Effects of Irrigation Methods on Population Dynamics of Brown Planthopper and Its Main Natural Enemies in High-Quality Late-Season Rice (Postprint)

Authors: Li Chao, Liu Yang, Chen Kailin, Fang Baohua, Tang Wenguang, Zhou Xueqi, Zhang Yuzhu, Chen Song

Date: 2017-11-07T00:00:00+00:00

Abstract

High-quality late-season rice is highly favored by consumers for its excellent taste. As irrigation regime constitutes one of the crucial cultivation measures for high-quality late-season rice, investigating its effects on the population dynamics of the brown planthopper, Nilaparvata lugens, and its primary natural enemies, identifying an irrigation method that can effectively suppress brown planthopper infestations, thereby reducing chemical pesticide usage and improving rice quality, is of paramount importance for achieving quality and efficiency enhancement. This study established four irrigation regimes: continuous flooding, intermittent irrigation, wet irrigation, and deficit irrigation, to examine the effects of different irrigation methods on the population dynamics of brown planthopper and its main natural enemies (the wolf spider Pardosa pseudoannulata and the green mirid bug Cyrtorhinus lividipennis) in high-quality late-season rice under two pest control strategies (biological control and chemical control) and under full and partial isolation with insect-proof nets, aiming to provide theoretical support for green cultivation of high-quality late-season rice. The results demonstrated that: Under biological control, the initial appearance of Cyrtorhinus lividipennis occurred later than that of the brown planthopper, exhibiting a primarily numerical response to the pest, and reliance on Cyrtorhinus lividipennis alone could not effectively control brown planthopper outbreaks. During the critical period of brown planthopper population growth in late-season rice (booting to milk-ripe stage), brown planthopper populations under continuous flooding were significantly lower than those under deficit irrigation, while Pardosa pseudoannulata populations under deficit irrigation were significantly lower than those under other irrigation regimes; population changes of Cyrtorhinus lividipennis and Pardosa pseudoannulata were significantly correlated with brown planthopper population changes ($P<0.05$). When field brown planthopper populations were below 1,891.1 individuals per hundred hills and the spider-to-planthopper ratio (Pardosa pseudoannulata: brown planthopper) exceeded 1:9.67, Pardosa pseudoannulata could completely suppress brown planthopper infestations. Under chemical control, chemical pesticides exerted severe lethal effects on Cyrtorhinus lividipennis across all irrigation regimes, whereas continuous flooding could effectively mitigate pesticide toxicity to Pardosa pseudoannulata. In conclusion, continuous flooding favors the conservation of primary natural enemies in paddy fields and provides the optimal control efficacy against brown planthopper. Integrating water-saving concepts into production, segmented continuous flooding could be implemented throughout the entire growth period of late-season rice, thereby achieving both water resource conservation and effective reduction of chemical pesticide usage.

Full Text

Effect of Irrigation Method on Population Dynamics of Nilaparvata lugens and Natural Enemies in High-Quality Late Rice Fields

LI Chao[1],[3], **LIU Yang**[1], **CHEN Kailin**[1], **FANG Baohua**[1], **TANG Wenguang**[2], **ZHOU Xueqi**[4], **ZHANG Yuzhu**[1], CHEN Song[5]

[1] Hunan Province Rice Research Institute, Changsha 410125, China; [2] Hunan Province Soil and Fertilizer Research Institute, Changsha 410125, China; [3] College of Agronomy, Hunan Agricultural University, Changsha 410128, China; [4] Heshan District Agriculture Bureau of Yiyang City, Yiyang 413002, China; [5] China National Rice Research Institute, Hangzhou 310006, China

Abstract

High-quality late-season rice is preferred by consumers for its good taste. As an important cultivation practice, irrigation method affects population dynamics of Nilaparvata lugens (Stål) and its main natural enemies. This study examined four irrigation methods—long-term irrigation, intermittent irrigation, wet irrigation, and deficit irrigation—under two pest control strategies (biological and chemical control) and two isolation methods (semi-partitioning and full-partitioning with fly nets) to identify effective irrigation practices that reduce N. lugens occurrence, decrease chemical pesticide use, and improve rice quality. Results showed that under biological control, Cyrtorrhinus lividipennis (Reuter) appeared later than N. lugens, exhibiting a following effect that alone could not effectively control planthopper populations. During the critical period of N. lugens population growth (booting to milk stage), long-term irrigation maintained significantly lower planthopper densities than deficit irrigation, while deficit irrigation supported significantly fewer Pardosa pseudoannulata (Bose. et Str., 1906) than other methods. Population changes of both natural enemies correlated significantly with planthopper populations ($P<0.05$). P. pseudoannulata achieved complete control when planthopper density remained below 1,891.1 individuals per 100 clumps and the spider:planthopper ratio exceeded 1:9.67. Under chemical control, pesticides caused severe mortality of C. lividipennis across all irrigation treatments, while long-term irrigation effectively reduced pesticide toxicity to P. pseudoannulata. In conclusion, long-term irrigation best protects major natural enemies and provides optimal planthopper control. Integrating water-saving concepts, segmented long-term irrigation should be explored for late rice production to conserve water while reducing chemical pesticide applications.

