha.	7.4	Rainy season during 1998 at Hangzhou, Zhejiang Province, China (30°12′N, 120°12′E)
GPS5: Direct-seeded rice; short cycle, high yielding, high tillering capacity cultivar; reasonably good water management; N fertilization of 60 kg/ha.	4.3	Rainy season during 1998 at Los Baños
GPS6: Direct-seeded rice; short cycle, high yielding, high tillering capacity cultivar; reasonably good water management; N fertilization of 90 kg/ha.	5.1	Rainy season during 1998 at Los Baños

[a] Derived from cropping practices PR1 through PR6 in Savary et al. (49).

[b] Attainable grain yield (yield in a noninjured crop, ton per ha) according to simulation with RICEPEST.

Simulation of yield losses under current production situations. RICEPEST was used to simulate yield losses in the six most common combinations of production situation by injury profile (49): GPS1 × IN1, GPS2 × IN1, GPS3 × IN3, GPS4 × IN1, GPS5 × IN2, and GPS6 × IN2. For each combination, the corresponding drivers (GPS and IN) were entered to compute yield losses (individual injuries and combined injury profile). GPS1 is unique because it represents fields that are grown during the rainy and dry seasons, which affect crop growth and yield mainly through large differences in radiation. Both seasons were considered separately in the simulation analyses of GPS1 × IN1. Weather data used for the simulations in each GPS are given in Table 1.

Simulation of the efficiency of current pest management methods. The following pest management methods used in lowland rice fields of tropical Asia were considered in the simulation

Parameters and initial conditions	**GPS1**	**GPS2**	**GPS3**	**GPS4**	**GPS5**	**GPS6**
FST	0.05	0.05	0.07	0	0.05	0.05
LEAFWi	10	6	17	15	8	8
MAXTIL	900	800	400	400	1500	1500
ROOTWi	5	3	7	10	4.5	4.5
STW	20	20	5	5	20	20
STEMWi	6	4	15	15	5	5
VTILi	250	180	150	150	400	400

Functions

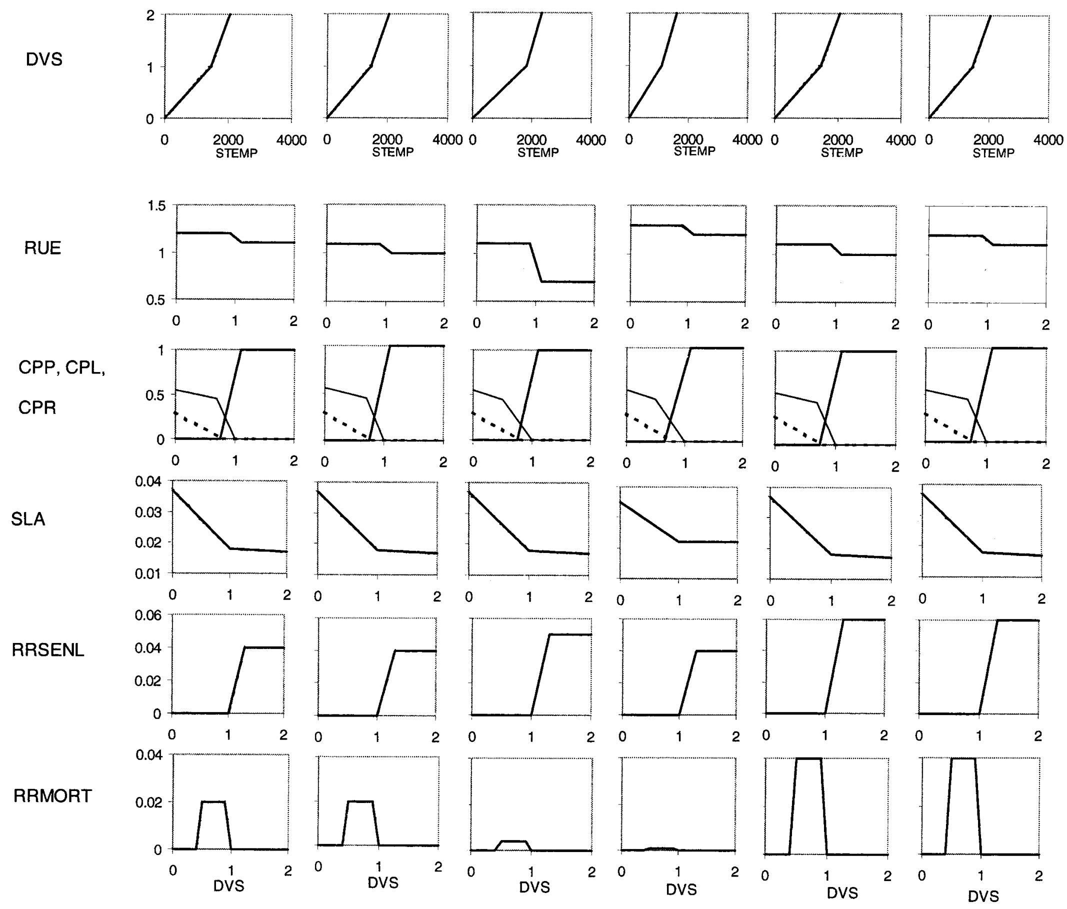

Fig. 1. Crop drivers in RICEPEST used for a set of generic production situations. Each column represents a generic production situation (GPS). The characteristics of GPS1 to GPS6 are given in Table 1. FST = fraction of sterile tillers after booting; LEAFWi = initial dry weight of leaves (g m^{-2}); MAXTIL = maximum number of tillers per m^2; ROOTWi = initial dry weight of roots (g m^{-2}); STW = number of young tillers per unit of biomass; STEMWi = initial dry weight of stems (g m^{-2}); VTILi = initial number of vegetative tiller per m^2; DVS = development stage (0 = sowing, 1 = flowering, and 2 = maturity); STEMP = sum of temperature above 8°C; RUE = radiation use efficiency (g MJ^{-1}); CPP = coefficient of partitioning towards panicles; CPL = coefficient of partitioning toward leaves; CPR = coefficient of partitioning toward roots; SLA = specific leaf area (m^2 g^{-1}); RRSENL = relative rate of leaf senescence (day^{-1}); and RRMORT = relative rate of tiller mortality (day^{-1}). In the functions for coefficients of partitioning, dotted lines represent CPR, plain lines represent CPL, and bold lines represent CPP. Details of the above parameters and functions in RICEPEST are given by Willocquet et al. (65,66).

