Kong Luen Heong · Jiaan Cheng
Monica M. Escalada *Editors*

Rice Planthoppers

Ecology, Management, Socio Economics and Policy

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Foreword

Rice has been cultivated in China for more than 7,000 years and is the staple food of more than half of the world and about 80 % of the Asian population. The yield per unit area has been increasing significantly since the first green revolution in the 1960s. However, the intensification of rice production using the technology developed in the first green revolution has caused negative externalities, such as environmental pollution, more pests, and food safety problems. With ever-increasing population, rice production has to be further doubled in the next 50 years with limited land and water available and it might be the only way to produce more rice through increasing yield per unit area.

Although China and many countries in the world are making progress in increasing yields per unit area, a substantial amount of food is also lost to insect damages. For example, China's rice production loses about a million tons every year and more than two million tons in some abnormal years due to the planthopper problems. The historical data indicates that planthopper problems are getting worse under the traditional intensified agricultural practices with increasing chemical fertilizer and insecticide inputs. Realizing this, scientists in Zhejiang University working with scientists from the International Rice Research Institute (IRRI) initiated the first international planthopper workshop at a modest scale in 2006. This was to be followed by a larger planthopper conference held in IRRI in 2008. More recently, in November 2012 Zhejiang University co-sponsored the International Rice Planthopper Conference that was held in the University's new campus in Zijingang, Hangzhou. A total of 170 scientists from nine countries presented 93 papers and posters of a wide range of topics ranging from genetics, ecology and sociology related to managing rice planthoppers.

Zhejiang University is one of the largest universities involved in agricultural research in China. The university proudly houses the National Key Laboratory of Rice Biology jointly with the China Rice Research Institute and the National Key Discipline of Plant Protection. These institutes focus research on pest issues, especially for rice pests. Professors from Zhejiang University led a consortium of research partners and won a prestigious National Basic Research Program of China to further explore the mechanisms for frequent outbreak of rice planthoppers and develop sustainable management strategies to improve planthopper management in China. The Zhejiang University led the consortium working closely with the International Rice Research Institute (IRRI) developed a comprehensive research program to address issues related to molecular biology, ecology, management, and policies related to planthopper pests.

The research had demonstrated that unlike other insect pests, planthoppers with high fecundity and high adaptability to intensified rice ecosystems are secondary pests that are frequently induced by inappreciated crop practices, especially in insecticide misuse. The 2012 Conference focused on addressing the ecological, management, and sociological issues surrounding the planthopper problem. Most had come to realize that such a pest problem cannot be fixed by technology alone and the integration of biological and ecological technology, social sciences, and policy research is necessary. This book provides summaries and analyses of key research works that will bear on developing management strategies. Clearly, China as well as other countries will need to focus on developing more sustainable 'green' approaches to solving pest problems and reaching higher yield per unit area simultaneously. I hope that this book will be a good guide to scholars, researchers, and students seeking for ideas and materials.

June 2014

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Preface

The International Conference on "Rice Planthoppers—Ecology, Management, Socio Economics and Policy" was held in Zhejiang university's new campus in Zhijinggang, Hangzhou, November 21–23, 2012. The conference brought together researchers from Australia, Cambodia, China, Indonesia, Japan, Myanmar, Philippines, South Korea, Thailand, the FAO, and IRRI. This conference came about as a result of numerous outbreaks of planthoppers in China, Philippines, Thailand, Indonesia, Bangladesh, India, and Myanmar from 2005 to 2012. Planthoppers are generally not pests as they are well controlled by natural biological control services that are abundant in rice ecosystems. However, when such services are compromised, their populations grow exponentially into outbreaks destroying crops, causing a symptom called 'hopper burn'. In addition, planthoppers are also vectors of several virus diseases that will destroy newly planted crops in the seasons following the outbreaks.

In the 1970s and 1980s, the early days of the Green Revolution, planthoppers became major threats to rice production following high use of subsidized fertilizer and pesticides and when the subsidies were removed the pest subsided. These same pests have returned with a vengeance, causing even more destruction and misery to farmers throughout East and Southeast Asia. Today, rice planthoppers have become rice's most serious pest problems. In the last few years they have caused crop losses of more than 10 million tons.

The most seriously affected country was Thailand. From 2008, Thailand's rice bowl in the central Plains has suffered continuous outbreaks for 14 consecutive seasons. In January 2010 the government of Thailand announced a 16 % reduction in their export forecasts. Thousands of farmers had lost their crops and in February 2010 the government announced a release of US $60 million to compensate farmers' losses. Economists quantified the 2010 dry season crop loss due to planthopper attacks to be more than US $50 million at farm gate price. In addition, the government spent more than US $1 million to launch 28 control campaigns in 14 provinces and released emergency funds of about US $16 million to purchase insecticides for distribution which contributed to the sustained outbreaks. In June 2011, the Rice Department in collaboration with the Thai Agro Business

Association (TABA) and IRRI launched a campaign to "stop the use of abamectin and cypermethrin" in rice. These two types of insecticides were major culprits to pest resurgences. The campaign reduced on-farm use of these insecticides but applications remain high as retailers very quickly introduced other products into the market.

Similarly, Indonesian farmers suffered the same threats and Java alone lost about a million tons in 2011. Losses in other years were however not quantified. Smaller patches of outbreaks had occurred in Malaysia, India, Myanmar, Bangladesh, Philippines, and India while China continues to lose about one million ton a year. In 2012, the southern provinces of China suffered the worst planthopper outbreaks in the last 20 years. Besides economic losses, thousands of farmers have suffered crop failures, pesticide poisoning, and severe debt problems, which have forced them into poverty and hunger and even suicide.

Planthoppers are secondary pests that are normally under natural control. Outbreaks are symptoms of unsustainable practices that destroy vital biodiversity and ecosystem services triggering exponential population growth resulting in outbreaks. Although abnormal weather like droughts and floods can also trigger outbreaks, the most consistent factor in Asia is insecticide misuse. Insecticide misuse in Asia is due to weak marketing regulations that permit pesticides to be sold as fast moving consumer goods (FMCGs), like toothpaste and soap. In addition, insecticide active ingredients are marketed in hundreds of trade names in plastic sachets packaging, like instant coffee and shampoo, and retailed by village general stores. To promote sales aggressive marketing campaigns are often used with numerous sales incentives, like gifts, free trips, lottery tickets, and even a trip to Mecca. At the grass-root level farmers rely on pesticide retailers for advice, recommendations, and supply of pesticides and this inevitably result in rampant misuse.

At the 2008 Planthopper Conference held at IRRI, scientists in attendance developed a consensus that planthopper problems are induced by insecticide misuse. Technologies such as resistant varieties alone are unable to solve the problem. At the 2012 Planthopper Conference, scientists further confirmed that planthopper problems are insecticide-induced and developed consensus that strategies to solve such problems would need intervention through the social sciences and policy reforms. Eleven papers from the conference that addressed ecology, management, socioeconomics, and policy were selected for this book. The first chapter describes the planthopper problems in China in the last half century by Prof. Jiaan Cheng who has been working on these problems since the 1960s. In Chap. 2, another veteran who has been working on planthoppers since the 1970s, Dr. K. Sogawa, describes how this man-made problem is occurring in all rice ecosystems in Asia. Chapter 3 is another synthesis paper prepared as a Working Paper for the Asia Development Bank (ADB) that summarizes the general findings from the Regional Research and Development Technical Assistance project that supported a lot of the work. The chapter extends discussions into the realm of policy weaknesses in pesticide control and calls for reforms and the 'professionalizing' of plant protection services similar to that of medical services. Dr. T. Wada, another planthopper veteran researcher, discusses the differences in the biology of rice planthoppers in tropical and temperature regions. This is followed in Chap. 5 by Prof. Yonggen Lou et al. discussing herbivore-induced defenses in rice that can be useful in avoiding pesticide use. The huge amounts of insecticide used in rice, especially in China, has resulted in rapid developments in resistance. Professor Zewen Liu et al. outline the mechanisms of insecticide resistance development in planthoppers in Chap. 6. Technologies alone are unable to manage planthopper problems and more ecologically based approaches are needed. Professor Geoff Gurr et al. in Chap. 7 explores the potential of ecological engineering methods for delivering ecosystem services that will render protection to rice crops. The pioneering work to introduce ecological engineering methods to manage planthoppers was carried out in Jin Hua, China by Zhongxian Lu and colleagues and this is described in Chap. 8. Farmers' insecticide applications are less than perfect and a large proportion of their sprays is unnecessary. In Chap. 9, K.L. Heong and colleagues examined insecticide use and yield data from more than 5,000 farms and found that there were very little productivity gains from farmers insecticide use. Planthopper outbreaks are unpleasant experiences that rice farmers are constantly fearful of. In Chap. 10, Monina Escalada et al. examine the social impacts of planthopper outbreaks on farmers in Central Thailand. Finally in Chap. 11, Geoff Norton et al. use a resilience model to encapsulate the ecological, social, and policy aspects surrounding the rice planthopper problem and suggest a conceptual framework for future use in tackling such a complex problem as the rice planthopper.

The last book on rice planthoppers published by IRRI in 2009 outlines new paradigms to chart sustainable ways to manage these secondary pests. We hope that this book will provide further thoughts on the new paradigms, especially in the application of ecological engineering methods and in 'fixing' the problem through policy interventions and reforms. The website http://ricehoppers.net/ will continue to update on issues related to rice planthopper management and ecological engineering methods.

We are grateful to the Ministry of Science and Technology for providing the National Basic Research Program of China (2010CB126200) and to Chinese National Natural Science Foundation for providing an International Cooperative Project (Grant No. 30771420) to enable the university scientists to work with IRRI scientists and to the Asia Development Bank for providing the Regional Research and Development Technical Assistance grant to IRRI that supported the research and conference. In particular are especially grateful to Dr. Lourdes Adriano, Principal Economist in the Bank who had provided great guidance.

June 2014

K.L. Heong
J. Cheng
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Chapter 1
Rice Planthoppers in the Past Half Century in China

Jiaan Cheng

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.

Keywords Brown planthopper · White-backed planthopper · Small brown planthopper · Intensified ecosystems · Sustainable management

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.

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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 2,395 to 6,687 kg during this time period. Thus, although the total area of rice has remained almost the same, at around 30 million ha, total rice production increased more than three times, from 59.7 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* (Horvath) white-backed 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 five virus diseases (Cheng 2009; Botroll and 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 paper, 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.