Keywords: Irrigation method; Pest control method; High-quality late rice; Nilaparvata lugens (Stål); Natural enemy; Population dynamics

Introduction

The advent of chemical pesticides led to explosive growth in chemical control of rice (Oryza sativa L.) diseases and pests. However, prolonged and extensive use of chemical pesticides has significantly enhanced pest resistance, resulting in increasingly frequent pest outbreaks [1-2]. Concurrently, pesticide usage has shown a year-by-year increasing trend, while rice quality has continuously declined. As consumer preferences have evolved, demands for rice quality have grown higher. In this context, high-quality late-season rice has gained increasing favor among consumers [3-4], particularly green and organic late-season rice. Rice pests represent a critical factor limiting high and stable yields of high-quality late-season rice. Among the three major rice pests, the rice leaf folder [Cnaphalocrocis medinalis (Guenee)] and the striped rice stem borer [Chilo suppressalis (Walker)] can be controlled through Trichogrammatid wasps [5-6], whereas the brown planthopper [Nilaparvata lugens (Stål)] remains a major challenge and hot topic in biological control.

Previous studies [7-9] have demonstrated that spiders (Araneae sp.) are important natural enemies of the brown planthopper, with the enemy function index (EF) confirming a significant negative correlation between EF values and the degree of rice damage caused by planthoppers. Paddy field spiders exert substantial control over planthoppers, effectively curbing their excessive reproduction. Among them, *Pardosa pseudoannulata* (Bose. et Str., 1906) and *Pirata subpiraticus* (Boes. et Str., 1906) represent dominant spider species in rice fields [10-11]. *Cyrtorrhinus lividipennis* (Reuter) serves as a crucial predatory natural enemy of the brown planthopper, primarily feeding on planthopper eggs while also preying on nymphs and short-winged adults [12-13]. In recent years, prolonged use of chemical pesticides has severely impacted the growth and reproduction of natural enemies in paddy fields, while planthopper resistance has intensified annually, leading to continuously increasing pesticide applications and placing unprecedented strain on the agricultural ecosystem. Irrigation methods constitute an essential component of green cultivation technology systems, yet research on their effects on pest and natural enemy population dynamics in rice fields remains scarce. Therefore, this study investigated population dynamics of the brown planthopper and its primary natural enemies under different irrigation methods, using chemical control as a control, to identify an irrigation method compatible with high-quality late-season rice production and provide theoretical support for green cultivation practices.

Materials and Methods

1.1 Experimental Site Description

Field experiments were conducted from 2013 to 2015 at the Zhongtang Experimental Base in Bijia Mountain Township, Heshan District, Yiyang City, Hunan Province (28°29 30 -28°29 50 N, 112°30 20 -112°30 40 E). The region features a subtropical continental monsoon humid climate with an average annual temperature of 16.5°C, average daily sunshine of 1,560 hours, and average annual rainfall of 1,465 mm. The experimental fields were previously cropped with rice and had uniform soil fertility. In the biological control area, soil alkali-hydrolyzable nitrogen, available phosphorus, available potassium, organic matter, and pH were 165.2 $\mathrm{mg \cdot kg^{-1}}$, 6.57 $\mathrm{mg \cdot kg^{-1}}$, 66.2 $\mathrm{mg \cdot kg^{-1}}$, 33.7 $\mathrm{g \cdot kg^{-1}}$, and 5.63, respectively. In the chemical control area, these values were 174.3 $\mathrm{mg \cdot kg^{-1}}$, 7.03 $\mathrm{mg \cdot kg^{-1}}$, 62.1 $\mathrm{mg \cdot kg^{-1}}$, 35.8 $\mathrm{g \cdot kg^{-1}}$, and 5.42, respectively. Rainfall and temperature-humidity conditions during the experimental period are shown in Figure 1 [Figure 1: see original paper].

1.2 Experimental Design

Experiments were conducted annually from July to November during 2013-2015, with 2013 serving as a pilot study. The rice cultivar used was 'Xiangwanxian 12' , provided by Hunan Nongfeng Seed Industry Co., Ltd.

(1) Semi-isolation experiment: Four irrigation treatments were established: long-term irrigation (A), wet irrigation (B), intermittent irrigation (C), and deficit irrigation (D). Long-term irrigation maintained a 3-5 cm water layer throughout the growth period, with water withdrawn one week before harvest. Wet irrigation maintained a 3-5 cm water layer during transplanting and heading stages, with soil moisture maintained above 60% during other periods. Intermittent irrigation maintained a 3-5 cm water layer during transplanting and heading stages, followed by alternate wetting and drying after heading, with water withdrawn one week before harvest. Deficit irrigation involved no artificial irrigation throughout the growth period except during transplanting, relying solely on natural rainfall. Each irrigation method was combined with two pest control approaches: biological and chemical control. The chemical control plots received chemical pesticides throughout the growth period, while the biological control plots received no pesticides, relying instead on artificial releases of Trichogramma wasps and natural paddy field enemies. Plots were isolated from each other using nylon screen mesh, with no isolation above the plots. Each treatment had three replicates.

