

## Effects of elevated CO<sub>2</sub> on the nutrient compositions and enzymes activities of *Nilaparvata lugens* nymphs fed on rice plants

ZENG YunYun<sup>1</sup>, HUANG WenKun<sup>2</sup>, SU Li<sup>3</sup>, WU Gang<sup>1\*</sup>, ZHUANG Jing<sup>1</sup>, ZHAO WanYun<sup>1</sup>,  
HUA HongXia<sup>1</sup>, LI JunSheng<sup>4</sup>, XIAO NengWen<sup>4</sup> & XIONG YanFei<sup>5</sup>

<sup>1</sup>Hubei Insect Resources Utilization and Sustainable Pest Management Key Laboratory, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan 430070, China;

<sup>2</sup>State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing 100193, China;

<sup>3</sup>Department of Plant Protection, Agricultural College, Guangxi University, Nanning 530005, China;

<sup>4</sup>State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China;

<sup>5</sup>Department of Biology, College of Science, Wuhan University of Technology, Hubei 430070, China

Received May 23, 2012; accepted August 12, 2012

Elevated CO<sub>2</sub> may reduce the tolerance of *Nilaparvata lugens* (*N. lugens*) to adverse environmental factors through the biological and physiological degeneration of *N. lugens*. In an artificial climate box, under 375 and 750 μL L<sup>-1</sup> CO<sub>2</sub> levels, the rice stems nutrient content, the nutrient content and enzyme activities of *N. lugens* nymph fed on rice seedlings exposed to ambient and elevated CO<sub>2</sub> were studied. The results showed that rice stems had significantly higher protein and total amino acid levels under ambient than elevated CO<sub>2</sub> levels. Nymphs had significantly higher protein levels in the ambient CO<sub>2</sub> treatment, while their glucose levels were significantly lower under ambient CO<sub>2</sub> conditions. Significantly higher trypsin activity was observed in nymphs grown in elevated CO<sub>2</sub>. Significantly lower activities of the protective enzymes total superoxide dismutase and catalase were observed in the nymphs under ambient CO<sub>2</sub>. Meanwhile, the activity of the detoxification enzyme glutathione S-transferase was significantly higher in the ambient CO<sub>2</sub> treatment. Measuring how energy and resources were allocated to enzymes in *N. lugens* nymphs under elevated CO<sub>2</sub> conditions can provide a more meaningful evaluation of their metabolic tolerances to adverse climatic conditions.

***Nilaparvata lugens*, elevated CO<sub>2</sub>, rice plants, total superoxide dismutase, detoxification enzyme, glutathione S-transferase**

**Citation:** Zeng Y Y, Huang W K, Su L, *et al.* Effects of elevated CO<sub>2</sub> on the nutrient compositions and enzymes activities of *Nilaparvata lugens* nymphs fed on rice plants. *Sci China Life Sci*, 2012, 55: 920–926, doi: 10.1007/s11427-012-4378-8

The global carbon dioxide (CO<sub>2</sub>) atmospheric concentration has increased from a pre-industrial value of about 280 to 379 μL L<sup>-1</sup> in 2005, and the levels have been rising steadily by 1.9 μL L<sup>-1</sup> with an annual rate per year in the past 10 years [1]. The levels of atmospheric CO<sub>2</sub> are anticipated to double by the end of this century [2]. These changes are

likely to have a direct influence on plant chemicals and metabolic enzymes of herbivorous insects.

Profound impacts of elevated CO<sub>2</sub> in the terrestrial ecosystem, especially on the growth and chemistry of plants are expected [3]. General increases in aboveground biomass, yield, and carbon:nitrogen (C:N) ratios, particularly of C3 plants, have been reported [4–6]. Also, more CO<sub>2</sub> enhances photosynthetic rate, plant growth, and water use efficiency

\*Corresponding author (email: wugang1976@163.com)

[7,8]. Yin [9] reported that both leaf mass-based N content and specific leaf area decreased under elevated CO<sub>2</sub> in their meta-analysis of 62 species. Kim *et al.* [10] recommended that a sufficient supply of N be maintained over the entire rice growing season to maintain increased dry matter production and thus maximize grain yields under enriched CO<sub>2</sub>. Wu *et al.* [11] reported that CO<sub>2</sub> level significantly influenced foliar total amino acids in cotton plants, and foliar protein content significantly decreased under elevated CO<sub>2</sub> compared with ambient CO<sub>2</sub>. These studies proved that elevated atmospheric CO<sub>2</sub> can alter plant growth and chemistry.