1.1 Historical Development of Rice Planthopper Problems

Before the twentieth 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 tracked back to AD 697 or 701. More detailed records indicate that outbreaks of planthoppers caused losses of 960,000 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 AD. Outbreaks of BPH have been authentically recorded rather more frequently in the twentieth century, with outbreaks occurring in 1912, 1921, 1922, 1923, 1926, 1929, 1935, 1940, 1944, and 1948 in Eastern Asia (Dyck and 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 1,000–3,000 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). Figure 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 number one pest based on outbreak areas. The 3rd stage was after the late 1990s. At the 3rd stage, SBPH came back again and all 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 three rice planthoppers and five 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 shown 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 coast of China is one of the highest-yielding rice-growing areas and all three rice planthoppers co-occur there. Figure 1.2 shows historical records of total numbers caught in light traps per year during 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

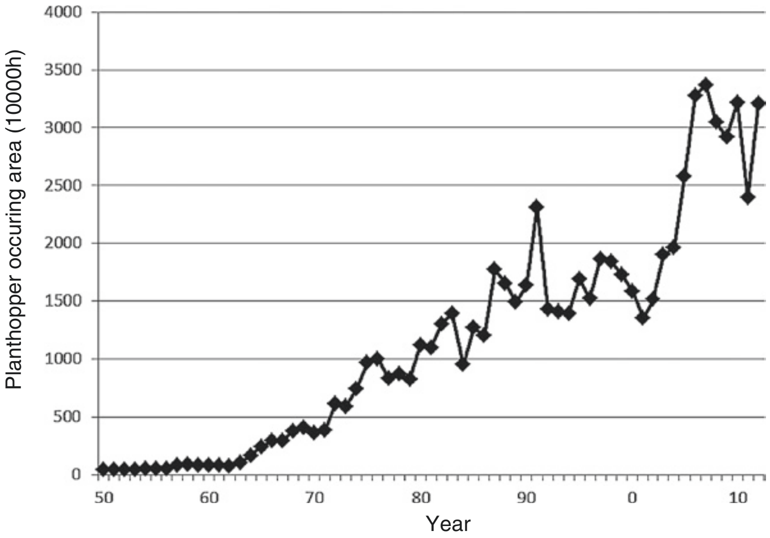


Fig. 1.1 Historical development of rice planthopper problems in China

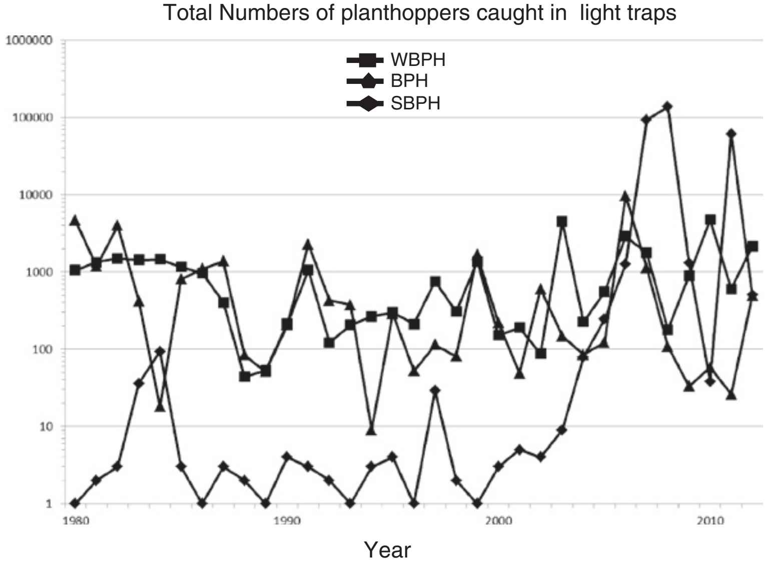


Fig. 1.2 Total numbers of the three planthopper species based on annual light trap counts during the key periods in Jiaxing, Zhejiang Province, China since 1980

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 137,351, 4,755, and 9,712 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.

Figure 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 the figure, peak population sizes fluctuate year by year and were more than 15,000 per 100 hills in the five 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 twentieth century were less than 1 million, 2.36 million, and 2.42 million, respectively. In the new century, the average peak densities of SBPH, BPH, and total planthoppers were 1.73 ± 0.57, 5.24 ± 0.86, and 6.52 ± 0.73 million, almost more than two times higher than the highest densities in the twentieth century. SBPH could cause 10–20 % yield losses by feeding on heads directly, which never happened in the twentieth century (Wang et al. 2007).

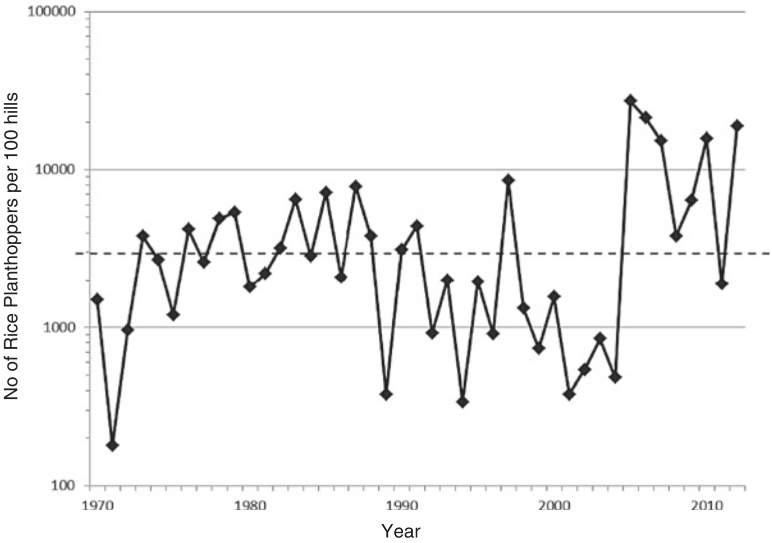


Fig. 1.3 Annual peak densities of rice planthoppers in monitored plots without any insecticide applications since 1970 in Jiaxing, Zhejiang province, China

1.2 Historical Efforts on Researches for Managing Rice Planthoppers

Research on rice planthoppers started in the mid-twentieth century when rice planthoppers began to cause serious damage. The number of papers published up to 2011 is 11,581, of which 7,612 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 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 1960s to the 1990s and a significant increase since the late 1990s for SBPH (Fig. 1.4). The data on publications indicate 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 new century (Lv et al. 2013).

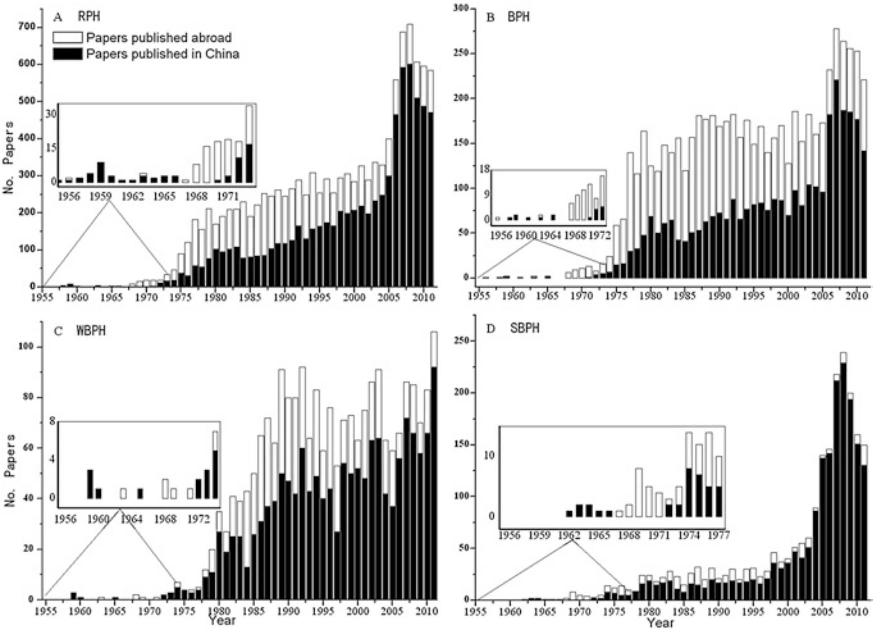


Fig. 1.4 Number of papers published worldwide on rice planthoppers since 1950 from Lv et al. (2013)

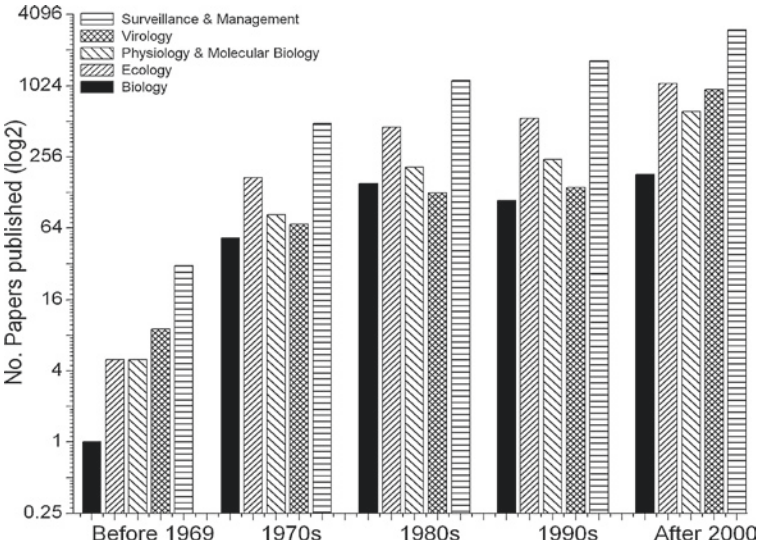


Fig. 1.5 Number of papers published worldwide on various rice planthopper topics since the 1960s from Lv et al. (2013)

Based on the topics addressed, all the papers published on planthoppers could be grouped into five areas, including biology, ecology, physiology and molecular biology, virology, and surveillanceand control as shown in Fig. 1.5. In all the time periods since 1970, the number of papers related to surveillance and control and ecology was ranked one and two. The numbers of papers in these two areas were 6,186 and 2,590 about 75.8 % of the total papers published, which indicates that most planthopper research has focused on planthopper surveillance and control (Lv et al. 2013). However, despite this effort, there were serious outbreaks of BPH in China in 2005–2007 that affected 6.6–9.4 million 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 and Schoenly 2012).

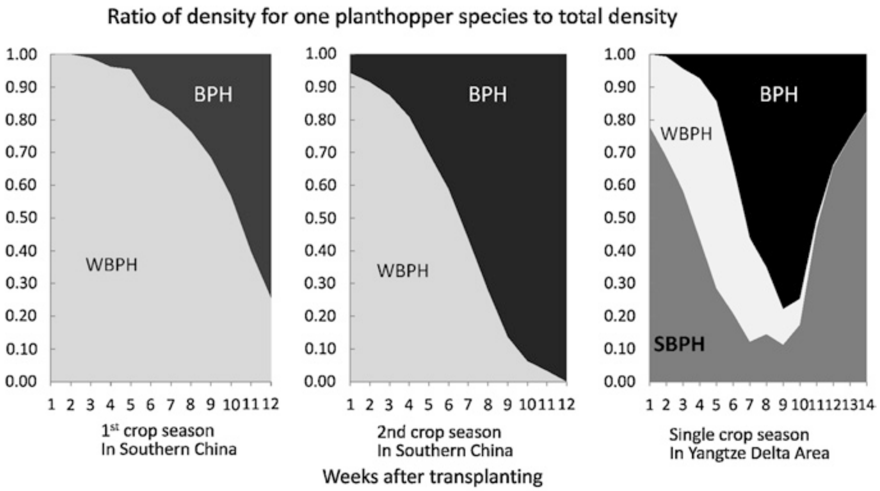
1.3 The Population Characteristics of Rice Planthoppers in China

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 diapause 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 and 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 and Cook 1994).

