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Assessment of impact of climate change with reference to elevated CO_2 on rice brown planthopper, *Nilaparvata lugens* (Stal.) and crop yield

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Impact of elevated CO_2 on the rice brown planthopper (BPH), *Nilaparvata lugens* (Stal.) population and rice yield was assessed in open-top chambers during kharif 2010 and 2011. Brachypterous females laid more eggs (324.3 ± 112.3 eggs/female) on the rice plants exposed to elevated CO_2 (570 ± 25 ppm) than 380 ppm ambient CO_2 (231.7 ± 31.8 eggs). Elevated CO_2 exhibited positive effect on BPH multiplication and resulted in more than a doubling of its population (435.4 ± 62.0 hoppers/hill) at peak incidence compared to ambient CO_2 (121.4 ± 36.8 hoppers/hill) during kharif 2010; corresponding populations being 113.0 ± 11.5 and 47.0 ± 8.1 hoppers/hill during kharif 2011 respectively. Besides, honeydew excretion was observed to be 74.41% more under elevated CO_2 (187.6 ± 44.8 mm^2/5 females) than ambient CO_2 (48 ± 20.1 mm^2/5 females). On the other hand, high CO_2 exhibited nutritive effect on uninfested rice crop through 21.6%, 15.3% and 14.1% increase in the number of tillers, reproductive tillers and seeds/panicle respectively, and as a consequence increased grain by 11.1% compared to ambient CO_2. However, despite the nutritive effect, crop under elevated CO_2 suffered higher yield loss (26.5%) due to higher BPH population as well as sucking rate compared to ambient CO_2 (12.4%).

Keywords: Brown planthopper, climate change, elevated CO_2, rice.

RICE (*Oryza sativa* L.) is the world's most important staple food for two-thirds of the human population[1]. In India, rice is grown on an area of 41.85 m ha with a production of 102 m tonnes[2]. However, rice productivity in India remains on the lower side due to many abiotic and biotic constraints[3]. Among the biotic factors, the brown planthopper (BPH), *Nilaparvata lugens* (Stal.) is one of the most important sucking pests of rice, causing huge crop losses during certain years[4]. Global climate change, the current burning issue around the world, poses a multitude of threats to biodiversity, and human life and livelihood. According to projections, the Earth's temperature has already increased by 0.74°C between 1906 and 2005 and CO_2 is expected to increase up to 445–640 ppm by 2050 due to increase in anthropogenic emissions of greenhouse gases[5].

In the context of climate change, temperature directly affects insects and CO_2 affects them through host plants[6]. Increase in atmospheric CO_2 will have a significant impact on plant growth and development primarily due to changes in photosynthetic carbon assimilation patterns[7,8]. Increase in growth and yield under elevated CO_2 has been reported in many species including rice[9]. Changes in atmospheric CO_2 affect not only the plant quality but also the herbivore performance[10]. The C : N ratio of the plant foliage generally increases when plants are grown in elevated CO_2 than in ambient CO_2. As a result, insect larvae of castor semilooper increased leaf consumption under elevated CO_2 to compensate for lower nitrogen in plant foliage[11]. However, certain pests such as wheat aphids were not affected by elevated CO_2 (ref. 12). Therefore, rise in CO_2 might impact the foodgrain production directly as well as indirectly through its effect on crop pests[13]. Owing to differential effects of elevated CO_2, it becomes imperative to assess the effect on different crop pests. As BPH is an important pest of rice, it was thus deemed

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necessary to evaluate the effect of elevated CO_2 on its population and crop–pest interactions. This would facilitate the adoption of appropriate adaptation measures, thereby helping in reducing yield losses due to the pest.

The effect of elevated CO_2 on BPH population and rice yield of Pusa Basmati 1 was studied in open-top chambers (OTCs) under elevated CO_2 (570 ± 25 ppm) vis-à-vis ambient CO_2 (380 ± 25 ppm) during kharif 2010 and 2011 at the Indian Agricultural Research Institute, New Delhi (28°36′36″N, 77°13′48″E). Each CO_2 concentration had a set of BPH-infested plants and an uninfested control in separate OTCs, and four OTCs were thus used in the study. Twenty-two-day-old rice seedlings were transplanted in pots under natural conditions and ten pots were transferred to each of the four OTCs 15 days after transplanting (DAT). Each OTC comprised treatment and each of the ten pots in an OTC constituted one replication. Five pairs of BPH adults were released in each pot, where the crop was to be infested, after 10 days of crop exposure to elevated CO_2. Weekly observations on the number of nymphs, wingless females, winged females and male were recorded.

