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Rice planthopper problems and relevant causes in China

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The new development of three rice planthopper species, including small rice planthopper, brown planthopper, and whitebacked planthopper, and historical profiles of relevant environmental factors in rice ecosystems in China were analyzed. The results indicated that the changes in cropping system and increase in susceptible hybrid varieties, fertilizers, pesticides, and temperature created vulnerable rice ecosystems, which increased initial populations and growth rates and resulted in high population sizes and frequency of outbreaks. The main parameters for higher initial population are earlier starting time, longer immigration period, and higher immigration size; those for higher growth rate are higher fecundity, more generations, and lower mortality; and those for lower control efficiency are changes in species structure, genetic structure, and temporal structure. The approaches for improving planthopper management by modifying cropping systems, building up system resistance, developing new control strategies, and strengthening international collaboration were discussed.

Keywords: small brown planthopper, brown planthopper, whitebacked planthopper, environmental factors, management

Laodelphax striatellus Fallen (small brown planthopper, SBPH), *Nilaparvata lugens* Stål (brown planthopper, BPH), and *Sogatella furcifera* Horvath (whitebacked planthopper, WBPH) have become major pests successively in the rice-growing areas of Asia and extensive studies have been carried out to develop control programs since the 1960s. Much money has been invested to prevent yield losses caused by rice planthoppers, for example, a national program for BPH control using resistant varieties and pesticides in Indonesia invested more than US$100 million per year between 1980 and 1987, but did not prevent planthopper outbreak and exacerbated problems of varietal breakdown, insecticide resistance, and resurgence in BPH (Kenmore 1991). It further demonstrated that rice planthoppers were typical artificial pests. The implementation of the Intercountry Rice IPM program sponsored by FAO in the late 1980s as well as the Farmer Participatory Research Program sponsored by IRRI in the 1990s changed farmers' perceptions in tropical countries on rice planthoppers,

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promoted natural biological control in rice ecosystems, and reduced risks of planthopper outbreak (Kenmore 1991, Escalada and Heong 2004). However, chemical control is still the main tactic for planthopper control in subtropical and temperate regions, such as China, Japan, and South Korea. Although field experiments showed that unreasonable use of insecticides could also cause BPH resurgence in subtropical and temperate areas, insecticides have still been extensively used in these countries (Wang et al 1994, Cheng 1995). Development of imidacloprid, a new insecticide with higher efficiency and a longer residual period, even stimulates negligence in applying insecticides and imidacloprid has been widely used in all the rice-growing areas of Vietnam, China, South Korea, and Japan since the early 1990s (Liang et al 2007). The frequency of BPH outbreak declined after the outbreak in the early 1990s and it seems that the BPH problem was solved by the new insecticide. However, the dream of solving the BPH problem by applying the new insecticide was shattered by the serious outbreak of BPH that resulted from high resistance to imidacloprid and other reasons in 2005 (Cheng and Zhu 2006). The continued outbreaks of rice planthoppers in 2006 and 2007 indicated the importance of redesigning a planthopper management program. This paper covers new developments in rice planthoppers in recent years and interactions between planthopper problems and ecological factors in rice ecosystems in China, as well as management strategies.

New planthopper problems in rice ecosystems in China

It has been more than 40 years since SBPH caused serious yield losses by transmitting virus diseases, such as rice stripe virus disease (RSV) and rice black streaked dwarf virus disease (RBSDV), in the mid-1960s in the Yangtze Delta area of China. BPH and WBPH became major pests in the late 1960s and late 1970s, respectively, and all three planthoppers have had frequent outbreaks since then. Figure 1 shows a historical profile of rice planthoppers based on data collected in 10 fields without using any insecticide applications every year in Jiaxing, Zhejiang Province, China (Cheng et al 2008). The value of the ordinate is the average peak density of total planthoppers per 100 hills. BPH or WBPH is ranked for 5 grades and grade 5 (more than 3,000 per 100 hills) is considered as an outbreak (Zhang 1995).

According to the data in Figure 1, the developmental history of rice planthoppers in the Yangtze Delta of China could be separated into three stages: exposure (from 1964 to 1978), development (from the late 1970s to early 2000s), and exacerbation (after the early 2000s). In the first stage (exposure), SBPH, BPH, and WBPH became major pests from potential pests successively, but only one species caused yield losses in some areas in the same year and BPH was considered as the number-one pest in the rice ecosystem (Cheng 1995). In the second stage (development), both BPH and WBPH caused yield losses in the same year and the occurring area of WBPH was continually expanding. WBPH became the number-one pest, especially in South China (Tang et al 1995), but SBPH occurred only occasionally in small areas. However, all three species were causing serious yield losses every year in the third stage (exacerbation). In the Yangtze Delta area, SBPH caused serious yield losses of wheat and rice

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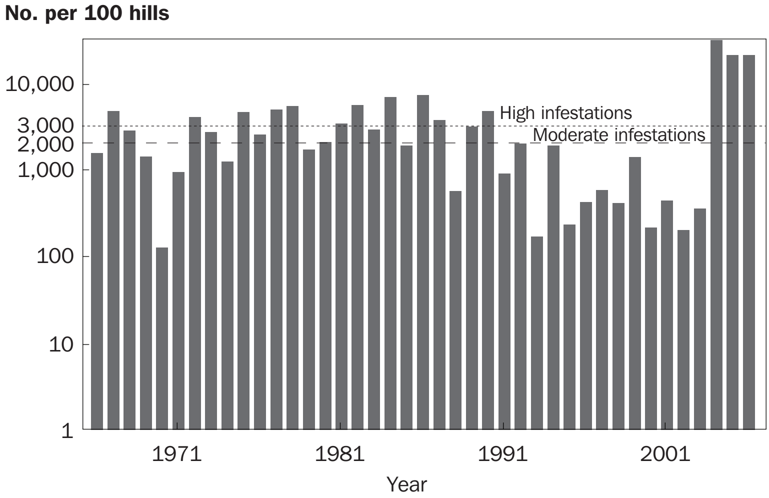

Fig. 1. Historical profile of rice planthoppers in Jiaxing, Zhejiang, China.

by transmitting virus diseases, WBPH caused hopperburn mainly in hybrid rice, and BPH caused hopperburn mainly in japonica rice.

To explore the real situation of rice planthoppers, historical data on the main population parameters of planthoppers were compared and the results revealed that new rice planthopper problems in recent years could be represented by the four most significant phenomena in planthopper history.

