Effects of Irrigation Regime on Immigration and Emigration of Nilaparvata lugens and Cyrtorhinus lividipennis in High-Quality Late Rice Fields: A Case Study from Yiyang, Hunan Province (Postprint)

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Abstract

Cyrtorhinus lividipennis is one of the important natural enemies of the brown planthopper (Nilaparvata lugens) and exhibits obvious concurrent migration phenomenon. Investigating the effects of irrigation methods on the immigration and emigration of brown planthoppers and C. lividipennis in high-quality late rice fields can provide theoretical and technical support for the integrated management of brown planthoppers in such fields. This experiment employed two isolation methods (semi-isolation and full isolation) to study the impacts of continuous irrigation, wet irrigation, intermittent irrigation, and insufficient irrigation on the immigration and emigration of brown planthoppers and C. lividipennis. The results indicated that: immigration and emigration of brown planthoppers and C. lividipennis in high-quality late rice fields varied considerably across years. In 2015, due to low temperatures and frequent rainfall during the mid-to-late growth stages of late rice, no immigration of brown planthoppers or C. lividipennis occurred under any irrigation treatment. In 2014, higher temperatures during the mid-to-late growth stages resulted in migration of both brown planthoppers and C. lividipennis. Regarding immigration, insufficient irrigation led to early occurrence and large base populations of brown planthoppers, resulting in the lowest immigration amount; intermittent irrigation exhibited the highest immigration ratio (immigration amount/population increase during immigration period); under insufficient irrigation and wet irrigation, the immigration period of C. lividipennis was approximately 8 days earlier than under other irrigation methods. Regarding emigration, continuous irrigation resulted in brown planthopper emigration approximately 11 days earlier than other irrigation methods; intermittent irrigation produced the largest emigration amount of brown planthoppers, while wet irrigation showed the highest emigration ratio (emigration amount/population decrease during emigration period); insufficient irrigation yielded the largest emigration amount and emigration ratio for C. lividipennis. These findings demonstrate that although insufficient irrigation reduced brown planthopper immigration, the population increase of brown planthoppers prior to immigration far exceeded the immigration amounts under other irrigation methods, and it promoted emigration of the natural enemy C. lividipennis, thereby increasing the risk of brown planthopper outbreaks and proving detrimental to integrated management; continuous irrigation effectively reduced both brown planthopper immigration and emigration of the natural enemy C. lividipennis; wet irrigation and intermittent irrigation promoted brown planthopper emigration, while intermittent irrigation significantly (P<0.05) reduced emigration of the natural enemy C. lividipennis.

Full Text

Effect of Irrigation Method on In-Out Migration of Nilaparvata lugens (Stål) and Cyrtorrhinus livdipennis (Reute) in High-Quality Late Rice Fields: A Case Study of Yiyang, Hunan Province

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Abstract: Cyrtorrhinus livdipennis (Reute) is one of the important natural enemies of Nilaparvata lugens (Stål) and exhibits a clear accompanying migration phenomenon. Studying the effects of irrigation methods on the immigration and emigration of N. lugens and C. livdipennis in high-quality late rice fields can provide theoretical and technical support for integrated pest management. This experiment established two isolation methods (semi-isolation and full isolation) to investigate the impacts of long-term irrigation, wet irrigation, intermittent irrigation, and deficit irrigation on the immigration and emigration of N. lugens and C. livdipennis. The results showed significant interannual variation in migration patterns. In 2015, due to low temperatures and frequent rainfall during the mid-to-late growth stages of late rice, no immigration of N. lugens or C. livdipennis occurred under any irrigation treatment. In 2014, higher temperatures during the mid-to-late growth stages facilitated migration. Regarding immigration, deficit irrigation resulted in the lowest immigration due to early pest occurrence and large base populations; intermittent irrigation showed the highest immigration ratio (immigration number/increase in population during immigration period); and both deficit and wet irrigation advanced C. livdipennis immigration by approximately 8 days compared to other methods. Regarding emigration, long-term irrigation caused N. lugens emigration approximately 11 days earlier than other methods; intermittent irrigation produced the highest emigration quantity; wet irrigation showed the highest emigration ratio (emigration number/decrease in population during emigration period); and deficit irrigation yielded the highest emigration quantity and ratio for C. livdipennis. These findings indicate that although deficit irrigation reduced N. lugens immigration, the pre-immigration population increase far exceeded the immigration quantities of other treatments and promoted emigration of the natural enemy C. livdipennis, increasing the risk of N. lugens outbreaks and complicating integrated control. Long-term irrigation effectively reduced both N. lugens immigration and C. livdipennis emigration. Wet and intermittent irrigation promoted N. lugens emigration, while intermittent irrigation significantly ($P<0.05$) reduced C. livdipennis emigration.

