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Determination of multiple-species economic injury levels for rice insect pests

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ABSTRACT

Yield loss to damage functions were established to determine multiple-pest economic injury levels (EILs) on Pusa Basmati 1 rice (*Oryza sativa* L.) at different crop growth stages through field and pot experiments in 2009 and 2010. The yield loss to damage functions were derived for two-pest combinations of leaf folder, *Cnaphalocrocis medinalis* Guenée, and stem borers, *Scirpophaga incertulas* (Walker) and *Sesamia inferens* (Walker), at reproductive crop stage during 2009 and for leaf folder and planthoppers, *Nilaparvata lugens* (Stål.) and *Sogatella furcifera* Horvath, at vegetative crop stage, and planthoppers and stem borers at reproductive stage during 2010. Single-species as well as multi-species EILs were determined. Across experiments, single-species EILs of leaf folder and stem borer ranged from 2.9–6.4% folded leaves and 1.9–3.0% whiteheads, respectively, while that of planthoppers varied between 5.5 and 7.3 hoppers per hill. Iso-loss equations, based on yield loss to damage functions, depicted various two-pest incidence combinations which resulted in economic damage. These joint incidence combinations showed that, although each pest was below its EIL, the combination of both pests inflicted economic damage. The multi-pest EILs can be useful to monitor simultaneous occurrence of two-pest species thereby helping to prevent yield losses.

1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop for more than two-thirds of the population in India with rice grown on 44.5 million hectares (Krishnaiah et al., 2008) with a production of 94 million tonnes during 2009–10. Intensification of agriculture has aggravated the problems of biotic stresses including insects, diseases and weeds on crops including rice. In productivity, India ranks 15th–18th among rice producing countries (Anonymous, 2010). Insect damage, especially due to the brown planthopper, *Nilaparvata lugens* (Stål.) (BPH), the white-backed planthopper, *Sogatella furcifera* Horvath (WBPH), stem borers, *Scirpophaga incertulas* (Walker), *Sesamia inferens* (Walker) and *Scirpophaga innotata* (Walker), and leaf folders, *Cnaphalocrocis medinalis* Guenée and *Marasmia patnalis* Bradley, constitutes one of the major causes for the poor productivity of rice in India. Rice crop in India suffered about 25% yield loss due to insect pests during 2007–08, amounting to 32 million tonnes of rice worth Indian rupees (₹) 240 billion (Dhaliwal et al., 2010). Yield loss data are useful for farmers, extension workers, researchers, and policy makers. Modern high tillering cultivars have greater capacity than traditional ones for compensation from insect pest damage, consequently suffering less yield loss. For improved control decisions, farmers thus need to assess the compensatory ability of the crop and severity of crop stress acting on it (Litsinger, 2009).

Insecticides have played an important role in realizing yield potential of crops. However, intensive rice cultivation with excessive pesticide use has created several pest and environmental problems and, as a result, the concept of integrated pest management (IPM) has gained importance over the years. Rice cultivars resistant to gall midge, *Orseolia oryzae* Wood-Mason, *N. lugens* and *S. furcifera* are extensively grown in rice tracts of Asia. Resistant cultivars paved the way for implementing IPM in many Asian countries including India (Panda, 2003). Host-plant resistance is compatible with cultural, biological and chemical control, which can make the IPM system more effective and sustainable. IPM programmes have been developed in India using resistant cultivars against *S. incertulas*, *N. lugens* and *O. oryzae*, pheromone mediated monitoring and mass trapping of *S. incertulas*, inundative releases of *Trichogramma* spp., balanced fertilizer use, water management, and need based pesticide application (DRR, 2007). Regular monitoring is of paramount importance in IPM to ensure timely intervention before economic damage occurs, thereby saving farmers unnecessary expenditure, avoiding environmental contamination and conserving natural enemies.

Development and implementation of economic thresholds is a rational approach to pest management designed to aid farmers in making pest control decisions (Way et al., 1991). In general, single-

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pest EILs are used as an aid in decision making. Simultaneous occurrence of more than one pest species in field is, however, commonplace rather than an exception. In such a situation, individual pests may be below their respective EILs, but pests may jointly inflict economic loss (Palis et al., 1990). There are three possible outcomes of combined pest infestations on crop yield *viz*., no interaction, greater than additive (synergistic) interactions and less than additive (antagonistic) interactions (Lamp et al., 1985). When interactions occur, the effects of combined pest populations are greater or less than the summed effects of each single-pest infestation (Johnson, 1990).

The EILs should account for the presence of multiple pests in the field as the capacity to make appropriate management decisions under multi-pest situations is an important goal of integrated pest management. An improved understanding of physiological responses to injury may be incorporated into EILs by developing standard equivalents for guilds of species with similar injuries (Pedigo et al., 1986). In multiple pest scenarios, the EIL for a pest declines linearly as the infestation level of another pest increases, forming an "iso-loss line". For two pests, the functional relationship between pest infestation levels and benefit from control measures can be visualized as a benefit plane that shows increasing benefit with increasing infestation levels of either pest (Blackshaw, 1986). It is thus important to determine multi-pest EILs for effective management of pests to prevent avoidable yield losses. With this background, the present study was undertaken to develop multi-pest EILs in rice.

2. Materials and methods

2.1. Field experiments

Field experiments, henceforth referred as field experiment 1 and field experiment 2, were conducted with Pusa Basmati 1 during rainy season in 2009 and 2010 at the Indian Agricultural Research Institute, New Delhi (28.66° N, 77.15° E) to determine multi-pest economic injury levels (EILs). Pusa Basmati 1, though highly susceptible to stem borer, *S. incertulas* (Reji et al., 2008), planthoppers, *N. lugens* and *S. furcifera* (Yadav and Chander, 2010) and other pests, is a popular scented rice variety.

Nursery was sown on 20th and 22nd June while 30-day old seedlings (two seedlings per hill) were transplanted on 20th July during the first year and 22nd July during the second year in 4 × 2.5 m plots with 20 and 15 cm row and plant spacing, respectively. Nitrogen (N), phosphorous (P_2O_5) and potash (K_2O) were applied in the form of urea, single super phosphate (SSP) and muriate of potash (MOP), respectively, at the recommended dose of 120:60:40 kg/ha. One-third of N and the entire amounts of P_2O_5 and K_2O were applied as basal dose after puddling with the remaining N applied in two splits, one at peak tillering and the other at panicle emergence stage.

Field experiment 1 had 17 treatments in a randomized block design with damage due to either leaf folder or stem borer or both (Table 1). Each damage level was maintained on 10 randomly selected marked hills throughout the field. In view of insufficient levels of natural pest infestation, artificial leaf clipping and detillering were used to mimic leaf folder and stem borer injury, respectively, at 60 days after transplanting (DAT) during reproductive stage. For leaf clipping, total number of leaves of a hill was counted and required injury level was carried out by clipping the top half portion of the top leaves of tillers, as leaf folder does not damage the entire leaf. Top leaves were clipped, because earlier research found leaf folder damage to the flag leaf and the penultimate leaf had a greater impact on yield, due to their higher photosynthetic rate especially during grain filling stage, than injury to the lower leaves on the tiller (Murugesan and Chelliah, 1983; Bautista et al., 1984). Likewise, total number of tillers of a hill was enumerated and required number of tillers was removed 1-cm above the ground from all sides of a hill with scissors.