Highest initial population

The initial populations of BPH and WBPH in Jiaxing, Zhejiang Province, are immigrants from South China, but the initial population of SBPH is the local overwintering population. The main initial population of SBPH for paddy rice is the adults of the first generation around mid-May to early June. WBPH immigrants arrive in May and peak in late June to early July, but BPH immigrants arrive in June and the main immigration period lasts from late July to early September. Figure 2 shows the historical profile of main initial population sizes under light traps in these peak periods since 1979. The highest peak population sizes under light traps for SBPH, WBPH, and BPH were 93,192, 4,502, and 9,712, which occurred in 2006, 2003, and 2007, respectively. The highest peak population sizes for the three species are at least two times higher than those in the 1980s and 1990s.

Highest growth rate

The growth rate, the ratio between the peak size of the initial population and the peak size of the highest peak population, is a most important population parameter, which indicates species capacity for increasing as well as the suitability of environmental conditions to the species. BPH is a well-known pest species with a high growth rate. The growth rates and standard errors of BPH from immigration to peak population,

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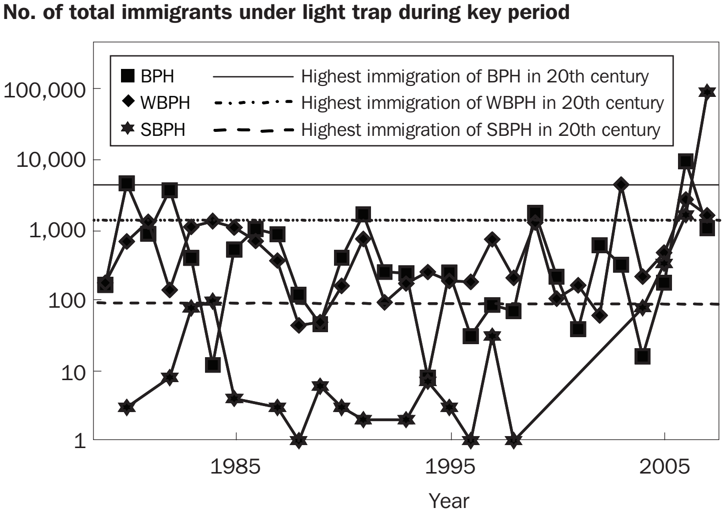

Fig. 2. Historical profile of initial population under a light trap in Jiaxing, China.

developing two generations after immigration, were 990.60 ± 193.48 in the second rice crop season during the 1970s and 1980s (Cheng 1996). Based on data from the same fields mentioned above, the growth rates and standard errors of SBPH and WBPH in the 1980s in the second rice crop season were 24.58 ± 12.72 and 283.95 ± 8.00. However, the growth rates from the initial population to the peak population for SBPH and BPH in the single rice crop season in the past three years were 1,335.25 ± 607.21 and 5,423.32 ± 1,739.33 in the same area. The results clearly indicate that average growth rates of BPH and SBPH in recent years were more than 4–8 times higher than those in the 20th century.

Highest peak population size

As Figure 1 showed, the peak population sizes fluctuated year to year and were more than 20,000 per 100 hills in the past 3 years, which clearly showed that the peak population sizes in the past 3 years were more than two times higher than the highest population size in the 20th century. Based on the historical data collected from these fields without any insecticide application, the highest peak densities for SBPH, BPH, and total planthoppers per 677 m^2 in the 20th century were less than 1 million, 2.36 million, and 2.42 million, respectively. But the average peak densities of the SBPH, BPH, and total planthoppers were 1.73 ± 0.57, 5.24 ± 0.86, and 6.52 ± 0.73 million in the past 3 years, which are also more than two times higher than the highest ones in the 20th century. SBPH could cause 10–20% yield losses by feeding on heads directly, which never happened in the 20th century (Wang et al 2007).

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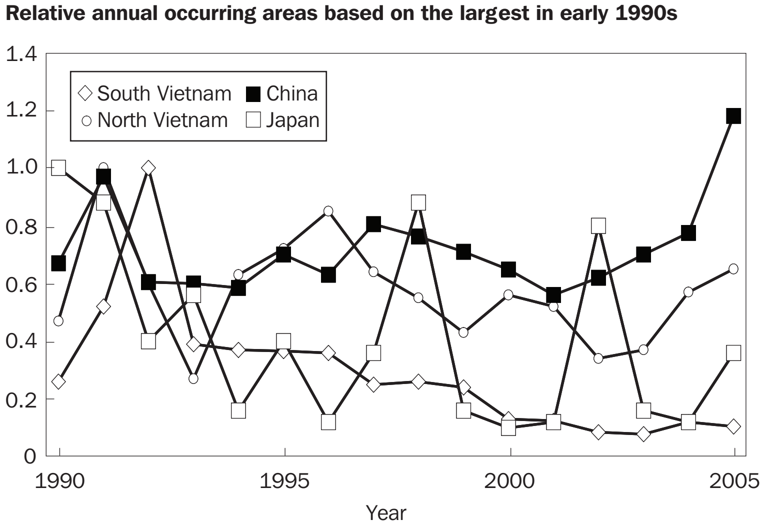

Fig. 3. Comparison of relative occurring areas of rice planthoppers among years in China, Japan, and Vietnam.

Highest outbreak frequency

Rice planthoppers, mainly BPH and WBPH, had outbreaks in the early 1990s and the occurring areas were considered as the largest in Vietnam, Japan, and China as shown in Figure 3. Rice planthoppers in 1991 in China occurred on 23.2 million ha (Tang et al 1995). However, the average annual occurring area in 2005-07 was about 26.7 million ha (Xia 2008). In 14 different years, peak population sizes were above 3,000 per 100 hills (outbreak) from 1967 to 2007. The outbreak years were separated individually before the mid-1970s, such as 1968, 1973, and 1976, and covered 2-year periods since the late 1970s, such as 1978-79, 1982-83, and 1987-88. But outbreaks continued for 3 years during 2005-07 since all three rice planthoppers had outbreaks.

Historical profile of main environmental factors

Rice planthoppers are secondary pests in high-yielding agricultural systems. Outbreaks of planthoppers have been triggered by misuse of insecticides, varieties with high nutrition, and other environmental factors related to cultural and climatic factors (Kiritani 1979, Kenmore et al 1984, Cheng 1995). These environmental factors, including cropping systems, variety, usage of chemical fertilizer and pesticide, and temperatures have been changing in the rice-growing areas of China.