Rice seedlings were raised in 14 pots in each of the control OTCs, i.e. uninfested plants under elevated and ambient CO_2. A pair of fully mature, gravid, brachypterous female and winged male was released on 30-day-old seedlings in each of the pots under elevated as well as ambient CO_2. Regular observations on nymphal emergence were recorded and emerged nymphs were removed. At the end, oviposition scars on leaf sheaths were dissected under a microscope and unhatched eggs were included in nymphal count.

Honeydew excretion by the newly emerged females of BPH was estimated using graphical method. Rice seedlings were raised in 14 pots in each of the control OTCs, i.e. uninfested plants under elevated and ambient CO_2. Next 9-cm diameter circles of Whatman No. 1 filter paper were prepared, which had a small hole at the centre and a longitudinal cut from the margin to the hole. The filter paper circles were dipped individually in bromocresol green powder (0.5%) solution, prepared in ethyl alcohol, and dried under shade. Cardboard sheets were cut into $12 \times 12\ cm^2$ pieces with a wide hole at the centre and these were inserted through leaf tips to the base of seedlings. The treated filter-paper circles were placed on the cardboard sheet and an inverted plastic cup with a hole at its base was inserted through the leaf tips onto the filter paper. Five one-day-old brachypterous BPH females, starved for 2 h, were released in each pot inside the cup and allowed to feed on seedlings for 24 h. Filter-paper areas that showed colour change due to honeydew excretion by females were measured graphically.

Plant parameters, viz. number of tillers, reproductive tillers, panicles and seeds/panicle, 1000-seed weight and yield were recorded for each of the ten plants in the four OTCs. Uninfested-plant parameters under the two CO_2 concentrations were compared using *t*-test to assess the effect of elevated CO_2 on rice growth and development. Likewise, yield loss due to BPH under elevated and ambient CO_2 was determined. Interactive effect of CO_2 and time interval on BPH multiplication was analysed through repeated measures ANOVA[14].

During both the years, the BPH population was found to be higher under elevated CO_2 than ambient CO_2. During the first year, the highest pest population was observed in the fifth week after adult release under both the CO_2 conditions (Table 1). Pest population under elevated CO_2 did not differ significantly from that under ambient CO_2 up to the fourth week of adult release, but the population was significantly higher under elevated CO_2 thereafter up to the eighth week.

During the second year, the peak pest population was observed in the third week after adult release under both the CO_2 concentrations. The BPH population under elevated CO_2 differed significantly from that under ambient CO_2 during the third to sixth week after adult release (Table 2). Peak BPH population was thus observed earlier in the second year than the first year because during the second year development of only one generation of the pest was observed, whereas during the first year two generations were recorded.

A brachypterous female laid higher number of eggs (324.3 ± 112.3 eggs/female) on the rice plants exposed to elevated CO_2 than on those exposed to ambient CO_2 (231.7 ± 31.8 eggs/female). Elevated CO_2 thus increased the BPH fecundity by 28.5% compared to ambient CO_2 (Table 3).

The highest number of BPH nymphs was observed in the fifth week during the first year and third week during the second year of adult release. Nymphal population under elevated CO_2 was significantly higher from the fifth to eighth week and third to sixth week during the first and second years respectively. Higher fecundity resulted in more nymphal population under elevated CO_2 than ambient CO_2 during both the years. The nymphal population thus followed the trend of total BPH population (Table 3).

Higher number of brachypterous females was recorded under elevated CO_2 than ambient CO_2 during both the years (Table 3). The highest number of brachypterous females was observed in the seventh and fifth week after release under elevated CO_2, and in the eighth and fifth week under ambient CO_2 during first and second years respectively. Peak female population was thus observed one week earlier under elevated CO_2 than ambient CO_2 during the first year, but in the same week as ambient CO_2 during the second year. Mean macropterous female population did not differ between the two CO_2 conditions during the two years. On the other hand, male population differed significantly under the two CO_2 conditions with peak population having been attained in the fifth week after adult release during the first year (Table 3).