Keywords: Irrigation method; Late rice; Nilaparvata lugens (Stål); Cyrtorrhinus livdipennis (Reute); Immigration; Emigration

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Cyrtorrhinus livdipennis (Reute) is an important predatory natural enemy of Nilaparvata lugens (Stål), the primary pest of rice (Oryza sativa L.) in Southeast Asia [1], and exhibits a clear accompanying migration phenomenon with its host [2]. Previous research has extensively investigated rice planthopper and C. livdipennis migration in relation to climate warming [3-4], typhoons [5], atmospheric circulation [6], and temperature-humidity conditions [7-9]. Qi et al. [10-11] used light trap methods to observe that C. livdipennis first appeared at light traps slightly later than N. lugens, after which its population dynamics synchronized with the planthopper. Millimeter-wave scanning insect radar revealed that N. lugens exhibits dawn-dusk bimodal migration patterns in South China rice regions, with lower takeoff numbers at dawn than at dusk. Summer migration altitudes primarily ranged from 400–1,800 m, occasionally reaching 2,000 m, while autumn migration occurred mainly at 300–1,100 m, sometimes up to 1,700 m. N. lugens showed aggregation layering strongly related to wind speed, with more females than males during summer migration and more males during autumn migration. Qin et al. [12] reviewed integrated management measures for N. lugens aimed at reducing paddy ecosystem vulnerability, including high-yield pest-suppressing cultivation, low-toxicity chemical control, physical control, biological control, and saturated niche regulation. Fertilizer and water management constitute key components of high-yield pest-suppressing cultivation. High nitrogen fertilizer significantly increases N. lugens virulence and ecological adaptability to adverse conditions [13-14], while planting density primarily affects the redistribution of immigrating planthoppers [15]. However, few studies have examined water management effects on rice planthopper migration. As an important cultivation practice in high-quality late rice production, the impact of irrigation methods on N. lugens and C. livdipennis migration remains poorly documented. This study investigated these effects using semi-isolation and full-isolation methods in Yiyang, Hunan Province, under the context of the "Two Reductions" initiative (reducing chemical fertilizer and pesticide use), aiming to provide theoretical support for integrated N. lugens management under different irrigation regimes.

1.1 Study Area Description

Field experiments were conducted from 2013–2015 at the Zhongtang Experimental Base in Bijia Mountain Township, Heshan District, Yiyang City, Hunan Province (28°29 N, 112°30 E). The region has a subtropical continental monsoon humid climate with an average annual temperature, 1,560 hours of annual sunshine, and 1,465 mm of average annual rainfall. Rainfall distribution during the 2014 and 2015 experimental periods is shown in [Figure 1: see original paper]. The experimental field was planted with early rice in the previous season and late rice in the current season, using the variety 'Xiangwanxian 12' . Soil fertility was uniform across the site. In the biological control area, soil alkali-hydrolyzable nitrogen, available phosphorus, available potassium, organic matter, and pH were 165.2 $mg \cdot kg^{1}$, 6.57 $mg \cdot kg^{1}$, 66.2 $mg \cdot kg^{1}$, 33.7 $g \cdot kg^{1}$, and 5.63, respectively. In the chemical control area, these values were 174.3 $mg \cdot kg^{1}$, 7.03 $mg \cdot kg^{1}$, 62.1 $mg \cdot kg^{1}$, 35.8 $g \cdot kg^{1}$, and 5.42, respectively.