Field experiment 2 comprised of 11 treatments including completely protected crop with three replications in a randomized block design (Table 2) wherein insecticides *viz*., imidacloprid 17.8 SL at 25 g a.i./ha and buprofezin 25 SC at 200 g a.i/ha for planthopper control, and cartap 50 SP at 500 g a.i./ha for leaf folder and stem borer control were applied at different frequencies and intervals to create differential infestation levels. Insecticide application frequency varied from one to a maximum of four during different

Table 1
Mean leaf folder (LF) damaged leaves (%) and stem borer (SB) whiteheads (%) on rice variety, Pusa Basmati 1 during reproductive stage in different treatments of field experiment 1 conducted to establish yield loss to damage function during rainy season 2009.

Treatment	Leaf folder damaged leaves (%) ± S.E.M.	Stem borer whiteheads (%) ± S.E.M.	Yield (Kg/ha) ± S.E.M.[a]
T_1-Only leaf folder	2.0 ± 0.13	0	6538 ± 263abc
T_2-Only leaf folder	4.0 ± 0.20	0	6860 ± 283ab
T_3-Only leaf folder	6.0 ± 0.20	0	6779 ± 279ab
T_4-Only Leaf folder	10.0 ± 0.15	0	5646 ± 231cde
T_5-Only stem borer	0	4.0 ± 0.84	6584 ± 224abc
T_6-Only stem borer	0	8.0 ± 0.79	5692 ± 326cd
T_7-Only stem borer	0	12.0 ± 0.76	5542 ± 231def
T_8-Only stem borer	0	16.0 ± 0.43	5058 ± 245def
T_9-Only stem borer	0	20.0 ± 0.51	4589 ± 253fgh
T_{10}-Only stem borer	0	24.0 ± 0.47	3186 ± 245i
T_{11}-Both LF + SB	1.0 ± 0.03	4.0 ± 0.84	5978 ± 231bcd
T_{12}-Both LF + SB	2.0 ± 0.13	8.0 ± 0.80	5332 ± 241def
T_{13}-Both LF + SB	3.0 ± 0.16	12.0 ± 0.77	5107 ± 408def
T_{14}-Both LF + SB	4.0 ± 0.18	16.0 ± 0.43	4724 ± 245efg
T_{15}-Both LF + SB	6.0 ± 0.08	20.0 ± 0.51	4090 ± 231hi
T_{16}-Both LF + SB	8.0 ± 0.13	24.0 ± 0.47	3715 ± 305ghi
T_{17}-None	0	0	7058 ± 356a
F[b]	–	–	11.6
P	–	–	<0.0001
LSD[c] ($p < 0.05$)	–	–	963

[a] Mean yields followed by the same letter do not differ significantly.
[b] df = 16, 32.
[c] LSD = Least significant difference.

crop growth stages to generate maximum variability in pest incidence (Table 2). Three applications were used against planthoppers (T_8) to ensure only the incidence of leaf folder and stem borers, while three applications against leaf folder and stem borers (T_9) were applied to have maximum incidence of the planthoppers alone. Four applications (T_{10}) were made to provide protection against all pests. Two applications against planthoppers (T_1), two applications against leaf folder and stem borers (T_3), one application each against leaf folder and planthoppers (T_2 and T_6), and one application each against planthoppers (T_4), and leaf folder and stem borers (T_5) were used to have variable levels of multiple pests at different crop growth stages. An untreated control (T_{11}) ensured maximum incidence of all the pest species.

Pest incidence was recorded on 10 randomly selected hills in each plot at 10-day intervals, beginning 40 days after transplanting (DAT) until crop maturity. Damage (%) due to leaf folder, *C. medinalis*, was assessed based on number of folded leaves and total leaves, while mixed damage (%) due to two stem borer species, *S. incertulas* and *S. inferens*, was derived from number of whiteheads and total reproductive tillers. Planthopper populations, comprising of *N. lugens* and *S. furcifera*, were enumerated on 10 randomly selected hills in each plot. The leaf folder and stem borer damage data were arcsin transformed, while planthopper population data were square root transformed before a one-way analysis of variance (ANOVA) using Microsoft Office Excel 2007. In ANOVA, treatments constituted fixed effects, while replications were random effects. Means were compared using the least significant difference (LSD) at $\alpha = 0.05$ significance level.

2.2. Pot experiments

Pot experiments during vegetative (experiment 1) and reproductive stage (experiment 2) were conducted during rainy season 2010 in a greenhouse with a roof of typical synthetic polycarbonate material with sides of nylon net that allowed free air movement. The pots were filled with soil and 33-day old seedlings of Pusa Basmati 1 were transplanted in pots (2 seedlings per pot) and maintained in accordance with fertilizer and irrigation recommendations. The pot experiments had 16 treatments each, including completely protected crop, with four replications in a completely randomized design (Tables 3 and 4), wherein each pot constituted one replication. Individual potted-plants were enclosed in mylar film cages that had the top covered with moistened muslin cloth. In pot experiment 1, required leaf folder damage levels were created by leaf clipping, and adult planthoppers collected from an untreated experimental rice field were introduced on potted-plants. In pot experiment 2, planthopper adults were introduced, whereas stem borer incidence was created by artificial detillering. In both experiments, the planthopper densities were maintained through removal of excessive insects with an aspirator. In the event of sudden population build up, buprofezin 25 SC at 0.05% and imidacloprid 17.8 SL at 0.006% were sprayed alternately with a pneumatic hand sprayer.

In field experiment 1 and pot experiments, leaf folder, stem borer and planthopper incidence levels were maintained according to information in Tables 1, 3 and 4. During vegetative stage, required levels of artificial leaf clipping were conducted at 40 DAT and maintained subsequently based on number of newer leaves to eliminate variability in leaf folder damage. During reproductive crop stage, leaf clipping and detillering were undertaken at 60 DAT and, as crop tillering has already ceased, no further detillering was needed. For planthoppers, adults were introduced at 40 and 60 DAT during vegetative and reproductive crop stages, respectively, and population levels were maintained for 15 days during each crop stage.

Table 2
Mean leaf folder (LF) damaged leaves (%), planthopper (PH) population and stem borer (SB) whiteheads (%) on rice variety, Pusa Basmati 1 in different treatments of field experiment 2 conducted to establish yield loss to damage function during rainy season 2010.

