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Rice Planthoppers in the Past Half Century in China

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Abstract: Historical developments of rice planthopper problems in China, as well as research efforts on these problems, in the past half century are reviewed. Compared with tropical rice ecosystems, population development patterns of rice planthoppers in Chinese rice ecosystems are characterized as multiple planthopper pest species, complex immigration sources, high growth rate, and high outbreak frequency. Historical data on rice planthopper problems reveal that frequent outbreaks of rice planthopper problems in China are mainly the result of vulnerable rice ecosystems associated with susceptible host plant varieties and weak natural regulation in intensive rice ecosystems and subject to variable immigration levels and meteorological conditions. To feed an increasing population in China given the limited arable land available, sustainable intensive rice ecosystems with high natural regulation of planthopper populations need to be established by enhancing the resilience of the system to rice planthoppers, developing international and regional collaboration and reforming decision-making systems for rice planthopper management.
Key words: Brown planthopper; White-backed planthopper; Small brown planthopper; Intensified ecosystems; Sustainable management

1.1 Introduction

World population started to increase quickly after the 2nd World War and reached 3 billion in 1960 and 7 billion before the end of 2011, which indicated that the world population has been increasing with a speed of 1 billion per 12 – 14 years and has more than doubled during the past half century. In China, the population in 1960 was about 0.66 billion, but has reached more than 1.34 billion now, which means the population has doubled in this half century, even where the One Child Per Family Policy has been implemented since the 1980s. At the same time, the total arable land in China which was 136 million ha in early 1950s, is now only around 120 million ha (MOA, 2012). How to feed ourselves given an increasing population and a limited and declining area of arable land is a major challenge for the future.

To address this challenge, the 1st Green Revolution began in the 1960s, based on new developments in science and technology, especially in genetics, synthetic chemicals and irrigation. New high yielding varieties, together with high inputs of chemical fertilizers and pesticides have significantly increased yield per unit area. For example, in China rice yield per ha increased from 2395 kg to 6687 kg during this period. Thus, although the total area of rice has remained almost the same, at around 30 million ha, total rice production increased more than 3 times, from 59.7 million tons to 191.90 million tons (MOA, 2012).

However, the high yielding measures developed in the 1st Green Revolution created favorable conditions for planthoppers and enhanced their high intrinsic capacity to increase. At the same time, the modern measures developed to control rice planthoppers reduced natural regulation and increased the vulnerability of the rice ecosystem significantly. Therefore, unexpected ecological consequences occurred, one of the most important changes is the structure of the arthropod community in rice agroecosystems during this period. The smaller sized herbivores, such as rice planthoppers, including *Nilaparvata lugens* (Stål) (brown planthopper, BPH), *Sogatella furcifera* (Horváth) (whitebacked planthopper, WBPH) and *Laodelphax striatellus* (Fallén) (small brown planthopper, SBPH), have replaced the larger size herbivores such as stem borers and became the most dominant herbivores in rice ecosystems in most Asian countries. The three rice planthoppers feed by inserting their styles into the vascular tissue of plant leaf blades and leaf sheaths and ingesting the sap. Heavy infestation can cause the complete drying and wilting of plants known as “hopperburn” and the pests also transmit 5 virus diseases (Cheng, 2009; Botroll & Schoenly, 2012).

While efforts have been made to develop various tactics and strategies to control these pests, the rice planthoppers have responded by developing new features to adapt to these changes, maintaining a high population and causing serious yield losses. Thus the historical developments associated with the green revolution in rice growing countries seem to show that rice planthopper problems constitute the principle contradiction between intensification and the sustainability of rice cropping systems. Meanwhile, the world population continues to increase and might reach 9 – 10 billions in another half century in which case further intensification will be a necessary to feed the increasing population. In this chapter, the future prospects for achieving both intensification and sustainability are explored by reviewing the history of rice planthopper problems in China and the strategies developed for rice planthopper management in a sustainable intensive rice ecosystem.

1.2 Historical Development of Rice Planthopper Problems

Before the 20th century, outbreaks of rice planthoppers were only recorded in eastern Asia. The earliest record for a rice planthopper outbreak was in Japan and outbreak records can be traced back to 697 A.D. or 701 A.D. More detailed records indicate that outbreaks of planthoppers caused losses of 96×10^4 t in 1897, which was equal to a loss in rice production of 18% for all of Japan. In China, the earliest recorded outbreaks were in 1578 and 1624 in Zhejiang Province. In Korea, hopper damage was reported as early as 18 A.D. Outbreaks of BPH has been authentically recorded rather more frequently in the 20th century, with outbreaks occurring in 1912, 1921, 1922, 1923, 1926, 1929,1935, 1940, 1944 and 1948 in eastern Asia (Dyck & Thomas, 1979; Cheng et al., 2003).

Since the 1950s, rice planthopper problems have become more serious in China, as well as other Asian countries. BPH outbreaks occurred in Hunan Province with a density of 1000 – 3000 per hill in 1957 and 1958 and it has become the major insect pest in southern China since the late 1960s (Cheng et al., 2003). SBPH outbreaks occurred in the Yangtze Delta and caused serious damage by transmitting rice stripe virus (RSV) and rice black streaked dwarf virus (RBSDV) in 1963 – 1967 (Hong et al., 2006). Rice ragged stunt virus (RRSG) and rice grassy stunt virus (RGSV) transmitted by BPH were found in southern China in the late 1970s (Zhang et al., 2001; Zheng et al., 2008). WBPH started to outbreak in the late 1970s and became one of the most important insect pests in southern China (Tang et al., 1996; Sogawa et al., 2009). A new virus disease transmitted by WBPH, south rice black streaked dwarf virus (SRBSDV), was found in 2001 and it started to outbreak in 2009: the outbreak area in China was about 1.2 million ha in 2010 (Zhai et al., 2011; Zhong et al., 2011). Fig. 1.1 shows the increasing area affected by the three rice planthopper species in China since the 1960s.

This historical development of rice planthopper outbreaks occurring in China can be grouped into three stages based on the areas affected and the major species concerned. The 1st stage was before the late 1970s. At this stage, only one of the three species caused serious yield losses in the same year and either SBPH or BPH was considered the major planthopper pest in a particular area. The 2nd stage is from the late 1970s to late 1990s, when WBPH started to be one of the major planthopper pests and both BPH and WBPH caused serious yield losses in southern China. At this time, SBPH occurred only occasionally in small areas, while the occurrence of WBPH was continually expanding and WBPH became the No. 1 pest based on outbreak areas. The 3rd stage was after the late 1990s. At the 3rd stage, SBPH came back again and all the three species were causing serious yield losses in most of these years (Cheng, 2009). Since one more virus (SRBSDV) transmitted by WBPH in China started to appear in 2009, all the three rice planthoppers and 5 virus diseases transmitted by them became major pests in rice ecosystems. Thus, since the 1960s, rice planthopper problems have taken a turn for the worse, as shown in the historical record in Fig. 1.1, indicating that rice planthoppers and associated virus diseases have become the most important pests threatening food security in China.

The Yangtze Delta area located on the east cost of China is one of the highest yielding rice growing areas and all the three rice planthoppers co-occur there. Fig. 1.2 shows historical records of total numbers caught in light traps per year during

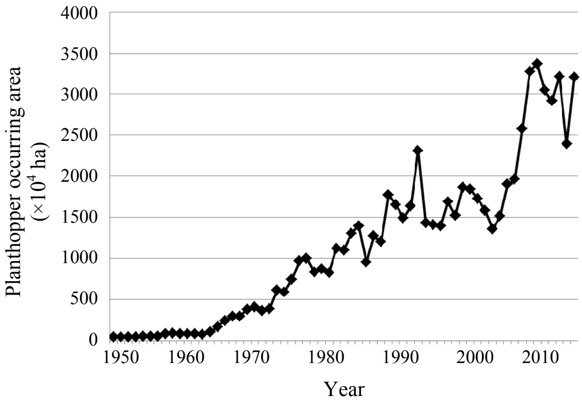

Fig. 1.1 Historical development of rice planthopper problems in China

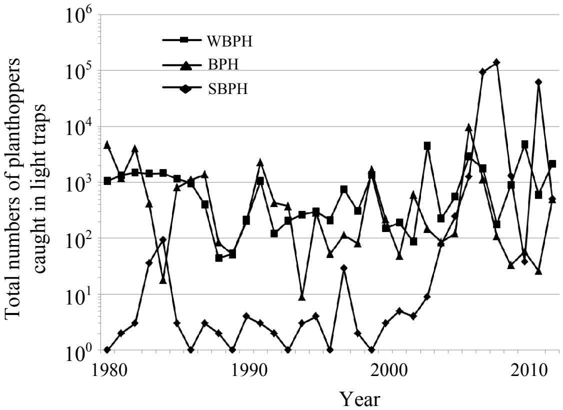

Fig. 1.2 Historical record of total numbers of the three planthopper species caught in light traps annually in Jiaxing, Zhejiang Province, China since 1980

the key immigration periods for the three planthopper species since 1980. The initial populations of BPH and WBPH in Jiaxing, Zhejiang Province, are immigrants from South China, but the initial population of SBPH is a mixed population from both the local overwintering population and immigrants from other source areas. The main immigration periods are around mid-May to early June, late June to early July, and July to early September, respectively for SBPH, WBPH and BPH. The highest peak population in light traps for SBPH, WBPH, and BPH were 137351, 4755 and 9712, in 2008, 2010 and 2007, respectively. The highest peak populations for the three species are at least two times higher than those experienced in the 1980s and 1990s.