*Nilaparvata lugens* Stål (Homoptera: Delphacidae) is one of the most destructive insect pests of rice [12]. It directly damages the plant by sucking phloem sap, causing hopper burn, and transmitting viral diseases. In 2005 and 2008, China reported a combined yield loss of 2.7 million tons of rice due to direct damage by *N. lugens* [13]. The impact of this pest was attributed to its ability to adapt ecologically and physiologically to environmental factors, as well as its direct and indirect impacts on rice yield [14].

Rice ecosystems are expected to respond to global climate changes (e.g., elevated atmospheric CO<sub>2</sub> concentration). A comprehensive review of rice arthropod communities under global warming showed that arthropods can evolve in diverse ways to adapt to the climate changes [15]. Lu *et al.* [14] reported that nymph survival, adult fecundity, and egg hatchability were significantly higher in *N. lugens* populations on rice plants with a high N regimen than those on rice plants with a low N regimen, indicating that the nitrogenous rice compounds enhanced the tolerance of *N. lugens* to adverse environmental stresses. Wu *et al.* [11] reported that foliar N content in cotton plants significantly decreased under elevated CO<sub>2</sub> compared with ambient CO<sub>2</sub>; elevated CO<sub>2</sub> and lower nitrogenous compounds can significantly destroy or inhibit enzyme activity in herbivorous insects. Zhou *et al.* [16] reported that glutathione S-transferase (GST) enzyme activity increased significantly after *N. lugens* fed on resistant rice varieties. Wu *et al.* [17] reported significantly higher activity of superoxide dismutase (SOD) and significantly lower activity of true choline esterase (TChE) in *Aphis gossypii* fed N-poor cotton plants under elevated CO<sub>2</sub> compared with ambient CO<sub>2</sub> treatment. There was a phenomenon that piercing-sucking insects had a positive response, such as higher compensation consumption and lower interspecific competition, to elevated CO<sub>2</sub>. Thus, elevated CO<sub>2</sub> has been implicated as causes of insect outbreaks and perceived as threats to ecosystem [18].

In this study, the nutrient compositions (seedling protein, free fatty acids, and total amino acids) of rice host plants in response to elevated CO<sub>2</sub> were measured. Also, the nutrient compositions (protein, glucose, and total amino acids), digestive enzymes (lipase and trypsin), protective enzymes

(total superoxide dismutase and catalase), and detoxification enzymes (glutathione S-transferase and acetylcholinesterase) activities in *N. lugens* nymphs fed on rice plants were analyzed. The objective was to quantify how physiological metabolism was allocated in nymphs fed rice plants in response to elevated CO<sub>2</sub>.

## 1 Materials and methods

### 1.1 Artificial climate box and setup of CO<sub>2</sub> levels

The growth chamber (PRX-500D-30; Haishu Safe Apparatus, Ningbo, China) was maintained at 75%±5% RH, (28±0.5)°C, and 16L:8D at 15000 LX of active radiation supplied by twelve 40 W fluorescent lamps.

Two levels of CO<sub>2</sub> concentration were continuously applied, in 375 μL L<sup>-1</sup> (current ambient level) and 750 μL L<sup>-1</sup> (double ambient level, representing the predicted level in about 100 years [15]). A self-assembly internal dynamic CO<sub>2</sub> gas chamber (closed dynamics CO<sub>2</sub> chamber, CDCC) was used as CO<sub>2</sub> control system, with infrared CO<sub>2</sub> measurement and control instrument (Ventostat 8102, Tellaire, USA).

### 1.2 *Nilaparvata lugens*

*N. lugens* were collected from greenhouses at the Huazhong Agriculture University and reared for 4 years in Hubei Insect Resources Utilization and Sustainable Pest Management Key Laboratory, Wuhan, China. A derivative colony was raised on Taichung Native 1 (TN1, susceptible rice) in the growth chamber (PRX-500D-30; Haishu Safe Apparatus, Ningbo, China).

### 1.3 Rice seedlings treatment

Seeds of TN1, a rice cultivar that is susceptible to *N. lugens*, were planted in glass cages filled with Kimura B nutrient solution (pH 5.4–6, China National Pharmaceutical Group, Beijing). After the seeds had sprouted, the cages were put into elevated CO<sub>2</sub> chambers. Three-leaf rice seedlings were used for feeding and chemistry assays. No chemical fertilizers or insecticides were used through the duration of the experiment. Stems cut from three-leaf stage were sampled and stored at -20°C for chemical composition assays.