study: (i) host plant resistance (55); (ii) pesticide use (2,18,30, 31,41,52); (iii) manual control (e.g., hand-weeding) (11,16,31); and (iv) natural control (6,17,18). The efficiency of a pest management method (Ey) is defined in terms of relative yield gains. It is the ratio of the yield gained from the use of the pest management method over the maximum possible yield gain, (i.e., the yield that would be gained if no yield loss occurred). According to this definition, Ey can be expressed as $Ey = (Y - Yp)/(Ya - Yp)$ in which Ya is the attainable yield, Y is the actual yield (achieved with the current pest management methods), and Yp is the primitive yield (yield that would be achieved in a field without any pest management) (68,70). Ey varies between 0 and 1, as yield increases from the primitive to the attainable yield levels.

For the seven combinations of GPS × IN described above, the efficiency of current pest management methods was simulated for each individual injury and the entire injury profile with the above equation. Attainable and actual yields were simulated as described above. The primitive yield was simulated by setting values in the injury driver to potential injury values (Ip) (i.e., considering the injury levels that would occur if no pest management method were used). When considering Ey for a particular injury, this injury was set to its potential value, while the other injuries were set to zero and when considering the entire injury profile, all injuries were set to their potential values. Ip was defined as $Ip = Ic/(1 - PIR/100)$ in which Ic is the current injury value, and PIR is the percentage of injury reduction resulting from the use of a pest management method (management efficacy). Estimates of PIR associated with current pest management methods were determined from the literature (Table 2). Since these estimates cannot be precise from the information currently available, it was decided to perform simulations with two PIR estimates (low and high) that provided results expressed as a range rather than as fixed values. Estimates (low and high) for the PIR for each pest in each production situation are given in Table 2.

Scenarios involving novel crop protection and crop production technologies. In addition to estimating current crop losses, the efficiencies of two novel, future components of pest management were considered, host resistance against SHB and stem borers, both currently pursued with biotechnology (1,8,24). It was assumed that genetically engineered resistance leads to reduction of injuries similar to that obtained through conventional breeding. Simulations of these technologies, alone or in combination, were performed for GPS1 only, which is the primary target of breeders for the deployment of these resistances (5). In these analyses, injuries caused by pests other than those whose management efficiency was being tested were set to their default level in the corresponding injury profile IN1. In each analysis, simulations were performed for a low (90%) and a high (95%) percentage in injury reduction caused by transgenic resistance.

Additional simulations were conducted to address future rice genotypes with increased potential yield. Genotypes based on a new type of plant architecture allowing high-harvest index and high-biomass production (New Plant Type [NPT]) (5,22,33,59, 67), as well as intervarietal and intersubspecific hybrids (60), are developed in research breeding programs to increase potential yield. Scenarios with NPT and hybrid rice grown in environments with optimized nutrient and water management (in which genetic potentials can be expressed) (33) were considered in simulation analyses. Two crop drivers were determined, a first one to simulate a rice crop with a direct-seeded NPT cultivar, and a second one for a transplanted hybrid rice crop. Both crop drivers were derived from GPS1. The following changes were made to reflect the performance of NPT cultivars (5,22,33): (i) higher radiation use efficiency; (ii) lower maximum number of tillers; (iii) lower specific leaf area; (iv) lower rate of tiller mortality; and (v) lower rate of leaf senescence. For a hybrid rice crop, the changes from GPS1 were as follows (33,60): (i) rapid leaf expansion; (ii) higher grain filling percentage; (iii) higher radiation use efficiency; (iv) higher specific leaf area; (v) lower rate of tiller mortality; and (vi) lower rate of leaf senescence. Simulations for either scenario (NPT or hybrid rice) were performed for the rainy and dry seasons. The injury driver IN1 was used as input, involving each individual injury in turn, followed by the entire IN1.