Treatment	Insecticides application at DAT[a]			Leaf folder damaged leaves (%) ± S.E.M.[b]		Planthopper population/hill ± S.E.M.[b]			Stem borer whiteheads (%) ± S.E.M.[b]	Yield (kg/ha) ± S.E.M.[b]
	Cartap	Imidacloprid	Buprofezin	60 DAT	70 DAT	60 DAT	70 DAT	80 DAT	80 DAT	
T_1-Multi-pests	–	60	68	7.4 ± 0.6a	7.9 ± 0.5ab	21.2 ± 1.8 a	19.3 ± 1.8ab	17.3 ± 1.0 b	7.1 ± 0.4bcd	4556 ± 227bc
T_2-Multi-pests	36	60	–	2.1 ± 0.3bc	8.1 ± 0.5ab	22.9 ± 1.8a	13.3 ± 1.5 c	17.6 ± 1.1b	7.0 ± 0.2cd	4222 ± 265bcd
T_3-Multi-pests	36, 66	–	–	2.6 ± 0.3b	8.3 ± 0.5ab	24.1 ± 1.7a	19.1 ± 1.9ab	24.0 ± 1.4ab	3.7 ± 0.5bcd	4044 ± 204cd
T_4-Multi-pests	–	60	–	7.1 ± 0.5a	8.7 ± 0.4ab	23.7 ± 1.5a	20.5 ± 1.8ab	18.3 ± 1.4b	8.8 ± 0.5a	3556 ± 227d
T_5-Multi-pests	36	–	–	6.0 ± 0.8a	8.3 ± 0.6ab	23.3 ± 1.2a	16.4 ± 1.0bc	32.0 ± 4.0a	6.6 ± 0.2abc	3422 ± 208de
T_6-Multi-pests	66	50	–	1.9 ± 0.2bcd	6.7 ± 0.6b	21.8 ± 2.4a	23.3 ± 2.5a	29.6 ± 3.2a	8.4 ± 0.3ab	3489 ± 231d
T_7-Multi-pests	66	50	60	2.2 ± 0.3bc	7.1 ± 0.8b	23.7 ± 1.6a	17.5 ± 1.4abc	28.3 ± 2.0a	6.1 ± 0.6d	4578 ± 288bc
T_8-LF + SB	–	50,60	68	7.6 ± 0.8a	10.0 ± 0.3a	1.0 ± 0.2b	2.0 ± 0.4d	3.0 ± 0.2c	0.5 ± 0.1e	5067 ± 227ab
T_9-Only PH	36, 50, 66	–	–	1.0 ± 0.1cd	1.0 ± 0.2c	22.5 ± 2.3a	23.3 ± 2.5a	30.0 ± 1.1a	8.8 ± 0.3a	4667 ± 216bc
T_{10}-Pest-free	36,66	50	60	0.5 ± 0.1d	0.5 ± 0.1c	0b	1.0 ± 0.2d	2.0 ± 0.2c	0.1 ± 0.03e	5733 ± 254a
T_{11}-Multi-pests	–	–	–	7.6 ± 0.9a	10.0 ± 0.3a	21.9 ± 1.5a	17.2 ± 2.4bc	23.0 ± 2.1ab	8.5 ± 0.3a	2578 ± 265e
F[c]	–	–	–	15.0	25.0	51.4	30.4	22.8	139.5	9.3
P				<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD[d] ($p < 0.05$)	–	–	–	2.9	2.5	0.6	0.7	0.8	1.1	850

[a] DAT = days after transplanting.

[b] Means followed by the same letter do not differ significantly.

[c] df = 10, 20.

[d] LSD = Least significant difference values are based on appropriately transformed pest incidence data.

Table 3
Mean leaf folder (LF) damaged leaves (%) and planthopper (PH) population on rice variety, Pusa Basmati 1 during vegetative stage in different treatments of pot experiment 1 conducted to establish yield loss to damage function during rainy season 2010.

Treatment	Leaf folder damaged leaves (%) ± S.E.M.	Planthopper population/hill ± S.E.M.	Yield (kg/ha) ± S.E.M.[a]
T_1-Only leaf folder	10.0 ± 0.35	0	6867 ± 492ab
T_2-Only leaf folder	15.0 ± 0.53	0	5533 ± 492bcd
T_3-Only leaf folder	20.0 ± 0.30	0	4067 ± 411d
T_4-Only planthopper	0	10.0 ± 0.39	5933 ± 613abc
T_5-Only planthopper	0	15.0 ± 0.50	5133 ± 467cd
T_6-Only planthopper	0	20.0 ± 0.57	5000 ± 509cd
T_7-Both LF + PH	10.0 ± 0.22	10.0 ± 0.50	5000 ± 529cd
T_8-Both LF + PH	10.0 ± 0.44	15.0 ± 0.29	4867 ± 290cd
T_9-Both LF + PH	10.0 ± 0.22	20.0 ± 0.29	4600 ± 346cd
T_{10}-Both LF + PH	15.0 ± 0.35	10.0 ± 0.76	4467 ± 419cd
T_{11}-Both LF + PH	15.0 ± 0.30	15.0 ± 0.30	4333 ± 437cd
T_{12}-Both LF + PH	15.0 ± 0.40	20.0 ± 0.33	4200 ± 455d
T_{13}-Both LF + PH	20.0 ± 1.00	10.0 ± 0.60	4800 ± 231cd
T_{14}-Both LF + PH	20.0 ± 0.54	15.0 ± 1.00	4867 ± 405cd
T_{15}-Both LF + PH	20.0 ± 0.59	20.0 ± 0.87	4733 ± 481cd
T_{16}-None	0	0	7333 ± 480a
F[b]	–	–	2.6
P	–	–	0.012
LSD[c] ($p < 0.05$)	–	–	1626

[a] Mean yields followed by the same letter do not differ significantly.
[b] df = 15, 48.
[c] LSD = Least significant difference.

2.3. Yield data

For field experiment 1, 10 designated hills under each treatment were harvested and threshed together and the fresh grain weight recorded. For field experiment 2, fresh yield per plot was measured. In pot experiments, plants were harvested and threshed individually. All yield samples were oven dried at 70 °C for 48 h and weighed. Yield data were analyzed with treatment as fixed effects using Microsoft Office Excel 2007. Means were compared using the least significant difference (LSD) at $\alpha = 0.05$ significance level.

2.4. Multi-pest yield loss to damage functions and economic injury levels

Pest incidence and yield data pertaining to different experiments were used to establish multi-pest yield loss to damage functions for two-pest combinations such as: (Abraham and Khosla, 1967; Quing et al., 1994)

$$Y = a - b_1X_1 - b_2X_2 \quad (1)$$

Where Y = crop yield, a = intercept, b_1 = regression coefficient of pest 1, b_2 = regression coefficient of pest 2, X_1 = incidence of pest 1 and X_2 = incidence of pest 2.

The crop yield as dependent variable was regressed upon incidence of two pests simultaneously, through multiple linear regression using Microsoft Office Excel 2007 and the coefficients a, b_1 and b_2 were determined.

Single-species economic injury level (EIL) were calculated using values of control expenditure in Indian rupees (₹) per hectare, market price of produce in rupees per quintal (q), regression coefficient (b) of yield loss to damage function for concerned pest species and control efficiency of pesticides (k) that was considered to be 60% based on own and farmers' experience: (Norton, 1976)

Table 4
Mean planthopper (PH) population and stem borer (SB) whiteheads (%) on rice variety, Pusa Basmati 1 during reproductive crop stage in different treatments in pot experiment 2 conducted to establish yield loss to damage function during rainy season 2010.