1.2 Experimental Design

Experiments were conducted from July to November during 2013–2015, with 2013 serving as a pilot year. Two isolation methods were implemented:

1) **Semi-isolation experiment**: Four irrigation treatments were established: long-term irrigation, wet irrigation, intermittent irrigation, and deficit irrigation. Long-term irrigation maintained a 3–5 cm water layer throughout the growth period, with water cut off 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 cut off one week before harvest. Deficit irrigation involved no artificial irrigation except during transplanting, relying solely on natural rainfall. Both experimental areas and surrounding regions employed biological control. Each plot was 100 m^2, with no pesticides applied throughout the growth period. Control was achieved through artificial release of Trichogramma and conservation of natural enemies. Plots were isolated from each other using nylon mesh screens, but the upper portions remained unscreened.

2) **Full-isolation experiment**: The upper portions of plots were fully covered with nylon mesh screens (30 mesh × 30 mesh) to prevent immigration and emigration of pests and natural enemies. Other design aspects followed the semi-isolation experiment.

1.4.1 Population Quantification

To minimize disturbance to the plot ecosystem, a non-destructive direct visual observation method was employed 26 days after transplanting, with surveys conducted every 8–10 days until harvest. Five sampling points were selected per plot using the five-point sampling method, with 10 rice hills examined per point. The numbers of C. livdipennis and N. lugens per 100 hills were then recorded.

1.4.2 Calculation of N. lugens Immigration and Emigration

By comparing N. lugens population dynamics between semi-isolation and full-isolation treatments, immigration and emigration periods were identified. The population increase in full-isolation plots during immigration periods (X) represented reproduction-based population growth, while the increase in semi-isolation plots (X) represented the sum of reproduction-based growth and immigration. The population decrease in full-isolation plots during emigration periods (X) represented the combined effects of natural mortality, predation, and reproduction, while the decrease in semi-isolation plots (X) represented natural mortality, predation, reproduction, and emigration. Assuming equal natural mortality, predation, and reproduction between semi-isolation and full-isolation conditions during both immigration and emigration periods, immigration quantity (Y) = X - X and emigration quantity (Y) = X - X . Immigration ratio (K) = Y /X and emigration ratio (K) = Y /X .

1.5 Data Processing

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

2.1 Effects of Temperature and Humidity on N. lugens Immigration and Emigration

Analysis of [Figure 2: see original paper], [Figure 3: see original paper], and [Figure 4: see original paper] revealed that N. lugens immigrated from September 15 to October 4 and emigrated from October 4 to 27 in 2014. As shown in [Figure 3: see original paper], N. lugens populations declined sharply from October 4 (milk ripe stage) to October 14 (wax ripe stage) at a rate significantly faster than other periods, while C. livdipennis populations increased during this time. Both species declined sharply from October 14 to 27. This indicates that emigration primarily occurred from the milk ripe to wax ripe stages for N. lugens and from wax ripe to maturity stages for C. livdipennis. Temperatures from October 4 to 12 remained above 20°C, averaging 22.6°C, while temperatures on October 13 and 14 dropped to 18.6°C and 18.8°C, respectively, averaging 18.7°C, with no rainfall. This suggests that the emigration temperature for N. lugens in Yiyang, Hunan is approximately 18.7°C. During the 2014 immigration period (September 15–October 4), average relative humidity was 85.3% (always above 80.0%), while during the emigration period (October 4–27) it was 77.3% (ranging 67–80%). Notably, average relative humidity from October 4 to 14 was only 75.2%, with minimal fluctuation from October 12 to 14, indicating that sudden temperature drops forced N. lugens emigration, representing the primary factor for planthopper exodus.

In 2015, N. lugens populations under both isolation methods were significantly lower than in 2014, showing minimal change throughout the rice growth period with almost no immigration or emigration. This demonstrates significant inter-annual variation ($P<0.05$) in late rice N. lugens migration. Analysis of 2014–2015 temperature and rainfall data revealed that continuous rainfall and low temperatures during the 2015 mid-to-late rice growth stages prevented immigration, confirming that sustained rainfall affects planthopper immigration and reaffirming temperature as the primary factor influencing N. lugens migration.