Fig. 1.3 shows the historical records of peak densities of total rice planthoppers in monitored plots without insecticide application in Jiaxing, Zhejiang Province since 1970. As shown in Fig. 1.3, peak population sizes fluctuate year by year and were more than 15000 per 100 hills in the 5 years since 2005, which indicates that population sizes in more than half of the years since 2005 were more than two times higher than the highest population size in the past century. Based on the historical data collected from the fields where no insecticide was applied, the highest peak densities of SBPH, BPH and total planthoppers per 667 m^2 in the 20th century were less than 1 million, 2.36 million, and 2.42 million, respectively. In the 21st century, the average peak densities of SBPH, BPH, and total planthoppers were (1.73±0.57) million, (5.24±0.86) million, and (6.52±0.73) million, almost more than two times higher than the highest densities 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).

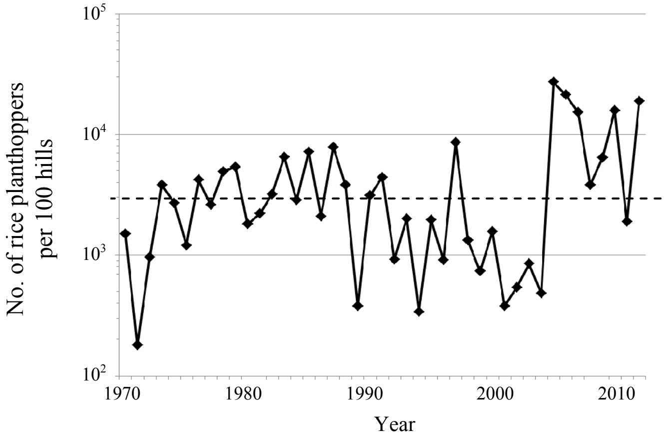

Fig. 1.3 Historical record of peak densities of rice planthoppers in monitored plots without any insecticide applications annually since 1970 in Jiaxing, Zhejiang Province, China

1.3 Historical Efforts on Researches for Managing Rice Planthoppers

Research on rice planthoppers started in the mid-20 century when rice planthoppers began to cause serious damage. The number of papers published up to 2011 is 11581, of which 7612 were published in China. In general, there are three phases in the publication of papers on brown planthopper—a significant increase in the 1960s and 1970s, a relatively stable period in the 1980s and the early part of the new century, and a sharp increasing in mid 2010. A similar pattern of papers published on all the three rice planthoppers is similar to that of brown planthopper since the number of papers on BPH accounts for about 60% of the total papers on the planthopper species. However, inspection of the publication data for the other two rice planthopper species shows only two stages, a significant increase in the 1970s to the 1990s and a stable period since 1990 for WBPH, and a slow increase in the 1960s to the 1990s and a significant increase since the late 1990s for SBPH (Fig. 1.4). The data on publications indicates that the research effort on rice planthoppers follows the extent of the rice planthopper problem. Rice planthopper studies started when they became major pests and caused serious damage in the 1960s; further effort was added when new problems occurred such as resurgence problems in the 1980s and resurrection in the 21st century (Lu et al., 2013).

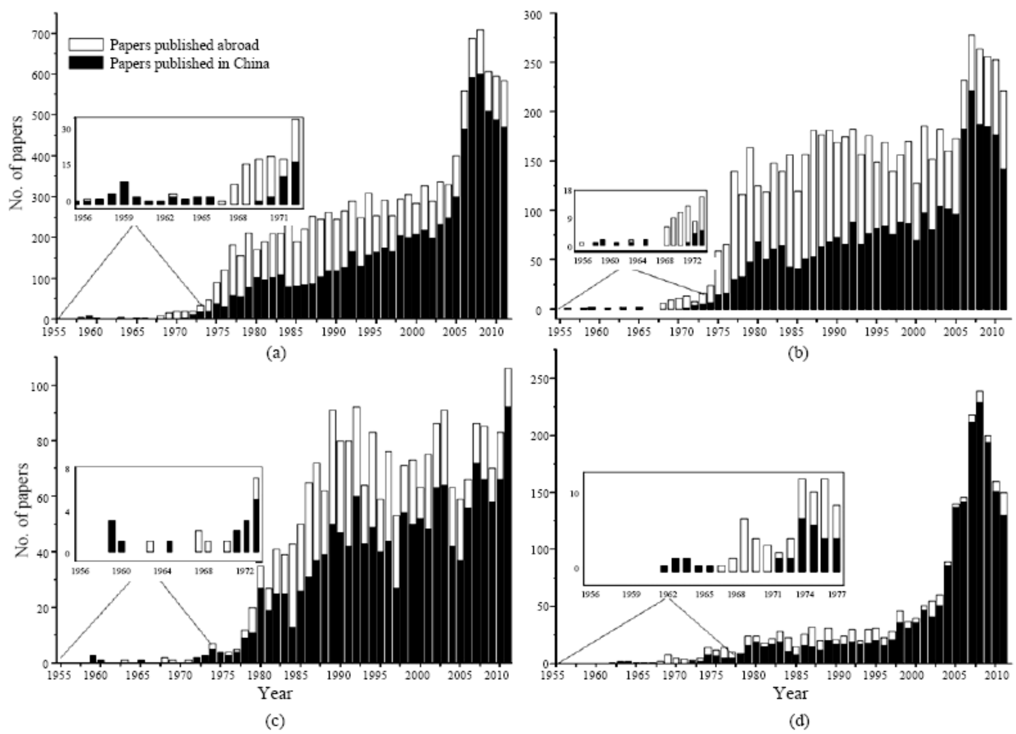

Fig. 1.4 The number of papers published on rice planthoppers in the world since 1950 (Lu et al., 2013). (a) RPH; (b) BPH; (c) WBPH; (d) SBPH

Based on the topics addressed, all the papers published on planthoppers could be grouped into 5 areas, including biology, ecology, physiology & molecular biology, virology, and surveillance & management as shown in Fig. 1.5. In all the time periods since 1970, the number of papers related to surveillance & management and ecology were ranked 1 and 2. The numbers of papers in these two areas were 6186 and 2590, about 75.8% of the total papers published, which indicates that most planthopper research has focused on planthopper surveillance & management (Lu et al., 2013). However, despite this effort, there were serious outbreaks of BPH in China in 2005 – 2007 that affected 6.6×10^4 – 9.4×10^4 ha of rice annually and exceeded those outbreaks ever recorded (Catindig et al., 2009;

Cheng, 2009). Rice planthoppers, as recurring threats to high-yielding rice production in Asia, were named as the ghosts of the green revolution (Botroll & Schoenly, 2012).