Treatment	Planthopper population/hill ± S.E.M.	Stem borer whiteheads (%) ± S.E.M.	Yield (kg/ha) ± S.E.M.[a]
T_1-Only planthopper	10.0 ± 0.50	0	5667 ± 315bc
T_2-Only planthopper	20.0 ± 0.29	0	5067 ± 278bc
T_3-Only planthopper	30.0 ± 0.29	0	2133 ± 336eg
T_4-Only stem borer	0	2.0 ± 1.00	5867 ± 353ab
T_5-Only stem borer	0	5.0 ± 0.49	5600 ± 362bc
T_6-Only stem borer	0	10.0 ± 0.95	4600 ± 403cd
T_7-Both PH + SB	20.0 ± 0.57	2.0 ± 1.40	3467 ± 336de
T_8-Both PH + SB	20.0 ± 0.81	5.0 ± 0.31	2533 ± 353ef
T_9-Both PH + SB	20.0 ± 0.31	10.0 ± 0.27	1866 ± 204fg
T_{10}-Both PH + SB	30.0 ± 0.63	2.0 ± 1.10	933 ± 147gh
T_{11}-Both PH + SB	30.0 ± 0.76	5.0 ± 0.51	333 ± 38h
T_{12}-Both PH + SB	30.0 ± 0.50	10.0 ± 1.60	133 ± 23h
T_{13}-Both PH + SB	100.0 ± 6.60	2.0 ± 1.56	0h
T_{14}-Both PH + SB	100.0 ± 11.30	5.0 ± 0.49	0h
T_{15}-Both PH + SB	100.0 ± 8.83	10.0 ± 1.50	0h
T_{16}-None	0	0	7067 ± 353a
F[b]	–	–	35.6
P	–	–	<0.0001
LSD[c] ($p < 0.05$)	–	–	1211

[a] Mean yields followed by the same letter do not differ significantly.
[b] df = 15, 48.
[c] LSD = Least significant difference.

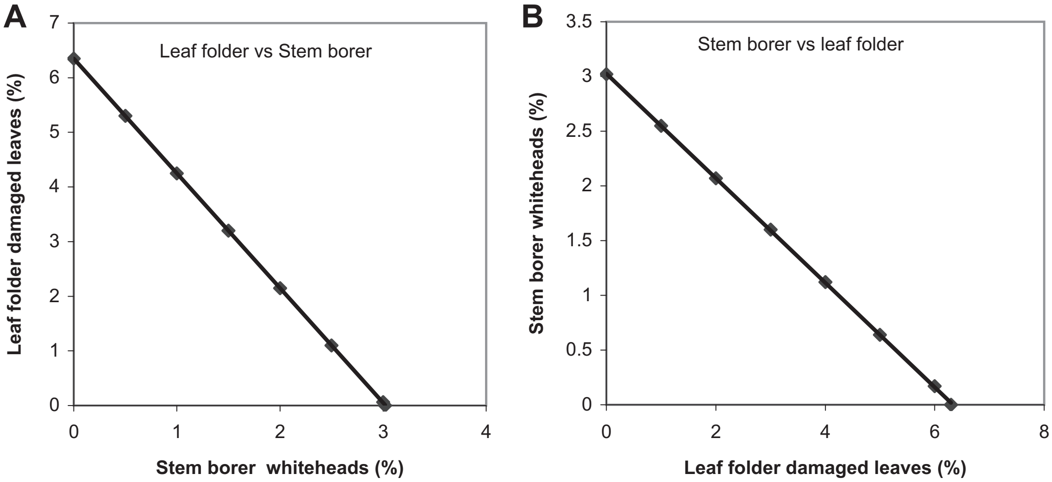

Fig. 1. Iso-loss curves depicting two-pest economic injury level (EIL) combinations during reproductive crop phase in field experiment 1 conducted during rainy season 2009.

$$\mathrm{EIL} = C/(P * b * k) \quad (2)$$

With no significant interaction between two species, the EILs under two-pest situation are expressed as: (Palis et al., 1990)

$$\mathrm{EIL}_{\mathrm{pest1}} = C/(P * b_1 * k) = (b_2 * \mathrm{EIL}_{\mathrm{pest2}})/b_1 \quad (3)$$

$$\mathrm{EIL}_{\mathrm{pest2}} = C/(P * b_2 * k) = (b_1 * \mathrm{EIL}_{\mathrm{pest1}})/b_2 \quad (4)$$

Control expenditure depended upon the optimum number of pesticide applications, which were two applications with cartap hydrochloride 50 SP at 500 g a.i./ha against leaf folder and stem borers in our study and Sahiti and Misra (2006a, 2006b), and one application of buprofezin 25 SC at 200 g a.i./ha and two applications of imidacloprid 17.8 SL at 25 g a.i./ha against planthoppers. Market price of Pusa Basmati 1 was used as ₹ 1500/q based on wholesale market price in Delhi.

Expenditure for two applications of cartap hydrochloride 50 SP at 500 g a.i./ha/spray was estimated as ₹ 3300 (quantity of the formulation needed for two sprays = 2 kg; cost of the formulation at ₹ 1200/kg = ₹ 2400; labour charges at ₹ 200/man-day for two man-days/spray/ha = ₹ 800; sprayer hire charges at ₹ 25/sprayer/day = ₹ 100).

Expenditure for two sprays of imidacloprid 17.8 SL at 25 g a.i./ha/spray was found to be ₹ 1524 (quantity of the formulation needed for two sprays = 250 ml; cost of spray formulation at ₹ 2500/litre = ₹ 624; labour charges at ₹ 200/man-day for two man-days/spray/ha = ₹ 800; sprayer hire charges at ₹ 25/sprayer/day = ₹ 100).

Similarly, the expenditure for one spray of buprofezin 25 SC at 200 g a.i/ha/spray was estimated as ₹ 1746 (quantity of the formulation needed for one spray = 800 ml; cost of the formulation at ₹ 1620/litre = ₹ 1296; labour charges at ₹ 200/man-day for two man-days/spray/ha = ₹ 400; sprayer hire charges at ₹ 25/sprayer/day = ₹ 50).

2.5. Iso-loss curves

The multi-pest yield loss to damage functions were used to determine various combinations of incidence of two species that amounted to economic damage. For example, for leaf folder and stem borer combined, each of 1, 2, 3, 4, 5, 6 and 6.1% leaf folder injury was considered in combination with each of 0.5, 1, 1.5, 2, 2.5, 3 and 3.1% whiteheads to determine different iso-loss combinations. Above injury levels were taken in accordance with single-species EILs (Section 3.2.1). Different pairs of incidence of two pests were input into yield loss to damage functions to determine yield loss. Two-pest incidence combination producing yield loss commensurate to that caused by either pest at its EIL was taken as the iso-loss combination that inflicted economic damage. Pest incidence levels in two-species combinations were mutually regressed to derive iso-loss equations (Palis et al., 1990) using Microsoft Office Excel 2007, such as:

$$\mathrm{Pest1} = a_{\mathrm{iso}} - b_{\mathrm{iso}} * \mathrm{pest2} \quad (5)$$

$$\mathrm{Pest2} = a_{\mathrm{iso}} - b_{\mathrm{iso}} * \mathrm{pest1} \quad (6)$$

The intercept of these lines represented single-species EIL. Iso-loss curves were drawn using the above equation, which depicted the contribution of each pest species towards two-species EIL in various incidence combinations.

3. Results

3.1. Optimum number of pesticide applications against pests

The field experiment 2 was designed to create variability in incidence of different pests during various crop stages through differential pesticide application. Unprotected crop (T_{11}) and single cartap spray (T_5) at 36 DAT had the lowest yields among all treatments (Table 2). The highest yield was recorded with two cartap sprays, and one spray each with imidacloprid and buprofezin (T_{10}) aimed at protecting the crop against all pests.

Against planthoppers, two applications of imidacloprid and one of buprofezin (T_8) proved as effective as one application of imidacloprid and one of buprofezin (T_1). However, yield in T_8 was also similar to T_{10}, while yield in T_1 was significantly lower than $T_{10.}$ Three pesticide applications were, therefore needed for protecting the crop from planthoppers.