- **Biological control area:** The surrounding area employed biological control, with plot size of 100 m^2.
- **Chemical control area:** The surrounding area employed chemical control, with plot size of 100 m^2 and soil fertility levels equivalent to the biological control area.

(2) Full-isolation experiment: The upper portion of plots was fully isolated with nylon screen mesh (30 mesh × 30 mesh) to prevent immigration and emigration of natural enemies and pests; other design aspects remained identical to the semi-isolation experiment.

1.3 Field Management

Rice was sown on June 15. Seeds were disinfected by soaking in 200× concentrated strong chlorinated solution, then coated with dry-nurse seed coating after germination at a rate of 3.5 kg of rice seed per kg of coating. Seedlings were raised in 308-hole nursery trays with approximately 35 g of seed per tray. Due to continuous rainfall in 2014, early rice exhibited delayed maturity, postponing transplanting to July 26; in 2015, transplanting occurred on July 17. Base fertilizer application consisted of rapeseed cake (600.0 $kg \cdot ha^{-1}$) and compound fertilizer (800.0 $kg \cdot ha^{-1}$, $N:P_2O_5:K_2O$ = 15:10:15). On August 3, urea (60.0 $kg \cdot ha^{-1}$) and KCl (140.0 $kg \cdot ha^{-1}$) were applied as tillering fertilizer. On August 23, urea (200 $kg \cdot ha^{-1}$) was applied as panicle fertilizer. Plot isolation was implemented on August 13.

In the chemical control area during 2014, 300 $g \cdot ha^{-1}$ of 10% bensulfuron-methyl wettable powder was applied on August 3 for broadleaf and sedge weed control; 600 $mL \cdot ha^{-1}$ of Dow AgroSciences Qianjin (100 $g \cdot L^{-1}$ cyhalofop-butyl) for controlling *Leptochloa chinensis*; 300 $mL \cdot ha^{-1}$ of Dow AgroSciences Daojie (25 $g \cdot L^{-1}$ penoxsulam) for barnyard grass control; 6 $g \cdot ha^{-1}$ of jinggangmycin on August 23 for sheath blight and false smut control; 150 $mL \cdot ha^{-1}$ of Kongkuan (200 $g \cdot L^{-1}$ chlorantraniliprole) on September 20 and October 5 for striped stem borer and leaf folder control; and 300 $g \cdot ha^{-1}$ of 10% imidacloprid wettable powder plus 25% buprofezin for brown planthopper control. In 2015, chemical control was applied on July 24, August 16, September 13, and September 28 using the same chemicals as in 2014.

In the biological control area, Trichogramma wasps were released uniformly at a rate of 150,000 individuals per hectare on August 19, September 11, and September 28 in 2014, and on August 13, September 5, and September 22 in 2015, for controlling leaf folders and stem borers. Except for jinggangmycin application for sheath blight control, no other pesticides were used throughout the rice growth period.

1.4 Measurements and Methods

Beginning 26 days after transplanting and continuing until rice harvest, populations of *Pardosa pseudoannulata*, *Cyrtorrhinus lividipennis*, and *Nilaparvata* *lugens* were surveyed every 8-10 days using non-destructive direct visual observation to minimize ecosystem disturbance. In each plot, five representative sampling points were selected using the five-point sampling method, with 10 rice clumps examined per point. Population densities were then calculated as individuals per 100 clumps.

1.5 Data Analysis

Data analysis and graphing were performed using DPS 14.50 and Microsoft Excel 2007 software.