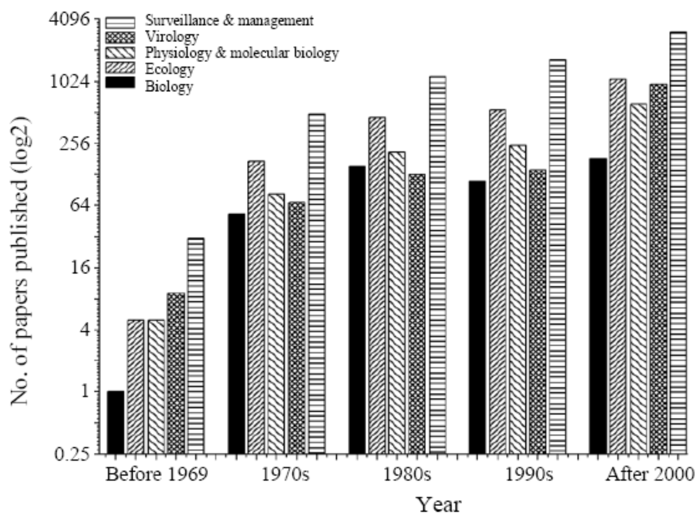

Fig. 1.5 The number of papers published worldwide on various aspects of rice planthoppers at different time periods since 1960 (Lu et al., 2013)

1.4 The Population Characteristics of Rice Planthoppers in China

Since it is rare for insect habitats to provide continuously favorable physical and biological conditions for population growth in both space and time, population continuity is achieved in two ways: through the ability to survive in unfavorable conditions through diapauses and/or having sufficient mobility to permit the species to track spatial displacement of the requisite habitat conditions in time for the majority of insect species (Southwood, 1977; Dingle 1972; Denno 1983; Perfect & Cook, 1994). As the monophagous (BPH) or oligophagous (WBPH and SBPH) insects have less tolerant to low and high temperature, all the three species have developed the ability to migrate and track spatial changes in the quality of host plants and seasonal temperature, and developed their population characteristics in various regions. Comparison of the main characteristics of population development patterns between tropical and Chinese rice ecosystems could provide additional information on underlying mechanisms of frequent outbreaks in China. The main population characteristics of rice planthoppers in Chinese rice ecosystems include multiple planthopper pest species, complex immigration sources, high growth rate and higher outbreak frequency, compared with the situation in tropical rice ecosystems where there is predominantly only one planthopper pest species, the initial population arises from a local source, it has a low growth rate and there is less outbreak frequency (Perfect & Cook, 1994).

1.4.1 Multiple Planthopper Pest Species

There are about 40 delphacid planthopper species which are able to use rice as a host plant in Asia, but only about half of them are found in China (Dupo & Barrion, 2009). Among them, BPH is the major pest in rice ecosystems from the tropics to about 42° N to 44° N across Asia while WBPH is the major pest in northern Vietnam and East Asia; SBPH is the major pest only in some areas of subtropical and temperate regions from about 30° N in East Asia.

The development patterns and compositions of the three planthopper species are closely related to host plant varieties and cropping system, as well as the latitude. In general, hybrid rice is susceptible to WBPH while japonica rice is resistant to it. Generally, SBPH is not able to develop well in tropical regions. There are mainly BPH and WBPH in southern China, but there are three planthopper species in some subtropical and temperate areas of China. In the southern China, there are two crop seasons a year and rice varieties are mainly hybrid. The planthopper population in field there mainly consists of WBPH and BPH, WBPH migrates into rice paddy early than BPH for both the 1st and 2nd seasons. Therefore, the number of WBPH in the early crop stage for each crop season accounts for a considerable proportion, especially in the 1st crop season. The number of BPH in the late crop stage for each crop season accounts for a considerable proportion, especially in the 2nd crop season as showed in Figs. 1.6(a) and 1.6(b). However, there is mainly one rice crop season a year in middle and northern China, and rice varieties used are mainly japonica and hybrid depending on areas. The planthopper population there may consist of the three rice planthopper species, especially in the Yangtze Delta area. Fig. 1.6(c) showed the temporal dynamics of the composition for the three planthopper species in the area. SBPH is the earliest one moving into the field since SBPH can overwinter locally and BPH is the last one moving into the field. The main planthopper species with highest percentage is varied through the crop season from SBPH, WBPH to BPH, then back to SBPH as showed in Fig. 1.6(c).

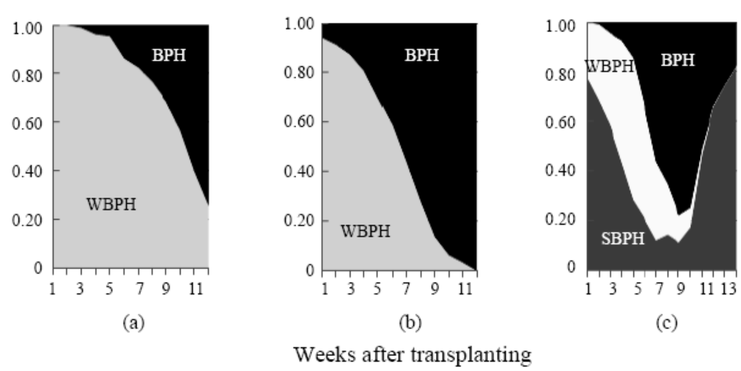

Fig. 1.6 Comparison of temporal dynamics of planthopper species compositions between geographic regions and cropping systems. (a) 1st crop season in southern China; (b) 2nd crop season in southern China; (c) Single crop season in Yangtze Delta area

1.4.2 Complex Immigration Sources

In tropical regions, BPH and WBPH immigrants may arrive in rice fields at any stage of crop development since immigration is highly variable in time. Nevertheless immigration can be described as seasonal since evidence suggests that most dispersal of BPH and WBPH in the tropics occurs over a distance of 5 – 30 km and that immigration is not associated with particular meteorological conditions but with local cropping patterns (Perfect & Cook, 1994). On the other hand, the sources for immigrant populations in Chinese rice ecosystems are associated with meteorological conditions, as well as cropping patterns. The early immigrants in southern tropical China are mainly from tropical countries since BPH and WBPH are able to overwinter there whereas the local overwintering population is very low. The source areas for these immigrants are mainly from the Indo-China Peninsula, including Vietnam, Thailand, Lao and Myanmar, but the exact source area for each immigrant population for a particular landing area varies depending on the cropping systems and meteorological conditions. In southern China, the earliest immigrants arriving around March might come from the middle east part of Indo-China Peninsula including middle Vietnam (16° N – 20° N) and the Vientiane Plain. The immigrant populations in April and May in the Nan Mountains area are likely to come from the northern part of the Indo-China Peninsula and partially from Hai-Nan inland (Hou et al., 2003; Sheng et al., 2011; Zhai, 2011).

However, the immigration populations of WBPH and BPH in the north of Nan Mountains, China are mainly from southern China although some immigrants may come from tropical areas directly depending on timing and meteorological conditions. A previous study has already identified the migration routes in eastern China from south to north in spring and summer and from north to south in autumn. There are five main immigration periods from south to north, during mid-April to early-May, mid-May to early June, mid-June to early-July, early-July to mid-July, and late-July to early August. Then there are about 3 – 4 emigration periods from north to south from late-August to early-October (Cheng et al., 2003). During these periods, migrants are continually move in or out, but show several peaks. The starting and peak time of immigration for each period, as well as the number of immigrants, for a particular area, varies since the migration process of planthoppers is affected by various meteorological and geographic factors. Each immigration population from a specific area may land in a main area, but spread to even a wider neighbor area.

Recent studies reveal that SBPH is also a migratory pest. SBPH can migrate from one place to another place within China, as well as from China to Japan and Korea. For example, studies using field investigation, light trap catches and dissection of planthopper ovaries indicate that the sources of SBPH immigrants for Haining, Zhejiang Province in late May to early-June might come from South Anhui Province, South Zhejiang Province, North-East Jiangxi Province, South Fujian and North Jiangshu Province since the wind fields on 850 hPa were changeable during the main immigrating period of SBPH there (He et al., 2012).

The source areas of SBPH immigrants for Fengtai, Anhui Province in early-mid June might come from Yangzhou, Jiangsu Province and Jining, Shangdong Province (Wang et al., 2011). SBPH immigrants in Jining, Shangdong Province in early June were mainly from Shuqian and Danyang, Jiangshu Province, but SBPH in Jining, Shangdong Province could migrate to Dalian, Dandong and Chaoyang, Liaoning Province in mid-June (Zhang et al., 2011). SBPH could also migrate to Kyushu, Japan from Jiangshu Province (Syobu et al., 2011). These results indicate that SBPH immigrants in June at a particular area might come from different source areas and SBPH emigrants from the same area might migrate to different landing areas.