For leaf folder and stem borer damage, yield with three cartap applications at 36, 50 and 66 DAT (T_9) was significantly lower than in $T_{10.}$ On the other hand, yield in T_3, which received two applications of cartap at 36 and 66 DAT, was identical to T_5 and T_6, and also similar to yield in T_9, which received three cartap applications. However, yield in T_5 and T_6 was significantly lower than in T_9. As leaf folder and stem borer effect on the crop could not be analyzed separately, two cartap applications were thus considered optimum for protecting the crop against them. The control expenditure was estimated to be ₹ 3300/ha, ₹ 1524/ha and ₹ 1746/ha for two cartap hydrochloride applications, two imidacloprid applications and one buprofezin application, respectively.

3.2. Multi-pest yield loss to damage functions and economic injury levels

3.2.1. Field experiment I during reproductive crop phase

Increasing pest incidence reduced crop yield in most treatments (Table 1). Multiple pest yield loss to damage function was significant for leaf folder (LF) and stem borer (SB) incidence at 80 DAT during the crop season ($F = 61.2$; df $= 2, 14$; $P < 0.0001$; $R^2 = 0.93$):

$$Y = 6866.7 - 57.6\ \mathrm{LF}(\%) - 121.7\ \mathrm{SB}(\%) \tag{7}$$

Single-species EILs were found to be 6.4% folded leaves ($\mathrm{EIL}_{\mathrm{LF}} = 3300 \ast 100/[1500 \ast 57.6 \ast 0.6] = 6.4$) and 3.1% whiteheads ($\mathrm{EIL}_{\mathrm{SB}} = 3300 \ast 100/[1500 \ast 121.7 \ast 0.6] = 3.1$) for leaf folder and stem borer, respectively. Iso-loss equations were established to be:

$$\mathrm{LF}(\%) = 6.352 - 0.097\ \mathrm{SB}(\%) \tag{8}$$

$$\mathrm{SB}(\%) = 3.028 - 0.476\ \mathrm{LF}(\%) \tag{9}$$

Iso-loss curves (Fig. 1A & B) based on these equations depicted various combinations of leaf folder and stem borer incidence that resulted in economic damage, though individually each pest was below its respective EIL. These curves can be used for monitoring joint incidence of the pests and timing of pesticide application to prevent avoidable yield loss.

3.2.2. Field experiment 2 during vegetative and reproductive crop phase

Differential pesticide application created variable incidence levels of leaf folder, planthoppers and stem borers (Table 2). In this experiment, data on leaf folder and planthopper incidence were collected at 40, 50, 60, 70, 80 and 90 DAT and data on stem borer incidence at 80 and on 90 DAT. However, pest incidence data only at crop stages having higher population levels (i.e. at 60 and 70 DAT for leaf folder, 60, 70 and 80 DAT for planthoppers, and 80 DAT for stem borers) are presented (Table 2). During vegetative stage, multiple pest yield loss to damage function involving leaf folder (LF) and planthoppers (PH) was significant at 60 DAT ($F = 6.5$; df $= 2, 8$; $P = 0.021$; $R^2 = 0.61$):

$$Y = 6045.8 - 127.9\ \mathrm{LF}(\%) - 63.3\ \mathrm{PH} \tag{10}$$

The EILs for leaf folder and planthoppers were determined to be 2.9% folded leaves ($\mathrm{EIL}_{\mathrm{LF}} = 3300 \ast 100/[1500 \ast 127.9 \ast 0.6] = 2.9$) and 5.7 hoppers per hill ($\mathrm{EIL}_{\mathrm{PH}} = 3270 \ast 100/[1500 \ast 63.3 \ast 0.6]$

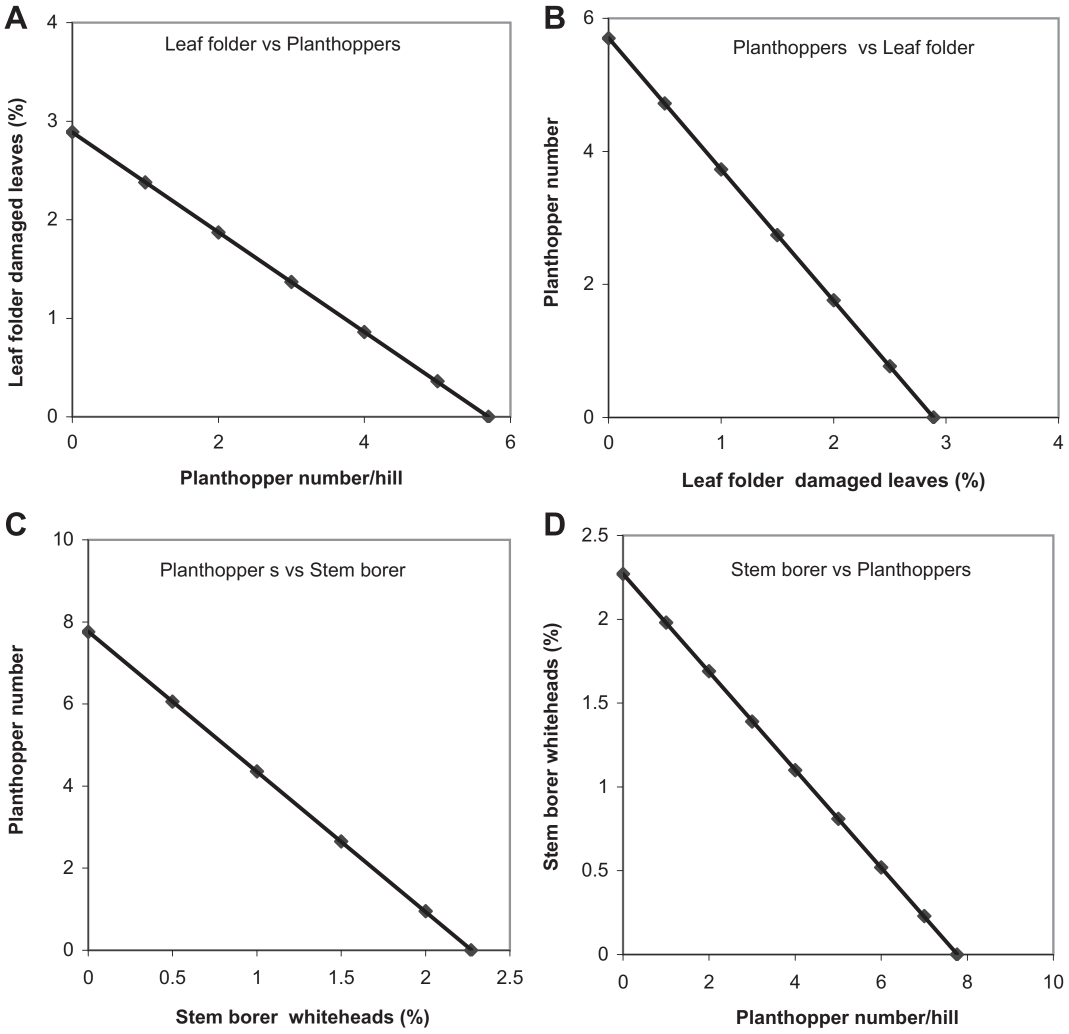

Fig. 2. Iso-loss curves depicting two-pest economic injury level (EIL) combinations during vegetative (A & B) and reproductive (C & D) crop phase in field experiment 2 conducted during rainy season 2010.