Table 1. Brown planthopper (BPH) population/hill (nymphs, males and females) in open-top chambers during kharif 2010

	*BPH population (nymphs + males + females)									
	Weeks after adult release									
Treatment	1	2	3	4	5	6	7	8	9	Mean ± SE
Elevated CO_2 (570 ± 25 ppm)	2 ± 0.7 $(1.7 \pm 0.2)^{ji}$	2.1 ± 0.7 $(1.7 \pm 0.2)^{ji}$	35.2 ± 10.4 $(5.5 \pm 0.8)^{fge}$	76.3 ± 12.1 $(8.6 \pm 0.7)^{dce}$	435.4 ± 62.0 $(20.4 \pm 1.5)^{a}$	321.0 ± 144.5 $(15.8 \pm 2.9)^{b}$	94.4 ± 13.9 $(9.5 \pm 0.8)^{cd}$	290.5 ± 85.2 $(14.9 \pm 2.8)^{b}$	7.1 ± 2.8 $(2.5 \pm 0.5)^{hji}$	140.4 ± 54.7 $(8.9 \pm 2.3)^{a}$
Ambient CO_2 (380 ± 25 ppm)	2.9 ± 0.4 $(1.9 \pm 0.1)^{ji}$	4.1 ± 1.2 $(2.1 \pm 0.3)^{ji}$	17.5 ± 3.9 $(4.1 \pm 0.4)^{hgi}$	52.7 ± 20.5 $(6.5 \pm 1.1)^{dfge}$	121.4 ± 36.8 $(10.4 \pm 1.3)^{c}$	56.9 ± 5.1 $(7.6 \pm 0.3)^{dfce}$	29.4 ± 4.6 $(5.4 \pm 0.4)^{hfg}$	30.9 ± 7.1 $(5.2 \pm 0.7)^{hfg}$	0.0 ± 0.0 $(1.0 \pm 0.0)^{j}$	38.9 ± 13.0 $(4.9 \pm 1.0)^{b}$
Mean ± SE	2.5 ± 0.5 $(1.8 \pm 0.1)^{e}$	2.1 ± 1.0 $(1.9 \pm 0.2)^{e}$	26.4 ± 8.9 $(4.8 \pm 0.7)^{d}$	64.5 ± 11.8 $(7.5 \pm 1.0)^{c}$	278.4 ± 157 $(15.4 \pm 5.0)^{a}$	189.0 ± 132.1 $(11.7 \pm 4.1)^{b}$	61.9 ± 32.5 $(7.4 \pm 2.1)^{c}$	160.7 ± 129.8 $(10.1 \pm 4.9)^{b}$	3.6 ± 3.6 $(1.7 \pm 0.7)^{e}$	–

Treatment: $F = (63.3)$; CD = (1.0); $P < 0.0001$. Week: $F = (40.7)$; CD = (2.1); $P < 0.0001$. Interaction (treatment × week): $F = (7.7)$; CD = (3.1); $P < 0.0001$. Planthopper counts with same superscripts do not differ significantly. *Mean of ten replications. Data in parenthesis are SQRT (X + 1) transformed values.

Table 2. BPH population/hill (nymphs, males and females) in open-top chambers during kharif 2011