1.3.1 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 and Barrion 2009). Among them, BPH is the major pest in rice ecosystems from the tropics to about 42–44° 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, and WBPH migrates into rice paddy early than BPH for both the 1st and 2nd season. 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 shown in Fig. 1.6a, 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. Figure 1.6c shows the temporal dynamics of the composition for the three planthopper species in the area. SBPH is the earliest one moving into 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 and then back to SBPH as shown in Fig. 1.6c.



(a) (b) (c)

Fig. 1.6 Comparison of temporal dynamics for planthopper species compositions between geographic regions and cropping systems

1.3.2 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 and 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 Indochina 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 Indochina Peninsula including Middle Vietnam (16°–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 Indochina 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 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, vary 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- to 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 and Cao 1990). Earlier immigrants might come from the Indochina 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′ 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, 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.

1.3.3 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 four times over the course of three generations in one crop season in Japan (Cook and Perfect 1994). In the recent years, we compared the growth rates of BPH and WBPH in the Philippines (Los Baños, Laguna) and China (Fuyang, Zhejiang) 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 and 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 to early July could develop three generations after immigration and more immigrants arrive around late July to early August and late August to early September. The growth rate of BPH for the single rice crop season in Yangtze Delta, China (Jiaxing, Zhejiang) in the new century reached 5,560.8 ± 1,672.4 (Cheng 2009).

1.3.4 Higher Outbreak Frequency

Historical data show that the outbreak frequency had been increasing in China since the 1960s and the outbreak frequencies were 10–20 % in 1960s, 50 % in 1970s, and 70 % in 1980s to early 1990s, respectively (Tang et al. 1996). Table 1.1

Table 1.1 Historical outbreak frequencies of rice planthoppers in China

Location	Years	Crop season	Planthopper species	Frequency (%) of population size (number per 100 hills)			References
				>3,000	3,000–1,000	<1,000	
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 and Cao (1990)
			WBPH	100.0	0.0	0.0	
Xiushan, Zhongqin Province	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	All the figures are calculated with local historical data by author. The area has been planted with japonica rice since 1960s
			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	

shows the outbreak frequencies of rice planthoppers in six provinces at various time periods from the 1970s to the new 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 1,000 planthoppers per 100 hills, and no application is needed for most of the paddy fields. The 2nd grade means the average population density is 1,000–3,000 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 3,000 per 100 hills, and hopper-burn could occur in some areas if no control action is taken. The data in Table 1.1 show the occurrence for these three levels of peak population densities in six 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 1,000 per 100 hills. These figures indicate that the outbreak frequency of rice planthoppers are high and hopper-burn could occur in about half of the years where no control action is taken.

1.4 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 naturalregulation functions, hostplant 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.

1.4.1 Initial Population (Immigration)

Population development in China usually starts with the macropterous adults migrating into the rice paddy since the initial source 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 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.

1.4.1.1 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 two and five times of peak population density, respectively.

The historical light trap data in various locations show 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 is March 5 and March 2 or April 29 and April 15 in Zhaoqin, Guangdong Province; March 24 and March 8 or May 14 and April 14 in Chenshou, Hunan Province; May 25 and June 3 or June 24th and July 12 in Jiaxin, Zhejiang Province (Chen et al. 2005, 2006; Shou and 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.

1.4.1.2 Magnitude of Immigration

The magnitude of an immigration can be represented by the total number of immigrants during the main immigration time period. Cook and 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 show 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 show 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 show that the difference between the highest and lowest peak densities in the fields without any insecticide application was 23.0 and 45.5 times in Zhaoqing, Guangdong Province and 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.

1.4.1.3 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 % (Wang et al. 2007). Recent experiments also showed that resistance indices of WBPH to imidacloprid and buprofezin were 12.2–23.1 and 28.0–35.0, respectively (Tang et al. 2008). The outbreak of Southern Rice Black-streaked Dwarf Virus (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 Province, China. However, outbreaks of SRBSDV occurred in Northern Vietnam (60,000 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 in 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.

1.4.2 Plant Resistance

All three species of rice planthoppers are monophagous or oligophagous insects, and rice is their most important host plant for their development. The spatial and temporal distribution of host plants affects not only 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.

1.4.2.1 Host Plant Variety

The most important revolution for rice production in the twentieth 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 (*sd*1) 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, but 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 the 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).

1.4.2.2 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 crop 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 in 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, about half of the rice-growing areas is still planted with double-cropping system in Hunan, Jiangxi, and Fujian, 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 Ling 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 Indochina Peninsula mainly migrate into the 1st crop season in double-cropping areas (South of Nan Ling); 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 one to three 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.

Figure 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 times were 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.

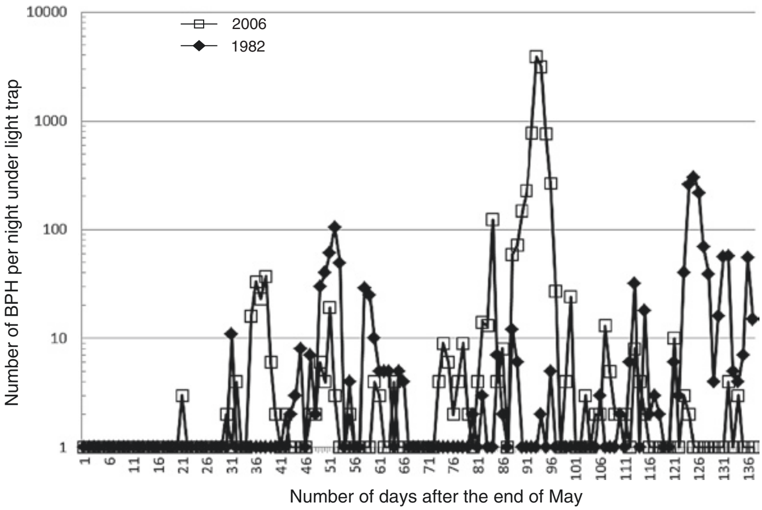


Fig. 1.7 Comparison of immigration patterns based on light trap catches in Jiaxing between 1982 and 2006 (Day 1 means the 1st of June)

1.4.2.3 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 worldwide. 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 and 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 (Lv and Heong 2009).

1.4.3 Environmental Resistance

The natural regulation of planthoppers in cropping systems involves two kinds of regulation: one is through hostplant 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.

1.4.3.1 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 easily 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.

1.4.3.2 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 provide not only 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 one 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.

1.4.3.3 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 over used (Cheng et al. 2003; Cheng 2009).

1.4.4 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: takeoff, 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.

1.4.4.1 Synoptic Patterns

The main source of BPH and WBPH in China is through migration from the Indochina 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 the 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 low-level jets from then on. The migration pathways of windborne rice planthoppers could be predicted by 850 hPa winds. Therefore, the spatial and temporal variations in low-level jets 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 in population size among years. For example, an outbreak of BPH and WBPH at the coastal area of the Bohai Sea in 1991, which was 1,500 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 (Tianjing) (Feng et al. 2002b). A huge immigration population from Anhui, 9,163 BPH per light trap and more than one 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).

1.4.4.2 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, and 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 and Kiritani 1989).

1.4.4.3 Temperature

Temperature is the main climatic factor affecting development, fecundity, and mortality of rice planthoppers. 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 the 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

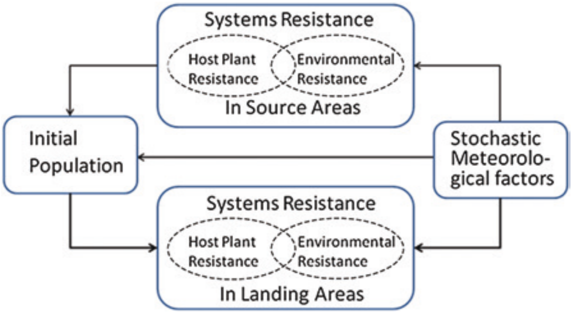


Fig. 1.8 Interactive relationships between the main environmental factors affecting the frequency of planthopper outbreaks in China

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 to 34 °C and fully lost its resistance at 31 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).

Figure 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 size of the initial population 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.

1.5 Next Steps for Sustainable Management

Rice planthopper outbreaks have occurred for half a century in China since the earliest outbreak of rice stripe virus and rice black-streaked dwarf virus 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 human population has been increasing and reached more than 1.3 billons, 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.

1.5.1 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.

1.5.1.1 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 the 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 and *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).

1.5.1.2 Enhancing Natural Regulation Function Through Ecological Engineering

Field investigations carried out in the 1970s show that there are more than 1,300 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 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).

1.5.2 Establishing International and Regional Collaboration Systems

As migratory pests, all 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.

1.5.2.1 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, are 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 south rice black-streaked dwarf virus transmitted by WBPH in 2010 provides another example (Zhong et al. 2011). Botrrell and 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.

1.5.2.2 Developing Inter-regional Management Systems

The rice-growing areas within China can be divided into several regions based on migration routes. There are about five migration routes from South to north in spring and summer and about three 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 are used to predict the risks of rice planthopper problems occurring, these technical programs are mainly designed by local technical service stations independently. In virtually all the regions, rice varieties with the same genetic background and the same pesticides are used, 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.

1.5.3 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 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.

1.5.3.1 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 (a hectare per 3–5 families) has become a larger, collective farming system (1–100 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.

1.5.3.2 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 the recent years, 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 (Lv et al. 2002).

The central government has been warned of the development of environmental pollution and food safety in the 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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Chapter 2
Planthopper Outbreaks in Different Paddy Ecosystems in Asia: Man-Made Hopper Plagues that Threatened the Green Revolution in Rice

Kazushige Sogawa

Abstract The brown planthopper (BPH), *Nilaparvata lugens* (Stål), and white-backed planthopper (WBPH), *Sogatella frucifera* (Horváth), are the rice monophagous species, which are inevitably associated with rice agriculture in Asia. In the 1970s, BPH suddenly occurred as the most preeminent insect pest of rice and threaten the green revolution in the tropical Asia. The BPH outbreaks in Southeast Asia were caused by disruption of ecological balance between BPH and natural enemies by insecticides, which were accepted as a technical component to ensure the high-yielding output of high-yielding varieties (HYVs) in the tropical paddy ecosystems. The outbreaks in India are primarily attributed to disruption of coevolutional interactions between BPH and local rice plants in the monsoon-prevailing paddy ecosystems by abrupt replacement of BPH-resistant traditional rice varieties with susceptible exotic HYVs by the high-yielding varieties program. Unsuccessful deployment of BPH-resistant IR varieties was critically reviewed in relation to the standardized seedbox screening test (SSST), which had been exclusively used to breed BPH-resistant IR varieties. Sixteen of 19 IR varieties incorporated with the *Bph1* and *bph2* genes were easily defeated with emergence of adaptive BPH biotypes so that their sequential releases could not stop BPH outbreaks. Only a few varieties such as IR36 and IR64 were found to have durable field resistance to BPH even after breakdown of their monogenic resistance. Field performance of IR36 and IR64 indicated that they have some other resistance traits that cannot be evaluated by the SSST. Incapability to evaluate field resistance traits commits a risk of insidious erosion of those traits during the process of SSST-dependent breeding. That could be a reason for a tentative resistance in most of the BPH-resistant IR varieties. WBPH outbreaks in Punjab plain, prevalence of WBPH and WBPH-vectored new virus disease in China and Vietnam, and ovicidal resistance to WBPH in *japonica* rice were referred with special reference to the wind-borne massive displacement biology of WBPH in the active monsoon rice areas.