= 5.7), respectively. Based on the following equations, iso-loss curves were drawn (Fig. 2A & B):

$$LF(\%) = 2.890 - 0.506\ PH \quad (11)$$

$$PH = 5.707 - 1.970\ LF(\%) \quad (12)$$

During reproductive stage, yield loss to damage function involving planthoppers (PH) and stem borers (SB) at 80 DAT was ($F = 8.5$; df = 2, 8; $P = 0.0104$; $R^2 = 0.68$):

$$Y = 6141.4 - 46.8\ PH - 160.5\ SB(\%) \quad (13)$$

The EILs for planthoppers and stem borers were determined to be 7.8 hoppers per hill ($EIL_{PH} = 3270 * 100/[1500 * 46.8 * 0.6] = 7.8$) and 2.3% whiteheads ($EIL_{SB} = 3300 * 100/[1500 * 160.5 * 0.6] = 2.3$), respectively. The iso-loss equations were derived by mutual regression of incidence of two pests (Fig. 2C & D):

$$PH = 7.769 - 3.408\ SB(\%) \quad (14)$$

$$SB(\%) = 2.274 - 0.292\ PH \quad (15)$$

3.2.3. *Pot experiment 1 during vegetative crop phase*

The uninfested crop (T_{16}) had the highest yield followed by treatments with only leaf folder incidence (T_1) and only planthopper incidence (T_4) (Table 3). The multiple pest yield loss to damage function was significant for both leaf folder (LF) as well as planthoppers (PH) at 55 DAT ($F = 11.3$; df = 2, 13; $P = 0.0007$; $R^2 = 0.63$):

$$Y = 6621.1 - 67.2\ LF(\%) - 67.2\ PH \quad (16)$$

The EIL for leaf folder and planthoppers was determined to be 5.5% folded leaves ($EIL_{LF} = 3300 * 100/[1500 * 67.2 * 0.6] = 5.5$) and 5.4 planthoppers per hill ($EIL_{PH} = 3270 * 100/[1500 * 67.2 * 0.6] = 5.4$), respectively. The iso-loss equations were (Fig. 3A & B):

$$LF(\%) = 5.406 - 1.0\ PH \quad (17)$$

$$PH = 5.396 - 0.998\ LF(\%) \quad (18)$$

3.2.4. *Pot experiment 2 during reproductive crop phase*

The planthopper population was initially planned to be 0 to 30 hoppers per hill; in some treatments (T_{13}–T_{15}), the population could not be maintained and reached up to 100 hoppers per hill and

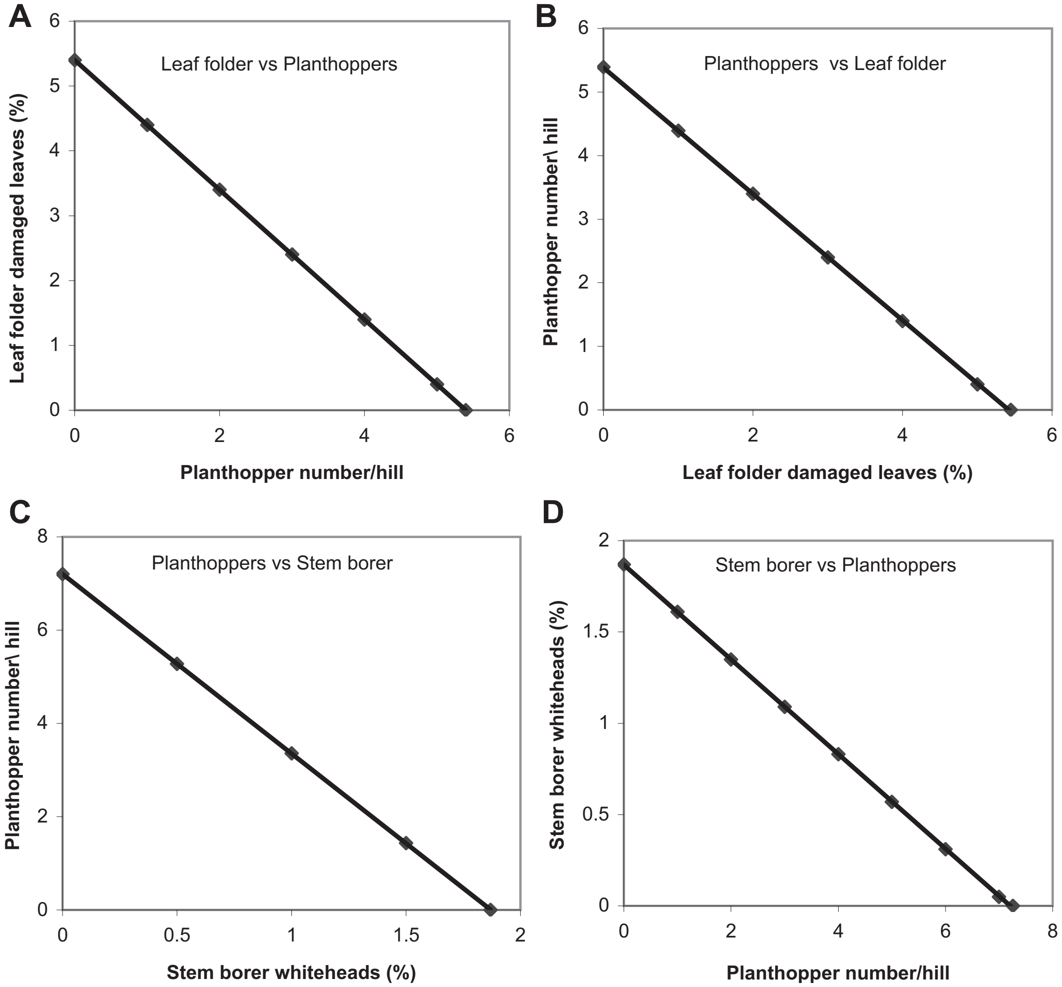

Fig. 3. Iso-loss curves depicting two-pest economic injury level (EIL) combinations during vegetative (A & B) and reproductive (C & D) crop phase in pot experiments conducted during rainy season 2010.

consequently no yield could be harvested. The uninfested crop (T_{16}) had the highest yield and substantial variability occurred among treatments (Table 4).

Multiple pest yield loss to damage function was significant both for planthoppers (PH) and stem borers at 75 DAT ($F = 13.3$; df = 2, 13; $P = 0.0007$; $R^2 = 0.67$):

$$Y = 5246.6 - 49.7\ \mathrm{PH} - 196.1\ \mathrm{SB}(\%) \tag{19}$$

The EIL for planthoppers and stem borers was determined to be 7.3 hoppers per hill ($\mathrm{EIL_{PH}} = 3270 * 100/[1500 * 49.7 * 0.6] = 7.3$) and 1.9% whiteheads ($\mathrm{EIL_{SB}} = 3300 * 100/[1500 * 196.1 * 0.6] = 1.9$), respectively. The iso-loss equations were derived as (Fig. 3C & D):

$$\mathrm{PH} = 7.206 - 3.845\ \mathrm{SB}(\%) \tag{20}$$

$$\mathrm{SB}(\%) = 1.871 - 0.259\ \mathrm{PH} \tag{21}$$

4. Discussion

Multi-pest EILs were established because occurrence of more than one pest species is commonplace in field situations and, though individually pests might be below their respective EILs, combinations of several pests might inflict economic damage jointly (Palis et al., 1990). In the absence of multi-pest EILs, treatments are generally not made until pest infestation reaches single-species EILs and insect injury related yield loss can occur. In our study, three pesticide applications, two of imidacloprid 17.8 SL at 25 g a.i./ha and one of buprofezin 25 SC at 200 g a.i./ha against planthoppers, and two applications of cartap hydrochloride 50 SP at 500 g a.i./ha against stem borers and leaf folder were found necessary for protecting the crop. Earlier research also reported two pesticide applications as essential for protecting the crop against leaf folder and stem borer (Sahiti and Misra, 2006a, 2006b).