Results

2.1 Effects of Irrigation Methods on Brown Planthopper Population Dynamics

Figure 2 [Figure 2: see original paper] shows that brown planthopper populations under long-term irrigation were lower than other irrigation treatments throughout all growth stages except maturity. Under biological control with semi-isolation (Fig. 2a), planthopper numbers in all irrigation treatments exhibited an initial increase followed by a decrease over time in 2014. Long-term irrigation consistently maintained the lowest planthopper populations, being significantly lower than deficit irrigation from September 7 (booting stage) to October 14 (wax ripening stage) and significantly lower than the other three irrigation methods from October 4 (milking stage) to October 14 ($P<0.05$), peaking on September 23. In contrast, the other three irrigation treatments all peaked on October 4. From September 7 to September 23 (heading stage), deficit irrigation harbored significantly more planthoppers than the other three methods ($P<0.05$), reaching 3,212 individuals per 100 clumps on September 23, indicating earlier infestation and greater damage severity under deficit irrigation. Under biological control with full isolation (Fig. 2b), planthopper numbers also showed an initial increase followed by decrease in 2014. Deficit irrigation maintained significantly higher planthopper populations throughout the entire growth period compared to other methods ($P<0.05$). All four treatments peaked on October 14, later than in semi-isolation, with deficit irrigation reaching 3,894.0 individuals per 100 clumps–37.3%, 34.3%, and 79.9% higher than wet, intermittent, and long-term irrigation, respectively. Under semi-isolation with biological control, maximum planthopper numbers in intermittent, deficit, and wet irrigation (except long-term irrigation) were all significantly higher than their full-isolation counterparts in 2014 ($P<0.05$), with populations declining sharply between October 4-14, indicating planthopper emigration under semi-isolation (unpublished data). Figure 1 shows that air humidity fluctuated minimally during October 4-14, with temperatures remaining above 20°C (average 22.6°C) from October 4-12, but dropping to 18.6°C and 18.8°C on October 13 and 14 without rainfall, suggesting temperature reduction was a key factor triggering planthopper emigration. In 2015, planthopper infestation across all irrigation treatments was significantly lower than in 2014, primarily due to continuous rainfall and lower temperatures during the mid-to-late growth period. Under chemical control (Figs. 2c, d), planthopper populations were significantly lower than under biological control ($P<0.05$), with no consistent pattern among irrigation methods, as chemical pesticide applications masked treatment effects.

2.2 Effects of Irrigation Methods on *Pardosa pseudoannulata* Population Dynamics

Figure 3a [Figure 3: see original paper] shows that under biological control with semi-isolation, *Pardosa pseudoannulata* populations exhibited wave-like fluctuations in 2014, increasing rapidly from August 20 to September 7, peaking on September 7, then declining slowly to a minimum on September 23. Over time, long-term irrigation showed a gradual upward trend, while the other three irrigation methods displayed initial increases followed by decreases, reaching minimum populations at rice maturity. This indicates that long-term and intermittent irrigation facilitate establishment of *P. pseudoannulata* populations during the late rice growth period. Significant differences in *P. pseudoannulata* populations were observed among irrigation methods ($P<0.05$), with deficit irrigation maintaining significantly lower populations than the other three methods across all growth stages ($P<0.05$), demonstrating that deficit irrigation is unfavorable for *P. pseudoannulata* development. Under full isolation (Fig. 3b), *P. pseudoannulata* populations in all irrigation treatments peaked on September 14, followed by a general decline through rice maturity, differing somewhat from trends observed under semi-isolation. In 2015, continuous rainfall during the mid-to-late growth period resulted in non-significant differences among irrigation treatments. Under chemical control with semi-isolation, the four irrigation methods showed no consistent pattern in *P. pseudoannulata* population dynamics (Fig. 3c). From August 20 to September 15, populations in all treatments showed alternating increases. From September 15 to maturity, long-term irrigation maintained significantly higher *P. pseudoannulata* populations than the other three methods ($P<0.05$), with deficit irrigation being the lowest. Under full isolation (Fig. 3d), no clear pattern emerged among the four irrigation methods, though long-term irrigation generally remained significantly higher than the other three, while deficit irrigation consistently maintained the lowest *P. pseudoannulata* populations throughout the late rice growth period. These results indicate that *P. pseudoannulata* populations under long-term irrigation were least affected by chemical pesticides, while those under deficit irrigation were most affected. Therefore, appropriate irrigation methods should be adopted to increase *P. pseudoannulata* populations, effectively harnessing natural enemy control and reducing chemical pesticide applications.

2.3 Effects of Irrigation Methods on *Cyrtorrhinus lividipennis* Population Dynamics

Figure 4 [Figure 4: see original paper] shows that in the biological control semi-isolation experiment (Fig. 4a), no *Cyrtorrhinus lividipennis* were observed before August 28, with small numbers first appearing on September 7. Subsequently, populations in all four irrigation treatments showed an initial increase followed by decrease, peaking on October 14 (wax ripening stage). From September 7 to October 4, *C. lividipennis* populations ranked as: deficit irrigation > wet irrigation > intermittent irrigation > long-term irrigation. After October 14, populations in deficit, intermittent, and wet irrigation declined sharply, while the decrease was more gradual under long-term irrigation. This indicates that deficit irrigation promoted large early populations but rapid later decline, whereas long-term irrigation supported smaller early populations but larger later populations. Under full isolation (Fig. 4b), patterns before October 11 were similar to semi-isolation, but after October 11, the decline in *C. lividipennis* populations was slower than under semi-isolation, primarily because full isolation prevented emigration (unpublished data). In 2015, *C. lividipennis* populations were significantly lower than in 2014, mainly due to lower brown planthopper populations limiting food availability and constraining natural enemy development. Under chemical control, no consistent pattern emerged among irrigation treatments, with extreme fluctuations across growth stages (Figs. 4c, d), indicating high sensitivity of *C. lividipennis* to chemical pesticides.