Parameters	IN1	IN2	IN3
SHR	1.3	3.6	7.3
NB	0	0.9	4.7
WH	2.4	1.9	5.8

Functions

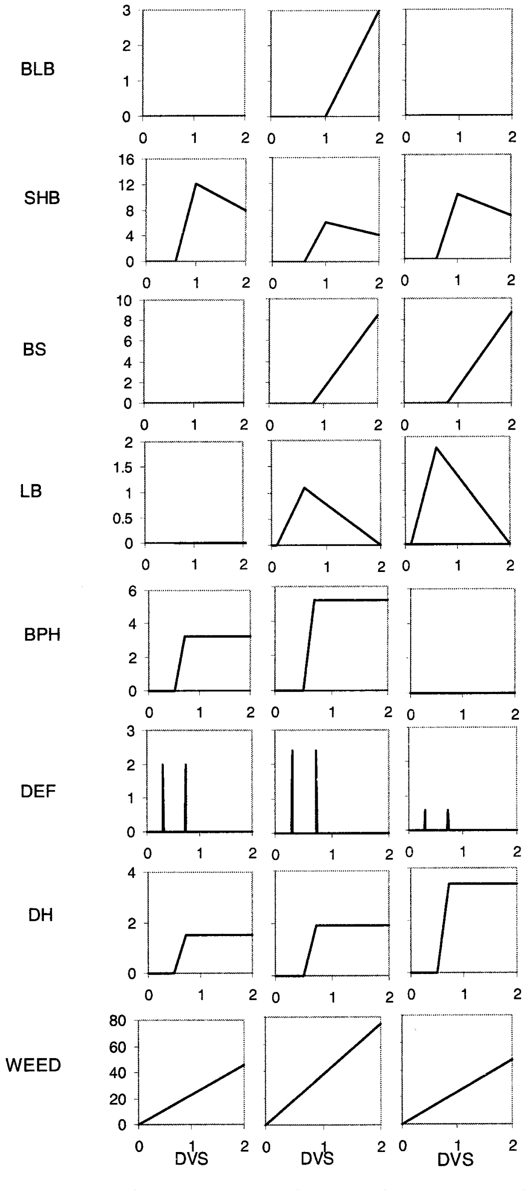

Fig. 2. Injury drivers of RICEPEST used for a set of pest injury profiles (IN). Each column represents an injury profile. The characteristics of IN1 to IN3 are described in the text. SHR = panicles injured by sheath rot (%); NB = panicles injured by neck blast (%); WH = panicles injured by white head (%); BLB = bacterial leaf blight severity (%); SHB = sheath blight severity (%); BS = brown spot severity (%); LB = leaf blast severity (%); BPH = dry weight of brown plant-hoppers (mg m^{-2}); DEF = leaf area damaged by defoliators (%); DH = accumulated number of tillers damaged by dead hearts (%); WEED = dry weight of weeds (g m^{-2}). DVS = development stage (0 = sowing, 1 = flowering, and 2 = maturity). Details of the above parameters and functions in RICEPEST are given in Willocquet et al. (65,66).

RESULTS

Simulated yield losses and efficiencies of pest management methods in current production situations. Simulated yield losses caused by the entire injury profile IN1 was 200 g m^{-2} (2 t ha^{-1}) in the dry season (Fig. 3A). The most damaging pests were weeds (causing losses of 110 g m^{-2}) and SHB (causing losses of 70 g m^{-2}). WH and SHR caused yield losses of 18 and 10 g m^{-2}, respectively. Simulated yield losses caused by other pests were <5 g m^{-2}. The ranking of pests in the rainy season was the same as that in the dry season, but simulated yield losses caused by individual injuries and the whole injury profile (IN1, 154 g m^{-2}) were lower than that in the dry season (Fig. 3B). The simulated efficiencies of pest management methods shared common patterns in both seasons (Fig. 3). Efficiency against BPH was large (>0.9) and ranged between 0.3 and 0.7 against defoliators, DH, WH, and weeds. It was zero against SHB and SHR and it could not be estimated for BS (which is not found in this GPS). The efficiency of pest management methods differed with seasons in two respects. First, the efficiency against the entire injury profile was higher in the rainy season (0.57 to 0.71) than that in the dry season (0.38 to 0.53). Second, the simulated efficiency of pest

TABLE 2. Estimates of percentage of injury reduction (PIR) from methods used to control rice pests in tropical Asia

	Management		Estimates of percentage of injury reduction in each production situation (GPS)[d]					
Injury[a]	methods[b]	References[c]	GPS1	GPS2	GPS3	GPS4	GPS5	GPS6
BLB	HPR	12,23,40,69	90-95	90-95	90-95	90-95	90-95	90-95
SHR	…		0	0	0	0	0	0
SHB	FUN[e]	49,54	0	0	0	50-70	0	0
BS	…		0	0	0	0	0	0
LB	HPR, FUN[f]	69	90-95	90-95	90-95	90-95	90-95	90-95
NB	HPR, FUN[f]	69	90-95	90-95	90-95	90-95	90-95	90-95
BPH	HPR, INS[g], NC	17,69	90-95	90-95	90-95	90-95	90-95	90-95
DEF	INS[g], NC	6,17,52,69	30-50	30-50	30-50	30-50	30-50	30-50
DH	HPR, INS[g], NC	6,17,52,69	50-70	50-70	50-70	50-70	50-70	50-70
WH	HPR, INS[g], NC	6,17,52,69	50-70	50-70	50-70	50-70	50-70	50-70
WEED	HAND, HERB	7,11,31,49,53	50-70	40-60	70-85	60-80	50-70	40-60

[a] BLB = bacterial leaf blight, SHR = sheath rot, SHB = sheath blight, BS = brown spot, LB = leaf blast, NB = neck blast, BPH = brown plant-hopper, DEF = defoliators, DH = dead heart, WH = white head, and WEED = weeds.

[b] HPR = host plant resistance, FUN = fungicides, INS = insecticides, NC = natural control, HAND = hand-weeding, and HERB = herbicide, and … = lack of available efficient management methods.

[c] References used to determine the estimates of percent of injury reduction from pest management methods.

[d] The characteristics of GPS1 to GPS6 are given in Table 1; in each column, the left number represents a low estimate and the right number represents a high estimate for percentage of injury reduction.

[e] Fungicides are used against SHB in GPS4 only (49).

[f] Fungicides are used against LB and NB in GPS4, GPS5, and GPS6 only (49).

[g] Insecticides are not used in GPS3 (49).