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2.1 Introduction

There is a small stone image of Buddha in Fukuoka, a northern city of Kyushu, Japan. It was enshrined for mourning a million farmers perished with historical famine caused by an outbreak of the brown planthopper (hereafter BPH), *Nilaparvata lugens* (Stål), devastated over the western part of Japan in 1732 (Suenaga and Nakatsuka 1958). Because BPH is rice monophagous and potentially outbreak-prone for its *r*-strategic biology, it has inevitably been associated with rice agriculture. Since the remote past, such sporadic BPH outbreaks were a catastrophic natural disaster in the traditional rice farming in Japan. The outbreaks were not related to any technical innovations in rice farming, but were caused by unpredictable massive overseas invasions of the pest.

In the tropical Asia, BPH was only a minor rice herbivore before the advent of the green revolution in rice in the 1970s. However, it dramatically came out as the most preeminent insect pest of high-yielding varieties (HYVs) of rice (Dyck and Thomas 1979). Insecticides and resistant rice varieties were thought to be essential means to ensure the high-yielding output of HYVs by suppressing the pest infestations.

However, prophylactic insecticide applications rather encouraged BPH to upsurge population density and plunged into a vicious spiral of BPH outbreaks and insecticide sprays in the tropical paddies (Kenmore et al. 1984; Heong and Schoenly 1998). Deployment of BPH-resistant IR varieties was neither a simplistic solution of the problems. Sequential releases of BPH-resistant IR varieties incorporated with different resistance genes were easily defeated with successive emergences of adaptive BPH biotypes (Sogawa 1982; Gallagher et al. 1994).

Persistent BPH outbreaks in the tropical Asia once declined and were put under control by the IPM extension projects by FAO and IRRI (Pontius et al. 2002). However, BPH is once again threatening the rice farming in Asia at far more serious scales than previous outbreaks under intensified cropping patterns, recovery of prophylactic insecticide applications, extension of hybrid rice, and changes in socio-economic and political situations surrounding the rice agriculture (Bottrell and Schoenly 2012). At present, it is intended to reconfirm the root causes of BPH outbreaks and the problems of BPH-resistant IR varieties in order to cope more rationally with the revival of the BPH problems.

2.2 Insecticide-Induced BPH Outbreaks

1. Initiation of BPH outbreaks at IRRI

BPH outbreaks in the tropical Asia started from the experimental farm of International Rice Research Institute (IRRI). The first infestation of BPH was found at IRRI in 1964 (IRRI 1964). It was only two years after inauguration of the institute and two years before release of IR8. BPH emerged soon after insecticides were used to control the rice stemborers in 1962. Population density of BPH increased quickly beyond its economic injury level under the routine applications of diazinon. Major outbreak of BPH occurred on diazinon-treated IR8 (IRRI 1971). Eventually, uncontrollable outbreaks continued from 1971 to 1976 (Pathak and Dhaliwal 1981).

Around 30 years later, hopperburn disappeared completely from the IRRI farm after drastic reduction (≥90 %) of insecticide use with adoption of IPM. When biodiversity restored in the IRRI farm, coincidently BPH infestation declined below sub-injurious levels as it used to be. The beginning and ending of the BPH events at IRRI implicate a big instruction about the genesis of BPH outbreaks in the tropical paddies (Heong et al. 2007).

BPH was previously a minor rice herbivore, but emerged soon as a pest form by prophylactic chemical control of the endemic rice stemborers. Insecticides were rationally applied following the most advanced technologies at the IRRI research farm. Therefore, the BPH outbreaks at IRRI cannot be attributed neither to misuse of insecticides nor to inadequate application practices. The BPH outbreaks terminated when prophylactic insecticide usages were restrained by the implementation of IPM practices without any other changes in the crop managements. Therefore, it is apparent that fertilization and susceptibility of paddy plants were not the primary causes of BPH outbreaks. The BPH history at IRRI indicates undoubtedly that insecticides are the ultimate cause of the BPH outbreaks. So that the BPH history at IRRI is the epitome of the BPH outbreaks, which had prevailed in the green evolution era and which is once again threatening the rice farming in the tropical Asia.

During the process of BPH outbreak at IRRI, diazinon lost its effect to BPH in 1969 after three years of its routine use. Reproduction of BPH was rather stimulated and hopperburn appeared in the diazinon-treated fields (IRRI 1970). It was the first sign of BPH resurgence induced by insecticides in the tropical paddies. However, little attention was paid yet to the ecological disorders of paddy ecosystems treated with insecticides. The population upsurge of BPH was attributed to a side effect of diazinon at sublethal dosages, microbial degradation of diazinon applied to submerged paddy soil, and development of insecticide resistance in BPH (IRRI 1970).

In 1980, Kenmore (1980) has first demonstrated evidently by his credible on-farm experiments such as life table analysis of BPH and natural enemy exclusion experiments that disruption of natural biological control functions by insecticides is the root cause of BPH outbreaks in the tropical paddies adopted the green revolution package technology. After that, BPH resurgence was reported not only with diazinon but also with various broad-spectrum organophosphorous and synthetic pyrethroid insecticides (Reissing et al. 1982a, b; Chelliah and Uthamasamy 1986; Heinrichs 1994). Some resurgence-inducing insecticides were ironically recommended as a tool to generate BPH population in field screening of resistant rice varieties against BPH (Heinrichs et al. 1978). It was also pointed out that resurgence-causing insecticides could accelerate biotype selection on resistant varieties (Aquino and Heinrichs 1979).

The outbreaks of BPH could be attributable to its potentially outbreak-prone *r*-strategic biology. However, its high intrinsic fecundity is usually poised with high mortality due to biological control by natural enemies. Such ecological balance between BPH and natural enemies is, however, highly vulnerable to broad-spectrum insecticides, because of their non-selective toxicity to natural enemies, non-ovicidal activity, and shorter residual period than the egg period of BPH. As the consequences, the BPH populations emerged from survived eggs enable to reproduce exponentially in the natural enemy-eradicated habitats. That is the basic mechanism of BPH resurgence in the paddy fields treated with insecticides. Harmful effects of pesticides on the balance of arthropod community in different agro-ecosystems were already been pointed out as early as in the 1950s (Ripper 1956). It has been criticized that the lack of an ecosystem concept in the main disciplines rendered the BPH phenomena unintelligible until the discovery of the rich and complex relationship between natural enemies and rice pests was beginning to unfold at IRRI in the 1980s (Anderson et al. 1991).

2. Devastation of BPH outbreaks in Indonesia

Indonesia is a prime example of the nations, which adopted the green revolution package technology to achieve rice self-sufficiency (Oka 1979). It is also said that Indonesia was a prime example of a country, which adopted the pesticide-dependent pest management systems developed in Japan (Soenardi 1972; Soekarna and Sundaru 1983; Sogawa et al. 1994). Insecticides were invested as an essential means to increase rice production. BPH was a minor rice pest before the advent of operational chemical control in the rice intensification programs (BIMAS/INMAS) in 1970 (Soenardi 1972; Yazawa 1987). The first large-scale chemical control was carried out in 0.8 million ha of paddies in Java to control the rice stemborers by aerial applications of phosphamidon, an organophosphorous insecticide (Singh and Sutyoso 1973). Since then, an agricultural air force played a major role in operational control of rice pests over the program areas. The plant protection brigades in each province also took charge of operational controls on the ground. The pesticide cost was subsidized at 85 % by the government and allocated to the program areas through the BIMAS authority, a government channel.

Hopperburn began to appear in HYVs sprayed with insecticides from 1972 onward (Mochida et al. 1977b; Mochida 1979). Coincidently, BPH-vectored grassy stunt and ragged stunt virus diseases also became epidemic. In spite of intensive aerial applications of diazinon, hopperburn spread rapidly over the major rice areas in the period from 1975 to 1979. BPH infested 350,000 ha of rice areas in Java and caused yield losses of 350,000 tons in the 1976/77 wet season. During those crop seasons, about 6,000 tons of organophosphorous insecticides, mainly diazinon, fenitrothion, chlorpyrifos, isoxathion, and dichorvos, were applied. Nevertheless, persisted BPH outbreaks inflicted serious damages on rice production, which was stagnated losing 0.4–0.5 million tons of rice. Indonesia became the world's largest rice importer in the BPH outbreak period (Whitten et al. 1990).

Fortunately, BPH populations declined on the new BPH-resistant variety IR36, which was introduced in 1978. IR36 was then compulsively planted in the BPH-epidemic areas and became the most popular rice variety in Indonesia in the early 1980s. More than 70 % of total rice areas were planted with only IR36. Rice production increased at average annual rate of 6.6 % from 1979 to 1983. The rice self-sufficiency was eventually attained upon IR36 in 1984.

It should be pointed out that insecticides supplied by the BIMAS authority increased steeply even after depression of BPH outbreaks and achievement of rice self-sufficiency upon IR36. More than 60,000 tons of diazinon, chlorpyrifos, fenthion, monocrotophos, and phenthoate were supplied for preventing possible pest infestations in 1986. Besides, IR36, which was efficient to suppress BPH infestations, was quickly replaced with IR42 and allied national HYVs such as Krueng Aceh and Cisadane after attainment of rice self-sufficiency, because the rice price of IR36 tumbled due to poor quality and over production (Mizuno 1987). Although the substituted new varieties possess the same BPH resistance gene as that of IR36, they were easily defeated with development of new virulent biotypes unlike IR36. In North Sumatra, IR42 was defeated by a new biotype in 1982 (Sogawa et al. 1984a, b). By 1986, over 70 % of paddy fields in Java were planted with Krueng Aceh and Cisadane and exposed to the newly developed virulent BPH biotypes (Sogawa et al. 1987). The rice areas infested by the new biotypes spread from 80,000 ha in 1985 to 200,000 ha in 1986 in Central Java in spite of maximized operational control with insecticides.