	*BPH population (nymphs + males + females)						
	Weeks after adult release						
Treatment	1	2	3	4	5	6	Mean ± SE
Elevated CO_2 (570 ± 25 ppm)	0.8 ± 0.2 $(1.3 \pm 0.1)^{f}$	18.6 ± 2.3 $(4.3 \pm 0.3)^{de}$	113.0 ± 11.5 $(10.6 \pm 0.5)^{a}$	55.8 ± 8.0 $(7.4 \pm 0.5)^{b}$	52.8 ± 6.8 $(7.2 \pm 0.5)^{b}$	28. 8 ± 4.6 $(5.3 \pm 0.4)^{c}$	44.9 ± 16.0 $(6.0 \pm 1.3)^{a}$
Ambient CO_2 (380 ± 25 ppm)	0.9 ± 0.3 $(1.3 \pm 0.1)^{f}$	20.9 ± 2.9 $(4.6 \pm 0.3)^{dc}$	46.6 ± 8.2 $(6.6 \pm 0.6)^{b}$	11.6 ± 1.4 $(3.5 \pm 0.2)^{e}$	14.4 ± 1.7 $(3.8 \pm 0.2)^{de}$	2.8 ± 0.9 $(1.8 \pm 0.2)^{f}$	16.2 ± 6.8 $(3.6 \pm 0.8)^{b}$
Mean ± SE	0.9 ± 0.1 $(1.3 \pm 0.0)^{e}$	19.8 ± 1.2 $(4.5 \pm 0.0)^{c}$	79.8 ± 33.2 $(8.6 \pm 1.9)^{a}$	33.7 ± 22.1 $(5.4 \pm 1.9)^{b}$	33.6 ± 19.2 $(5.5 \pm 1.7)^{b}$	15.8 ± 13.0 $(3.6 \pm 1.8)^{d}$	–

Treatments: $F = (140)$; CD = (0.40); $P < 0.0001$. Weeks: $F = (94.11)$; CD = (0.69); $P < 0.0001$. Interactions (treatment × week): $F = (15.70)$; CD = (0.97); $P < 0.001$. Planthopper counts with same superscripts do not differ significantly. *Mean of ten replications. Data in parenthesis are SQRT (X + 1) transformed values.

Table 3. *Mean number of BPH development stages at population peak and during the entire season, and fecundity and honey dew under elevated and ambient CO_2 in open-top chambers

	Nymphs/hill				Brachypterous females/hill				Macropterous females/hill				Males/hill					
	2010		2011		2010		2011		2010		2011		2010		2011			
CO_2 conc. (ppm)	#Peak	Season	Peak	Season	Peak	Season	Peak	Season	Peak	Season	Peak	Season	Peak	Season	Peak	Season	Fecundity (eggs/female)	Honey dew (mm^2/5 females)
Elevated (570 ± 25)	388^{a}	112^{a}	111^{a}	41.8^{a}	13.2^{a}	4.9^{a}	3.0^{a}	1.0^{a}	25.3^{a}	6.3^{a}	0.6^{a}	0.3^{a}	13.9^{a}	3.5^{a}	4.4	1.8	324.3^{a}	187.6^{a}
Ambient (380 ± 25)	90.6^{b}	24.2^{b}	44.5^{b}	14^{b}	7.5^{b}	2.3^{b}	0.7^{b}	0.3^{b}	20.3^{a}	6.2^{a}	0.7^{a}	0.4^{a}	8.3^{b}	2.4^{b}	5.3	1.5	231.7^{a}	48.9^{b}

*Mean of 10 replicates. #Values with same superscript in the same column do not differ significantly.

Table 4. Rice growth and yield parameters under elevated and ambient CO_2

Parameters*	Uninfested Elevated CO_2 (570 ± 25 ppm)	Uninfested Ambient CO_2 (380 ± 25 ppm)	Uninfested *t*-Statistics	Infested Elevated CO_2 (570 ± 25 ppm)	Infested Ambient CO_2 (380 ± 25 ppm)	Infested *t*-Statistics
No. of tillers/hill	31.5 ± 2.2	25.9 ± 1.8	$t = 1.9$ ($P = 0.03$)	36.9 ± 2.7	34 ± 1.6	$t = 0.9^{NS}$
No. of reproductive tillers/hill	26.4 ± 2.5	22.9 ± 2.1	$t = 1.9^{NS}$	34.3 ± 2.1	32.2 ± 1.8	$t = 0.8^{NS}$
Seeds/panicles	88.9 ± 9.9	77.9 ± 9.8	$t = 0.8^{NS}$	83.4 ± 12.4	74 ± 5.9	$t = 0.7^{NS}$
1000 seed weight (g)	22.5 ± 0.9	20.02 ± 0.5	$t = 2.4$ ($P = 0.01$)	18.8 ± 2.1	19.8 ± 0.6	$t = 0.4^{NS}$
Yield (g)	49.1 ± 4.1	44.2 ± 2.4	$t = 1.0^{NS}$	36.1 ± 5.2	38.7 ± 5.1	$t = 0.4^{NS}$
Yield loss (%)	–	–	–	26.5	12.4	

*Average of ten replications. NS, Non-significant.