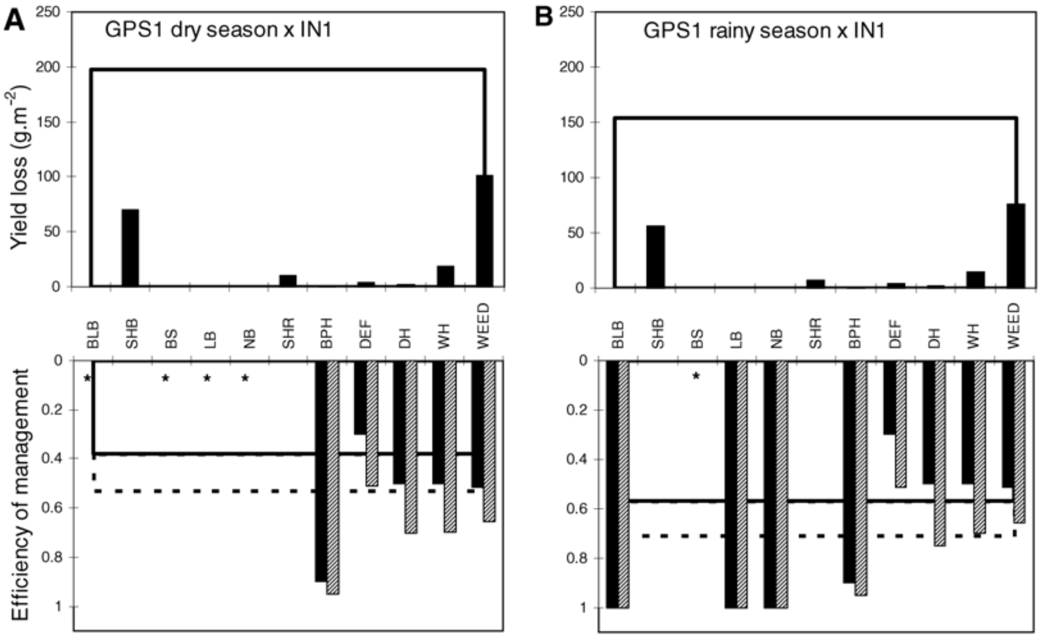

Fig. 3. Simulated yield losses and efficiency of rice pest management methods in terms of relative yield gains for the generic production situation GPS1, affected by the injury profile IN1 in **A,** the dry season and **B,** the rainy season. In the upper panels, each bar represents yield losses caused by individual injuries, and the upper bound of the frame represents yield losses caused by the entire injury profile. In the lower panels, solid bars represent the efficiency of pest management methods for each individual injury under the hypothesis of low reduction in injury levels, and shaded bars represent the efficiency of management for each individual injury under the hypothesis of high reduction in injury levels. The plain and dotted lines that bound the frames represent the efficiency of management for the entire injury profile under the hypotheses of low and high reduction in injury levels, respectively. Asterisks are indicated when the efficiency of pest management method could not be estimated because of the absence of a particular pest species from the injury profile. BLB = bacterial leaf blight; SHB = sheath blight; BS = brown spot; LB = leaf blast; NB = neck blast; SHR = sheath rot; BPH = brown plant-hopper; DEF = defoliators; DH = dead heart; WH = white head; and WEED = weeds. GPS1 and IN1 are defined in Table 1 and in the text, respectively, and drivers for GPS1 and IN1 are given in Figures 1 and 2, respectively.

management methods against BLB, LB, and NB were 1.0 in the rainy season, but could not be estimated in the dry season when these injuries do not occur.

The patterns obtained for GPS2 (Fig. 4A; GPS2 × IN1 combination) were similar to that of GPS1 in the rainy season (simulated combined losses of 142 g m^{-2}). However, simulated yield losses to individual pests and the entire injury profile IN1 were slightly lower. Simulated yield losses in GPS3 (Fig. 4B; GPS3 × IN3 combination) indicated a larger number of pests contributing to overall losses (weeds, SHB, BS, SHR, and WH and to a lesser extent, LB and NB). Simulated yield loss caused by this injury profile was 186 g m^{-2}, which is lower than losses accumulated by individual injuries (242 g m^{-2}). High levels of management efficiencies (>0.9) were simulated for BLB, LB, and NB, while intermediate efficiencies (0.3 to 0.7) were simulated for defoliators, DH, WH, and weeds. Simulated efficiencies for SHB, BS, and SHR were zero (Fig. 4B). The overall efficiency of pest management methods against the entire injury profile IN3 in GPS3 ranged from 0.58 to 0.65. Simulated yield losses in GPS4 (Fig. 4C; GPS4 × IN1) were similar to those obtained in GPS1 in the dry season. Simulated management efficiencies in GPS4 were similar to those in GPS1 (rainy season), except that the efficiency against SHB ranged from 0.56 to 0.77 (whereas it was zero in GPS1 in the rainy season). Yield losses simulated in GPS5 (Fig. 4D; GPS5 × IN2) indicated that several pests contributed to yield losses, as in the GPS3 × IN3 combination, but with a different pattern (high yield losses [110 g m^{-2}] were caused by weeds, losses due to BS and SHB were 51 and 27 g m^{-2}, respectively, SHR and WH caused losses ranging between 9 and 18 g m^{-2}, and BLB, LB, NB, BPH, defoliators, and DH caused yield losses <6 g m^{-2}). All 11 injuries considered in this study caused yield loss in the GPS5 × IN2 combination. Simulated management efficiencies against BLB, LB, NB, and BPH were >0.9 (Fig. 4D). Management efficiencies against defoliators, DH, WH, and weeds ranged between 0.3 and 0.7, but management was ineffective against SHB, BS, and SHR. In the GPS5 × IN2 combination, the overall efficiency of pest management (entire injury profile) ranged between 0.43 and 0.55. In the case of the GPS6 × IN2 combination (Fig. 4E), simulated losses were slightly higher than that in GPS5, but the efficiency of pest management methods was similar.