Government faced with resurrected BPH menace and bankruptcy of newly achieved rice self-sufficiency, and a special task force affiliated to the National Development Planning Board (BAPPENAS) urgently conducted field inspections and disclosed that massive provision of subsidized insecticides through the government channel was the root cause of the BPH problems. Based on this assessment, Presidential Decree No. 3 was issued on November 5, 1986, by which the national crop protection policy was drastically shifted from unilateral dependence upon insecticides to ecosystem-orientated IPM, and 57 broad-spectrum insecticides were immediately banned from using in paddy fields (Southern 1987). Subsidies for insecticides were completely removed by 1989. The agricultural air force was also disorganized. This paradigm shift broke the vicious spiral of insecticides and BPH outbreaks. An insect growth regulator buprofezin extinguished hopperburn, which acts selectively to BPH and is safe to natural enemies (Sogawa 1989, 1993). After that, Indonesian National IPM program was launched with technical and funding supports by the FAO rice-IPM program in 1989 (Oka 1991; FAO-IPM Secretariate 1993; Oka 1996). BPH outbreaks were suppressed by a new variety IR64 with durable field resistance to BPH under restrained insecticide use with implementation of IPM.

3. Set back of IPM and revival of BPH outbreaks

Thirty years ago, we have learned serious ill effects of insecticides to paddy ecosystems from unanticipated BPH outbreaks happened in the green revolution schemes during the 1970s–1980s. However, our previous lessons have not been properly exploited to the management of tropical paddies.

In Indonesia, for example, BPH outbreaks were once suppressed by IPM. However, IPM declined due to the change in the rice policy from self-sufficiency to free trade after the Asian economic crisis in 1997 and subsequent political power shift in the early 2000s. The Presidential Decree was substantially castrated. According to the FAO statistics, insecticide imports increased more than 30-folds after shifting the rice policy and are still increasing at higher rates. Insecticides for rice pest control were once restricted to only a few chemicals such as buprofezin by the Presidential Decree, but now, more than 130 insecticides are registered (Trisyono 2012). IPM was merged into integrated crop management (ICM) or crop total management (CTM) as a tactical tool of crop management with insecticides, in which the ecosystem-based strategies of IPM became vague and routine prophylactic sprayings of insecticides designed by pesticide dealers were recommended to rice farmers.

Besides, hybrid rice was politically introduced so as to revitalize rice agriculture in 2005. Cost of hybrid rice seeds was subsidized (GRAIN 2007). Heavy inputs of insecticides and fertilizers are essential for its high-yielding cultivation. When hybrid rice areas expanded to 650,000 ha in 2009, the BPH plague came back to Indonesia together with prophylactic insecticide sprays (Baehaki 2009; Cabunagan et al. 2010; Muhsin 2010; Heong 2011; Horgan 2011a, b; Winarto et al. 2011a, b; Baskoro and Winarto 2012). Hopperburn appeared in IR64 with field resistance indicates serious disruption of paddy ecosystem functions by indiscriminate insecticide applications.

4. Repeated BPH outbreaks by insecticides in Thailand

Quality rice has been an important export commodity in Thailand, where BPH broke out twice in the past. The first outbreak happened on BPH-susceptible Thailand varieties in 1980–1981, after sudden upsurge of pesticide use in 1978–1979 (Kenmore 1991). After that, resistant varieties such as RD21 (with *Bph1* gene from IR26) and RD23 (with *bph2* gene from IR32) were released in 1981 and planted widely. However, those varieties became susceptible by 1986. New resistant variety Suphan Buri 60 (with *bph2* gene from IR48) was then released in 1987. Because of its high-yielding ability and excellent grain quality, Suphan Buri 60 became the most popular rice variety in the central plain. The second outbreak happened mostly on Suphan Buri 60 in 1989–1990, within two years after its release (den Braber and Meenakanit 1992). The outbreak was closely associated with intensive use of synthetic pyrethroid, deltamethrin, which is well known as a typical insecticide to induce BPH resurgence.

In 1991, soon after the second outbreak, a neonicotinoid insecticide, imidacloprid (admire), was introduced to control BPH. Imidacloprid did not induce BPH resurgence, because of its long-lasting (more than 40 days) systemic toxicity. Its residual period is enough long to cover a whole life cycle of BPH and did not allow resurging the BPH populations from survived eggs. As the results, BPH was well controlled for a first few years. However, it was not a long-lasting solution of BPH problems. BPH became resistant to imidacloprid (Fabeller et al. 2010; Gorman et al. 2008; Harris 2006). Decline of control effect of imidacloprid to BPH was first reported in 2003. After that, the imidacloprid-resistant BPH spread in the central plain during the mid-2000s. Infestations by the imidacloprid-resistant BPH became serious in the paddies, where natural enemies were eradicated by its long-lasting toxity of imidacloprid.

Abamectin, cypermethrin, and chlorpyrifos substituted for imidacloprid to control imidacloprid-resistant BPH (Luecha 2010a). Those substituted insecticides, which have not long-lasting residual toxicity, readily induced resurgence of imidacloprid-resistant BPH. Eventually, the third BPH outbreaks started in the Thai rice-bowl at far more serious scales than previous outbreaks in the period from 2009 to 2012 (Thongdeethae 2009; Wattanesk 2010; Luocha 2010b; Soitong et al. 2011; Chaiyawat 2011; Rattanakarn et al. 2012a, b). Repeated BPH outbreaks induced by insecticide-dependent pest managements in Thailand warn us that insecticides cannot solve the BPH problems in the tropical paddies.

2.3 BPH Outbreaks Induced by Exotic HYVs

BPH outbreaks also happened in South Asia in the green revolution era. However, those were different from the insecticide-induced outbreaks in Southeast Asia. BPH, which was recorded as *fulgorid* hopper or rice *fulgorid*, had already been an endemic pest of rice in the irrigated double-cropping rice areas in Orissa, Andhra Pradesh, Tamil Nadu, and Kerala along the coastal tract of the Bay of Bengal in the period from 1920 to 1970 (Gorman 1974; Israel and Rao 1954; Rao 1961). For example, BPH occurred in a pest form in Andhra Pradesh as early as in 1927. In Tamil Nadu, the rice farmers have long known the BPH infestations as "pugayan."

BPH became very rapidly a major rice pest in India since around 1970. Light trap data from several AICRIP (All-India Coordinated Rice Improvement Project) centers recorded massive upsurges of the BPH population in 1971–1972 (Kalode 1976). BPH began to occur in an epidemic scale, particularly in the eastern coastal tracts and southern India since around 1972. Although hopperburn damages by BPH were also recorded in the single cropping areas in the central and northern parts of India as well, the infestations were rather sporadic and localized.

The HYVs program, which was launched in India in 1965, is greatly responsible for the change in the pest status of BPH in the double-cropping rice areas. A number of semidwarf HYVs such as TN1 and IR8 were introduced on a large scale in 1966 and 1967. Simultaneously, AICRIP bred locally adapted HYVs such as Jaya and Padma using IR8 as a parent. All those varieties were highly susceptible to BPH. BPH began to occur in an epidemic scale in the exotic HYVs since around 1972, while indigenous local varieties suffered only slightly (Das et al. 1972; Gopalan 1974; Kulshreshtha 1974; Abraham and Nair 1975; Prakasa Rao et al. 1976).

The BPH-epidemic areas in India belong to an active Indian monsoon region. Monsoon influences greatly the BPH ecology, which assists long-range and massive displacements of BPH between remote rice areas. Sudden massive invasions of BPH could be a serious threat to the traditional rice farming in the monsoon-prevailing regions (Fig. 2.1). It is relevant to the evidence that most of the resistant rice germplasms were found among traditional *indica* landraces in South India and Sri Lanka (Ikeda et al. 1993; Khush 1979). BPH resistance could

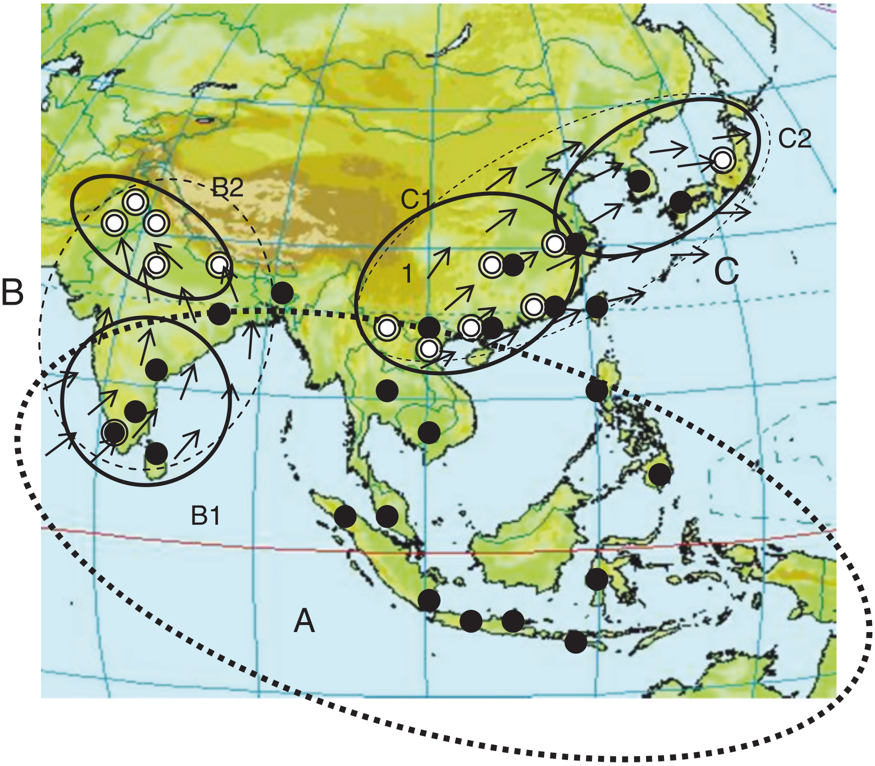

Fig. 2.1 The rice planthopper epidemic areas in different paddy ecosystems in Asia. Closed (●) and open double spots (◎) indicate the areas where the outbreaks of BPH and WBPH were recorded, respectively. A: Tropical paddy ecosystems, where the BPH is endemic, has a non-voltine life cycle and reproduces perennially if host plants are available. BPH outbreaks in Southeast Asia were induced by prophylactic insecticide investment into the paddy fields as a packaged technology for the Green Revolution. B: Indian monsoon-dependent paddy ecosystems. The BPH-resistant rice landraces distributed abundantly in South India (B1), while most of the WBPH-resistant genes came from the northern parts of Indian subcontinent (B2), where WBPH invades into the summer rice by the aid of monsoon, but cannot over winter there. Outbreaks of BPH and WBPH in these paddy ecosystems were primarily caused by the careless introduction of susceptible exotic HYVs for the Green Revolution. C: East Asian monsoon-dependent paddy ecosystems, in which both the BPH and WBPH make long ranged migrations from the northern part of Indochina Peninsula to the Far East Asia by the predominant monsoon and reproduce some generations in the spring and summer paddy fields, but cannot survive in winter. C1 indicates the Chinese hybrid rice-prone areas, where WBPH shifted from a minor to the pre-eminent insect pest of rice, and new viral disease SRBSDV vectored by WBPH became epidemic. The *japonica* rice is planted in the C2 areas, where the *japonica* rice evolved ovicidal resistance to cope with massive monsoon-borne invasions of WBPH

be an indispensable self-defense trait of the local rice plants to cope with monsoon-borne massive invasions of BPH and to complement to biological control by indigenous natural enemies.