Therefore, immigration sources are complex and an immigrating population for a particular rice crop season in Chinese rice ecosystems may come from several source areas at various time. The species and numbers of immigrants also depend on crop stage and meteorological conditions. For example, immigrants can continually migrate into Chenzhou located in southern Hunan Province at 25°5′ N and 113°1′ E. The earliest immigrants arrive around late March to early-April for WBPH and mid-April for BPH, and the main immigration periods are around mid-April, mid-May and early- to mid-June for WBPH and late-April to early-May, late-May and late-June to early-July for BPH (Shou & Cao, 1990). Earlier immigrants might come from the Indo-China Peninsula and later immigrants might come from the Guangdong and Guangxi Province in China (Cheng et al., 2003). SBPH, WBPH and BPH can also continually move into Jiaxing located in northern Zhejiang Province at 30°8′ N and 120°9′ E from May to early October and show several immigration peaks at around late-May to early-July for SBPH; mid-June, early- to mid-July and around mid-August for WBPH, and around late-June to early-July, late-July to early August, late-August to early September, and late September to early October for BPH. The WBPH and BPH immigrants before mid-August may mainly come from Guangdong, Guangxi, Hunan, Jiangxi and Fujian provinces, but the immigrants after mid-August may mainly come from western and northern part of China. The source area for each batch of immigrants varies depending on the cropping system and population development patterns in the source area, as well as the meteorological conditions (Qin et al., 2002; Cheng et al., 2003). All the phenomena indicate the complexity of immigration sources for Chinese rice ecosystems.

1.4.3 Higher Growth Rate

Population development of BPH has been extensively studied in both tropical and temperate regions. The growth rate, that is, the ratio between peak density and initial immigrant density, is used as a key parameter representing the capacity for planthopper population increase in a specific ecosystem. The net growth rate per crop season is significantly different at 3.2 for tropical populations compared to 513 for populations in Japan. The growth rate of WBPH is less than that of BPH and

WBPH increasing only 4 times over the course of three generations in one crop season in Japan (Cook & Perfect, 1994). In recent years, we compared the growth rates of BPH and WBPH in the Philippines (Los Baños, Laguna) and China (Fuyang, Zhejiang Province) using the same rice varieties and the same amount of fertilizer. The results showed that the growth rates were 30.5±10.7 and 791.3±533.7 for BPH and 10.8±2.4 and 116.5±46.3 for WBPH, respectively for the Philippines and China. This comparison indicates that the growth rates for the two species in China were significantly higher than those in Philippines. However, the growth rates of planthoppers in high yielding Chinese rice paddies without any pesticide application are even higher. During 1970s – 1980s, the average growth rate for BPH and WBPH could reach 990.60±193.48 and 515.5±164.5, respectively (Qin et al., 2002; Cheng, 1995). The population peak could appear at the 1st or 2nd generation after immigration in Philippines, but it might be in the 2nd or 3rd generation after the early immigration peak depending on the cropping system in China (Perfect & Cook, 1994; Cheng, 2009). The growth rate of BPH in rice crop systems having a longer growth period, the single rice cropping season planted in June, is much higher since early immigrants arriving in late June – early July could develop three generations after immigration and more immigrants arrive around late July – early August and late August – early September. The growth rate of BPH for the single rice crop season in Yangtze Delta, China (Jiaxing, Zhejiang Province) in the 21st century reached 5560.8±1672.4 (Cheng, 2009).

1.4.4 Higher Outbreak Frequency

Historical data shows that the outbreak frequency had been increasing in China since the 1960's and the outbreak frequencies were 10% – 20% in the 1960s, 50% in the 1970s and 70% in the 1980s – early 1990s respectively (Tang et al., 1996). Table 1.1 shows the outbreak frequencies of rice planthoppers in 6 provinces at various time periods from the 1970s to the 21st century. The average peak population sizes per 100 hills were ranked for three grades. The 1st grade means the average population density is less than 1000 planthoppers per 100 hills and no application is needed for most of the paddy fields. The 2nd grade means the average population density is 1000 – 3000 per 100 hills and pesticide application is necessary for most of the rice paddy fields to avoid economic losses. The 3rd grade means the average population density is above 3000 per 100 hills and hopper-burn could occur in some areas if no control action is taken. The data in Table 1.1 shows the occurrence for these three levels of peak population densities in 6 provinces, China. The frequencies of the 3rd grade in the 1st and 2nd or single rice crop seasons are (52.4±15.4)% and (48.3±9.1)% for BPH and (83.9±8.7)% and (52.1±13.3)% for WBPH, respectively. The peak population densities of WBPH in Jiaxing, where japonica rice has been planted since the 1960s, have been kept below 1000 per 100 hills. These figures indicate that the outbreak frequency of rice planthoppers is high and hopper-burn could occur in about half of the years where no control action is taken.

Table 1.1 Historical outbreak frequencies of white-backed planthopper and brown planthopper in China

Location	Year	Crop season	Planthopper species	Frequency (%) of population size (number per 100 hills)			References
				>3000	3000 – 1000	<1000	
Shaoqing, Guangdong Province	1990–1999	1st crop season	BPH	30.0	30.0	40.0	Li et al., 2003
			WBPH	70.0	20.0	10.0	
	1990–2001	2nd crop season	BPH	16.7	58.3	25.0	Lu et al., 2003
			WBPH	16.7	66.6	16.7	
Chengzhou, Hunan Province	1977–1987	1st crop season	BPH	45.5	45.5	9.1	Shou & Cao, 1990
			WBPH	100.0	0.0	0.0	
Xiushan, Zhongqin Municipality	1990–1999	Single rice crop season	BPH	50.0	30.0	20.0	Yan et al., 2012
			WBPH	50.0	40.0	10.0	
	2000–2009		BPH	50.0	30.0	20.0	
			WBPH	30.0	70.0	0.0	
Ganzhou, Jiangxi Province	1980–1990	1st crop season	WBPH	81.8	18.2	0.0	Qin et al., 2002
		2nd crop season	BPH	25.0	37.5	37.5	
Qianshan, Anhui Province	1980–1995	Single rice crop season	WBPH	81.8	18.2	0.0	Yang et al., 1996
Jiaxing, Zhejiang Province*	1967–1995	2nd crop season	BPH	39.3	42.9	17.8	
			WBPH	0.0	0.0	100.0	
	2005–2012	Single rice crop season	BPH	75.0	25.0	0.0	
			WBPH	0.0	0.0	100.0	
			SBPH	50.0	12.5	37.5	

*All the figures are calculated with local historical data by the author. The area has been planted with japonica rice since the 1960s

1.5 Factors Related to Frequent Outbreaks

Rice planthoppers are *r*-strategy insects and secondary pests in high-yielding agricultural ecosystems. Since the initial planthopper population is usually not from local sources, the main cause for their frequent outbreaks could relate to three factors: initial population, ecosystem vulnerability and stochastic weather conditions. The system vulnerability to rice planthoppers indicates the capacity of the ecosystem to suppress population development of rice planthoppers in the rice ecosystem; frequent outbreaks could occur in rice ecosystems with high vulnerability. Ecosystem vulnerability is related to two kinds of natural regulation functions, host plant resistance (the regulation function through host plant directly) and environmental resistance (the regulation function through other environmental factors). Management practices can directly and indirectly affect all these factors.

1.5.1 Initial Population (Immigration)

Population development in China usually starts with the macropterous adults migrating into the rice paddy since the initial sources of BPH and WBPH are mainly from remote source areas. Therefore, immigration is a key determinant for population development patterns, peak density and potential crop losses. Immigration includes three parameters—timing, magnitude and genetic structure, however, all the three parameters are influenced by the spatial and temporal distribution of the source population, insect flight range, and meteorological factors. In the meantime, the spatial and temporal distribution of the source population is influenced by cropping patterns and the temporal distribution by the degree of cropping asynchrony, within the flight range of the planthoppers.

1.5.1.1 Timing of Immigration

Timing of immigration involves not only the time at which immigrants start to migrate into paddy fields but also the patterns of immigration related to duration, that is, the time period for immigration and the rate of immigration in terms of the number of immigrants per day during the period. However, the starting time of immigration is the most important factor. Holt et al. (1989) investigated the effects of timing using a simulation model of BPH in a tropical rice ecosystem. The results show that immigration starting early in the season could result in damaging *N. lugens* population later in the season and immigrants arriving later than 30 days after transplanting need to number 10 times those arriving earlier in the season to cause an outbreak. Cheng et al. (1991) investigated the effects of timing using a BPH simulation model for a subtropical rice ecosystem and the results show that 10 and 20 day earlier for the same immigration population (same size and same pattern) in the 2nd rice crop season could increase about 2 and 5 times of peak population density, respectively.

The historical light trap data in various locations shows that there are large variations for the starting time of initial immigration of both BPH and WBPH in China. The date of the earliest or the latest 1st light trap collections for WBPH and BPH are March 5th and March 2nd, or April 29 and April 15 in Zhaoqin, Guangdong Province; March 24th and March 8th or May 14 and April 14 in Chenshou, Hunan Province; May 25th and June 3rd or June 24th and July 12th in Jiaxin, Zhejiang Province (Chen et al., 2005; 2006; Shou & Cao, 1990). Comparison of these dates for each location and species indicated that the difference between the date of the earliest and the latest 1st light trap collection was about 1 month at least, which is equal to the time period for developing one generation. The outbreaks of the two species often resulted from the early immigration time.