The leaf folder EIL was found to be 2.9% damaged leaves at 60 DAT during vegetative stage (field experiment 2) and 6.4% damaged leaves at 80 DAT during reproductive crop stage (field experiment 1). In pot experiment 1, leaf folder EIL was 5.5% damaged leaves at 55 DAT during vegetative stage. The leaf folder EIL was thus higher with artificial leaf clipping in pot experiment under greenhouse conditions compared to natural field infestation during vegetative crop phase. Earlier research found that leaf folder damaged leaves served as entry points for fungal and bacterial infections due to presence of larval excreta (Pathak, 1975), which might render natural leaf folder infestation more injurious than artificial leaf clipping, thereby reducing EIL under natural infestation. Previous studies had reported leaf folder EIL to vary from 3–5% (Bautista et al., 1984; Samalo et al., 1996; Saikia and Parameswaran, 1999; Chander and Singh, 2001; Asghar et al., 2009).

The stem borer EIL was determined to be 3.1% whiteheads (field experiment 1) and 2.3% whiteheads (field experiment 2) at 80 DAT, while it was found to be 1.9% whiteheads at 75 DAT in pot experiment 2 in the greenhouse. The stem borer EIL thus differed to a less extent than leaf folder EIL between field and greenhouse conditions. A direct comparison between stem borer natural infestation and artificial detillering could not be conducted, as some amount of detillering was undertaken in field experiments to make up for low pest infestations. Earlier research indicated stem borer EIL to be 2–4% whiteheads for high value rice varieties (Andow and Kiritani, 1983; Singh et al., 2003, 2008; Litsinger et al., 2006; Samiayyan et al., 2010).

In the field experiment 2, planthopper EIL was 5.7 hoppers per hill at 60 DAT during vegetative stage and 7.8 planthoopers per hill at 80 DAT during reproductive stage. In pot experiments, planthopper EIL was 5.4 hoppers per hill at 55 DAT during vegetative stage (pot experiment 1) and 7.3 hoppers per hill at 75 DAT during reproductive stage (pot experiment 2). The planthopper EILs were thus similar under field conditions and in pot experiments under greenhouse conditions during respective crop growth stages. In both field and pot experiments, artificial injury mimicking planthopper injury was not used. The leaf folder and planthoppers both were observed to be more injurious during vegetative crop stage than reproductive stage because crop tolerance against these might increase with advancing crop age.

The planthopper EILs ranged between 5.4 and 7.8 hoppers per hill and were lower during vegetative crop phase compared to reproductive phase in our study. However, planthopper EIL had earlier been found to vary over a wide range of 2–20 hoppers per hill (Dyck and Orlido, 1977; Chiou and Cheng, 1978; Chiang, 1979; Sellammal and Chelliah, 1982; Cheng, 1984; Xi et al., 1995; Lin et al., 1999; Samiayyan et al., 2010). This large variability in planthopper EIL could be attributed to differing crop stages, cultivars, crop management conditions, environmental conditions, insecticides and produce prices.

Yield loss to damage functions for determining EILs depend on either natural variability in pest incidence in field or on variability generated through differential pesticide application. In view of insufficient pest attack, mechanical injury can also be undertaken (Reji et al., 2008), as was the case for leaf folder and stem borer in our study. However, use of insecticides and mechanical injury both have limitations. Due to stimulatory effect of insecticides, plants might sustain greater pest population, thereby reflecting higher pest EIL than under natural infestation (Chander and Phadke, 1994). A sub lethal dosage of insecticide might also impair the feeding ability of insects (Hirata and Sogawa, 1976; Beeman and Matsumura, 1978). More individuals might therefore be required to inflict the same amount of damage. However, in our study, planthopper EIL was similar, respectively being 5.7 hoppers per hill and 5.4 hoppers per hill during vegetative crop stage, with insecticide use (field experiment 2) and without insecticide (pot experiment 1). Likewise, EILs were similar during reproductive crop stage, being 7.8 hoppers per hill with insecticide use (field experiment 2) and 7.3 hoppers per hill without insecticide use (pot experiment 2). The crop response to planthopper injury did thus not seem to vary with insecticide application.

The stem borer EIL was 2.3% whiteheads with insecticide use under natural plus artificial detillering (field experiment 2), which was similar to 1.9% whiteheads under artificial detillering in pot experiment 2 in the greenhouse. The effect of artificial detillering had previously been found to be similar to natural stem borer infestation (Reji et al., 2008). The artificial detillering in our study, therefore, could be considered similar to natural infestations of stem borers. The study did not indicate that crop response to stem borer injury was modified due to pesticide application. Plant response to leaf folder injury with and without insecticide use could not be compared for lack of data. The leaf folder EIL with insecticide use during vegetative crop stage (field experiment 2) was lower under artificial leaf clipping (pot experiment 1), thereby suggesting that no stimulatory effect of insecticides occurred.

The EIL depends upon multiple factors including control expenditure, market value of produce, pest severity and pesticide control efficiency. Lower planthopper EIL (5.4–7.8 hoppers per hill) in our study, compared to prescribed EIL of 5–10 or even up to 25 hoppers per hill on rice cultivars in India (Dhaliwal and Arora, 2010), could be attributed to the higher market price of Pusa Basmati 1, a scented rice variety, than coarse rice. Earlier research found inverse relationship between market price of rice and planthopper EILs (Sujithra et al., 2011).

Interest on control expenditure was not included in EIL calculations. Interest at 12% per annum for six months on control expenditure of ₹ 3300 for leaf folder and stem borers and ₹ 3270 for planthoppers would correspond to an increase of ₹ 198 and of ₹ 196, respectively, in control expenditure. Increased control expenditure would have increased leaf folder EIL from 6.4 to 6.8% damaged leaves during reproductive crop stage (field experiment 1), 2.9 to 3.0% during vegetative stage (field experiment 2) and 5.5 to 5.8% damaged leaves during vegetative stage (pot experiment 1); stem borer EIL from 3.1 to 3.2% whiteheads (field experiment 1), 2.3 to 2.4% (field experiment 2) and 1.9 to 2.0% whiteheads (pot experiment 2); the planthopper EIL from 5.7 to 6.1 planthoppers per hill during vegetative stage and 7.8 to 8.2 planthoppers during reproductive stage (field experiment 2), 5.4 to 5.7 planthoppers during vegetative crop stage (pot experiment 1), and 7.3 to 7.4 planthoppers per hill during reproductive stage (pot experiment 2). The inclusion of interest in EIL determination would have caused only marginal increase in pest EILs due to relatively low cost of control.