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Cropping systems

The change in area with a double-rice cropping system in China since the 1950s looks like a mountain peak. The area for double-rice cropping started increasing in the 1950s and reached a peak in the 1970s, then declined in the 1980s and 1990s (Huang 1997). The areas with a first rice crop system accounted for only about 20% in 1950, but about 40% of the total rice-growing area in 1980 in China. In general, areas with a second rice crop system are equal to the sum of the first rice crop area and the area used for seedling beds of a second rice crop. Therefore, the rice-growing area for the first and second rice crop was more than 80% of the total rice-growing area in China, and almost 100% in South China at the peak in the 1970s. However, the first rice crop area declined in the 1980s and reached about 20% of the total rice-growing area again in recent years (MOA 2006). Most of the double rice-cropping system is found in Guangdong, Guangxi, South Hunan, and Jiangxi and the single-rice cropping system accounts for more than 90% in the Yangtze Delta area, including Jiangsu, Shanghai, and Zhejiang (NBSC 2006). Figure 4A showed that areas growing a single-rice crop have been increasing dramatically as the areas growing a first crop declined in Zhejiang Province (ZPBS 2006).

In the meantime, areas growing winter crops have been changing. Areas growing wheat increased from 1980 to 1990 and declined after 1990 in both Jiangsu and Zhejiang provinces. The ratios between wheat fields and rice paddy in Jiangsu and Zhejiang in recent years were about 0.8 and 0.1, respectively (NBSC 2006). The high ratio in Jiangsu indicated that the cropping system was becoming mainly a wheat-rice system. In contrast, the ratio in Zhejiang was becoming lower and only about 40% of fields were used for winter crops, including barley, oil rape, and broad bean (Fig. 4A). More than half of the fields became fallow with graminaceous weeds and this means that these fields had only one rice crop per year, which was a pure single-rice crop. Both wheat fields and fallow fields are usually plowed in June after adults of the first generation of overwintering SBPH emerged and moved to the rice paddy.

Another important change in the rice farming systems in the Yangtze Delta area since the 1990s is the increase in area using the direct sowing technique for wheat and rice. Wheat is directly sowed in rice paddies before the rice harvest in Jiangsu and rice is directly sowed around late May in Shanghai and Northern Zhejiang. The rice-growing area using direct sowing has accounted for about 80% of the total rice-growing area in the Yangtze Delta in recent years.

Variety

The most important revolution for rice in the 20th century was probably the development of hybrid rice. Hybrid varieties started to be released widely in 1976 in China. It was reported that the yield of hybrid rice per hectare could be increased by about 1,500 kg compared with conventional rice. Therefore, hybrid rice growing area expanded rapidly and reached about 10 million hectares in about 10 years. In 1990, hybrid rice area exceeded 15 million hectares and accounted for about 50% of the total rice-growing area in China. Since then, the percentage of hybrid rice area has increased gradually to about 60% as shown in Figure 4B (Mao et al 2006). The main

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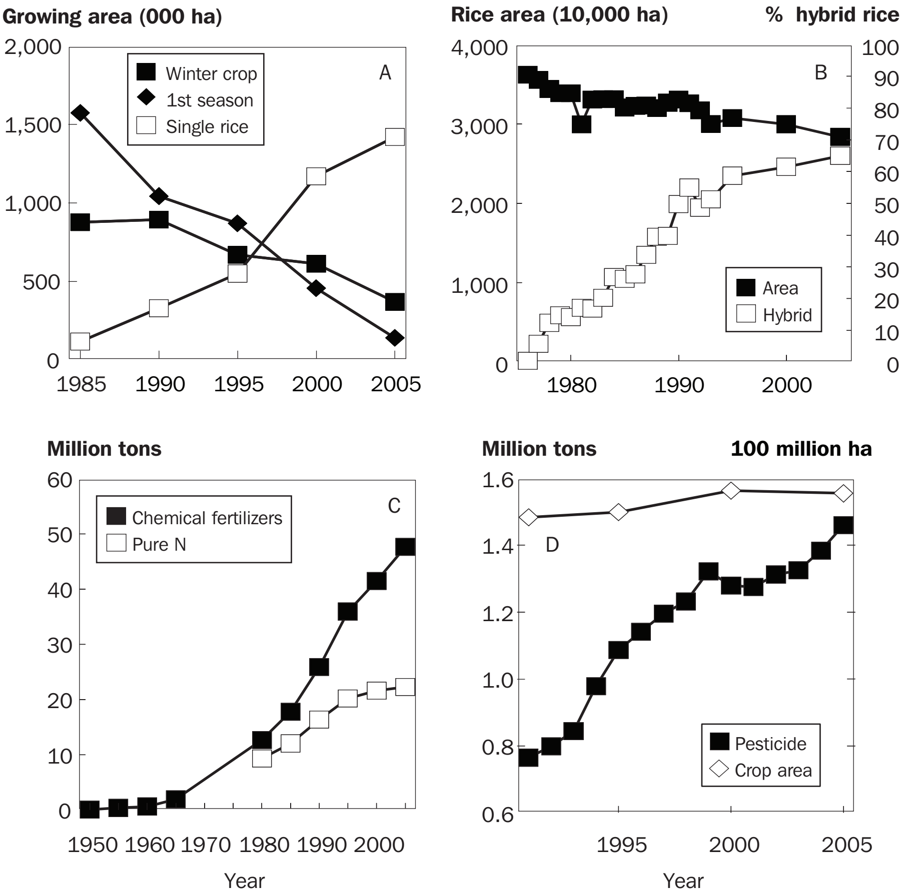

Fig. 4. Historical profiles of main agricultural practices in China. (A) Cropping systems in Zhejiang, (B) areas growing rice and hybrid rice, (C) chemical fertilizers, (D) chemical pesticides.

sterility system used for hybrid varieties comes from Minghui 63, which is susceptible to rice planthoppers, and the main mother parents used are IR36 and IR64, which are susceptible to WBPH, but resistant to Biotypes 1 and 2 of BPH. Therefore, the main varieties of hybrid rice, such as Shan-you, Wei-you, D-you, Gang-you, and Liang-you, are susceptible to WBPH, with some resistance to BPH (Mao et al 2006). Based on field testing, only about 12% of the newly developed varieties were ranked at grades 0–5 for the levels of resistance to BPH (Chen et al 2005).

Interactions between variety and BPH have been extensively studied, and some resistant varieties were developed and applied in small areas in China. For example, resistant varieties incorporating resistance genes from IR26, IR28, and IR54 started to be used in 1989, and then the area growing resistant varieties expanded quickly, reaching about 80% of the total rice-growing area in Jiaxing, Zhejiang Province, in

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1991 (Cheng 1996). However, it is not an indispensable condition to have resistance genes for planthoppers in variety breeding programs. Many varieties resistant to planthoppers were developed and the proportion of area growing resistant varieties declined significantly to almost zero in the late 1990s, when the BPH problem was becoming less serious.