1.5.1.2 Magnitude of Immigration

The magnitude of immigration can be represented by the total number of immigrants during the main immigration time period. Cook & Perfect (1985) investigated the relationship between immigration sizes of *N. lugens* and *S. furcifera* on population development by comparing water trap catches and population growth over a range of rice habitats where immigration sizes differed within a season. The results show that there is no clear relationship and high peak densities often are associated with the lowest levels of immigration and vice versa. Cheng et al. (1991) investigated the relationship between immigration size of *N. lugens* and peak population size by comparing light trap catch and peak population size in fields without any insecticide application from 1978 to 1989. The results show that population size is significantly correlated with the light trap catches in early July (r=0.6603*) and early August (r=0.7950*).

Historical light trap data in various locations shows that there are large variations in the size of immigration populations for both BPH and WBPH in China. The same historical data mentioned above also shows that the differences between the largest and smallest immigration sizes during the main immigration period were 58.4 and 20.8 times in Zhaoqing, Guangdong Province, and 86.22 and 181.6 times in Jiaxing, Zhejiang Province, respectively for WBPH and BPH. The same historical data shows that the differences between the highest and lowest peak densities in the fields without any insecticide application were 23.0 and 45.5 times in Zhaoqing, Guangdong Province, 5.1 and 120.2 times in Jiaxing, Zhejiang Province, respectively for WBPH and BPH, since japonica variety resistant to WBPH was planted in Jiaxing, Zhejiang Province (Chen et al., 2005; 2006). The comparison indicated that the peak densities were closely related to immigration sizes, but could be mediated by host plant varieties.

1.5.1.3 Genetic Structure of Immigration

Having been major pests for about half a century, over this period the genetic structure of rice planthoppers has evolved to adapt to the changes in rice ecosystems. The adaptations include virulence to host plant variety, resistance to pesticide and the capacity to transmit virus diseases. The dominant population of BPH in China mainly consists of biotype 2 while the proportion of biotype 3 is increasing (Lin et al., 2011). Therefore, all the hybrid varieties inherited from the WA-CMS line, but with *Bph1*, are susceptible to both WBPH and BPH (Lin et al., 2011). The resistance indices of BPH to imidacloprid were about 79 – 811 (Wang et al., 2008) and control efficiencies of buprofezin and imidacloprid for SBPH were only 22.9% and 36.5%, respectively (Wang et al., 2007). Recent experiments also showed that resistance indices of WBPH to imidaclopridand buprofezin were 12.2 – 23.1 and 28.0 – 35.0, respectively (Tang et al., 2008). The outbreak of SRBSDV in recent years is a typical example that illustrates the importance of population structure (the proportion of individuals carrying virus) on rice planthopper problems. Although the virus disease was found in Guangdong more than 10 years ago, the disease was mainly causing damage in a small area in Guangdong and Hainan provinces, China. However, outbreaks of SRBSDV occurred in northern Vietnam (60000 ha in 29 provinces) and southern China (1.3 million ha in 13 provinces) in 2010 (Zhai et al., 2011). All the phenomena mentioned above demonstrate that the genetic change of migratory planthopper species can occur more quickly than expected, because the same management practices have been used in all the areas along planthopper migratory routes in the globalizing world.

1.5.2 Plant Resistance

All the three species of rice planthoppers are monophagous or oligophagous insects and rice is the most important host plant for their development. The spatial and temporal distributions of host plants not only affect their survival and reproduction in local rice ecosystems, but also the timing, magnitude and virulence of immigrants in the landing areas. Host plant resistance is related to host plant variety, crop stage and nutrition of the host plant.

1.5.2.1 Host Plant Variety

The most important revolution for rice production in the 20th century is probably the development of high yielding varieties, which has involved three steps in China. The 1st step was the development of short-stem high yielding varieties with the semi-dwarf gene (*sd1*) in the 1950s and their wide adoption in the 1960s. The 2nd step was the development of hybrid varieties, which started in 1970 and the hybrid rice growing area accounted for about 60% of the total rice-growing area in 1990 (Cheng, 2009). The 3rd step was the development of super rice, starting in the 1990s and the area growing super rice has now reached about one quarter of the total growing area in China (CNRRI, 2012). These programs to breed high yielding varieties have made a great contribution to increasing rice yield and the average yield per ha in China has been increased from about 2.5 t to more than 6.6 t in the recent half century (CNRRI, 2012).

However, the 1st priority for breeding a new variety has been high yield, and the resistance to rice planthoppers has not been considered as a key criterion for approval of new varieties in China. Although many resistant varieties with *Bph1* had been developed since the 1970s, these resistant varieties have lost their resistance since the dominant population of BPH in China became biotype 2. In recent years, only about 12% of the newly developed varieties were ranked at grades 0–5 for resistance to BPH (Cheng, 2009). The susceptible high yielding varieties widely planted became the basis for vulnerable rice ecosystems to rice planthoppers. A typical example is the use in dominant hybrid varieties of

Minghui 63, a super susceptible variety to WBPH, as the sterile system, which has resulted in the outbreak of WBPH since the 1970s (Sogawa, 2009). Therefore, WBPH became the No. 1 pest in Chinese rice ecosystems in the 1990s (Tang et al., 1996).

1.5.2.2 Cropping Pattern

Cropping pattern, the special and temporal arrangement of host plants, is directly related to the variety and to the crop stage of the host plants when planthoppers migrate into the rice ecosystem. Although cropping patterns could be affected by various factors, the cropping system is the most important one. The area planted with the first and second rice crops in China accounted for more than two thirds of the total rice-growing area in the 1980s. At that time, most of the rice growing area south of the Yangtze River was a double cropping system. However, the area of single rice cropping has been increased significantly since then and reached about two thirds of the total rice-growing area currently due to the lower economic benefits of growing rice. Double cropping systems have only been maintained in Guangdong, Guangxi and Hainan provinces, about half of the rice growing areas is still planted with double cropping system in Hunan, Jiangxi and Fujian provinces, but single rice cropping system is dominant in other provinces (MOA, 2010; CNRRI, 2012). The change in cropping system from double rice cropping to single rice cropping has mainly occurred in the areas between Nan Mountains and Yangtze River. In these areas, rice cropping systems are mixed with both double and single rice cropping, so rice is transplanted from April to July and harvested from July to October. Under the new pattern of rice cropping, the early immigrants from the Indo-China Peninsula mainly migrate into the 1st crop season in double cropping areas (South of Nan Mountains); later generations progressively migrate to the north and become the main source of immigrants for areas planted with mixed cropping system and single cropping systems. The expansion of asynchronous mixed cropping areas provides benefits for both BPH and WBPH through providing rice paddy fields with rice plants at tillering stage for each batch of immigrants to develop 1 to 3 generations. In the meantime, the asynchronous cropping systems in these areas could also affect the patterns of immigration to northern China, as well as Japan and Korea, creating longer immigration periods for these areas.

Fig. 1.7 shows the change in light trap counts of immigrants in Jiaxing, Zhejiang Province between 1982 and 2006. As more single rice crops were planted in 2006, the immigration peak time was earlier. Immigrants from source areas before mid-July mainly migrated into the late transplanted 1st crop season in 1982, but in the single rice crop season in 2006. These immigrants could only develop one or less than one generation in the 1st crop season and their offspring would probably be destroyed during harvest. However, the immigrants during mid-June to late-July would mainly migrate into fields at the tillering stage in the single rice crop in mixed cropping systems in 2006 and subsequently develop three generations there. Under the new cropping systems with more single rice crops, there is a peak of immigrants during late August to early September from early maturing single rice crops in source areas and these immigrants could then migrate into areas planted with the later single cropping season and develop one more generation there. However, returning immigrants during late September to early October from the northern part of the old cropping system in 1982 would do very little damage since the rice is almost ready for harvesting in the new single cropping systems (Qi et al., 2012). These phenomena demonstrated that cropping systems are closely related to host plant suitability through the interaction between crop stage and immigration.