Simulated yield gains in scenarios of deployment of resistance against SHB and stem borers. In the dry season, attainable yield was 772.4 g m^{-2}, and simulated yield gains derived from resistance against SHB were 59.7 and 62.5 g m^{-2} with the

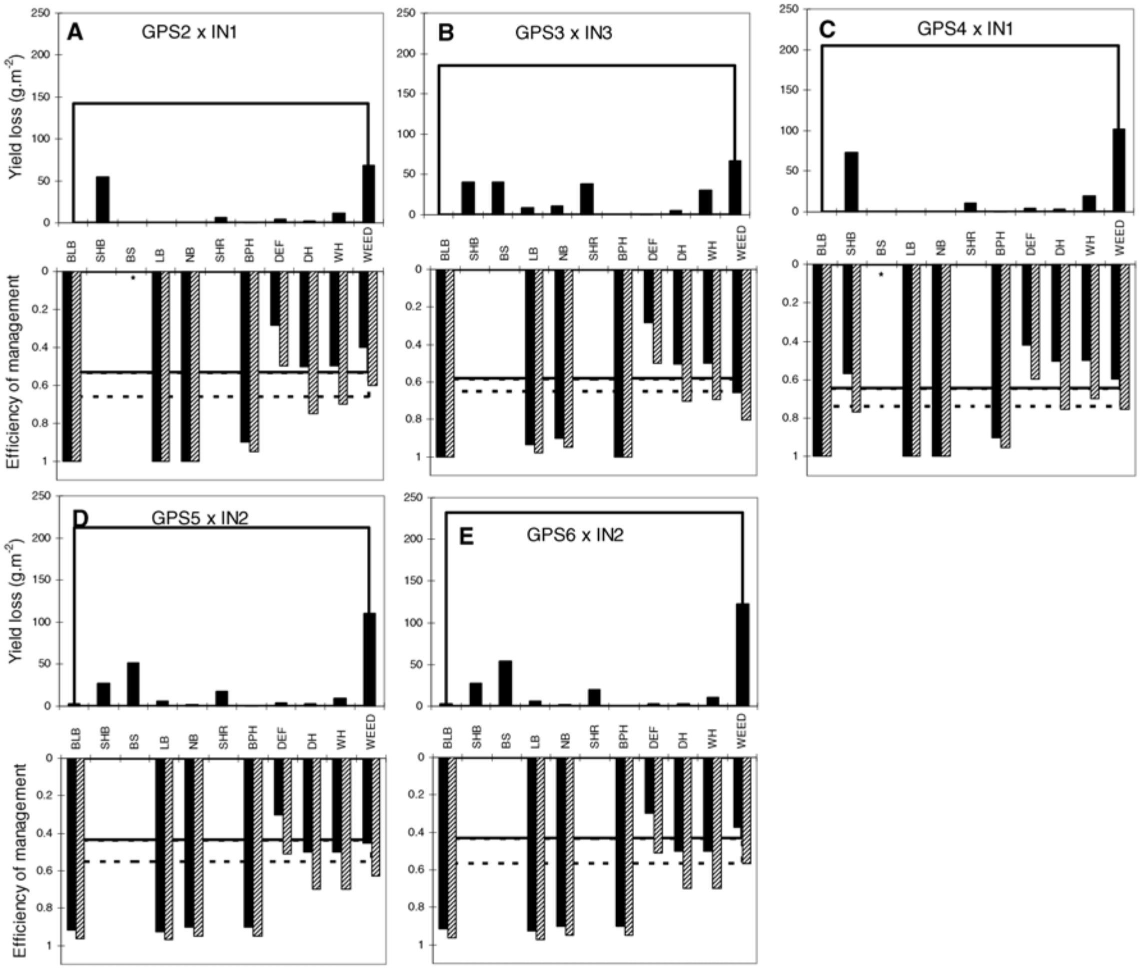

Fig. 4. Simulated yield losses and efficiency of rice pest management methods in terms of relative yield gains. **A,** generic production situation GPS2 affected by the injury profile IN1. **B,** GPS3 affected by IN3. **C,** GPS4 affected by IN1. **D,** GPS5 affected by IN2. **E,** GPS6 affected by IN2. In the upper panels, each bar represents yield losses caused by individual injuries, and the upper bound of the frame represents yield losses caused by the entire injury profile. In the lower panels, solid bars represent the efficiency of pest management methods for each individual injury under the hypothesis of low reduction in injury levels, and shaded bars represent the efficiency of management for each individual injury under the hypothesis of high reduction in injury levels. The plain and dotted lines that bound the frames represent the efficiency of management for the entire injury profile under the hypotheses of low and high reduction in injury levels, respectively. Asterisks are indicated when the efficiency of pest management method could not be estimated because of the absence of a particular pest species from the injury profile. BLB = bacterial leaf blight; SHB = sheath blight; BS = brown spot; LB = leaf blast; NB = neck blast; SHR = sheath rot; BPH = brown plant-hopper; DEF = defoliators; DH = dead heart; WH = white head; and WEED = weeds. GPS2 to GPS6 and IN1 to IN3 are defined in Table 1 and the text, respectively, and drivers for GPS2 to GPS6 and IN1 to IN3 are given in Figures 1 and 2, respectively.

hypotheses of low and high reduction in injury levels, respectively (Table 3). Simulated gains from reduction of DH were low (2.1 to 2.2 g m^{-2}), and simulated gains from WH reduction were intermediate (13 g m^{-2}). Simulated yield gained from combined resistance against SHB and stem borers reached 75 to 79 g m^{-2}. In the rainy season, the attainable yield was 588.6 g m^{-2}, and simulated yield gains from resistances against pests were lower than that in the dry season.

Simulated yield losses in scenarios of deployment of improved rice. The simulated dynamics (root, stem, leaf, and panicle dry weights) are given for a crop exposed to the entire injury profile (IN1) and for a noninjured crop (Fig. 5). All simulations shared the following similar general pattern: (i) dry weight of leaves increasing from crop establishment to flowering and then declining as a consequence of physiological senescence; (ii) stem dry weight increasing until flowering and then decreasing with accumulated starch being translocated toward the panicles; (iii) dry weight of roots increasing to a stable upper limit at flowering; and (iv) panicle dry weight increasing from flowering to crop maturity. Attainable panicle yield of NPT was 1,084 and 697 g m^{-2} in the dry and rainy seasons, respectively (Fig. 5A and B). Attainable yield of hybrid rice was 4% higher than that of NPT. Injuries affected the biomass dynamics of stems, leaves, and panicles in all simulations. Simulated crop growth was much higher in the dry season (Fig. 5A and C) than in the rainy season (Fig. 5B and D). The difference in simulated growth and yield between noninjured and injured crops was higher in the dry than in the rainy season. Simulated growth for NPT (Fig. 5A and B) was slightly lower than simulated growth for hybrid rice (Fig. 5C and D). The dynamics of the dry weights of various plant parts and the resulting final yield were more affected by injuries for NPT than for hybrid rice.