Chemical fertilizer and insecticide

Although the one child per family policy has been in place since the 1970s, the population still increased from about 1 billion to 1.3 billion in the past 25 years in China. To feed the increasing population with limited arable land, yield per unit area has to be raised by using modern technology. The yield of rice increased from 4.13 to 6.26 t ha^{-1}and the yield of food crops increased from 2.72 to 5.23 t ha^{-1} during the past 25 years. During the same period, the usage of total chemical fertilizers and nitrogen increased from 12.69 and 9.34 million tons to 47.66 and 22.29 million tons, respectively (MOA 2006).

The total usage of pesticides also kept increasing and almost doubled in the past 15 years. Total pesticide use was about 0.76 million tons in 1991 and about 1.46 million tons in 2005 (MOA 2006). During the same time period, striped stem borer started to be resistant to Shachongshang and triazophos, and methamidophos was banned because of its high toxicity. To replace these pesticides, new pesticides, including regent, imidacloprid, and pyrethrum, were widely applied. Although use of these new pesticides per unit area is much less than that of old pesticides, the total use of pesticides kept increasing (Yang 2007). The high control efficiency and cheap price of imidacloprid made farmers believe that this pesticide was the most popular "magic drug" and pesticide products containing imidacloprid, but with different names or formulas, were more than 400 in China. They were used in all the rice-growing areas in China and 3–5 applications, as a main component of a "cocktail pesticide," were made per crop season. In the meantime, imidacloprid was also widely used in Vietnam, South Korea, and Japan (Liang et al 2007).

Temperature

Temperature is the main climatic factor affecting development, fecundity, and mortality. Figure 5 shows the annual monthly average temperatures from 1954 to 2007 in Jiaxing, China, and the broken lines in each small figure are the average monthly temperatures during this period. The monthly average temperatures fluctuated, but they clearly showed that weather conditions were getting warmer, especially in winter and spring. The monthly average temperatures for most of the months in recent years were higher than, or at least close to, the average temperature during the 54 years. The highest or the second highest monthly average temperatures in most months occurred in recent years.

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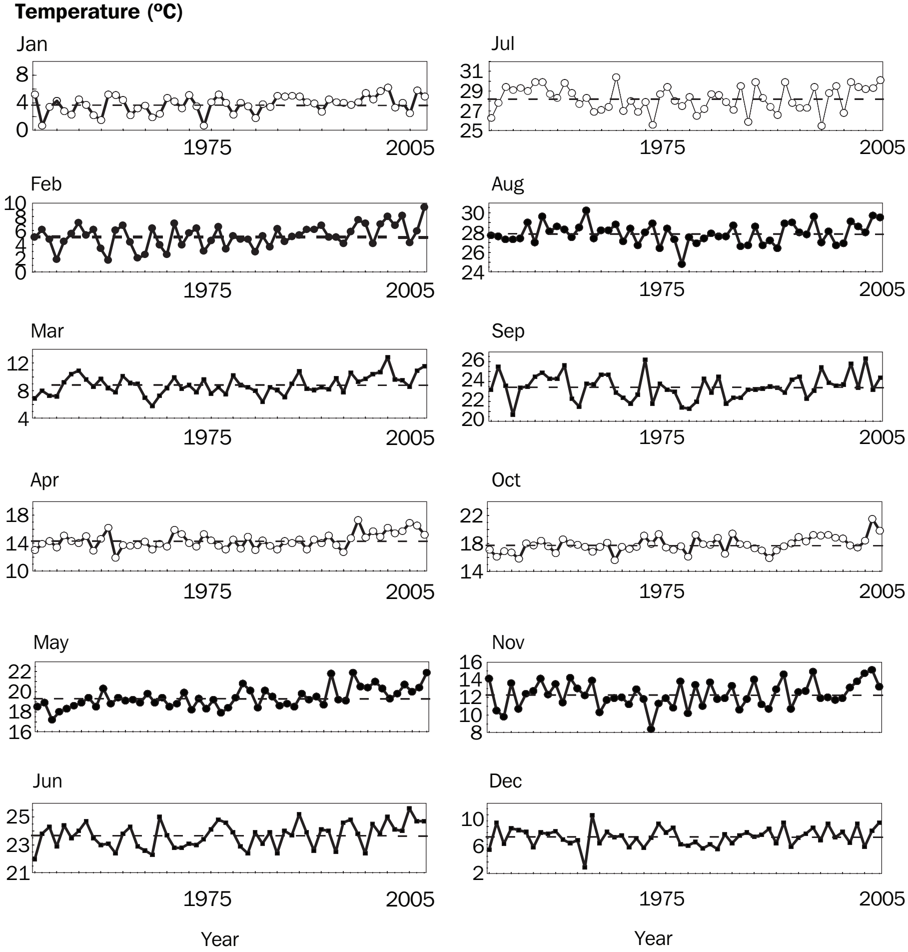

Fig. 5. Historical profile of monthly average temperature in Jiaxing, China.

Interactions between planthoppers and main environmental factors

Based on ecological principles, total population size of rice planthoppers (total N) could be described using the following equation:

$$\text{Total } N_t = \sum N_{i,t} = \sum N_{i,0} * R_{i,t} * (1 - P_{i,t}) \ (i = 1, 2, 3)$$

where N is population size, t is the number of generations, N_0 is initial population size and N_t is population size at generation t, i is number of species and there are three planthopper species, R is growth rate, and P is control efficiency of agricultural practices. The equation indicates that total population size is equal to the sum of population

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sizes of the three rice planthopper species. All the environmental factors will affect total population size through their impact on the three parameters mentioned in the equation: initial population, growth rate, and control efficiency.

Impacts on initial population

The initial population is the population from source areas and fields and it is the seed population for the field we are dealing with. The population parameters related to initial population are mainly starting time (the time for earliest initial population arriving in the rice paddy), pattern (temporal distribution of initial population during the immigration period), and size (total population size moving into the rice paddy) (Cheng and Holt 1990). The cropping system could affect population development through its effect on the three parameters of initial population.