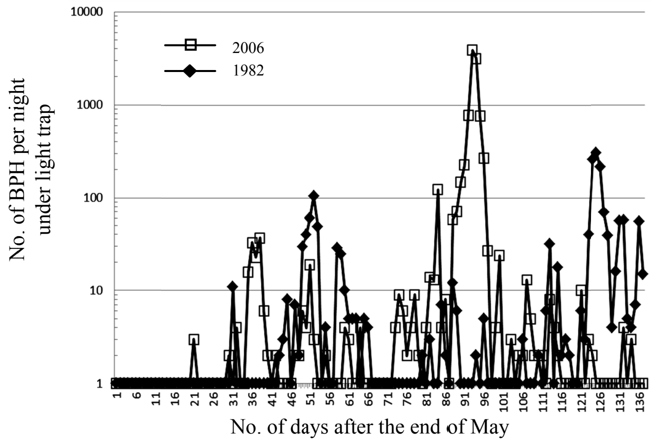

Fig. 1.7 Comparison of immigration patterns under light trap in Jiaxing between 1982 and 2006 (Day 1 means the 1st of June)

1.5.2.3 High Nitrogen Fertilizer Inputs

The rice growing areas in China account for less than 20% of the total rice growing area of the world, but the nitrogen fertilizer used for rice production in China accounts for about 37% of the total usage of nitrogen for rice production world-wide. The average usage of nitrogenous fertilizer in China is about 180 kg per ha, which is about 75% higher than the average usage for rice production in the world, but the recovery efficiency for N is only 30% – 35%. However, in the high yielding areas, such as the Yangtze Delta area, the usage of nitrogenous fertilizer could be 270 – 300 kg per ha and here the recovery efficiency for N is only about 20% (Peng et al., 2002; Li & Tang, 2006). Heavy applications of nitrogenous fertilizer may not affect insect biology directly but bring about changes in host-plant morphology, biochemistry, and physiology, which could improve the plant's nutritional condition for herbivores and reduce host resistance to them (Barbour et al., 1991). Thus, the excessive use of nitrogenous fertilizers creates favorable food conditions for rice planthoppers. Many experiments have demonstrated that planthoppers tend to increase their feeding rates on nitrogen-enriched plants; planthopper nymphal survival rates are positively related to nitrogen content, whereas nymphal duration decreases with an increase in nitrogen content. Female progenies are heavier, lived longer, and more eggs are laid; while the increasing planthopper size can have negative effects on predation as it can affect predator handling time and egg hatchability also increases with nitrogen content. Field studies have also repeatedly demonstrated that rice planthopper populations respond positively to nitrogen fertilization (Lu & Heong, 2009).

1.5.3 Environmental Resistance

The natural regulation of planthoppers in cropping systems involves two kinds of regulation, one is through host plant resistance directly and the other is through natural enemies. Environmental resistance represents the natural regulation function through natural enemies but this could be affected by many other factors, particularly the arthropod community structure, habitat conditions, and chemical pesticide application.

1.5.3.1 Arthropod Community Structure

Natural enemies can have a substantial impact on the population development of rice planthoppers. Although parasitoids are usually selected over predators in classical biological programs and significant levels of parasitism of BPH eggs have been observed, predation primarily by spiders and the insects *Microvelia douglasi atrolineata* Bergroth and *Cyrtorhinus lividipennis* can effectively prevent BPH outbreaks in tropical rice ecosystems (Kenmore, 1980; Kenmore et al., 1984). These predators are mainly generalists, which may show some advantages as well as disadvantages for controlling rice planthoppers since they could easy to find alternative prey to maintain their persistence in the field when rice planthopper populations are low. On the other hand, predation of rice planthopper by *Pardosa pseudoannulate* and *Erigonidium graminicola* could be reduced where alternative prey, such as collembolans, coexists (Settle et al., 1996; Pang et al., 1998). Field experiments have shown that pest abundance could be reduced significantly by assemblages of generalists, but the factors influencing positive and negative interactions within the arthropod community should be managed to enhance the regulation function of natural enemies (Symondson et al., 2002).

An investigation carried out recently to compare arthropod community structures between tropical and Chinese rice ecosystems showed that the species richness in Chinese rice ecosystems was significantly less than that in tropical rice ecosystems. The dominant arthropod species were mainly neutral insects and natural enemies in tropical rice ecosystems, but were rice planthoppers in Chinese rice ecosystems. The ratios of natural enemies to rice planthoppers were 1.41 in tropical ecosystems and 0.53 in Chinese rice ecosystems. These parameters relating to the arthropod community have revealed that the natural regulation function in tropical rice ecosystems is significantly higher than that in Chinese rice ecosystems.

1.5.3.2 Non-Rice Habitats

As an annual crop, rice can be planted and harvested 1 – 3 times a year depending on the geographic area, so the arthropod community in rice ecosystems would be reestablished after planting and destroyed when harvesting occurs. Although initial rice planthoppers might migrate into the rice ecosystem through long distance migration, natural enemies and other arthropod species are mainly derived from habitats around the rice paddy. Since most of the predators are generalists and the main parasitoids, such as *Anagrus* spp. can also parasite the eggs of other leafhopper and planthopper species, non-rice habitats not only provide a refuge but also the main source of alternative foods for these natural enemies. Therefore, the conditions in these non-rice habitats are extremely important for the reestablishment of arthropod communities, as well as the natural regulation function to rice planthoppers (You et al., 2004). The flowering plants on non-crop habitats in cropping systems could provide food sources and shelters for natural enemies and improve natural control functions (Zhu et al., 2012). Compared with tropical rice ecosystems, there are less non-rice habitats in the high intensified rice ecosystems in China. Rice is often planted synchronously in a large mono-cropping area and the bunds between paddy fields are narrow with less grass. There might be no flowering plants to provide pollen to parasitoids in these non-rice habitats. During winter, the populations of natural enemies could be significantly suppressed by the cold weather. Therefore, the sources of natural enemies would significantly less than those in tropical areas. A comparison carried out recently indicated that the ratios of natural enemies to herbivores 1 week after transplanting were 2.3±0.5 in tropical Philippines and 0.4±0.2 in Chinese rice ecosystems, which demonstrates the importance of non-rice habitats on arthropod community structure.

1.5.3.3 High Chemical Pesticide Inputs

The resurgence caused by overuse of pesticides has been demonstrated since the 1980s in tropical areas as well as in China in the 1990s (Kenmore, 1984; Gallagher et al., 1994; Cheng et al., 1995). However, most Chinese farmers and technicians still believe that high yields are not reachable without pesticide application. Since yield is directly linked to annual income for farmers and food security for the country, pesticide application is considered one of the most important high yielding techniques and farmers are reluctant to take the risk of not using pesticides. Since pesticide distribution is completely commercialized and government provides special subsidies to farmers for pesticide application, overuse of pesticide is very common. In high yielding areas, farmers may apply pesticides 5 – 6 times in one crop season and use “cocktail pesticide” with 2 – 3 kinds of pesticides for each application. Therefore, total pesticide use has increased from around 0.76 million tons in 1991 to about 1.46 million tons in 2005 so that total pesticide use has almost doubled in the past 15 years (Cheng, 2009). The result is that in high yielding areas, resurgence has occurred in fields where early insecticides (triazophos and deltamethrin) have been applied and subsequently hopperburn has occurred in fields without any insecticide application in most of the years. This implies that the natural regulation function in Chinese high yielding ecosystems has been reduced to a critical level and may be completely destroyed if insecticides are still continually overused (Cheng et al., 2003; Cheng, 2009).

1.5.4 Stochastic Meteorological Factors

In general, seasonal changes in climatic conditions provide regular and predictable fluctuations over an annual time scale resulting in changes in the suitability of habitats for reproduction and population growth over time. However, climatic conditions in a particular season are likely to be stochastic and unpredictable, which will significantly affect the timing and abundance of rice planthopper populations. As migratory insects with a certain sensitivity to temperature, rice planthoppers migrate from south to north in spring and summer, then from north to south in autumn, based on the subtropical high (Hou et al., 2003). The migration process includes three steps: take off, flight and landing. Although planthoppers have relatively low flight speed, they do not rely on ascending air currents to carry them aloft. They take off by themselves at dusk or dawn based on the light intensity and temperature, although flight and landing could be greatly affected by other meteorological factors (Cheng et al., 2003; Ji, 2012). Therefore, planthopper population development patterns in a particular year could be largely affected by the synoptic patterns, downward air-current and temperature.