The multiple pest yield loss to damage functions were significant during 55–60 DAT during vegetative crop growth phase and 75–80 DAT during reproductive crop phase over different experiments, reflecting consistency of the results. Damage due to different two-pest combinations of leaf folder and stem borers, leaf folder and planthoppers, and planthoppers and stem borers was non-interactive and hence additive because damage mechanisms of the species differed. In earlier research also, damage due to leaf folder and stem borer was observed to be non-interactive during vegetative as well as reproductive crop phase (Palis et al., 1990). Mechanistic approach of crop loss assessment takes into consideration the pest damage mechanisms, i.e. physiological basis of pest damage (Aggarwal et al., 2004). The three pest species involved in our study differed in their damage mechanisms, which were a tissue consumer (leaf folder), a stand reducer (stem borer), and an assimilate sapper (planthopper). The injuries caused by these pests were not overlapping, and their effects were thus deemed to be non-interactive and additive. Their effects would have been synergistic or antagonistic only if interaction occurred. The multi-pest damage functions for two-pest combinations were thus derived directly without the interaction term between two pests.

Empirical EILs developed through regression models are highly location specific and dynamic and depend upon control expenditure, market value of produce and pest damage severity. Such EILs need to be established for each location separately, which is challenging as blanket EILs are used for most pest species. The use of EILs is still advisable as a decision support tool that helps to avoid unwarranted pesticide application, save unnecessary expenditure and conserve the environment. The EILs can be readily simulated for different locations through crop growth simulation models. The crop simulation models are detailed crop physiological and ecological models that are coupled with different pest damage mechanisms thereby accounting for physiological basis of pest damage (Boote et al., 1983; Teng et al., 1987; Aggarwal et al., 2006). These models can be adapted for crop management and weather conditions of different locations by researchers to provide farmers with location-specific EILs for management of pests.

Hutchins et al. (1988) proposed a method for refining EIL-based decision making through an injury equivalency system. The regression coefficients of yield loss to damage functions in our study also represented a sort of injury equivalency through the effect of pests on crop yield. Damage coefficients pertaining to different pests indicated that yield decline with unit increase in incidence was 127.9 kg/ha during vegetative stage in field experiment 2 (Table 5) and 57.6 kg/ha during reproductive stage in field experiment 1 (Table 5) for leaf folder, 121.7 kg/ha and 160.5 kg/ha during reproductive stage in field experiment 1 and field experiment 2 (Table 5), respectively, for stem borers, and 63.3 kg/ha during vegetative crop stage and 46.8 kg/ha during reproductive crop stage in field experiment 2 (Table 5) for planthoppers. The effect of leaf folder and planthoppers on crop yield was greater during vegetative than reproductive crop phase, which was reflected through lower EILs of these pests during vegetative crop phase. The 1% leaf folder damage was commensurate to the damage caused by two planthoppers per hill during vegetative stage, while during reproductive crop phase, 1% stem borer whiteheads was equivalent to 3.4 planthoppers per hill and 2.1% leaf folder damaged leaves.

Yield loss with unit increase was 67.2 kg/ha during vegetative stage in pot experiment 1 (Table 5) for leaf folder, 67.2 kg/ha during vegetative stage in pot experiment 1 (Table 5) and 49.7 kg/ha during reproductive crop phase in pot experiment 2 (Table 5) for planthoppers, and 196.0 kg/ha during reproductive crop phase in pot experiment 2 (Table 5) for stem borer. Therefore, 1% leaf folder damage proved to be equal to the damage by 1 planthopper per hill during vegetative crop phase, while 1% whitehead was commensurate to 2.9 planthoppers per hill during reproductive crop phase. The leaf folder and the planthopper damage coefficient ratio (1% leaf folder damaged leaves = 1 planthopper per hill) in pot experiment 1 differed from that during vegetative phase in field

Table 5
Yield loss to damage functions established for determining multi-pest economic injury levels (EILs) on Pusa Basmati 1 rice.

Experiment	Crop phase	Regression equation	*t*-statistics	*p*-value
Field experiment 1	Reproductive	$Y = 6866 - 57.6\ \text{LF} - 121.7\ \text{SB}$ ($R^2 = 0.93$, $F = 61.2$, $P = <0.0001$, df = 2, 14)	−2.113 (LF)[a] −11.757 (SB)[b]	0.05 (LF) 0.005 (SB) df = 16
Field experiment 2	Vegetative	$Y = 6046 - 127.9\ \text{LF} - 63.3\ \text{PH}$ ($R^2 = 0.61$, $F = 6.5$, $P = 0.021$, df = 2, 8)	−2.235 (LF) −2.588 (PH)[c]	0.055 (LF) 0.032 (PH) df = 10
	Reproductive	$Y = 6141 - 46.8\ \text{PH} - 160.5\ \text{SB}$ ($R^2 = 0.68$, $F = 8.56$, $P = 0.0104$, df = 2, 8)	−2.745 (PH) −2.797 (SB)	0.025 (PH) 0.023 (SB) df = 10
Pot experiment 1	Vegetative	$Y = 6621 - 67.2\ \text{LF} - 67.2\ \text{PH}$ ($R^2 = 0.63$, $F = 11.3$, $P = 0.0014$, df = 2, 13)	−3.362 (LF) −3.362 (PH)	0.005 (LF) 0.005 (PH) df = 15
Pot experiment 2	Reproductive	$Y = 5247 - 49.7\ \text{PH} - 196.0\ \text{SB}$ ($R^2 = 0.67$, $F = 13.3$, $P = 0.0007$, df = 2, 13)	−4.377 (PH) −1.885 (SB)	0.0007 (PH) 0.08 (SB) df = 15

[a] LF = leaf folder damaged leaves (%).
[b] SB = Stem borer whiteheads (%).
[c] PH = Planthopper population/hill.

experiment 2 (1% leaf folder damaged leaves = 2 planthoppers per hill) because leaf folder natural infestation proved to be more injurious than artificial leaf clipping by also serving as a source of disease infection on larval excreta, besides direct damage (Pathak, 1975) as discussed earlier in this paper.

Iso-loss curves showed that, as incidence of one pest increased towards its EIL, the incidence of another decreased from its EIL eventually reaching zero. In between, various combinations of joint incidence of two pests resulted in economic damage. Quantum of increase and decrease in incidence of two pests depended upon their respective regression coefficient in multi-pest yield loss to damage function. These curves can be used to decide on the need for management interventions under joint incidence of pests. In the absence of stem borer incidence (Fig. 1A), insecticide application is needed for 6.3% leaf folder damaged leaves. However, in the presence of 1 and 2% stem borer whiteheads, only 4 and 2% leaf folder damaged leaves, respectively, are required to inflict economic damage. Both the pests below their individual EIL can jointly cause economic damage, which is not accounted for with single-species EILs. Either curve (Fig. 1A & B) can be used for management decisions under joint incidence of leaf folder and stem borer. However, it is suggested that in case of the leaf folder being dominant, Fig. 1A be used and, when the stem borer is dominant, Fig. 1B be used for convenience. A similar use is recommended for all other figures for the different combinations of pests.

Yield loss and damage functions have been determined for multiple pest complexes including more than one insect feeding in the same growth stage or same pest feeding in two growth stages (Palis et al., 1990; Quing et al., 1994; Litsinger et al., 2011a, 2011b), and also for joint incidence of insect pests and diseases (Castilla et al., 1993; Chau et al., 2002). The multi-pest EILs are helpful in monitoring joint incidence of rice pests and facilitate timely action thereby preventing avoidable yield loss. Their implementation would ensure action even when pests, though below their individual thresholds, might inflict economic damage jointly.

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