It has also been known the BPH populations in India are originally more virulent than those in Southeast Asia. The BPH-resistant IR varieties with the *Bph1* and *bph2* genes were susceptible to the Indian populations (Verma et al. 1979a, b; IRPS 1982; Velusamy et al. 1984). Sympatric distribution of BPH-resistant rice germplasm and virulent BPH biotypes in South India indicates that there had been long coevolutional interactions between rice plant and BPH. Easy replacement of indigenous BPH-resistant local varieties with exotic susceptible HYVs disrupted genetic balance (or coevolutional interactions) between paddy plants and BPH populations and caused BPH outbreaks. Insecticide-induced resurgence was not the primary cause of BPH outbreaks in South India.

In Godavari area in Andra Pradesh, for example, the locally improved MTU and SLO varieties were commonly planted in the period from the 1930s to 1960s. The MTU and SLO varieties were selected from predominated native rice landraces. Complicated genetic resistance to BPH in the MTO and SLO varieties was indicated by their variable responses to the IRRI biotypes of BPH (Sogawa 1979). This is an example of genetic diversity of BPH resistance retained in the local rice germplasm in South India.

There are another examples of resistant and tolerant local rice varieties to BPH and other insect pests and diseases that are commonly available and recommended in the pesticide-free SRI (system of rice intensification) paddies in the coastal states of the eastern India (SDTT 2010). The multiple resistances to rice pests in the local rice varieties could be evolved through intensive tritropic interactions among rice plants, pests, and natural enemies in the monsoonal Indian paddy ecosystems. Those local rice varieties are the good materials to understand the actual properties of intrinsic BPH resistance in rice evolved in the paddy ecosystems.

2.4 Deployment of Host Plant Resistance in BPH Management

1. Breeding of BPH-resistant HYVs

Host plant resistance and biological control are ecological approaches to manage crop pests (Kennedy et al. 1987). These are also compatible components of IPM strategies. IRRI started screening of insect-resistant rice germplasm in 1966 by imitating a seedling plant method, which was originally used to evaluate resistance to small sucking insects in crop plants by Painter (1951). After the first BPH-resistant traditional *indica* variety Mudgo was discovered in 1967, the seedling plant method was established as standardized seedbox screening test (SSST) (Heinrichs et al. 1985). The SSST-based resistance breeding for BPH had started without any ecological aspects on the host plant resistance to BPH in rice plants.

In the SSST, BPH resistance was instantly evaluated based on relative damage scores of the seedlings submitted to a side-by-side sucking preference response by newly emerged BPH nymphs. Such behavioral response of newly emerged BPH nymphs does not represent holistic ecological interactions between BPH and rice plants in the paddy ecosystem. The SSST is, however, technically elegant and has a great advantage in screening a large number of materials, and it was exclusively adopted to screen BPH-resistant germplasm and to breed BPH-resistant IR varieties at IRRI and other Asian countries.

By the mass screening of rice germplasm, several BPH resistance genes were identified by the SSST. All the planthopper resistance genes are of monogenic and are designated by numerical codes with prefix *Bph* (Khush and Brar 1991), which were easily manipulated in conventional breeding programs.

2. Tentative vertical resistance in IR26 and IR42

The BPH resistance genes identified by the SSST were incorporated into IR varieties as an essential trait to cope with the BPH outbreaks. The BPH-resistant IR varieties were widely introduced into the BPH-epidemic tropical paddies since the first BPH-resistant IR26 with *Bph1* was released in 1973. However, those IR varieties were not the panacea for the BPH problems. Most of them were easily defeated with prompt emergence of adaptive BPH biotypes (Sogawa 1982).

The resistance genes *Bph1* and *bph2* were incorporated into 19 IR varieties by 1980, but 16 were readily defeated by virulent BPH biotypes. For instances, IR26 with *Bph1* and IR42 with *bph2* were highly resistant to BPH when they were released. However, within a few years, they lost genetic resistance with emergence of matching virulent biotypes (Gallagher et al. 1994). Consequently, sequential release of IR26 and IR42 failed to stop the outbreaks of BPH.

The resistance genes *Bph1* and *bph2* are monogenic factors to disrupt sustained BPH sucking from the phloem of rice plants (Sogawa 1982). On the other hand, the BPH populations retain polygenic flexibility to modify their biotype compositions to overcome the sucking blockage by *Bph1* and *bph2* (den Hollander and Pathak 1981; Roderick 1994; Tanaka 1999). Accordingly, IR26 and IR42 showed only temporary vertical (resistance gene and biotype specific) resistance until a BPH population adjusts their biotype makeup so as to feed on those resistant varieties.

3. Varietal resistance-breaking planthopper biotypes

The BPH populations, which have differential ability or inability to infest rice varieties with specific BPH resistance genes identified by SSST, are commonly referred to as biotypes, although there are some controversies about genetic status and nomenclature of biotype populations (Claridge and den Hollander 1982).

Mass-rearing inbred BPH populations established on TN1, Mudgo, and ASD7 were designated as biotypes 1, 2, and 3 at IRRI (IRRI 1976; Pathak and Heinrichs 1982). So far as these biotypes 1, 2, and 3 concern, they show phenotypically a vertical virulence specific to the BPH resistance genes *Bph1* and *bph2*, as if there were a gene-for-gene relationships between the virulence of biotypes and host plant resistance conferred by each BPH resistance gene (Gallun and Khush, 1980). However, naturally developed field populations of biotypes do not exist as genotypically uniform variants. Therefore, the nomenclatures of IRRI biotypes cannot be applied to the field populations (Clarige and den Hollander 1980, 1983).

In Southeast Asia, sequential releases of IR varieties with different BPH-resistance genes (e.g., IR26 with *Bph1* and IR42 with *bph2*) led significant changes in varietal resistance-breaking performance in the BPH populations (Feuer 1976; Varca and Feuer 1976; Huynh 1977; Mochida et al. 1977a; Aquino and Heinrichs 1979; Staplay et al. 1979; Medrano and Heinrichs 1980; Sogawa et al. 1984a, b; Ho 1985; Sogawa et al. 1987; Huynh and Nhung 1988; Chau 1990; Pathak et al. 1990; Chau 1992; Thuat et al. 1992; Chau et al. 1993). Present BPH populations in Southeast Asia exhibit complicated variations in their virulence patterns depending upon the history of rice variety shifts in each locality, where gene-for-gene patterns are no longer recognized between the BPH populations and rice varieties (Claridge and den Hollander 1982).

Majority of the BPH resistance genes are originated in the southern parts of Indian subcontinent. This indicates that there have been more intensive coevolutional interactions between BPH and rice landraces in South Asia than in the rest of distribution areas in Southeast Asia. As the results, the BPH populations in South India and Sri Lanka are virulent to the IR varieties with *Bph1* and *bph2* (Velusamy et al. 1984).

4. Genetic flexibility in the BPH biotype populations

Local BPH populations from different rice varieties in the different places in Sri Lanka showed different virulence patterns and specific adaptation to the respective local host rice plants, on which they fed and reproduced (Claridge and den Hollander 1982). Interestingly, a perennial wild rice *Oryza rufipogon* is universally susceptible to all the local BPH populations. Several other studies also showed considerable variations among local BPH populations in fitness or performance to different host varieties even among populations that were in close geographic proximity (Claridge and den Hollander 1982; Gallagher 1988; Huynh and Nhung 1988). These field evidences indicate that the natural BPH populations retain highly diversified genetic pool to maximize their fitness to the locally available host plant resources.

Selection experiments revealed that BPH populations could easily adapt to the resistance varieties carrying the *Bph1* and *bph2* genes within 5–10 generations under continuous inbred conditions (Clarige and Den Hollander 1982; Pathak and Heinrichs 1982; Sogawa and Kilin 1987). Heritability for BPH biotypes is estimated based on the data of selection experiments. The estimated heritability is sufficiently high to suggest that significant amounts of genetic variation exist in the BPH populations for survival on rice varieties containing different genes for resistance (Roderick 1994).

In a similar manner, the BPH biotypes developed repeatedly in the irrigated tropical rice areas, where IR varieties with different BPH resistance genes were sequentially planted. Newly gained virulence is generally persistent in the local BPH populations for considerably long period. For example, the BPH populations in the Philippines retain the ability to infest the rice varieties with *Bph 1* gene, which had not been planted for many years after emergence of virulent biotypes. Previously and newly gained virulence are retained independently in the same populations. A significant portion of BPH individuals also was found to have dual virulence against the both *Bph1* and *bph2* genes in North Sumatra, Mindanao, and South Vietnam, where IR varieties with the *Bph1* and *bph2* genes were sequentially released (Sogawa et al. 1984a, b; Medrano and Heinrichs 1985; Huynh and Nhung 1988). Recent field BPH populations in South Vietnam show very wide cross-virulence to the *Bph5*, *bph6*, *Bph7*, *bph8*, and *Bph9* genes, which are not yet deployed in the breeding programs (Phuong et al. 1997). Another experiments further demonstrated that BPH could adapt simultaneously to 2–3 genes for BPH resistance (Nemoto and Yokoo 1994).

All these experimental and field evidences indicate that the biotype shift is not achieved by a simple replacement of genotypes, but progressed by a modification of genotypic composition and combination within each reproductive populations under a selection pressure by genotypic variations in the host plants. Highly diversified polygenic adaptation to the BPH resistance genes indicates that the BPH populations enable to overcome any modes of usage of the BPH resistance genes identified by the SSST, such as pyramiding or sequential release and also rotation, mixing, or mosaic cultivation. Moreover, it is noteworthy that BPH populations have abilities to defeat even some exotic resistance factors derived from the non-host plants like *Oryza officinalis* by the SSST. Breakdown of BPH resistance in MTL98 in Vietnam is an example (CLRRI 1997, personal communication).

5. Durable horizontal resistance in IR36 and IR64

Easy breakdown of BPH resistance posed serious distrust to BPH-resistant IR varieties for controlling BPH. However, we found a few IR varieties such as IR36 and IR64 possessed remarkable field resistance to BPH. Even after breakdown of its *bph2*-resistance, IR36 showed a durable field resistance to BPH and effectively curbed its outbreaks. Rice self-sufficiency was temporarily attained upon IR36 in the Philippines and Indonesia through its field resistance.

When IR64 was released in 1985, its *Bph1*-resistance had already been useless, because it was defeated by adaptive biotypes long before. Nevertheless, IR64 was accepted widely for its stable field resistance to BPH. BPH did not break out on IR64 for more than two decades in the Philippines and Indonesia (Medina et al. 1996; Cohen et al. 1997; Alam and Cohen 1998a). IR36 and IR64 showed durable horizontal resistance to different biotypes.