### 1.4 Nymphs feeding treatments

Fifty pairs (1:1 sex ratio) were treated at each CO<sub>2</sub> concentration. Their eggs were stocked in each chamber and the fresh *N. lugens* were reared on the soilless seedlings in the organic glass cage (50 cm×38 cm×80 cm). Neonates that hatched within 12 h of one another each rearing cage were collected, and reared on three-leaf rice seedlings in each

cage with different treatment. *N. lugens* were transferred to fresh seedlings every six days. Three replicates each were put in the ambient CO<sub>2</sub> chamber (375 μL L<sup>-1</sup>) and elevated CO<sub>2</sub> chamber (750 μL L<sup>-1</sup>). This procedure continued for about 15 d, until the nymphs reached the fourth instar.

### 1.5 Stems chemical composition assays

Fresh three-leaf rice seedling stems were ground in liquid N<sub>2</sub> with a mortar and pestle, then homogenized at 9 times (mg mL<sup>-1</sup>) of NaCl solution in a 5 mL centrifuge tube. The homogenate was centrifuged at 4000 r min<sup>-1</sup> for 10 min, and the supernatant was analyzed. Protein content was determined using the Bradford method (1976), with bovine serum albumin (Nanjing Jiancheng, Nanjing, China) as the standard. Six replicates were analyzed for each CO<sub>2</sub> treatment. The content of free fatty acids and total amino acids were also analyzed according to the manufacturer's directions (Nanjing Jiancheng, Nanjing, China). Each test was replicated at less three times.

### 1.6 Insect biochemical assays

After weighing, five fourth-instar nymphs per treatment were placed into 2 mL centrifuge tubes, ground in liquid N<sub>2</sub> with a glass rod, then homogenized at 9 times or 99 times (mg mL<sup>-1</sup>) of NaCl solution. The homogenate was centrifuged at 4000 r min<sup>-1</sup> for 10 min, and the supernatant was analyzed. Protein content was determined using the Bradford method (1976), with bovine serum albumin (Nanjing Jiancheng, Nanjing, China) as the standard. Four replicates were analyzed for each CO<sub>2</sub> treatment.

Biochemical assays were conducted to test whether host-plant CO<sub>2</sub> level significantly changed metabolism in *N. lugens* nymphs. The content of protein, glucose, and total amino acids and the activities of two digestive enzymes (lipase and trypsin), two protective enzymes (total superoxide dismutase and catalase) and two detoxification enzymes (glutathione S-transferase and acetylcholinesterase) were measured according to the directions of reagent kits (Nanjing Jiancheng, Nanjing, China). Enzyme activities were calculated relative to total protein content. Test was replicated at least three times.

### 1.7 Data analysis

The mean content of protein, free fatty acids, and total amino acids in rice seedlings subjected to ambient versus elevated CO<sub>2</sub> treatments were compared with *t*-tests (SAS 6.12, SAS Institute Inc., Cary, NC, USA) [19]. Mean protein, glucose, and total amino acids content and enzyme activities in *N. lugens* fed those stems were also compared using *t*-tests ( $P < 0.05$ ).