Earlier starting time. The earliest initial SBPH population is mainly from its local overwintering areas, but immigrants of BPH and WBPH are from their source regions. In general, the starting time of initial population depends on two factors, population development patterns in source areas and cropping systems in local areas. Figure 6 shows the population of three rice planthoppers under light traps in Jiaxing in the 1980s, 1990s, and the early 21st century, and the figure indicated that the starting time to catch three rice planthopper species under light traps was becoming earlier. One of the main reasons for the earlier starting time might be the warm winter and spring as shown in Figure 5, and all the monthly average temperatures from February to June increased about 1–2 °C since the 1980s. But the most important way to consider the starting time, the parameter related to arriving time in fields, could be the length of the period for planthopper development from arriving to peak of emigration in fields. In double-rice cropping, the initial populations of planthoppers move into fields growing a first rice crop transplanted around May and harvested in late July to early August or fields growing a second rice crop transplanted in late July to early August and harvested in November. There will be only about 1–2 months for population development from the time the initial population arrives to harvesting time in the first crop season and about 2–3 months in the second rice crop. The single-rice crop, however, is usually sown in late May to early June or transplanted in June and the harvesting time is in October to November. Therefore, rice planthoppers could develop 1 or 2, about 2, and 3–4 generations a season, respectively in the first-, the second-, and the single-rice crop seasons, respectively. This means that the time for initial populations to arrive in the single-rice crop season is much earlier than for the first- or second-rice crop season based on population development pattern (Fig.7C, D).

Longer immigration pattern. The temporal distribution of the immigration population is related to the population development pattern in the source area as well as crop season in the local area, and both the population development pattern in the source area and crop season in the local area are related to the cropping system. In general, macropterous adults increase after the heading stage and more macropterous planthoppers emigrate when rice is maturing because of poor food conditions (Cheng et al 1979). A change in cropping systems in source areas must affect crop stages, as

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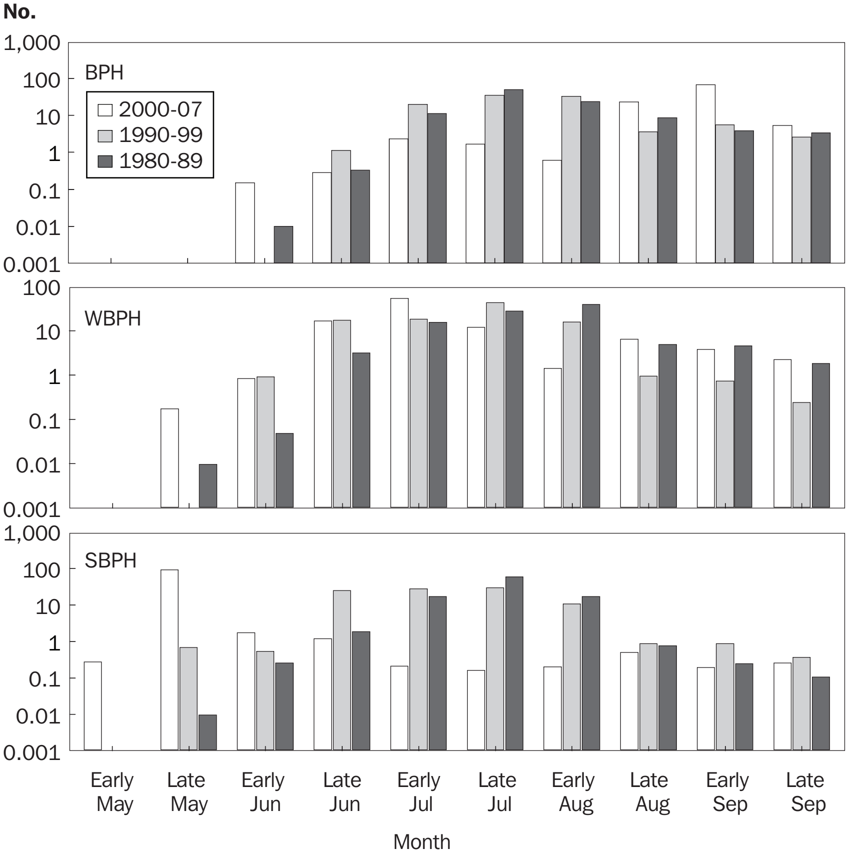

Fig. 6. Comparison of population development patterns of three rice planthoppers under light traps in 1980s, 1990s, and early 21st century in Jiaxing, China.

well as food conditions, in a specific calendar period. The source areas for Yangtze Delta areas are mainly around South Mountain areas, including Guangdong, Guangxi, Guizhou, Fujian, Hunan, and Jiangxi (Cheng et al 1979). There were mainly two immigration peaks of BPH, which were around late June to early July and late July to early August in the Yangtze Delta and the peak around late August was very low, when the rice cropping system was mainly a double-rice crop season there before the 1990s (Fig. 7A). However, the late immigration peak around late August to early September was very high in the single-rice cropping system in recent years (see Fig. 7B) because these immigrants were from single-rice crop fields and population sizes were already very high after developing two or three generations there.

Higher initial population size. Based on the historical profile of immigrants under light traps from 1979 to 2007, total immigrants in the main immigration periods, late May to early June for SBPH, late May to early July for WBPH, and late June to early

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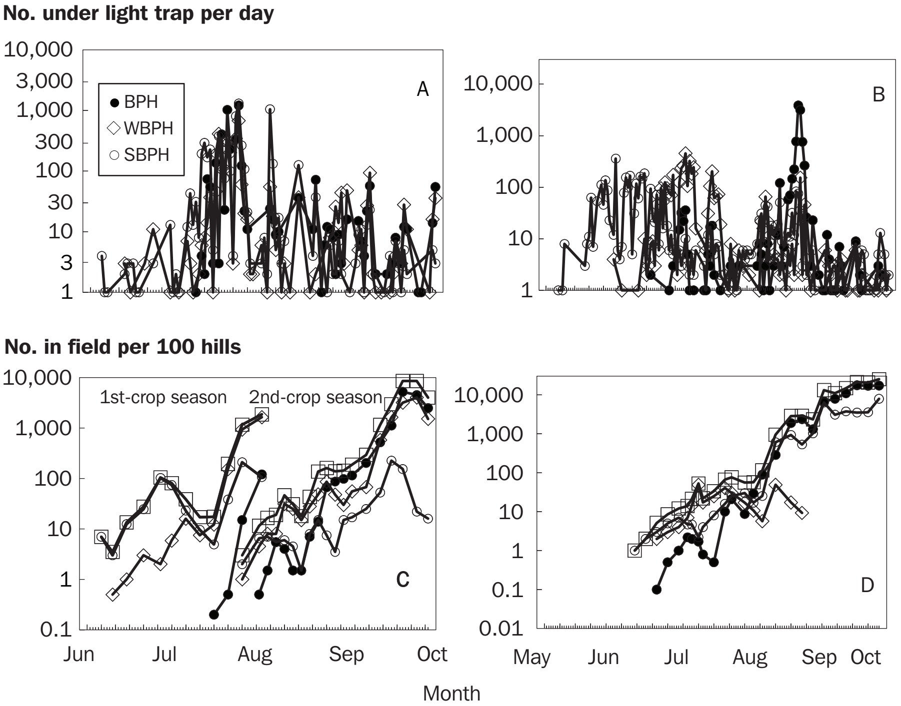

Fig. 7. Comparison of development patterns of populations under a light trap and in fields between the 1980s and 2000s. (A) Population under light trap in double-rice cropping system, (B) population under light trap in single-rice cropping system, (C) population in fields in double-rice cropping system, (D) population in fields in single-rice cropping system.