IR64 indicates that some unidentified genes, which are independent from the BPH resistance genes identified by the SSST, play significant roles in the expression of field resistance to BPH (Alam and Cohen 1998b). However, the genetic background and mechanisms of field resistance have been poorly understood.

6. Field resistance to BPH in rice

Herein, the term "field resistance" is tentatively used to describe various rice plant traits to reduce fitness of BPH, which are conferred by other than the BPH resistance genes identified by the SSST. Field resistance is conceivable as a common and basic self-defense mechanism in wild host plant and traditional crop cultivars to coexist with the associated herbivores.

IR26 and IR64 have the same *Bph1* gene for BPH resistance from TKM6 and Mudgo, respectively, but their performance against the *Bph1* resistance-breaking biotypes is distinctive. IR26 became highly susceptible when its *Bph1* resistance was defeated by virulent biotypes emerged, while IR64 retained remarkable moderate resistance to the IR26-defeated biotypes. It has been shown that IR64 has several QTLs that impart slight to moderate levels of antibiosis, antixenosis, and tolerance, and their combinations confer the durable and horizontal field resistance. Overall field resistance has only been assumed as different levels and combinations of resistance components, antixenosis, antibiosis, and tolerance (Panda and Heinrichs 1983; Cohen et al. 1997). Diversified parentages of IR64 could be the source of those QTLs for durable field resistance. IR64 is a descendant of 20 traditional local varieties from 8 countries.

IR36 and IR42 are the sister varieties shearing the *bph2* gene for BPH resistance from the same sources of PTB18 and PTB21. Within 5 years after their release, BPH populations that are able to feed on IR36 and IR42 appeared. However, IR36 retained moderate resistance against the IR42-defeated BPH biotypes. The population growth of IR42-defeated biotype was strongly suppressed on IR36 (Sogawa et al. 1984a, b). It is also evident that the BPH populations that fully adapted to IR36 have not evolved for long years in the IR36 monoculture areas. Selection experiments showed that BPH populations could readily adapt to IR42 within 5 generations under isolated inbred condition (Sogawa and Kilin 1987), while fully adapted population hardly developed on IR36 even after continuous selections for more than 30 generations (Sogawa unpublished data). Some extra genes other than the *bph2* gene confer the durable field resistance to BPH in IR36, which are not inherited to IR42.

From the above-mentioned examples, it is evident that the BPH-resistant IR varieties could be divided into two categories with special reference to their differences in the genetic background of BPH resistance (Fig. 2.2). One is the IR varieties that have only the resistance genes identified by the SSST, but field resistance traits were lost during the process of breeding. IR26 and IR42 are the examples of this category. They show temporary vertical resistance. The other one is the IR varieties retain field resistance traits to BPH in addition to the resistance genes identified by the SSST such as IR36 and IR64. They show durable and horizontal resistance to different biotypes of BPH.

Traditional cultivars such as Kenchana, Utri Rajapan, Triveni, Wagwag, and Baosyan 2, which are moderately resistant to BPH and had ever been widely grown by farmers, will provide us with precious aspects on the intrinsic nature of durable field resistance to BPH in paddy fields (Mochida et al. 1979; Ho et al. 1982; Panda and Heinrichs 1983; Wu et al. 1984; Velusamy et al. 1986). The local varieties that are recommended to plant in the pesticide-free SRI paddies in the eastern coastal tracts in India are also interesting materials to study the practical field resistance to multiple pests and diseases (SDTT 2010). Those local varieties are expected to have unknown resistant and tolerant traits that cannot be evaluated by the SSST.

Although field resistance is generally not so strong as varietal resistance conferred by the resistance genes identified by the SSST, it would be durable and act across all biotypes, and combinations with natural enemies in the IPM context will provide sustainable rice planthopper management in the tropical paddy ecosystems (Kartohardjono and Heinrichs 1984; Way and Heong 1994; Cuong et al. 1997). Instead, IPM practitioners argued that high level but temporary resistance conferred by the genes identified by the SSST is not necessary to manage BPH in the rice areas, where insecticide use is low and natural enemies are well conserved (Medina et al. 1996). A special emphasis has been placed on durable horizontal resistance to preclude upsurges of highly mobile insect pests that are already present in the crop ecosystem, and host plant resistance is considered as the basic foundation on which all elements of integrated control strategy are built (Buddenhagen and de Ponti 1983; Maxwell 1991).

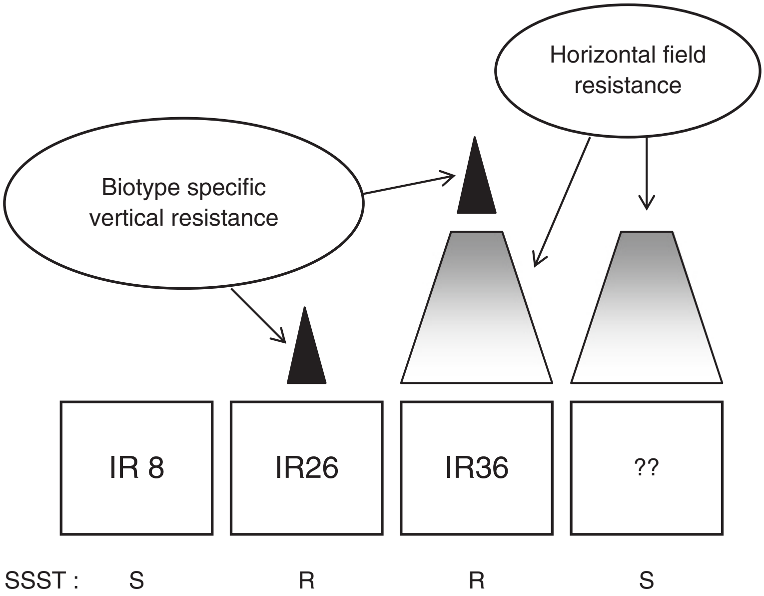

Fig. 2.2 IR varieties with different genetic backgrounds for BPH resistance and their responses to BPH by the SSST (R: resistance, S: susceptibility). Square base of each figure indicates high-yielding genetic domain of selected IR varieties and Hypothetical varieties having only field resistance. Triangular tips indicate the BPH-resistant genes identified by the SSST. The trapezoid portions indicate the traits (or QTLs) for field resistance to BPH, which cannot be evaluated by the SSST, and mostly eroded insidiously during the process of the SSST-dependent resistance breeding. The hypothetical varieties have equivalent field resistance to BPH to the IR36 and IR64, but they were eliminated as susceptible plants by the SSST

7. Erosion of field resistance in SSST

One of the decisive defects of SSST is incapacity to evaluate field resistance to BPH, which in turn commits a great risk of insidious erosion or decline of useful field resistance traits from rice plants. This defect of SSST is homologous to the "Vertifolia effect," which means insidious loss or decline of field resistance during the breeding for a particular vertical resistance (van der Plank 1984).

The resistant crop varieties suffered "Vertifolia effect" from their breeding process become highly susceptible when their particular genetic resistance is defeated with the emergence of virulent biotypes of BPH as in the cases of IR26 and IR42. In those varieties, field resistance traits of their ancestral traditional rice varieties were completely eroded during the process to incorporate the *Bph1* and *bph2* genes by the SSST. In particular, when large amounts of breeding lines are submitted to the SSST at the earlier stages of breeding, the field resistance traits will be massively eroded, because the breeding lines having only field resistance traits will be eliminated as susceptible ones in the SSST (Fig. 2.2).

Modern breeding of high-yielding IR varieties has been successful in the improvement of high-yielding capacity, quality of rice grain, and agronomic suitability and also to incorporate the monogenic BPH resistance genes identified by the SSST. On the other hand, the levels of field resistance decline insidiously to a dangerous low level in some IR varieties. High vulnerability to BPH infestations in some IR varieties could be attributed to the decline of field resistance. Degradation of field resistance traits from rice varieties perturbs the tritrophic balance among the host plants, BPH and its natural enemies in the tropical paddy ecosystems and will trigger the eruptive population growth of *r*-strategic BPH. That is a possible reason why most of the BPH-resistant IR varieties did not succeed in sustainable BPH management. Buddenhagen and Ponti (1983) has emphasized the preventive breeding, which means breeding a crop so as to prevent the increase of minor pests and pathogens already present in the crop ecosystem in the tropics.

8. Evaluation of field resistance

Varietal resistance in IR varieties with the *Bph1* and *bph2* genes is expressed by the blockage of sustainable phloem sucking of BPH (Sogawa 1982). In this regard, the *Bph1* and *bph2* are the sucking-inhibitory genes to confer antixenotic resistance to BPH. The SSST is able to evaluate preferential sucking response of BPH by the subsequent damage scores of rice seedlings, but unable to evaluate neither antibiotic resistance nor tolerance that are expressed through the post-feeding interactions between BPH and rice plants.

Field resistance to BPH in rice plants must be evaluated from more holistic and ecological viewpoints based on the population dynamics of BPH in relation to the phenology of paddy plants in the paddy ecosystems. The interactions between BPH and rice plant can be divided into the following three major events.

(a) Immigration and host plant selection: Colonization of BPH in a paddy field starts with random immigrations of macropterous adults (Kuno 1968). After alighting on a plant, the planthopper commences stylet probing to discriminate host plants (Sogawa 1982). At this process, antixenotic factors in host plants, which act via insect sucking, play a key role in the expression of varietal resistance in the paddies. Honeydew excretion by macropterous female and the density of macropterous immigrants in the field plants are the parameters to evaluate host plant antixenosis.

(b) Reproduction: Population growth of BPH depends largely upon the brachypterous females emerged from the progeny of macropterous immigrants (Kisimoto 1965), while the macropterous adults emigrate out from the breeding habitats and do not contribute to the subsequent population growth in the original habitat. Therefore, the host plant traits, which affect the ratio of brachyptery, fecundity of brachypterous females, egg mortality, etc., will act as important antibiotic factors for varietal resistance during the process of insect reproduction.

(c) Infestation: Established BPH colonies function as an "extra sink" affiliated to the host plants, which intercept translocation of photosynthates and vital metabolic substances in the sieve elements of host plants (Sogawa 1994). The population density decides the size of the extra sink. Density of nymphal population is a powerful parameter to indicate the overall levels of antibiosis. Functional biomass interactions between the insect population and host plant decide plant damage intensity and yield losses, which is also a useful parameter to indicate the level of host plant tolerance (Panda and Heinrichs 1983; Reese et al. 1994).

Recent advance of QTL-based analyses of genetic traits as well as gene-tagging and marker-assisted selection (MAS) technologies offer us more efficient approach for analyzing the complex and quantitative field resistance traits (Mohan et al. 1997; Alam and Cohen 1998b; Yencho et al. 2000). Both monogenic and polygenic traits are equally analyzed in this approach. The QTL-based approach requires a well-saturated molecular marker map, appropriate recombinant inbred rice populations, and ecologically significant phenotyping procedures. Comparisons of the QTLs detected by ecological phenotyping methods suggest directly ecological mechanisms of field resistance. Until now, most of the gene mappings for planthopper resistance traits have been undertaken by using the SSST. The SSST may detect some traits, which are strongly associated with the insect feeding. However, SSST-dependent phenotyping does not detect field resistance traits, because those traits mostly operate in the post-feeding ecological and physiological interactions between the grown host plants and the insect populations.