2.4 Correlation Analysis Between Natural Enemies and Brown Planthoppers Under Biological Control

Under semi-isolation conditions (Fig. 5 [Figure 5: see original paper]), the correlation between brown planthopper numbers and *Pardosa pseudoannulata* numbers reached significance ($R^2 = 0.5378$, $P = 0.05$), with planthopper populations showing a parabolic trend of initial increase followed by decrease as *P. pseudoannulata* increased. Derivative analysis of the curve equation revealed that the maximum point corresponded to *P. pseudoannulata* and planthopper populations of 195.6 and 1,891.1 individuals per 100 clumps, respectively. This indicates that when field planthopper populations remain below 1,891.1 individuals per 100 clumps and the *P. pseudoannulata*:planthopper ratio exceeds 1:9.67, *P. pseudoannulata* can achieve complete control of planthopper infestation; otherwise, reliance on this single natural enemy species proves insufficient for effective control. The correlation between planthopper numbers and *Cyrtorrhinus lividipennis* numbers showed highly significant positive correlation ($R^2 = 0.8773$, $P = 0.01$). Under full isolation (Fig. 5), the correlation between planthopper numbers and *P. pseudoannulata* numbers was highly significant and negative ($R^2 = 0.8671$, $P = 0.01$), with planthopper populations decreasing as *P. pseudoannulata* increased. This contrasts with semi-isolation results, primarily because full isolation prevented planthopper immigration and emigration, thereby increasing predation probability within experimental plots and reaffirming that increasing *P. pseudoannulata* populations effectively reduces planthopper damage. The relationship between *C. lividipennis* and planthoppers under full isolation was similar to that under semi-isolation. Under full isolation, a quadratic polynomial regression with planthoppers (Y) as the dependent variable and *C. lividipennis* (X_1) and *P. pseudoannulata* (X_2) as independent variables yielded the equation: $Y = 329.56 + 0.32X_1 - 5.23X_2 - 0.00021{X_1}^2 + 0.0055X_1X_2$. F-test analysis revealed $F = 12.54$, $P = 0.00128$, reaching highly significant levels, indicating a highly significant regression relationship between natural enemies and brown planthoppers. Significance testing of individual regression coefficients yielded P-values of 0.097, 0.028, 0.047, 0.079, and 0.049 for X_1, X_2, ${X_1}^2$, and X_1X_2, respectively, demonstrating that X_2, ${X_1}^2$, and X_1X_2 were the primary factors influencing planthopper populations (Y).

Discussion

3.1 Effects of Irrigation Methods on Brown Planthopper Population Dynamics

Cultivation practices represent one of the important traditional measures for rice pest control. Previous studies have shown that nitrogen fertilizer and planting density significantly affect brown planthopper occurrence [14-17]. Liu et al. [18] reported that hand-transplanted rice experienced the most severe brown planthopper infestations, followed by mechanically transplanted rice, with direct-seeded rice being the least affected. As an important cultivation practice for high-quality late-season rice, the effects of irrigation methods on population dynamics of major rice pests have been documented. Under long-term flooding conditions, rice plants develop poor root systems and weak stems, favoring planthopper reproduction, while sunning fields can suppress planthopper propagation [19]. Our study demonstrates that under biological control, planthopper peaks occurred during later growth stages under both isolation methods, with long-term irrigation maintaining lower planthopper numbers than other treatments at all times. This suggests that long-term irrigation conditions are unfavorable for planthopper growth and reproduction, possibly because frequent water level fluctuations under long-term irrigation hinder planthopper oviposition and egg hatching, or directly submerge eggs, causing asphyxiation. This finding contradicts Luo et al. [20], who reported lighter planthopper infestations under water-saving irrigation compared to traditional flooding. However, their study did not specify the pest control method employed; if chemical control was used, their results might only indicate that planthopper resurgence after chemical control is more likely under traditional flooding than water-saving irrigation, without fully elucidating the true effects of irrigation methods on planthopper populations. Under biological control, deficit irrigation promoted earlier planthopper infestation with greater damage severity compared to other methods. This may be attributed to the strong hydrophilic nature of the key natural enemy *Pardosa pseudoannulata*, resulting in smaller populations under deficit irrigation and consequently larger initial planthopper populations. Additionally, deficit irrigation lacks water level fluctuations that would submerge planthopper eggs, leading to more severe early-season infestations. The specific mechanisms require further investigation. Jiang et al. [21] found no significant correlation between annual average temperature/rainfall and planthopper damage area or rice yield loss. Our study observed substantial inter-annual variation in planthopper occurrence, likely because low temperatures and frequent rainfall affected planthopper immigration, while locally reproduced planthoppers were completely controlled by natural enemies. Therefore, chemical pesticide use in production should be determined based on annual climate conditions combined with field monitoring. When planthopper populations are low during early late-rice growth, natural enemy control should be maximized. When populations reach economic injury levels, application of highly effective, low-toxicity pesticides should be employed to minimize pesticide usage, avoid waste, and reduce environmental pollution, thereby supporting China's 'Two Reductions' initiative.