September for BPH, were 98 (1984), 1,359 (1984), and 4,707 (1980) in double-rice cropping systems, but 93,192 (2006), 4,502 (2003), and 9,712 (2007) in single-rice cropping systems (see Fig. 2). The initial populations in the single-rice cropping system are much higher than those in the double-rice cropping system because of the effects of cropping systems on the population development pattern in source areas. The higher initial population size of SBPH mainly resulted from the increase in wheat and fallow fields where an SBPH overwintering population could develop normally until the adults of the first generation emerged and dispersed to the rice paddy. The higher immigrants of BPH mainly resulted from the increase in area under a single-rice cropping season in source regions, where the BPH emigration population in late August to early September is much higher than in late July to early August from fields with a first-rice cropping season as mentioned above. The higher immigrants of WBPH mainly resulted from the expansion in hybrid rice growing area in source areas, including Vietnam and southern China.

Impacts on growth rates

Based on the data collected from fields in Jiaxing, Zhejiang, during 1976 to 2007, the growth rates of total planthoppers, including SBPH, BPH, and WBPH, from immigra-

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tion to peak population, developing two generations after immigration, in fields with a second-rice crop season were about 1,000 in the 1980s and 1990s, but the growth rates in recent years have been more than 5,000 in fields with a single-rice crop season because of the following higher population parameters.

Higher fecundity. Rice planthoppers are r-strategic pests with high fecundity and high-yielding techniques that promote their capacity for increasing fast. Lu et al (2004) reported that high nitrogen could increase BPH fecundity by improving food nutrition. The wide use of hybrid varieties provides better nutrition for WBPH and experiments showed that fecundity of WBPH on hybrid varieties was 2–9.7 times higher than on other varieties (Huang et al 1994). Laboratory and field experiments showed that pyrethrum, triazophos, and chlorpyrifos could cause a resurgence of BPH by stimulating fecundity. A sublethal dose of triazophos could double female macropterous fecundity. The application of chlorpyrifos could increase BPH fecundity by 39.2–47.3% and population sizes of WBPH by 130–160% in fields (Heinrichs 1994, Wang et al 1994, Cheng et al 1995). Nonetheless, triazophos and chlorpyrifos were still recommended to replace methamidophos in rice pest management and pyrethrum became the main component in cocktail pesticides for leaffolder control after methamidophos was banned in 2004. Since the 1980s, herbicides have been widely used in rice-growing areas and herbicide usage doubled in the past 10 years. The proportion of herbicides to total pesticides is more than 30% in recent years. Wu et al (2001) reported that the commonly used herbicides, including butachlor, metoachlor, oxadiazon, and bentazon, could significantly stimulate BPH fecundity by increasing BPH feeding rate and reducing the resistance of rice plants. The fecundity of rice planthoppers is also affected by temperature and the optimum temperature for fecundity of BPH and WBPH is about 26–28 °C (Chen et al 1986, Feng et al 1985). September is the main developmental period for BPH due to the high proportion of short-wing-form females and better nutrition around heading stage, but the temperature starts to decline in September and average temperature is only 21.84 °C at in late September. Therefore, higher temperature in autumn could increase fecundity (Cheng et al 1992).

More generations. In general, rice planthoppers could develop more generations in fields with a single-rice crop because of the longer cropping period, but the number of generations they can develop in fields with a single-rice crop depends on the time when the field is transplanted as well as the temperature. The single-rice crop in the Yangtze Delta is transplanted around mid-June to early July, but sown around late May to early June. The earlier the single-rice crop is transplanted or sown, the more generations it can develop. Compared with the second-rice cropping system, planthoppers could develop one or two more generations in single-rice cropping because of the earlier arrival of planthoppers and longer growing period of rice (see Fig. 6). The average temperature in September 2005 was the highest since 1954 and it was 26.3 °C and 2.8 °C higher than the average, which made BPH develop an additional generation.

Lower mortality. As an r-strategic pest, rice planthoppers are subject to high mortality caused by natural control agents. Kenmore et al (1984) reported a preadult survivorship of only 4% in the Philippines and Gao et al (1988) reported a natural

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control effect of 63% in the Yangtze Delta area. The major natural control agents are *Anagrus* spp., *Cyrtorhinus lividipennis*, and *Haplogonatopus* spp. Field investigations in Jiaxing showed that egg parasitic rates for rice planthopper eggs by *Anagrus* spp. were about 20–30% and the parasitic rates of planthopper nymphs and adults by *Haplogonatopus* spp. and nematodes were about 15–30% and 20% during the 1980s, respectively (Gao et al 1988). However, parasitic rates for eggs and two other development stages by these parasitoids are only about 10% each in recent years. The densities of various predators also declined significantly. Experiments showed that predatory capacities of *C. lividipennis* Reuter on BPH eggs and young nymphs were negatively related to the nitrogen contents of the host plants. The reduction in *C. lividipennis* natural control function could be one of the crucial factors inducing the outbreak of BPH populations in rice fields receiving excessive nitrogen fertilizer (Lu et al 2005).

Effects on control efficiency

Rice planthoppers have been managed mainly by using pesticides in China because of the lack of resistant varieties as well as the perception of farmers and technicians on pesticides. Extensive research on pesticide control strategy has been carried out and the key tactics for a control strategy are timing of application and type of pesticides to be used. Field experiments and a simulation study demonstrated that the best strategy is to apply pesticide with higher efficiency and a longer residual period at 30 days after transplanting based on the control threshold in the second-rice cropping season (Cheng et al 1990). However, the changes in population structure of rice planthoppers resulting from changes in ecological conditions made pesticide control become less efficient in reducing yield losses.