2.2 Immigration and Emigration Periods of N. lugens Under Different Irrigation Methods

[Figure 3: see original paper] shows that under semi-isolation conditions, maximum N. lugens populations in intermittent, deficit, and wet irrigation treatments exceeded those in full-isolation treatments, with explosive population increases from September 15 to October 4 that were significantly higher ($P<0.05$) than in full-isolation plots. This indicates that intermittent, deficit, and wet irrigation were the primary periods for N. lugens immigration. Under long-term irrigation, N. lugens populations peaked on September 23 with a gradual increase, suggesting that long-term irrigation was unfavorable for immigration. Under semi-isolation, intermittent, deficit, and wet irrigation treatments showed sharp population declines after October 4, while long-term irrigation showed gradual decline after September 23. In contrast, full-isolation treatments showed increasing populations from October 3 to 14 across all irrigation methods. This demonstrates that under semi-isolation, long-term irrigation caused N. lugens emigration approximately 11 days earlier than the other three methods, though with lower emigration quantities.

2.3 Immigration and Emigration Periods of C. livdipennis Under Different Irrigation Methods

Cyrtorrhinus livdipennis is an important long-distance migratory natural enemy that cannot overwinter in Hunan [16]. Therefore, initial populations in early rice fields originate from immigration, while late rice field populations derive from surrounding habitats after early rice harvest and long-distance immigration. Due to extremely low C. livdipennis populations in 2015, analysis focused on 2014 data. [Figure 4: see original paper] shows that no C. livdipennis were observed before August 28 in semi-isolation plots. Small numbers began immigrating on September 7 under deficit and wet irrigation, and on September 15 under intermittent and long-term irrigation. Populations subsequently increased then decreased with rice development, peaking on October 14 (wax ripe stage) across all four irrigation methods in both semi-isolation and full-isolation treatments. After October 14, populations in deficit, intermittent, and wet irrigation treatments declined sharply, while long-term irrigation showed a more gradual decline. Under full-isolation, all irrigation methods showed gradual declines after October 14, indicating emigration occurred after October 14 across treatments, with long-term irrigation showing significantly ($P<0.05$) lower emigration than other methods.

2.4 Effects of Irrigation Methods on N. lugens Immigration and Emigration Ratios

Due to extremely low N. lugens populations in 2015 ([Figure 3: see original paper]), analysis focused on 2014 data. shows that immigration quantity (Y) ranked: intermittent irrigation > wet irrigation > long-term irrigation > deficit irrigation. Intermittent irrigation values were 31.8, 2.1, and 16.5 times those of deficit, wet, and long-term irrigation, respectively, with significant differences between intermittent/wet irrigation and deficit/long-term irrigation, but no significant difference between deficit and long-term irrigation. Emigration quantity (Y) ranked: intermittent irrigation > wet irrigation > deficit irrigation > long-term irrigation, with intermittent irrigation being 1.4, 1.1, and 5.8 times higher than the other treatments, respectively. Immigration ratio (K) differed significantly among treatments, ranking: intermittent irrigation > wet irrigation > long-term irrigation > deficit irrigation, with intermittent irrigation being 19.4, 1.4, and 3.4 times higher than the others. Emigration ratio (K) also differed significantly, ranking: wet irrigation > intermittent irrigation > deficit irrigation > long-term irrigation, with wet irrigation being 1.3, 1.1, and 1.8 times higher than the others. These results demonstrate that irrigation methods significantly affect both immigration and emigration of N. lugens.

2.5 Effects of Irrigation Methods on C. livdipennis Immigration and Emigration Ratios

shows that under semi-isolation conditions, no significant differences in C. livdipennis immigration quantity (Y) were observed among irrigation methods, and no long-distance migration settlement occurred, suggesting that field populations primarily established through immigration from surrounding habitats. Emigration quantity (Y) was highest under deficit irrigation, followed by wet and intermittent irrigation, with long-term irrigation showing the lowest values. Deficit irrigation increased emigration by 102.9%, 127.2%, and 1,709.1% compared to wet, intermittent, and long-term irrigation, respectively. Emigration ratio (K) was highest under deficit irrigation, followed by wet and long-term irrigation, with intermittent irrigation showing the lowest values. Deficit irrigation increased emigration ratio by 7.0%, 83.4%, and 49.7% compared to wet, intermittent, and long-term irrigation, respectively.