However, male population did not differ significantly under elevated and ambient CO_2 during the second year.

Higher fecundity and higher nymphal and adult population under elevated CO_2 contributed to increased BPH population compared to ambient CO_2. Increased BPH fecundity and population under elevated CO_2 might also be attributed to favourable microenvironment that resulted from increased tillering and dense plant growth under elevated CO_2 conditions. Earlier elevated CO_2 has been observed to increase fecundity in cotton aphid, *Aphis gossypii*[15]; whitefly, *Bemisia tabaci*[16], and grain and peach aphid, *Myzus persicae*[12,17]. In field conditions also, closer spacing of rice hills leads to higher BPH population compared to wider spacing[18]. Besides, more number of brachypterous females also might have contributed to higher BPH population under elevated CO_2. It has been observed that under nutrient-rich diet, the BPH diverts more nutrients for producing more brachypterous females that in turn produce more eggs than the winged form[18]. In the present study, plants were healthier with luxuriant growth under elevated CO_2, which might have resulted in conditions similar to nutrient-rich diet. Changes in plant quality under enriched CO_2 and/or O_3 conditions have been found to affect performance of insects[19]. Contrary to the present study, elevated CO_2 did not affect alate formation in wheat aphid[12]. Plant quality has been observed to affect the relationship between female size and the number of offspring produced in Homoptera[20], Orthoptera[21], Lepidoptera[22], Coleoptera and Hymenoptera[23].

Honeydew excretion was found to be 74.4% higher ($t = 2.82$, $P = 0.006$) under elevated CO_2 (187.6 ± 44.8 mm^2/5 females) than ambient CO_2 (48 ± 20.1 mm^2/5 females). More honeydew excretion by BPH under elevated CO_2 was indicative of its higher sucking rate compared to ambient CO_2 and it was evident through severe hopper burn under elevated CO_2. Planthoppers have been reported to excrete 40.4% of their sucked assimilates as honeydew[24,25]. Sap feeders excreted more honeydew on plants exposed to elevated CO_2 (ref. 26). Sucking insects need more nitrogen (amino acids) for their growth and development; however, less nitrogen availability (higher C : N ratio) in plants grown under elevated CO_2 might enhance BPH feeding to make up for the nitrogen deficit[27,28]. A positive relation was observed between phloem C : N ratio and aphid sucking[29].

Under elevated CO_2, uninfested plants had higher number of tillers (21.6%), reproductive tillers (15.3%) and seeds/panicle (14.1%) compared to uninfested plants under ambient CO_2 (Table 4). Increase in the number of tillers, reproductive tillers and seeds/panicle led to increase in grain yield of plants (11.1%) grown under elevated CO_2. Doubling of tillers under elevated CO_2 resulted in increased plant densities[30,31], and increased growth and yield of rice[9]. Increased tillering was attributed to higher photosynthesis rate and lower respiration, which resulted in increased carbohydrate levels in rice plants grown under elevated CO_2 (refs 32 and 33). Elevated CO_2 was also found to increase yield in C3 plants by 20–34% (refs 34 and 35).

Despite the nutritive effect of elevated CO_2 on rice crop, higher BPH population coupled with increased sucking rate resulted in higher yield loss (26.5%) compared to that under ambient CO_2 (12.4%; Table 3). Plants suffered severe hopper burn under elevated CO_2 compared to ambient CO_2. Yield loss due to BPH damage was thus more under elevated CO_2 than under ambient CO_2.

Elevated CO_2 not only exhibited nutritive effect on rice growth and yield, but also stimulated BPH multiplication through increase in both fecundity and number of brachypterous females. Despite plant growth promoter effect of CO_2, the BPH inflicted higher yield loss in rice under elevated CO_2. Increasing concentration of CO_2, as is being projected for the future, would thus increase yield loss in rice due to BPH infestation. However, the ultimate effect of climate change on pest dynamics and crop yield would depend upon the interactive effect between elevated CO_2 and temperature, which would be addressed in due course.

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