Changes in species structure. Species structure here refers to the composition of three rice planthopper species in various rice crop stages. The long evolutional development of the three planthopper species not only made them develop their specific niches to avoid competition in the rice ecosystem but also made them develop a strategy for mutualism among them. Serious yield losses were usually caused only by one planthopper species during the 1960s and 1970s and by two planthopper species in the 1980s and 1990s, but by three species in recent years. Therefore, species structure has become more diversified in recent years and three species co-occur in the same fields in most crop stages. Field investigations showed that species structure was closely related to cropping systems and varieties (see Fig. 8). In Yangtze Delta areas, the main planthopper species are SBPH and WBPH in the first-rice cropping season, but varied in the second-rice and single-rice cropping seasons depending on varieties. Mainly SBPH and WBPH occur in hybrid rice, SBPH and BPH in japonica rice, and the three species together in indica rice. Therefore, interactions among the three species become more important for population development. Laboratory experiments on the interspecific effects of BPH and WBPH indicated that interspecific interactions between BPH and WBPH provided positive effects for the two species at low and medium density, with less than 6 per seedling. Nymphal development duration, emergence rate, adult longevity, and fecundity of the two species reared in mixed

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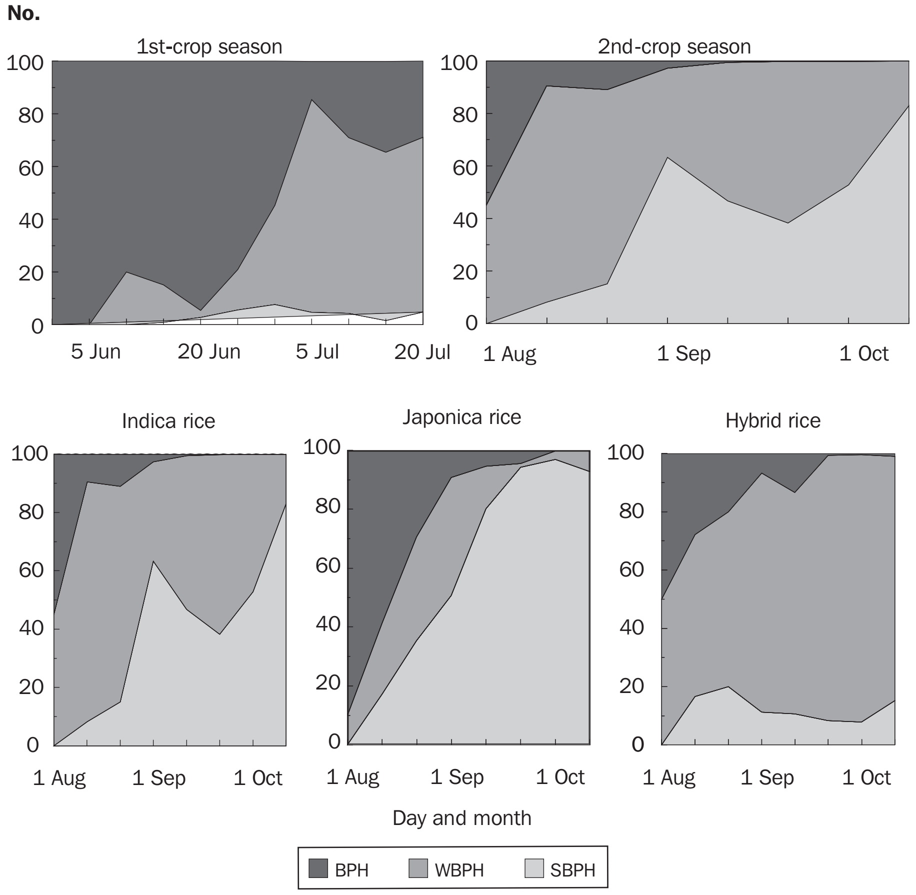

Fig. 8. Relationship of species structure to cropping system and varieties.

culture with other species were usually lower or higher than for those reared in pure culture. But the positive effects were also related to species and rice varieties. WBPH showed more positive effects under mixed culture conditions than BPH. The positive effects for both BPH and WBPH were higher on unsuitable varieties than on suitable varieties (Cheng et al 2001). The co-occurrence of planthopper species might also help them to escape from predation. Field investigation using monoclonal antibodies revealed that food shifting of spiders from one prey species to another in the field was mainly related to the proportions of density of these prey species to the density of total preys. *Pardosa pseudoannulata* mainly preys on midges when WBPH starts to migrate into paddy fields around June and on WBPH when BPH starts to migrate into paddy fields around July because densities of midges and WBPH at those times are much higher than those of WBPH and BPH, respectively (Zhao 2003). These two phenomena imply that the co-occurrence of these planthopper species benefits their

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population development at the early stage. The variance in sensitivity of the three planthopper species to varieties and insecticides makes the choice of management programs more complex.

Changes in genetic structure. The excessive use of insecticide led to the development of insecticide resistance in rice planthoppers and SBPH was the earliest rice planthopper species being detected as resistant to malathion and other organophosphates, as well as BHC, in the rice ecosystem in the mid-1960s. Between 1967 and 1979, immigrants of BPH developed resistance to several insecticides, including carbaryl, MTMC, malathion, diazinon, and fenitrothion. Research revealed a distinct contrast in the rapidity of the development of insecticide resistance between migratory rice planthoppers (BPH and WBPH) and the less migratory planthopper (SBPH) and the development of resistance in BPH and WBPH had historically been rather slow when compared with SBPH (Heinrichs 1994). Although there were reports on various problems, pesticide resistance for yellow stem borer to BHC in the mid-1960s, rice green leafhopper to malathion and other organophosphates in the early 1970s, striped stem borer to Shachongshuang and triazophos in the 1990s, and rice planthoppers to organophosphates and carbamates (Long 2005), pesticides are still used extensively for rice planthopper control. The sudden occurrence of high resistance of BPH to imidacloprid indicated that the resistance problems of rice planthoppers were more serious than what we thought. Further experiments showed that resistance indices of BPH to imidacloprid were about 70–557 (Yang 2007) and control efficiencies of Applaud and imidacloprid for SBPH were only 22.9% and 36.5% (Wang et al 2007). Recent experiments also showed that resistance indices of WBPH to imidacloprid and Applaud were 12.2–23.1 and 28.0–35.0, respectively (Tang et al 2008). The high resistance to imidacloprid for BPH that occurred suddenly from Vietnam to Japan in the same year, 2005, revealed that the genetic change of migratory planthopper species could occur more quickly than what we expected because the same pesticide could be used in all the areas along migratory routes in the globalizing world. The composition of virulent populations in local areas is also affected by that in source areas (Li et al 1999).