3.1 Effects of Irrigation Methods on N. lugens Migration

Rice planthoppers are among the most important migratory rice pests, with temperature, humidity, and rainfall being critical factors affecting their migration [17]. This study found that the average immigration temperature for N. lugens in Yiyang, Hunan was 25.0°C (not below 23.0°C), with average relative humidity of 85.3% (not below 80.0%). The average emigration temperature was 21.6°C, with an optimal emigration temperature of 18.7°C, demonstrating that low temperatures promote emigration. The average emigration relative humidity was 77.3% (range 67–80%). These findings align with previous reports that ground temperatures of 19-30°C (optimal 24–29°C) facilitate planthopper immigration to Guilin, with a minimum emigration temperature of 18°C and average immigration/emigration relative humidity above 70% [7-9]. Interannual climate variations in temperature, humidity, and rainfall thus cause differences in planthopper immigration. Jiang et al. [18] found no significant correlation between annual mean temperature/rainfall and N. lugens damage area or yield loss. However, this study revealed substantial interannual differences, likely because low temperatures and frequent rainfall prevented immigration, while locally reproduced planthoppers were completely controlled by natural enemies. Therefore, chemical pesticide applications should be based on annual climate conditions and field surveys to minimize usage, reduce waste, and decrease environmental pollution, thereby advancing China' s "Two Reductions" initiative.

Post-immigration control of N. lugens represents a major challenge in rice pest ecological management. Current approaches primarily involve physical, biological, and transgenic measures [19-22]. Previous cultivation-based research has focused mainly on scientific fertilization [23] and rational planting density [15]. Effective control below economic injury levels requires integrated technologies combining resistant varieties, cultivation techniques, biological control, and ecological management rather than single approaches. As a crucial cultivation practice in rice green management, the effects of irrigation methods on N. lugens immigration and emigration remain unclear. This study revealed that under semi-isolation, long-term irrigation caused N. lugens emigration earlier than the other three methods, but with lower emigration quantities. Irrigation methods significantly affected both immigration and emigration. Deficit irrigation showed the lowest immigration quantity and ratio because early pest occurrence with large base populations promoted population development, causing plant malnutrition and yellowing before immigration. Since planthoppers exhibit strong preferences for green, tender tissues and shaded habitats [7], this resulted in the lowest immigration. Long-term irrigation significantly reduced immigration compared to wet and intermittent irrigation, possibly because the canopy environment under continuous flooding was unfavorable for planthopper landing. The lowest emigration quantity and ratio under long-term irrigation likely resulted from low initial pest populations that minimally affected plant physiology, ensuring adequate nutrition during mid-to-late growth stages and providing favorable conditions for planthopper reproduction. Additionally, high canopy humidity under long-term flooding may have inhibited emigration. Comparison of two years' data revealed significant differences in N. lugens immigration and emigration among irrigation treatments in 2014 but not in 2015, indicating substantial interannual variation, particularly in drought years that exacerbate planthopper problems. This study provides preliminary insights into migration differences among irrigation methods, though underlying mechanisms require further investigation.