3.2 Effects of Irrigation Methods on *Pardosa pseudoannulata* and *Cyrtorrhinus lividipennis* Population Dynamics

Pardosa pseudoannulata and *Cyrtorrhinus lividipennis* are important natural enemies of the brown planthopper. Current research has extensively examined the effects of nitrogen application rates, transplanting methods, and chemical pesticide types/dosages on *Pirata subpiraticus*, *Ummeliata insecticeps* [18,22-24], and *C. lividipennis* [18,25-28]. However, few studies have investigated how irrigation methods affect population dynamics of *P. pseudoannulata* and *C. lividipennis*. Our study demonstrates that under biological control, *P. pseudoannulata* populations generally showed an initial increase followed by decrease. Early population growth was primarily driven by increasing pest populations, while later declines may have resulted from temperature drops and planthopper emigration. Long-term irrigation facilitated establishment of *P. pseudoannulata* populations during the late rice growth period, playing an important role in controlling late-season planthoppers. Deficit irrigation maintained significantly lower *P. pseudoannulata* populations than the other three methods throughout the rice growth period, indicating that deficit irrigation is unfavorable for *P. pseudoannulata* development, possibly due to the strong hydrophilic nature of this spider species. This finding differs from Zhu et al. [29], who reported no significant difference between film-mulched dry cultivation and conventional flooding on late-season spider populations. Chemical pesticides significantly impact *C. lividipennis*, with chlorantraniliprole notably reducing population growth and exhibiting strong lethal effects [27,30]. Our study found that *P. pseudoannulata* populations under long-term irrigation were least affected by chemical pesticides, while those under deficit irrigation were most affected. Therefore, appropriate irrigation methods should be employed to increase *P. pseudoannulata* populations, effectively utilizing natural enemy control and reducing chemical pesticide usage. However, long-term irrigation wastes substantial water resources, necessitating exploration of segmented flooding irrigation patterns that conserve water while protecting field natural enemies like *P. pseudoannulata*. Our study found that *C. lividipennis* appeared later than planthoppers, increasing with planthopper populations, indicating that planthoppers serve as an important food source for *C. lividipennis* development. However, this represents primarily a following effect, and relying solely on *C. lividipennis* cannot effectively control major planthopper outbreaks. Under deficit irrigation, *C. lividipennis* exhibited large early populations with rapid later decline, whereas long-term irrigation showed small early populations with large later populations, mainly because planthopper infestation occurred earlier under deficit irrigation and later under long-term irrigation. Under full isolation, *C. lividipennis* patterns before October 11 were similar to semi-isolation, but after October 11, population declines were slower across the four irrigation treatments compared to semi-isolation, primarily because full isolation prevented *C. lividipennis* emigration (unpublished data).

3.3 Correlations Between Major Natural Enemies and Brown Planthoppers Under Biological Control

Li et al. [31] established a multi-species coexistence system comprising the natural enemies *Ummeliata insecticeps*, *Pirata subpiraticus*, and *Clubiona japonicola* with brown planthoppers, using quadratic general rotary combination design to analyze interactions among natural enemies and between enemies and pests. When the density ratio of *U. insecticeps*, *P. subpiraticus*, and *C. japonicola* was 6.9:4.8:2.5, interspecific interference was minimal, achieving maximum predation of 33.19 individuals with a predation rate of 66.38%. From an optimal control perspective, higher natural enemy densities are not always better when pest density is fixed; optimal natural enemy ratios must be considered to minimize intra- and interspecific interference and avoid resource waste. Wang et al. [10] reported that when the *P. subpiraticus*:planthopper ratio reached 1:20.2, spiders exhibited obvious control capacity. Our study indicates that when field planthopper populations remain below 1,891.1 individuals per 100 clumps and the spider:planthopper (*P. pseudoannulata*:planthopper) ratio exceeds 1:9.67, *P. pseudoannulata* can achieve complete control of planthopper infestation; otherwise, reliance on this single natural enemy species cannot achieve satisfactory control. This finding is generally consistent with Wang et al. [10], though our spider:planthopper ratio is smaller, possibly because *P. subpiraticus* has stronger predation capacity than *P. pseudoannulata*. Previous laboratory simulation studies have used the mirid:planthopper ratio (*C. lividipennis*:planthopper) to evaluate *C. lividipennis* control efficacy, suggesting that certain ratios can effectively control planthopper damage without chemical pesticides. However, reported ratios vary widely, including 1:1 [32], 1:1.1 [33], 1:8 [34], 1:9.4 [35], and 20:1 [36]. Our study demonstrates that *C. lividipennis* appears later than planthoppers, exhibiting a following effect, consistent with Qi et al. [33]. Quadratic polynomial regression analysis of planthoppers with *C. lividipennis* and *P. pseudoannulata* revealed that *P. pseudoannulata* and its interaction with *C. lividipennis* significantly affect planthopper population dynamics. *P. pseudoannulata* plays an important role in controlling early-season planthopper populations, while the interaction between *P. pseudoannulata* and *C. lividipennis* primarily controls post-infestation population growth.