Change of temporal structure. The temporal structure is the age structure of a planthopper population through a crop season. The most important structure related to population development is the proportion of immigrants to all adults during the crop season, which is related to the effects of immigrants on population development from outside of fields. The reasons for higher efficiency to take control action at 30 days after transplanting, around late August, in the second-rice crop season are the short immigration period and short development period for BPH populations in it. The main immigrants usually arrive in the second-rice crop season around late July and early August and the main immigration period is only about 10–20 days. The time period good for population development is about 2 months because the temperature around late September might be too low for population reproduction (Cheng et al 1992). Although the pesticides used could kill only adults and nymphs, but not eggs, adults developed from these eggs laid by immigrants in August may not be very effective for population development because it is already close to late September. However, there

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might be three main immigration periods, late June to early July, late July to early August, and late August to early September in the new single-rice cropping systems now. Therefore, the immigration period could last about 3 months and one pesticide application is unable to cover the whole period in a single cropping season. The best control strategy used for a second-rice cropping season in the double cropping system is not able to get the same efficiency in a single-rice cropping system. Field investigations in 2006 showed that the immigration population arriving in early September was more than 2.6 macropterous adults and reached about 87.5 nymphs and adults per hill after one generation, and caused economic loss. This indicated that the effective immigration period could last from July to early September and yield losses could be caused by the generation produced directly by immigrants.

Developing new management programs

The new rice planthopper problems mentioned above revealed that planthopper outbreaks resulted from the high intrinsic capacity for a population increase in rice planthoppers and changes in environmental factors in their habitats in recent years, which provided favorable conditions for them to show this high capacity for increase. This verified three basic principles for rice planthopper management: it is impossible to obtain sustainable control for rice planthoppers by using pesticide only, even with a highly efficiency insecticide such as imidacloprid; a key strategy for planthopper control is to reduce their capacity for increase by managing the three key parameters mentioned in the earlier equation; and, it is better to design management programs on a large geographic scale for migratory pests.

Managing initial populations by modifying cropping systems

Field investigation and simulation study indicated that an early transplanting time (early starting time for immigration), an early immigration peak, and a high immigration rate all tended to favor BPH outbreaks (Cheng et al 1990). Expansion of the single-rice crop season in Yangtze Delta areas shifted transplanting time to around June, 1–2 months earlier than that for the second-rice crop season, as it did for starting time for immigrants. Expansion of the single-rice crop season in source areas extended the immigration period (late August to early September) and 1 more month increased the immigration rate. Field investigations in 2006 showed that earlier immigrants played a more important role. The earlier immigrants, 2.26 per 100 hills in early July, could develop 7,804 times and they reached 17,637 per 100 hills in late September. But late immigrants, 172 per 100 hills in early September, could develop only 33.7 times and reach 5,836 per 100 hills. This comparison clearly showed that small earlier immigrants could cause serious problems and the starting time for immigration was closely related to the cropping system. The starting time for immigration could be postponed if the transplanting time was postponed. Field experiments showed that plant infection rates of rice stripe virus disease and densities of BPH immigrants could be reduced by about 50% and 70%, respectively, if the time for sowing and transplanting could

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be postponed from 15 May and 15 June to 29 May and 29 June. The yields in the two treatments had no significant difference.

Managing growth rate by building up system resistance

Based on historical data collected from fields without any insecticide applications, the average peak densities of immigration generations in most of the 14 outbreak years were about 3 macropterous adults per 100 hills and the growth rates after 2–3 generations in these years were more than 1,000. The high growth rates mainly resulted from high nutrition (susceptible varieties and high nitrogen input), low natural mortality (overuse of pesticides), high humidity (dense canopy), higher autumn temperature, and stimulative effects of pesticides on fecundity in high-yielding rice ecosystems. It is important to develop a management program that will harmonize high yield and system resistance to rice planthoppers. System resistance means the general capability of a rice ecosystem to reduce the growth rate of rice planthoppers. The basic approaches for building up system resistance could include the development of resistant varieties, enhancement of natural biological control, and improvement of nutritional management. Although virulence to resistant varieties could be developed, varietal resistance should still be considered as one of the basic components of planthopper management, especially for an ecosystem such as China, where natural biocontrol agents are weak due to the long history of pesticide overuse.

Managing yield losses by developing a new control strategy

The high growth rate and unusual high immigration in some years in subtropical and temperate regions make urgent control action an important component for a management program of rice planthoppers to reduce or avoid economic yield losses. The sudden occurrence of high resistance of BPH to imidacloprid on a large scale in 2005 after the unreasonable use of the pesticide revealed that the development of a scientific control strategy for using control measures wisely might be more important than the development of new control measures. Most control strategies developed before were mainly based on the population development pattern of one particular planthopper species and the differences in population development patterns and sensibility to varieties and pesticides among species could reduce the control efficiency of these traditional strategies. Therefore, a new control strategy should be developed with a view of the rice ecosystem, which should take the three rice planthoppers, as well as other pests, into consideration. To improve the traditional strategy relying on chemicals, new environment-friendly control measures should be developed.

Managing rice planthoppers through establishing international collaboration

As migratory pests, both BPH and WBPH migrate among South Asia, China, South Korea, and Japan and planthopper problems in one country will always be related to planthopper problems in other countries. The immigrants in one country/region are from another country/region and the starting time, pattern, rate, and genetic structure of the immigration population in one country must be related to the population in

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another country. Since BPH and WBPH move from one country to another country every year, biological characteristics of the two planthopper populations in one country, especially for genetic structure, could be a mixture of the populations in many of the countries. The development of virulence to varieties and resistance to insecticides for BPH provided examples to demonstrate that a management program in the globalizing world should be designed on an international basis. International collaboration should not only include surveillance of population development patterns, virulence, and pesticide resistance for the development of management programs but also diversified techniques for high yield to be used for a delay of virulence and the development of resistance. In the meantime, cropping systems in both source and local areas could be designed based on population development pattern at a migratory scale to manage planthopper problems.

The increase in food requirements by the increasing population in the world will make high yield the first priority for rice production, but rice planthopper problems have been exacerbated by traditional high-yielding practices since the 1960s. A comparison of rice planthopper problems between tropical rice ecosystems and subtropical and temperate rice ecosystems revealed that the most important task would be to develop sustainable management programs for rice planthoppers by building up system resistance to reduce their initial population and capacity for increasing in subtropical and temperate rice ecosystems.

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Notes

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