TABLE 3. Simulated yield gains for the generic production situation GPS1 and injury profile IN1 in scenarios with transgenic rice cultivars resistant toward sheath blight and stem borers[a]

	Simulated yield gain (g m^{-2})			
	Dry season[b]		Rainy season[b]	
Injuries targeted	Low resistance[c]	High resistance[d]	Low resistance[c]	High resistance[d]
Sheath blight[e]	59.7	62.5	46.6	49.0
Dead hearts[e]	2.1	2.2	2.4	2.5
White heads[e]	12.7	13.4	9.6	10.2
Combined resistances[e,f]	75.6	79.4	59.5	62.6

[a] GPS1 and IN1 are defined in Table 1 and in the text, respectively.

[b] Attainable yield of 772.4 and 588.6 g m^{-2} in the dry and rainy seasons, respectively.

[c] Genetically engineered plants with low resistance, reduction in injury due to sheath blight and stem borers of 90%.

[d] Genetically engineered plants with high resistance, reduction in injury due to sheath blight and stem borers of 95%.

[e] All other injury levels set to their default level in the injury profile IN1.

[f] Yield gained by all three resistances combined.

In terms of yield losses, there were four features common to the four considered plant type-injury profile scenarios (NPT × IN1, dry and rainy seasons and hybrid rice × IN1, dry and rainy seasons; Fig. 6): (i) weed infestation caused the highest yield losses (90 to 150 g m^{-2}), and losses caused by SHB were high also (50 to 120 g m^{-2}); (ii) losses caused by SHR, WH, DH, and defoliators were <30 g m^{-2}; (iii) there was no loss from BS, LB, NB, and BPH; and (iv) the simulated yield losses caused by individual pests and the entire injury profile were higher in the scenarios for both new rice types (NPT and hybrid) than in the control (GPS1 × IN1 based on the currently deployed modern

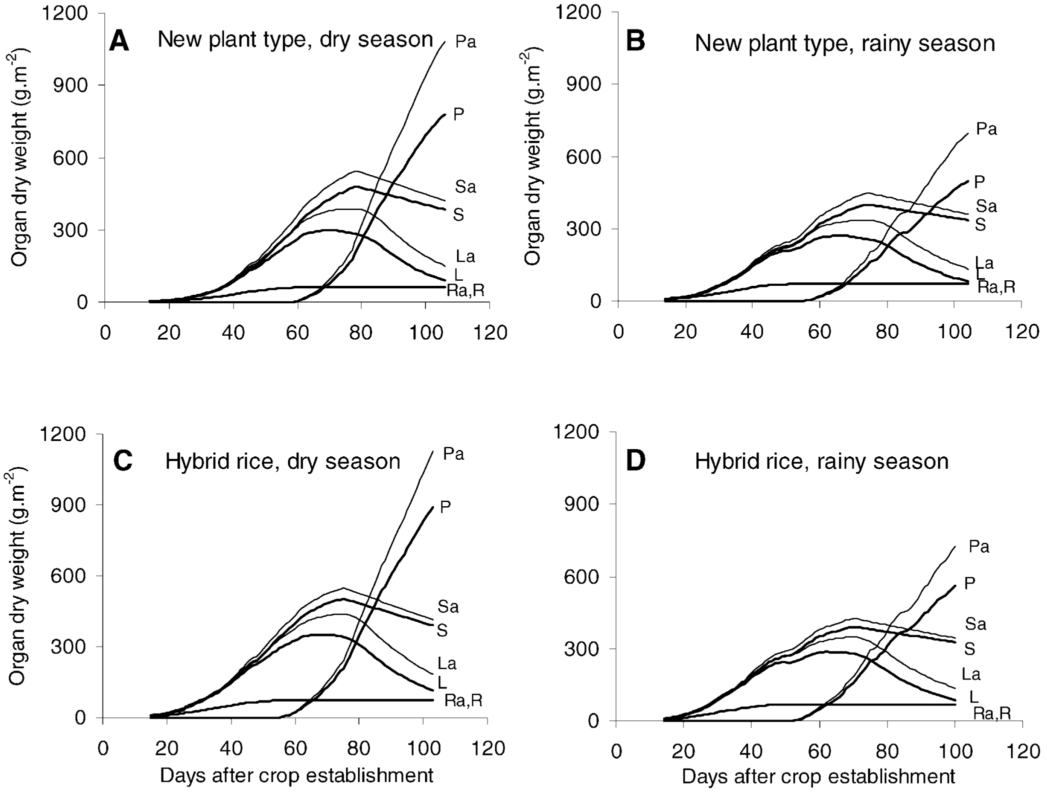

Fig. 5. Simulated dynamics of the dry weight of rice organs for crops established with **A and B,** New Plant Type and **C and D,** hybrid rice grown during the **A and C,** dry or **B and D,** rainy season. For each crop type and season, simulations are shown for crops injured by the entire injury profile IN1 (described in the text) and for uninjured crops. La = dry weight of leaves for uninjured crop; L = dry weight of leaves for crop injured by injury profile IN1; Ra = dry weight of roots for uninjured crop; R = dry weight of roots for crop injured by injury profile IN1; Sa = dry weight of stems for uninjured crop; S = dry weight of stems for crop injured by injury profile IN1; Pa = dry weight of panicles for uninjured crop; and P = dry weight of panicles for crop injured by injury profile IN1. Injury drivers for IN1 are given in Figure 2.

varieties). There were two differences in scenarios involving hybrid rice and NPT compared with the control. First, simulated yield losses caused by SHB and defoliators were lower for hybrid rice than in the control (Fig. 6C and D), whereas the opposite was obtained when comparing NPT with the control (Fig. 6A and B). Second, simulated yield losses were higher in the NPT (200 and 300 g m^{-2} in the rainy and dry seasons, respectively) than in the hybrid rice (180 and 230 g m^{-2} in the rainy and dry seasons, respectively). Overall, simulated yield losses were higher in the dry season than they were in the rainy season.