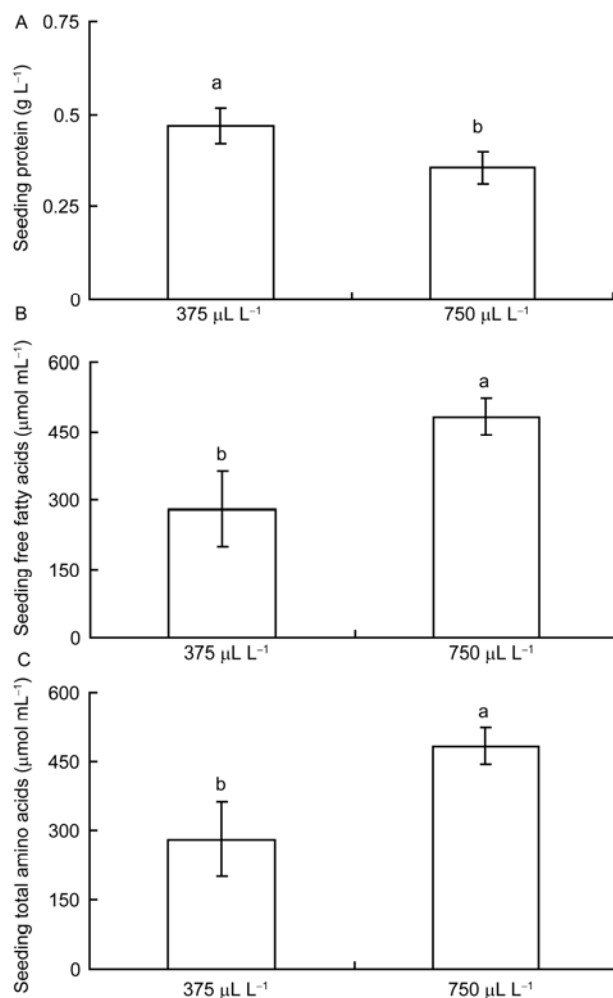
## 2 Results

### 2.1 Rice seedling chemical composition

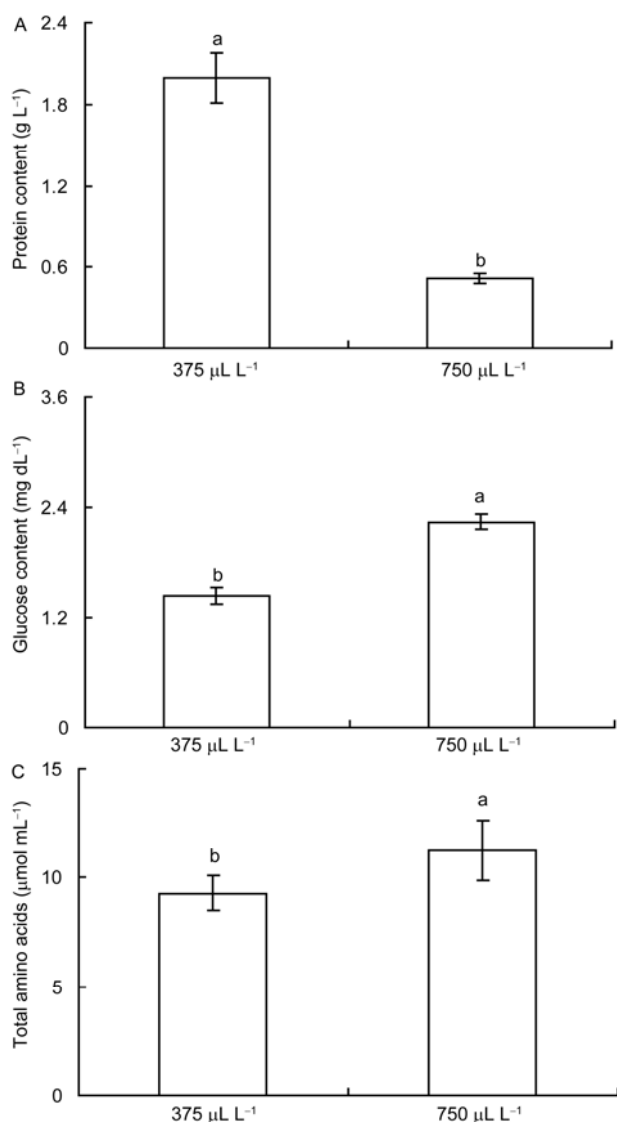
Protein levels were significantly higher in rice stems under ambient CO<sub>2</sub> treatment compared with elevated CO<sub>2</sub> treatment ( $|t|=5.15$ ,  $df=15$ ,  $P=0.0001$ ; Figure 1A). There was no significant difference in the amount of free fatty acids between the two treatments ( $|t|=3.13$ ,  $df=4$ ,  $P=0.0353$ ; Figure 1B). Rice stems grown in ambient CO<sub>2</sub> concentration had significantly more total amino acids than those grown in elevated CO<sub>2</sub> ( $|t|=4.71$ ,  $df=6$ ,  $P=0.0033$ ; Figure 1C).