3.2 Effects of Irrigation Methods on C. livdipennis Migration

Cyrtorrhinus livdipennis overwinters as adults in tropical and south subtropical rice regions but cannot survive winter in Hunan [16,24]. As an important predatory natural enemy of N. lugens and a typical migratory rice field predator, it primarily feeds on planthopper eggs [25-26]. Large-scale accompanying migration of natural enemies demonstrates multi-trophic interactions among "natural enemy-host-plant" systems, holding important ecological and behavioral significance [27]. Despite being a key accompanying natural enemy of N. lugens, systematic studies on C. livdipennis migration remain lacking. Previous research using field surveys, light trapping, and mountain net capture confirmed its long-distance migration habits, with first appearance slightly later than N. lugens but subsequent migration periods largely synchronized [16,24]. Aerial net capture [28-29], aircraft netting [2,30], and marine capture [31] further confirmed these long-distance migration patterns. As an important cultivation practice in rice green management, irrigation effects on C. livdipennis immigration and emigration remain unclear. This study found no significant differences in immigration quantity among irrigation methods, but significant differences in emigration quantity: deficit irrigation > wet irrigation > intermittent irrigation > long-term irrigation. The highest emigration under deficit irrigation likely resulted from early N. lugens occurrence providing abundant food resources, enabling rapid C. livdipennis population establishment, while late-season water deficit and massive planthopper emigration subsequently promoted natural enemy emigration, consistent with Hu et al. [32] who found that co-occurrence of C. livdipennis and N. lugens facilitates mutual emigration. The emigration ratio trend (deficit irrigation > wet irrigation > long-term irrigation > intermittent irrigation) largely matched emigration quantity trends. The higher emigration ratio under long-term irrigation compared to intermittent irrigation resulted from lower planthopper populations and consequently lower natural enemy populations, yielding lower absolute emigration but a higher ratio due to the smaller population base. Zhu [24] noted that C. livdipennis reproduces rapidly, providing significant N. lugens control when immigration occurs early with large populations. Wang et al. [33] observed synchronized population dynamics between C. livdipennis and N. lugens, with high late-season populations. Therefore, chemical pesticides should be minimized during light N. lugens outbreaks to facilitate C. livdipennis immigration and maximize its control of planthopper populations. During severe outbreaks, highly effective but low-toxicity pesticides or biological agents should be selected, minimizing application frequency and prohibiting highly toxic chemicals. This approach effectively controls N. lugens while protecting natural enemies, promoting virtuous cycles in paddy ecosystems.

In summary, migration of N. lugens and C. livdipennis is strongly climate-dependent, primarily influenced by temperature and rainfall. In 2015, low temperatures and frequent rainfall during late rice mid-to-late growth stages prevented immigration of both species. In 2014, higher temperatures facilitated migration. Regarding immigration, deficit irrigation resulted in the lowest N. lugens immigration (only 0.6% of the highest value under intermittent irrigation) due to early pest occurrence and large base populations; intermittent irrigation showed the highest immigration ratio, being 19.4, 1.4, and 3.4 times higher than deficit, wet, and long-term irrigation, respectively; and deficit and wet irrigation advanced C. livdipennis immigration by approximately 8 days. Regarding emigration, long-term irrigation caused N. lugens emigration approximately 11 days earlier than other methods; intermittent irrigation produced the highest emigration quantity, being 1.4, 1.1, and 5.8 times higher than deficit, wet, and long-term irrigation, respectively; wet irrigation showed the highest emigration ratio, being 1.3, 1.1, and 1.8 times higher than deficit, intermittent, and long-term irrigation, respectively; and deficit irrigation yielded the highest C. livdipennis emigration quantity and ratio, increasing emigration quantity by 102.9%, 127.2%, and 1,709.1% and emigration ratio by 7.0%, 83.4%, and 49.7% compared to wet, intermittent, and long-term irrigation, respectively. These results indicate that while deficit irrigation reduced N. lugens immigration, pre-immigration population increases far exceeded immigration quantities of other treatments and promoted natural enemy emigration, increasing outbreak risk and complicating integrated control. Long-term irrigation effectively reduced both N. lugens immigration and natural enemy emigration. Wet and intermittent irrigation promoted N. lugens emigration, while intermittent irrigation significantly ($P<0.05$) reduced natural enemy emigration. Therefore, adopting long-term irrigation during early-to-mid growth stages and intermittent or wet irrigation during mid-to-late stages in high-quality late rice production is expected to reduce N. lugens immigration, promote emigration, and minimize natural enemy emigration, maintaining both populations within relatively safe ranges to maximize natural enemy efficacy. The underlying mechanisms require further investigation.

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