DISCUSSION

Simulation modeling enables integration of previous results and analysis of future scenarios. In plant pathology, it allows one to address current yield losses as well as potential yield gains. The approach used here mobilizes knowledge on processes (crop physiology and injury mechanisms), data obtained from multiple-site field experiments, and data from regional surveys to link empirical knowledge and modeling, thus allowing one to address complex interactions among a crop, its pests, and pest management methods that occur within agroecosystems. Estimating overall outputs from such complex interactions at a regional scale is difficult because of inherent biological variation in the systems addressed. The structure of RICEPEST allows one scaling-up from the organ level to the field. The use of crop and injury drivers representing ideotypes of fields within a region allows one additional scaling-up step from the field to the region. This aggregation makes it possible to assess the current importance of rice pests, the current efficiencies of management tools, and the prospective consequences of new technologies, thereby providing background for setting research priorities.

Statistics for rice yields from FAO (15) indicate very large (mean) differences across countries in tropical Asia. Taking into account the inherent error of measuring yields at the field level (35), the range of figures are 456 to 756, 208 to 384, 224 to 384, and 280 to 540 (minimum to maximum) g m^{-2} for countries such as China, India, the Philippines, and Vietnam, respectively, between 1993 and 2002. This fits well with RICEPEST simulated actual yields for the production situations found in these countries (450 to 550, 280 to 320, 245 to 550, and 250 to 300 g m^{-2}, respectively).

Rice pests can be classified into two broad categories with respect to simulated yield losses and management efficiencies. One group consists of pests that currently cause large yield losses and are poorly or moderately managed. This group includes: weeds, the most important pest (70 to 120 g m^{-2} yield losses and management efficiency between 0.35 and 0.7); SHB, the second pest in importance (30 to 70 g m^{-2} yield losses across all GPSs and management efficiency between 0 and 0.75); and BS, which caused no damage in some GPS × IN combinations, but contributed 40 to 55 g m^{-2} yield losses where water supply or management problems occurred (GPS3 × IN3, GPS5 × IN2, and GPS6 × IN2) (49) and for which no efficient management tool is currently deployed. A research priority for this first group consists in developing effective pest management tools. The second group consists of rice pests which are well managed today (simulated yield losses <12 g m^{-2}) but which are potentially very harmful and highly variable over space and time (LB, NB, BLB [2,30,72], and BPH [in some GPSs only; 17,52]). Current management systems (primarily host plant resistance) may not be durable. Maintenance of the efficiency of these current management methods for these pests is another priority.

This work proposes an operational framework for addressing pest management efficiency expressed in terms of yield gain. This