1.5.4.1 Synoptic Patterns

The main source of BPH and WBPH in China is through migration from the Indo-China Peninsula and specifically through five migration waves in the spring and summer from south to north (during the summer monsoon) and three migration waves in autumn from north to south (during the winter monsoon). All these movements are associated with seasonal changes in the prevailing wind-field and the occurrence of specific synoptic weather patterns. Feng et al. (2002a) reported that the northern boundary of the immigrating population during March to May coincided to 16.5 °C isotherm of low-level jets (LLJ) and the northern boundary of LLJ from then on. The migration pathways of windborne rice planthoppers could be predicted by 850 hPa winds. Therefore, the spatial and temporal variations of LLJ and relevant meteorological factors are likely to affect the migration pathways, as well as the landing areas. For example, huge immigrant populations of WBPH and BPH were observed to move from northern Vietnam to Guangxi by strong low-level southwest jets in late-April and late-May in 2007 but in late-May to early-June in 2008 (Qi et al., 2010; 2011). Therefore the LLJ can be used as a means of monitoring and forecasting the risk of rice planthopper outbreaks (Feng et al., 2002a; 2003).

However, unusual meteorological conditions often result in unusual immigration patterns, which could affect population development and increase variations of population size among years. For example, an outbreak of BPH and WBPH at the coastal area of the Bohai Sea in 1991, which was 1500 km from the planthopper source area, resulted from a large scale and sustained northward LLJ during mid July to early August, which transported the migrant population from southern China (Jiangxi Province) to northern China (Tianjin) (Feng et al., 2002b). A huge immigration population from Anhui, 9163 BPH per light trap and more than 1 macropter per hill in paddy field, migrated into the area within 10 days during late August to early September in 2006, and caused a sudden outbreak in the history after one generation in early October. The density reached more than 60 per hill in Jiaxing, Zhejiang Province (Qi et al., 2012).

1.5.4.2 Downward Air-Current and Rainfall

During the immigration period, a strong downward flow or rainfall could enforce rice planthoppers to land. Field observation indicates that descent of rice planthoppers is closely related to rainfall, the average percentage of days with WBPH descent was (82.1±5.0)% during immigration period, but (53.2±4.6)% during emigration period in the raining days (Hu et al., 1987). Studies of the relationship between the features air stream and the landing of BPH during migration reveal that most brown planthopper landings occurred in regions located in the rain field associated with the weather front at the time of northward migration. However, most of the insect landing regions are located in the downward current for both the subtropical wedge weather type during northward migration and continental cold high weather type during southward migration (Tan et al., 1984). There is also some circumstantial evidence to suggest that local mesoscale meteorological features could lead to the concentration of planthoppers in specific areas. Putative landing sites for BPH have been identified in the lee position of valley transverse to the prevailing wind direction and at valley heads in valleys parallel to the wind. The landing of BPH has been associated with rain belts in front systems and with descending air in cold fronts in both China and Japan (Tan et al., 1984; Noda & Kiritani, 1989).

1.5.4.3 Temperature

Temperature is the main climatic factor affecting development, fecundity, and mortality of rice planhoppers. Annual average monthly temperatures from 1954 to 2007 in Jiaxing, China clearly showed that temperature conditions have been getting warmer in recent years. The monthly average temperatures for spring (March, April and May) and autumn (September) since mid-1990s were higher than, or at least close to, the average temperature during these 54 years (Cheng, 2009). A higher temperature in the spring could reduce the overwintering mortality and increase development speed of SBPH, but a higher temperature in summer could suppress development, increase mortality and reduce fecundity of SBPH (Zhang et al., 2008). However, a higher temperature in September could increase fecundity of BPH. The simulation study using the historical weather data in Jiaxing showed that the timing and density of the peak population of BPH could be significantly affected by the temperature in September. Comparing the warmest year with the coolest year in September, peak populations were 9 days earlier and had a density 2.25 times higher (Cheng et al., 1991). A recent study has revealed that a higher temperature could also modify the resistance performance of rice varieties to *N. lugens* (Stål). IR36 still had moderate resistance at normal temperatures but its resistance decreased gradually when the temperature increased from 25 °C to 34 °C, and fully lost its resistance at 31 °C and 34 °C. Two-way ANOVA indicated significant effects of temperature and rice variety on contents of soluble sugar and oxalic acid in rice plants (Wang et al., 2010).

Fig. 1.8 illustrates the interactive effects of all four groups of factors on population development of these rice planthopper species. Although the initial populations in all the rice ecosystems in China are mainly from immigration, the development patterns are mainly affected by the resistance of the local ecosystem after the immigrants have arrived. However, the initial population size for a particular rice ecosystem is mainly related to the population size in the source area, which is also affected by the system resistance in its source area. On top of this, stochastic meteorological factors could also influence population development through affecting immigration and environmental resistance in both source and landing areas.

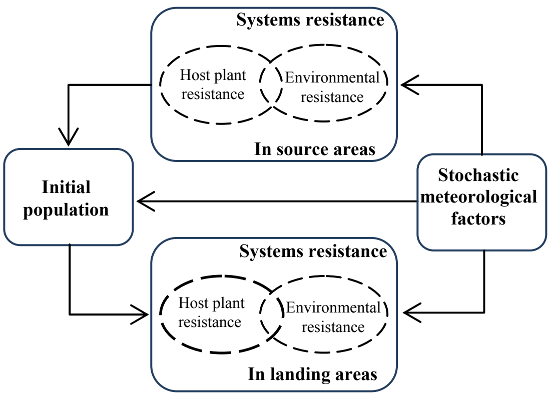

Fig. 1.8 Interactive relations among the main environmental factors related to frequent outbreak in China

1.6 Next Steps for Sustainable Management

Rice planthopper outbreaks have occurred for half a century in China since the earliest outbreak of RSV and RBSDV transmitted by SBPH in 1963. Rice planthoppers are considered the most destructive pests in rice ecosystems based on the areas affected and yield losses. We have been fighting with rice planthoppers for half a century, and have come to the realization that these frequent outbreaks are the result of various intrinsic and extrinsic factors in agro-ecosystems, which are resulting in rice planthopper problems, as well as being associated with various social, economic and political factors, which are not favorable for managing rice planthoppers sustainably. This is the consequence of our impatience to increase rice production to feed an increasing population, using high chemical fertilizer and pesticide inputs on susceptible high yielding varieties, and increasing the vulnerability of rice ecosystems and enhancing the capacity for increased population development of rice planthoppers.

As mentioned above, the population in China has been increasing and reached more than 1.3 billon, but the area of arable land has declined to about 120 million ha in China. In the past 30 years, the rice growing area has reduced by about 10% but total rice production has increased by about 30% due to average yield per unit area having increased by about 60% (MOA, 2012). These figures indicate that perhaps the only way for Chinese to feed ourselves given the limited area of arable land will be by increasing yield per unit area. However, the highest incidence of outbreaks and the highest population sizes for all the three planthopper species occurred in the past few years. The pollution problems caused by overuse of chemical fertilizers and pesticides are getting worse, especially in the east-coast areas with high intensification cropping systems. All these phenomena reveal that intensified cropping systems with high chemical fertilizer and pesticide inputs are not sustainable and rice planthopper problems are not able to be managed successfully by relying on pesticides. Therefore, we have to find a way to manage rice planthoppers sustainably under high yielding conditions and to reach the target of sustainable intensification. We have to establish sustainable management systems for rice planthoppers through the following approaches.

1.6.1 Enhancing System Resistance in Intensified Rice Ecosystems

Traditional intensified rice ecosystems, which rely on high yielding varieties supported by high inputs of chemical fertilizer and pesticides, are characterized as high vulnerability to rice planthoppers. The high intrinsic capacity for rice planthopper populations to increase in these systems is enhanced through increased host plant susceptibility and reduced natural regulation functions. Therefore, the basic strategy for sustainable management of rice planthopper problems should be enhancement of natural regulation functions by building up ecosystem resistance.

1.6.1.1 Developing Green Super Rice Varieties with Resistance to Rice Planthoppers

The results from a comparative study of population development patterns in tropical (Philippines) and subtropical (China) rice growing areas showed that the population development patterns for both BPH and WBPH were significantly different between the two areas. The growth rates and peak population sizes in the two areas were significantly related to the rice varieties used, but the effect of variety on population growth rate interacted with location. The growth rates of BPH and WBPH were significantly affected by host plant varieties in Chinese subtropical areas, but not in tropical areas due to the high natural control effects in tropical ecosystems. To pursue higher rice production with the limited arable land in China, a program called Super Rice was launched in the 1990s and about one quarter of the rice growing area has been planted with super rice in recent years. Some of the super rice varieties are resistant to BPH and/or WBPH, such as Guang-liang-you 476 containing *Bph14* and Tian-you-hua-zhan containing genes resistant to WBPH. The yields of these varieties could reach 8 – 10 t per ha. A large number of parental rice lines containing multi-resistant polymerization genes have been cultivated: *Bph14/Bph15* and *Bph14/Bph15/Bph18* have been polymerized into a restorer line (Ming-Hui 63) for a three-line hybrid system, as well as CMS and restorer lines for parents of the two-line hybrid system (9311), which have provided a fundamental basis for breeding green super rice which are high yielding and high resistance to rice planthoppers (Lin et al., 2011).