In summary, this study investigated the effects of irrigation methods on population dynamics of brown planthoppers and their primary natural enemies in high-quality late-season rice. Preliminary conclusions indicate that under biological control, long-term irrigation provides the best pest control by natural enemies, while deficit irrigation performs worst. Under chemical control, long-term irrigation effectively reduces pesticide toxicity to *Pardosa pseudoannulata*, though further research is needed to elucidate specific mechanisms. Additionally, rice yields under long-term irrigation with biological control were significantly higher than other methods (unpublished data), though effects on rice quality require further investigation. Long-term irrigation wastes substantial water resources, conflicting with water-saving principles. Therefore, exploring segmented long-term irrigation (shallow irrigation during seedling stage, drainage and field sunning during peak tillering, flooding from booting to milk stage, and alternate wetting-drying from milk to maturity stage) is necessary. Integrating traditional pest control methods with chemical control to maintain planthopper populations below economic injury levels [37-38] can achieve water savings while maximizing natural enemy control, reducing chemical pesticide usage and providing scientific support for green high-quality late-season rice development.

References

[1] Cai H L, Bai L Y, Zhou X M, et al. Research on insecticide resistance of *Nilaparvata lugens* [J]. *Acta Agriculturae Jiangxi*, 2007, 19(4): 58-61

[2] Yu Y S, Xue S, Wang F, et al. Pest resurgence induced by pesticides [J]. *Chinese Bulletin of Entomology*, 2008, 45(1): 15-20

[3] Xu D Z, Cheng H, You A Q, et al. Industrialization research on high quality in Hubei Province [J]. *Modern Agricultural Science and Technology*, 2010(20): 114-115

[4] Chen G X, Zhou C G, Shi Y H, et al. Situation and countermeasures of high quality rice industry development in Yuanjiang City [J]. *Hunan Agricultural Sciences*, 2014(13): 70-72

[5] Huang Z N, Zhang Y Z, Zhu G Q, et al. Evaluation of control effect of *Trichogramma japonicum* against *Cnaphalocrocis medinalis* and *Chilo suppressalis* [J]. *Acta Agriculturae Jiangxi*, 2012, 24(5): 37-40

[6] Chen H F, Huang S S, Zhang Y Z, et al. Control efficacy of *Trichogramma japonicum* against *Chilo suppressalis* and *Chilaraea auricilia* [J]. *Chinese Journal of Applied Ecology*, 2010, 21(3): 743-748

[7] Liu X D, Zhang X X, Luo Y J, et al. The diversity of arthropod community and control function to brown planthopper (BPH) in rice field [J]. *Acta Entomologica Sinica*, 2002, 45(3): 359-364

[8] Zhou H D, Pei Q, Yan X H, et al. Temporal niches of brown planthopper and white-backed planthopper and their natural enemies [J]. *Journal of Southwest China Normal University: Natural Science Edition*, 2010, 35(5): 80-86

[9] Liu X D, Zhang X X, Guo H F, et al. Control function of spider community to planthopper in the rice field [J]. *Acta Ecologica Sinica*, 2001, 21(1): 100-105

[10] Wang Z, Yan H M, Lü Z Y, et al. Control of paddy spiders on rice population of rice planthopper leafhopper [J]. *Life Science Research*, 2001, 5(1): 76-79

[11] Li C, Chen K L, Liu Y, et al. Effects of different nitrogen rate on population dynamics of *Pardosa pseudoannulata* and planthoppers in late rice [J]. *Hunan Agricultural Sciences*, 2014(20): 37-40

[12] Wu G R, Chen X. Studies on the biology of the mirid, *Cyrtorrhinus lividipennis* Reuter (hemiptera: miridae) and its efficacy as a predator [J]. *Journal of Zhejiang Agricultural University*, 1987(2): 102-107

[13] Chen C M, Xiao T G, Hu S H. Preliminary observation on biological characteristics of *Cyrtorrhinus lividipennis* Reuter [J]. *Journal of Hunan Agronomy*, 1981(3): 15-20

[14] Wang L, Huang S W, Lin X Q, et al. Effects of two nitrogen applications on yield components and occurrence of major diseases and insect pests of super hybrid rice [J]. *Plant Protection*, 2007, 33(3): 76-79

[15] Zhang G F, Lu C T, Shen X C, et al. The synthesized ecological effect of rice density and nitrogen fertilizer on the occurrence of main rice pests [J]. *Acta Phytophylacica Sinica*, 1995, 22(1): 38-44

[16] Chen L X, Zhou S Q, Chen Y G, et al. Effects of different fertilization treatments on diseases and insect pests and occurrence of natural enemies [J]. *Crop Research*, 2006(4): 330-334

[17] Huang B C, Xiao H X, Zhang Y, et al. Effect of different nitrogen utilization on the occurrence of rice insect pest and diseases [J]. *Guangdong Agricultural Sciences*, 2006(5): 41-43