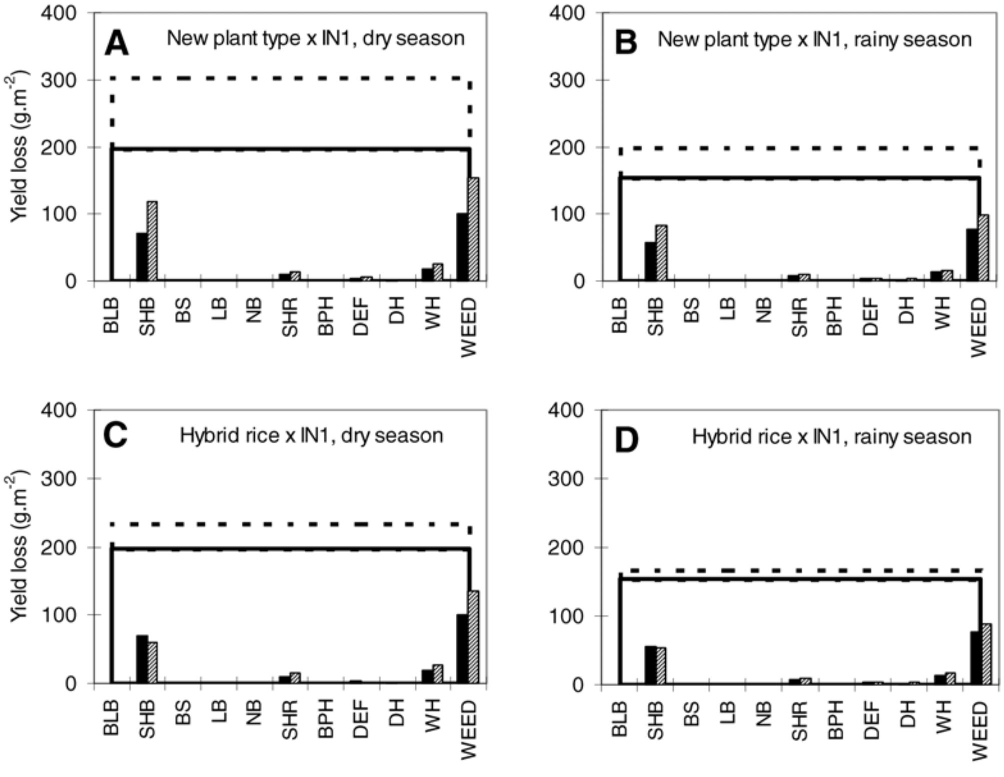

Fig. 6. Simulated yield losses for rice crops planted with **A and B,** New Plant Type (a new type of rice plant with high-harvest index and high-biomass production) and **C and D,** hybrid rice affected by the injury profile IN1. In each graph, each bar represents yield losses caused by individual injuries, and the upper bound of the frame represents yield losses caused by the entire injury profile. Within each graph, the solid bars and solid line frame represent the current production situation GPS1, and the shaded bars and dotted line frame represent future production situations, with the New Plant Type or hybrid rice. BLB = bacterial leaf blight; SHB = sheath blight; BS = brown spot; LB = leaf blast; NB = neck blast; SHR = sheath rot; BPH = brown plant-hopper; DEF = defoliator; DH = dead heart; WH = white head; and WEED = weeds. GPS1 and IN1 are defined in Table 1 and in the text, respectively, and injury drivers for IN1 are given in Figure 2.

framework is used to address not one, but several pests at a time, which corresponds to a reality at the individual field level (20,21, 34,47,50,55,69,70). It is also used to address injury profiles within production situations, which concurs with large-scale pest management issues (48,49). Research priorities can then be derived from the prospective gains generated by the current technologies or expected from future technologies. The PIR values estimated from the literature (Table 2) were used as input into the model to simulate the Ey. When individual injuries were considered, Ey was numerically close to PIR. However, these variables refer to two different concepts: (i) Ey refers to pest management efficiency and translates into yield gains, while (ii) PIR refers to management efficacy and translates in injury reduction. Considering that the ultimate goal of pest management is to increase yield (and not to remove pests) (58,70), it is relevant to assess Ey in terms of yield gains, rather than in terms of pest population effects. Another reason for simulating Ey is to estimate the efficiency against entire injury profiles. Combining efficacies of pest management (i.e., against BPH and weeds in population terms) leads to conceptual difficulties and problems of differences in dimensions of the considered variables. Also, Ey makes reference to yield gain rather than yield loss, which is relevant when addressing pest management issues (10).

In each of the considered GPS × IN combinations, simulated yield losses due to combined injuries (injury profiles) were lower than the accumulated yield losses corresponding to individual injuries. Such interactions have been documented in multiple-pest systems in potato (21), peanut (50), and rice (48). Consideration of an individual pest while disregarding other components of the injury profile overestimates the yield losses it causes and will lead to overestimating the efficiency of management methods. This also implies that the efficiency of a specific management tool depends on the other tools with which it is combined with in a production situation. Similar conclusions were derived when considering interactions of pests in terms of population dynamics (e.g., 9,21,51,61).

The simulated yield gains of (genetically engineered) resistance against SHB could be much higher than that against stem borers. This result is a reflection of the simulated losses the two pests cause when considered individually. When considered in combination, and within the context of entire injury profiles, however, resistance against the two pests would reduce the overall yield loss by approximately one-third.

New production technologies, such as NPT and hybrid rice, combined with improved nutrient and water management would generate a new production situation characterized by higher attainable yields. These gains in attainable yield will only translate into harvested, actual yield gains if appropriate, improved pest management methods are simultaneously deployed. Simulation results indicated that this is particularly true in the case of NPT. Yield losses caused by weeds, SHB, and by the entire injury profile were much higher (200 to 300 versus 180 to 200 g m^{-2}) in the projected, NPT-based production situation than in the current reference production situation, GPS1. The vulnerability of NPT to SHB and weeds derives from the lower leaf area index developed in a crop cycle in comparison with GPS1 (conventional high-yielding varieties) and hybrid rice. Another concern is that NPT in particular, and hybrid rice to a lesser extent, have a relatively low tiller density. This corresponds to a decreased tolerance (increased vulnerability) to injuries on tillers such as DH.

The analyses did not consider the effect of new production situations on the evolution of injury profiles. A few hypotheses can be proposed here. Improving nutrient and water management may have an overall favorable effect on SHB epidemics (45,46), while transplanted rice appears more favorable to SHB epidemics than direct-seeded rice (45,63). On the other hand, improvement of water management may decrease (31,45), while direct seeding may favor weed infestation (11,31,43). As a whole, if we disregard pest management improvement, it could be expected that new production situations with (transplanted) hybrid rice would be affected by an injury profile with more SHB injury and weed infestation than in the current injury profile IN1. In the case of (direct-seeded) NPT, the effects of crop establishment methods and nutrient and water management on both SHB and weeds are conflicting, making the corresponding injury profile difficult to predict.

Depending on the considered combination of generic production situations by injury profiles, simulated yield losses due to combined rice injuries ranged from 140 (GPS2 × IN1) to 230 g m^{-2} (GPS6 × IN2), and the efficiency of pest management methods against injury profiles varied between 0.38 (GPS1 × IN1, dry season) and 0.74 (GPS4 × IN1). This range of efficiencies is very large and shows the large potential yield gains that could be achieved in GPS1, representing the 'Rice Bowls' of Asia's urban poor (16,19), if more efficient management tools could be deployed. While this analysis concurs with previous results (48,49) in showing that yield losses are very unevenly distributed, it also shows that current management efficiencies, prospective yield gains, and research priorities depend on production situations and injury profiles of tropical Asia. Our simulations indicate that between 120 and 200 × 10^6 tons of grain yield are lost yearly to pests over the 87 × 10^6 ha (28) of lowland rice crops in tropical Asia. This amount of grain yield also represents the potential gain (10,68) that future pest management strategies could achieve, if deployed.

ACKNOWLEDGMENTS

We thank T. W. Mew and M. Hossain at IRRI and R. Herdt at the Rockefeller Foundation for their support in this study. This research was conducted under a scientific agreement between the International Rice Research Institute (IRRI) and the Institut de Recherche pour le Développement (IRD). This research was partly supported by a grant from the Rockefeller Foundation.

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