1.6.1.2 Enhancing Natural Regulation Function Through Ecological Engineering

Field investigations carried out in the 1970s show that there are more than 1300 species of natural enemies in rice ecosystems in China. Among them, about two thirds of the species are insects and a quarter are spiders. The parasite rates for parasitoids (*Anagrus* sp. and *Haplogonatopus* sp.) and the nematode (*Agamermis unka*) are about 10% – 30% in some areas (Cheng, 1996). However, field investigations carried out in recent years showed that all the parasite rates of these natural enemies were below 10%. A comparative study showed that the ratios of natural enemies to rice planthoppers in fields in the Philippines were significantly higher than those in China. The weak natural regulation function by natural enemies in China is a key factor causing the high growth rate and frequent outbreaks. An international program called Ecological Engineering carried out in Jinhua, Zhejiang Province, China to restore natural regulation by reforming high yielding technology, including selecting resistant varieties, adjusting transplanting times, reducing nitrogen input, increasing non-rice habitat diversity, planting sesame and soybean to provide pollen and honey sources for parasitoids, and so on. After three-year practice, the densities of egg parasitoids and spiders have more than doubled and the densities of frogs and dragon flies increased 5 – 10 times.

Pesticide use has been reduced by about 80% and the yield has reached 8.73 t per ha, which is not significantly different with farmer's fields. This shows that natural regulation in rice ecosystems can be restored through ecological engineering and the growth rate of rice planthoppers in Chinese rice ecosystems could be reduced through this approach (Lin et al., 2011).

1.6.2 Establishing International and Regional Collaboration Systems

As migratory pests, all the three rice planthopper species migrate between countries, as well as within a country. Planthopper problems in one country or region will always be related to planthopper problems in other countries and regions since immigrants in one country/region are often from other countries/regions and the starting time, pattern, rate, and genetic structure of the immigrant population in one country or region will be related to the populations from these other countries or regions. For example, the biological characteristics of planthopper populations in one country or region could be affected by management practices implemented in more than one country or region. The development of virulence to varieties and resistance to insecticides for BPH provides examples that demonstrate the need for a management program to be designed through international or regional collaboration.

1.6.2.1 Establishing International Surveillance Systems

Rice planthopper problems have been the most destructive pests in many countries of Asia and immigrants are migrating from south to north in spring and summer, but from north to south in autumn. The starting time of immigration, as well as the patterns, magnitude and genetic structure of immigrant populations in China, Japan and Korea, is dependent on the population development patterns in countries located in tropical Asia. However, the returning migration from north to south might also affect the development of genetic structure of the rice planthoppers in tropical countries, since the evolution process could be affected by local environmental conditions through the migration routes. Therefore, the information on timing, development patterns and genetic structure of rice planthoppers in source areas could provide useful information to predict the population development pattern and to design management strategies in the landing area. The information from subtropical and temperate countries could also provide useful information for tropical countries to help avoid unexpected outbreaks. The unexpected outbreak of BPH in 2005 that resulted from high resistance to imidacloprid provides a good example of the importance for exchanging information on planthopper problems among countries. The outbreak of SRBSDV transmitted by WBPH in 2010 provides another example (Zhong et al., 2011). Botrrell & Schoenly (2012) recommend that a comprehensive Asian-wide multidisciplinary, multi-institutional coordinated effort should be launched to determine the specific triggers leading up to planthopper migration. The international cooperative surveillance system should include an effective and feasible network for monitoring population development patterns, virulence to varieties, resistance to pesticides and percentages of planthoppers carrying viruses and developing an information exchange system to share the information with all relevant countries.

1.6.2.2 Developing Inter-Regional Management Systems

The rice growing areas within China can be divided into several regions based on migration routes. There are about 5 migration routes from south to north in spring and summer, and about 3 migration routes from north to south every year (Cheng et al., 2003). Therefore, there is interaction between population development patterns among regions. Although there is a national surveillance system in China to monitor population development patterns in all the counties and the information collected by these pest forecasting stations in all the counties is used to predict the risks of rice planthopper problems occurring, these technical programs are mainly designed by local technical service stations independently. Eventually, rice varieties with the same genetic background and the same pesticides are used in all the regions, both helping to promote the development of planthopper resistance to pesticides. A typical example is the experience of increasing BPH resistance to imidacloprid that has occurred from south to north, generation by generation, within China in 2005: the resistance indices are 79.1 in Guilin, Guangxi Province, 200.4 in Changde, Hunan Province and 551.8 in Nanjing, Jiangsu Province (Wang et al., 2008). Therefore, an inter-regional program should be designed to include the following key components, such as managing planthopper populations in source areas to reduce immigrants for the landing area; adjusting transplanting time to reduce early immigration and virus transmission based on population development patterns in source areas; diversifying the genetic background of high yielding varieties to delay virulence development; applying pesticides alternatively if necessary to avoid pesticide resistance, and so on.

1.6.3 Reforming Decision-Making Systems for Planthopper Management

Although the ecological mechanisms associated with frequent planthopper outbreaks and improved management strategies of rice planthoppers have been extensively studied for more than half a century, the results and implications of this research have not reached key players involved in managing rice planthoppers, such as policy makers, extension agents, pesticide dealers and farmers. The main reason for this is the pursuit of instant economic benefits with "ecological myopia". For example, governments provide subsidies to farmers to implement chemical control and provide incentives to the pesticide industry to produce more pesticides. Policy makers and extension agents want to establish "pest free", high yielding demonstration areas, while pesticide dealers recommend farmers to use "cocktail" pesticides to get higher benefits. At the same time, the national policy for plant protection "integrated pest management" formulated in the 1970s has become hollow words. The usage of chemical pesticides has kept increasing and rice planthopper problems have been getting worse. The decision making systems for planthopper management need to be reformed.

1.6.3.1 Reforming Technique Transferring and Implementing System

As urbanization has increased in China, with more farmers moving into urban areas, their paddy fields are transferred to the remaining farmers. The traditional small farming system operated by an individual farmer (1 ha per 35 families) has become a larger, collective farming system (1100 ha per farmer/collective unit), which provides a chance for reforming the techniques used and establishing more sustainable ecosystems. As the operating scales are increasing, farmers pay more attention to cost/benefit analysis and would like to learn more about new technologies that could provide higher economic returns. The results from experiments using ecological engineering to manage rice planthoppers and other pests in Jinhua, Zhejiang Province have demonstrated that new techniques were more easily accepted and implemented in the larger production system. The long-term impacts of ecological engineering in restoring ecosystem resistance were easier to demonstrate in large farming systems. Three key players have the potential to achieve significant improvements in planthopper management in these larger rice production systems and to avoid the excessive influence of pesticide dealers. These three key players are researchers, providing new technology, extension agents, involved in helping to transfer the technology, and farmers, in making decisions for implementing the new technology.

1.6.3.2 Reforming Policy System for Sustainable Development

Since food security is always the most important issue for China with the high pressure from the increasing population and declining arable land, the central government has worked out a series of policies to promote food production. In recent years, the government has raised the price for buying rice from farmers every year to encourage farmers to grow more rice and increase yields. However, most of these efforts are focused on the short term. For example, chemical fertilizers and pesticides have been overused for many years, yet government policies still encourage the production and use of more chemicals. Rice planthoppers have been the most important pests for about half a century, yet resistance to rice planthoppers has not been set as a key criterion for variety breeding programs and about 80% – 90% of new varieties are susceptible to rice planthoppers since it is believed that insect pests can be easily controlled by pesticides (Lu et al., 2002).

The central government has been warned of the development of environmental pollution and food safety in recent years, which provides a chance to reform the policy environment for sustainable development. The 2nd Green Revolution should be considered as the basis for solving the food security problem in China. The policies for improving planthopper management should focus on reforming the pesticide production and marketing systems, the development and extension systems for agricultural technology, the pricing policy system for agricultural products, food safety and environmental protection systems, and so on.

The rice planthopper problem has resulted from the traditional technology developed and implemented in the 1st Green Revolution. Extensive studies in the past half century have revealed the ecological mechanisms associated with frequent outbreaks of rice planthoppers and have provided us with new directions for managing rice planthoppers sustainably. It is to be hoped that we would be able to manage rice planthoppers sustainably in the near future.

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