### 2.2 Nilaparvata lugens chemical composition

*Nilaparvata lugens* nymphs in the ambient CO<sub>2</sub> treatment contained significantly more protein ( $|t|=15.47$ ,  $df=6$ ,  $P=0.0001$ ; Figure 2A), significantly less glucose ( $|t|=16.33$ ,  $df=10$ ,  $P=0.0001$ ; Figure 2B), and significantly less total amino acid ( $|t|=2.46$ ,  $df=6$ ,  $P=0.0494$ ; Figure 2C) than



**Figure 1** Changes (mean±SD) in seedling protein (A), free fatty acid (B) and total amino acid (C) content of rice stems grown in ambient and elevated CO<sub>2</sub> treatments. Different lowercase letters indicate significant differences between treatments by the *T* test ( $P < 0.05$ ).



**Figure 2** Changes (mean $\pm$ SD) in protein (A), glucose (B) and total amino acid (C) content in nymphs of *N. lugens* fed on rice grown in ambient and elevated CO<sub>2</sub> treatments. Different lowercase letters indicate significant differences between treatments by the *T* test ( $P < 0.05$ ).

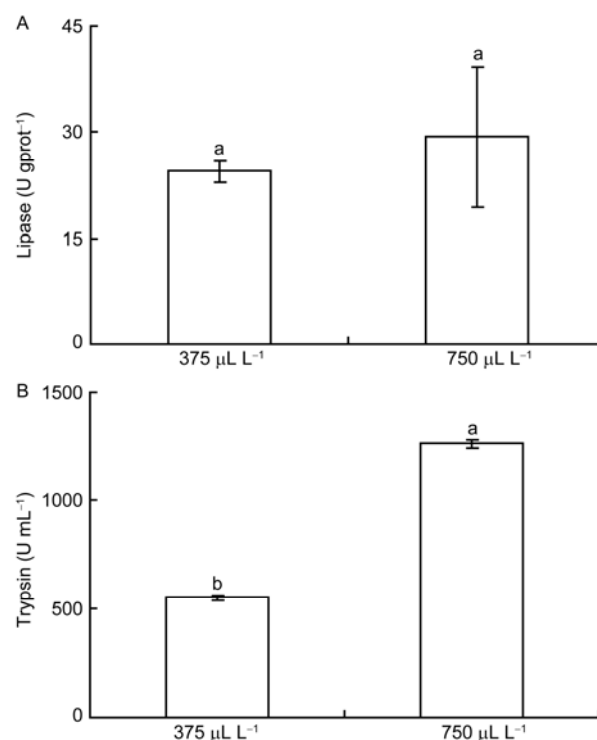
nymphs in the elevated CO<sub>2</sub> treatment.

### 2.3 *Nilaparvata lugens* digestive enzyme activities

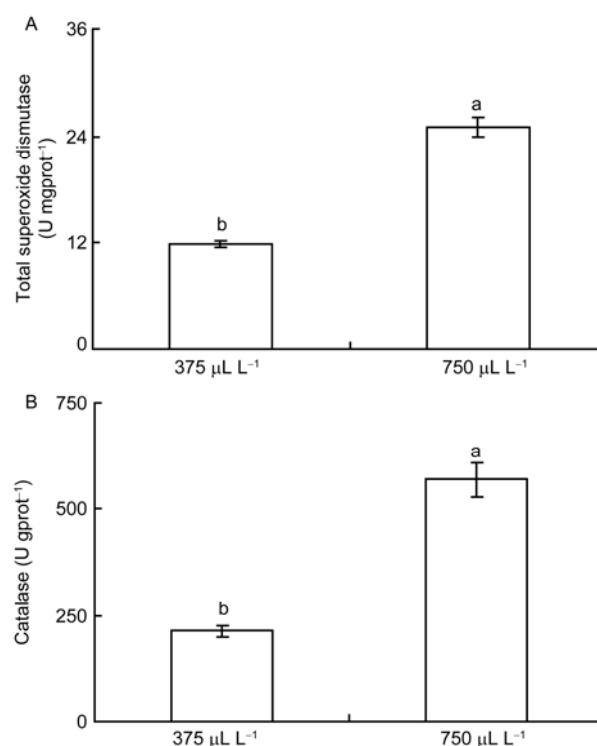
There were no significant differences in nymph lipase activity between ambient and elevated CO<sub>2</sub> treatments ( $|t|=0.48$ ,  $df=4$ ,  $P=0.6565$ ; Figure 3A). However, *N. lugens* nymphs in the elevated CO<sub>2</sub> treatment had significantly higher trypsin activity than those in the ambient CO<sub>2</sub> treatment ( $|t|=31.48$ ,  $df=4$ ,  $P=0.0001$ ; Figure 3B).