[18] Liu F, Jiang T, Zhao J L, et al. Effects of different planting patterns on population number of *Nilaparvata lugens* Stal and its enemies [J]. *Jiangsu Agricultural Sciences*, 2009(6): 159-161

[19] Huang R Z, Shen R W, Wu D R. Effect of different irrigation and treatment on brown planthopper number of late rice [J]. *Jiangxi Plant Protection*, 1986(1): 5-8

[20] Luo Y F, Fu H L, Bai K H, et al. Effects of water-saving irrigation on community structure and dynamics of arthropod community in paddy fields [J]. *Journal of Irrigation and Drainage*, 2014, 33(4/5): 338-342

[21] Jiang S L, Quan Y H, Huang K Y, et al. Assessment on economic-yield loss caused by key pests of rice in paddy fields of Shandong Province—A case in Tancheng County [J]. *Biological Disaster Science*, 2014, 37(1): 20-25

[22] Lin Y, Zhou X Z, Bi S D, et al. The dominant species of predatory natural enemies of three kinds of planthoppers and impact of pesticides on natural enemies in paddy field [J]. *Acta Ecologica Sinica*, 2013, 33(7): 2189-2199

[23] Wang Z, Song D X, Zhu M S. Study on the ecological niches of spiders and target pests in rice field [J]. *Journal of South China Agricultural University*, 2005, 26(2): 47-51

[24] Yu M Q, Lin X W, Zhu Z R, et al. High density of spiders is the important factor resulting in the light occurrence of rice planthoppers [J]. *Bulletin of*

Science and Technology, 2011, 27(3): 371-375

[25] Sun D W, Su J Y, Shen J L, et al. Safety evaluation of insecticides to *Cyrtohinus lividipennis* (Reuter) (Hemiptera: Miridae), a predator of *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae) [J]. *Scientia Agricultura Sinica*, 2008, 41(7): 1970-1976

[26] Sun D W. Effects of insecticides on *Cyrtohinus lividipennis* (Reuter) (Hemiptera: Miridae), a predator of *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae) [D]. Nanjing: Nanjing Agricultural University, 2007

[27] Yang H, Wang Z, Jin D C. Effects of chlorantraniliprole on experimental populations of *Cyrtorhinus lividipennis* (Reuter) (Hemiptera: Miridae) [J]. *Acta Ecologica Sinica*, 2012, 32(16): 5184-5190

[28] Liu F, Xi B G, Bao S W, et al. Control effectiveness of chlorantraniliprole on *Cnaphalocrocis medinalis* and evaluation of its safety to beneficial arthropods in the rice fields [J]. *Plant Protection*, 2009, 35(5): 139-144

[29] Zhu Z R, Wu L H, Wu G Q, et al. The effects of filmed ground and dry growing conditions on the occurrence of rice pests, natural enemies and saprophagous insects [J]. *Acta Phytophylacica Sinica*, 2000, 27(4): 295-301

[30] Wang Z, Yang H, Jin D C. Effects of chlorantraniliprole on predatory capacity of *Cyrtorhinus lividipennis* (Hemiptera: Miridae) [J]. *Acta Entomologica Sinica*, 2012, 55(5): 618-624

[31] Li J Q, Zhao Z M, Wu S Y, et al. Control function of three spiders for brown plant hopper in coexistent system [J]. *Acta Arachnologica Sinica*, 2001, 10(1): 35-40

[32] Fu Z B, Zhuo W X. The characteristic of *Cyrtorhinus lividipennis* (Reuter) and its conservation and utilization [J]. *Fujian Agricultural Science and Technology*, 1980(3): 8-10

[33] Qi H H, Zhang Y H, Jiang C X, et al. Accompanying migration by *Cyrtorhinus lividipennis* (Reuter) with its host insect, *Nilaparvata lugens* (Stål) [J]. *Chinese Journal of Biological Control*, 2014, 30(2): 171-177

[34] Chen C M, Xiao T G, Hu S H. Preliminary study of *Cyrtorrhinus lividipennis* Reuter [J]. *Journal of Plant Protection*, 1985(1): 69-73

[35] Zhou J Z, Chen C M. Study on the predation of *Cyrtorrhinus lividipennis* Reuter to brown Planthopper egg and its simulation model [J]. *Hunan Agricultural Sciences*, 1986(6): 22-25

[36] Stapley J H. The brown Planthopper and *Cyrtorhinus* spp. predators in the Solomon Islands [J]. *Rice Entomology Newsletter*, 1976, 4: 15-16

[37] Lou Y G, Zhang G R, Zhang W Q, et al. Biological control of rice insect pests in China [J]. *Biological Control*, 2013, 67(1): 8-20

[38] Cook S M, Khan Z R, Pickett J A. The use of push-pull strategies in integrated pest management [J]. *Annual Review of Entomology*, 2007, 52(1): 375-400

Note: Figure translations are in progress. See original paper for figures.