### 2.4 *Nilaparvata lugens* protective enzymes activities

Significantly lower activities of both total superoxide dismutase ( $|t|=11.48$ ,  $df=10$ ,  $P=0.0001$ ; Figure 4A) and catalase



**Figure 3** Changes (mean $\pm$ SE) in lipase (A) and trypsin (B) activities in nymphs of *N. lugens* fed on rice grown in ambient and elevated CO<sub>2</sub> treatments. Different lowercase letters indicate significant differences between treatments by the *T* test ( $P < 0.05$ ).



**Figure 4** Changes (mean $\pm$ SE) in total superoxide dismutase (A) and catalase (B) activities in nymphs of *N. lugens* fed on rice grown in ambient and elevated CO<sub>2</sub> treatments. Different lowercase letters indicate significant differences between treatments by the *T* test ( $P < 0.05$ ).

( $|t|=8.44$ ,  $df=10$ ,  $P=0.0001$ ; Figure 4B) were observed in *N. lugens* nymphs in the ambient than in the elevated  $CO_2$  treatment.

## 2.5 *Nilaparvata lugens* detoxification enzyme activities

The *N. lugens* nymphs in the elevated  $CO_2$  treatment had significantly less glutathione S-transferase activity than those in the ambient  $CO_2$  treatment ( $|t|=3.56$ ,  $df=10$ ,  $P=0.0052$ ; Figure 5A). However, there was no significant difference in acetylcholinesterase activity between the two treatments ( $|t|=0.91$ ,  $df=4$ ,  $P=0.6565$ ; Figure 5B).

## 3 Discussion

### 3.1 Rice seedling chemical composition

In general, plants (especially C3 plants, like rice) respond to elevated  $CO_2$  with increased photosynthesis and growth and decreased foliar N and total amino acids, primarily because of the accumulation of non-structural carbohydrates [11,20–22]. Brodbeck *et al.* [23] reported that the total amino acid content in the xylem strongly correlated with the survival and development rates of xylem-feeding insects. Chen *et al.* [24] indicated that spring wheat grown at elevated  $CO_2$  generally had more sucrose, glucose, total non-structural carbohydrates, free amino acids, and soluble protein and less ear fructose and nitrogen. In this study, rice

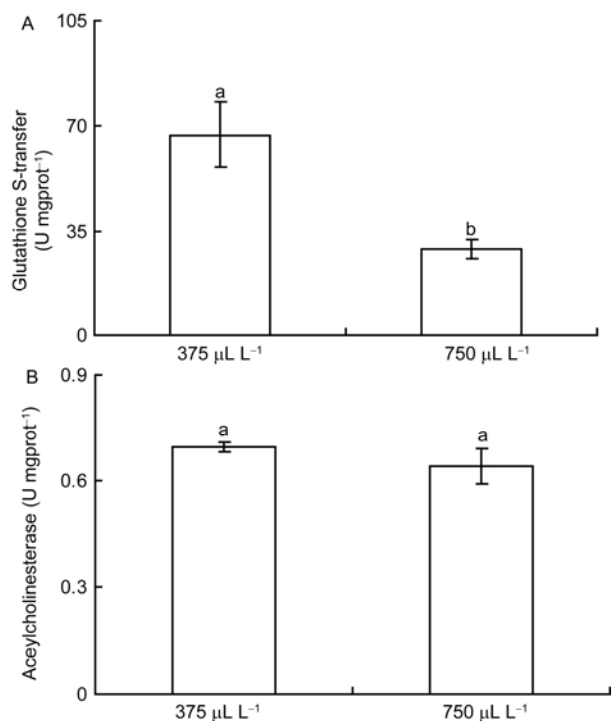
seedling had lower protein and total amino acid content in the elevated  $CO_2$  treatment compare with the ambient  $CO_2$  treatment, which indicated that limited N availability may reduce the tolerance of *N. lugens* to adverse environmental factors through the biological and physiological degeneration of the insects.

### 3.2 *Nilaparvata lugens* chemical composition and enzyme activities

A reduction in nutrient content often results in poorer insect performance as measure by behavioral or physiological parameters [25]. Most herbivorous insects responded to elevated  $CO_2$  by increasing development times and reducing growth and survival rates, population densities and fitness, presumably because of the increased levels of carbohydrates in host plants [26]. Nitrogen in rice plants plays a major role in the behavior and physiology of *N. lugens*. On N-rich host plants, *N. lugens* survive better and were more fecund [27,28]. Nymph and adult survival, fecundity, and egg hatchability were all significantly increased by higher N in rice plants. In choice tests, *N. lugens* adults preferred to feed and oviposit on N-rich over N-poor plants [29]. In the present study, significantly lower protein was observed in nymphs of *N. lugens* in the elevated  $CO_2$  treatment than the ambient  $CO_2$  treatment, which indicated that *N. lugens* individuals on rice plants with fewer nitrogenous compounds may have difficulty in obtaining nutrients and energy to find new habitats and migrate over long distances, such as to neighboring rice fields and newly-transplanted fields, resulting in low ecological fitness and reduced outbreak potential.

Changes in the chemical composition of host plants can be expected to affect the activities of some enzymes in their herbivores. Digestive proteases played two critical roles in an insect's physiology: breaking down proteins into amino acids essential for growth and development, and inactivating ingested protein toxins [30–32]. Lipases were fundamental to many physiological processes underpinning insect reproduction, development, defense from pathogens and oxidative stress, and pheromone signaling [31,33]. In this study, significantly higher trypsin levels were observed in nymphs grown in elevated  $CO_2$  compared with ambient  $CO_2$  levels, however, there was no significant difference in lipase levels between the two treatments. The enhanced activity of trypsin nymphs under elevated  $CO_2$  was accordant with decreasing nitrogenous content in their host plants.

The protection and detoxification enzymes of herbivorous insects were their most important defenses against host plants [34,35] or adverse environmental conditions [36,37]. Wu *et al.* [38] found that  $CO_2$  level significantly affected the activities of catalase (CAT) and true choline esterase (TChE) in cotton bollworm. Climate changed rice plant nutrition content, thus indirectly affected the physiological metabolism enzyme activities of *N. lugens*. In this study,



**Figure 5** Changes (mean $\pm$ SE) in glutathione S-transferase (GSH-ST) (A) and acetylcholinesterase (B) activities in nymphs of *N. lugens* fed on rice grown in ambient and elevated  $CO_2$  treatments. Different lowercase letters indicate significant differences between treatments by the *T* test ( $P<0.05$ ).

significantly higher catalase and total superoxide dismutase activities were observed in *N. lugens* nymphs under elevated compared with ambient CO<sub>2</sub>. However, glutathione S-transferase activity significantly decreased in nymphs under elevated versus ambient CO<sub>2</sub> treatment. The results showed that the increasing ecological adaptation and fitness of *N. lugens* in response to elevated CO<sub>2</sub> was strongly correlated to the enhanced activities of protection enzymes rather than digestive and detoxification enzymes.

### 3.3 Ecological consequences of global warming to *Nilaparvata lugens*

Climate change caused by increasing atmospheric CO<sub>2</sub> will probably have significant effects on agricultural insect pests [39]. In general, in a warmer climate, the pests will grow and develop faster. They may have more generations per year, causing more damage [40]. Elevated CO<sub>2</sub> causes the *N. lugens* to expand into nearby suitable habitats and migrate to other districts. Zhao [41] reported that under elevated CO<sub>2</sub>, *N. lugens* not only grows in perennially wintering areas, but also expand to new habitats, thus expanding their wintering areas. The northern winter boundary of *N. lugens* varies over 1–2 degrees latitude. However, their overwintering populations may be geographically restricted by the distributions of their host crops. The changes in rice crop coverage due to climate warming will result in a northward spread of *N. lugens*.

## 4 Conclusion

Our studies provide a profile of the direct effects of elevated CO<sub>2</sub> on the enzyme activities of *N. lugens* nymphs. Measuring how herbivorous insects allocate N to enzymes in response to elevated CO<sub>2</sub> can provide a more meaningful evaluation of their metabolic tolerances to adverse climatic conditions when eating N-poor plants. Therefore, these analyses should be considered in developing and implementing integrated pest management (IPM) strategies for herbivorous insects under rising CO<sub>2</sub> environmental conditions.

*This work was supported by the National Natural Science Foundation of China (Grant Nos. 31071691 and 31171846), the Major Projects of Cultivated Varieties of Genetically Modified Organisms (Grant No. 2011ZX08012-005) and the Self-determined and Innovative Research Funds of Wuhan University of Technology (Grant No. 2011-1a-037), China.*

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