2.5 Whitebacked Planthopper and Host Plant Resistance

1. The whitebacked planthopper (WBPH)

There is another rice planthopper, the whitebacked planthopper (WBPH), *Sogatella frucifera* (Horváth). WBPH and BPH are equally rice monophagous *r*-strategists and sympatric to each other. However, their population ecologies are distinctive due to their differential feeding behavior. BPH can utilize rice plants throughout the cropping season and reproduces continuously 3–4 generations. On the other hand, WBPH prefers to feed on fresh leaves of rice plants at tillering stage and reproduces only one or two generations in a crop cycle. WBPH emigrates from the paddy fields at reproductive growth stages. WBPH has a macroptery-biased wing dimorphism to facilitate frequent habitat shifts. Because of this biology, WBPH usually dominates in the monsoon-prevailing rice areas outside of its tropical endemic habitats (Fig. 2.1).

2. Outbreaks in Punjab

Punjab is famous for successful green revolution in both wheat and rice. WBPH was not an important rice pest before 1965 when farmers grew traditional tall *indica* local varieties in Punjab, the northwestern segment of the Indo-Gangetic plain in India. Rice is a summer crop planted in the monsoon season (kharif) from June to December. WBPH began to cause serious damages to rice in Punjab, when the HYVs program was launched with the introduction of exotic semi-dwarf HYVs.

The first outbreak of WBPH was recorded in 1966, which coincided with the introduction of TN1. Since then, the outbreaks of WBPH occurred in 1972, 1975, 1978, and 1981 on the HYVs derived mainly from TN1 and IR8 (Kulshreshtha et al. 1970; Dhaliwal and Singh 1983; Dhaliwal et al. 1985). In 1983 kharif season in the Punjab, the population density of WBPH reached to 200–500 insects per hill and eventually caused hopperburn over 1,000 ha of paddy fields (Saini 1984). PR106 was most seriously damaged, which was expected to be less susceptible to WBPH when introduced in 1976.

In the Punjab plain, WBPH infestations usually start at 15–25 days after transplanting. WBPH populations increase on the paddy rice during the mid-tillering stage in September to October (Sehgal et al. 2001). Incidence of BPH also increased in the same period, but the population density of WBPH outnumbered that of BPH. Simultaneously, WBPH became a major insect pest of rice after introduction of HYVs in the hilly tracts of Haryana, Madhya Pradesh, and Uttar Pradesh adjacent to Punjab (Petel 1971; Verma et al. 1979a, b; Kushwaha et al. 1982; Shukla et al. 1986). In Uttar Pradesh, WBPH has attack rice regularly since 1969. Infestation was severe in 1972 and 1977, when typical hopperburn occurred in the paddy fields at late tillering stage (Verma et al. 1979a, b). In 1982, more than 3,000 ha of paddy fields in the Kathmandu Valley, Nepal, were seriously infested with WBPH (Pradhan et al. 1983).

Since then, WBPH has continuously been one of the major insect pests of rice in the rice–wheat cropping system in the Indo-Gangetic plain (Sehgal et al. 2001). Since insecticide use was very minimal, outbreaks cannot be attributed to the insecticide-induced resurgence. Concentrated distribution of WBPH-resistant rice germplasm in the northern corridor of Indian summer monsoon indicates that WBPH resistance was an important self-defense trait of summer rice to cope with massive monsoon-borne invasions of WBPH. Abrupt outbreaks of WBPH were caused by careless replacement of indigenous WBPH-resistant local rice with WBPH-susceptible exotic HYVs by the HYVs program.

3. Varietal resistance to WBPH in rice

Based on the SSST, several WBPH resistance genes were identified among *indica* rice varieties. All the WBPH resistance genes identified by the SSST are of monogenic and are designated by numerical codes with prefix *Wbph* (or *Wph*) (Khush and Brar 1991).

Of 48,554 accessions of traditional cultivars from the IRRI world collection of rice, 401 (0.8 %) were selected for resistance to WBPH by the SSST at IRRI (Romena et al. 1986). About 10, 3, and 2 % of the resistant accessions selected came from Pakistan, Nepal, and India, respectively, which occupied about 88 % of the total resistant accessions selected (Romena et al. 1986). Almost 70 % of WBPH resistant traditional rice varieties in India distribute in the northwestern semiarid areas of Uttar Pradesh, Rajasthan, Gujarat, Madhya Pradesh, and Punjab and 15 % in the northeastern hilly tracts of Assam and Meghalaya. On the other hand, the WBPH-resistant traditional varieties are not found among the accessions from Kerala, Andra Pradesh, and Tamil Nadu in South India, from which most of the BPH-resistant germplasms were found. Likewise, the accessions from Philippines, Laos, Vietnam, and Cambodia were all susceptible to WBPH (Romena et al. 1986). It seems to indicate that majority of WBPH-resistant *indica* rice was originated in the northern corridor of Indian summer monsoon, the northern periphery of the Indian subcontinent.

Distinct difference in the virulence to rice varieties was found between the Southeast and South Asian populations of WBPH. Forty of 118 varieties were resistant to the WBPH population at IRRI, but susceptible to the population in Hyderabad, India. On the contrary, nine varieties were resistant at Hyderabad, but susceptible at IRRI (IRRI 1978). The WBPH population in Punjab was further virulent to 8 of 17 varieties that were resistant to both the Hyderabad and IRRI populations, and the varieties with the *Wbph1* gene were mostly susceptible to the Punjab population (Gupta and Shukla 1986). Likewise, N22 with the *Wbph1* gene was not resistant at Pantnagar, Uttar Pradesh (Lal et al. 1983).

These reports indicate the WBPH populations in South Asia are more virulent than the Southeast Asian populations. Particularly, the Punjab population in the northwestern part of India is the most virulent. Coincidental distribution of virulent WBPH populations and WBPH resistant rice germplasm indicates that there has been an intensive coevolutional interaction between WBPH and *indica* rice landraces in the northern parts of South Asia.

The mechanism of WBPH resistance in the local rice in Punjab has not been known except for their possible sucking-inhibitory properties indicated by the SSST. However, the resistance genes identified by the SSST could not be responsible for all of their resistance traits. So far, five genes for WBPH resistance have been identified by the SSST at IRRI, but none of them were incorporated into the IR varieties. Therefore, 27 IR varieties from IR5 to IR62 are all susceptible to WBPH in the SSST. However, of them, 16 varieties were found to be moderately resistant in the modified SSST, where 20-day-old seedlings are used instead of 7-day-old ones in the SSST. Furthermore, population growth of WBPH was adversely affected by IR5, IR36, IR56, IR60, and IR62 (Velusamy and Heinrichs 1985). In addition, IR48, IR52, IR60, and IR62 were found to be moderately resistant to WBPH in the Indo-Gangetic plain (Sehgal et al. 2001). The above information indicates that there are some other host plant traits confer WBPH resistance in IR varieties, which cannot be identified by the SSST.

4. Prevalence of WBPH in Chinese hybrid rice

Hybrid rice boosted rice production in China. However, it is also evident that it caused pest outbreaks. Of them, WBPH became the most preeminent insect pest of hybrid rice (Hu et al. 1992; Sogawa 2001). WBPH was only a secondary insect pest of rice before the 1970s in China. However, immediately after release of hybrid rice in 1976, the first WBPH outbreak happened on a hybrid rice Nanyou 2 in Hunan Province in 1977 (Tan 1987). In 1982, about 1,600 ha of Shanyou 6 fields were severely infested with WBPH, and of 80 ha were completely destroyed in the hybrid rice pilot areas in Guangdong Province, South China, where Shanyou 2, Shanyou 6, and Weiyou 6 were introduced deliberately (Feng and Huang 1983). Field density of WBPH in Fujiang Province increased significantly for the period from 1978 to 1987. Before 1980, the average field density was below 5 insects per hill, but increased up to 40 insects her hill in 1987 (Lin 1989). Frequency of WBPH outbreaks was positively correlated with the expansion of hybrid rice areas in the period from 1980 to 1990 in Guangdong Province and similarly in Hunan and Guangxi Provinces (Hu et al. 1992). Light trap catches of WBPH exceeded those of BPH at Shantou, Guangdong Province by 1985, and became the most predominated insect pest (Lin 1994).

In Central China, unusually high density of WBPH was first found in a hybrid rice Shanyou 6 in Zhejiang Province in 1979. Observations at farmer's fields for 3 years from 1980 to 1982 showed that the population density of WBPH was 8–38 times higher than that in inbred rice (Ruan 1983). After that, it was demonstrated that rate of WBPH reproduction in Shanyou 6 was 2.6–3.9 times higher as compared with that in three inbred rice varieties (Huang et al. 1985). Higher fecundity of WBPH on hybrid rice such as Shanyou 6, Shanyou 63, and Weiyou 35 was also recorded (Zhu et al. 1990; Yu et al. 1991; Shi and Lei 1992; Cooperative Research Group on the Population Dynamics and Ecology of White-backed Planthopper 1992; Huang et al. 1994). These field evidence and observations showed that WBPH is much more reproductive in Chinese hybrid rice than in inbred rice.

High susceptibility to WBPH in a Chinese hybrid rice Shunyou 63 is primarily inherited from the WA-CMS (wild abortive cytoplasmic male sterile) line, which is extremely vulnerable to the WBPH infestation (Sogawa et al. 2003b). Field experiments revealed that population density of WBPH in the CMS lines "Zhenshan 97A" and "Xieqingzao A" was much higher than that in the susceptible TN1 (Liu et al. 2003). In addition, greater tolerance to WBPH infestations in Shanyou 6 due to heterotic vigorous growth is further attributed to the unusual upsurge of WBPH populations on it (Sogawa et al. 2003b).

WBPH has been only a minor insect pest of monsoon rice in the Red River Delta (RRD) in Vietnam. WBPH caused, however, a historical outbreak in about 153,000 ha of the winter–spring rice planted with Chinese hybrid rice in the RRD in 2000 (Dinh et al. 2001, 2002). Since then, WBPH is steadily increasing as a new important economic insect pest of rice in the rice granary of Vietnam. Chinese hybrid rice was first introduced to Vietnam in early 1990s and quickly extended over 70–80 % of rice areas in the RRD. Subsequent intensive applications of insecticides are spoiling the previous great efforts for the implementation of IPM and causing the paddy ecosystem crisis. In the northern Laos, possible influx of insecticide-resistant WBPH from adjacent to the northern Vietnam and China was pointed out (Komine et al. 2008).

Prevalence of WBPH in Chinese hybrid rice caused significant increase of overseas migrations of this insect from China to Japan. Immigration density of WBPH started to increase from the mid-1970s, which coincides introduction of hybrid rice in China (Naba 1991; Watanabe et al. 1994). Massive immigration surges reached not only to the southwestern Japan facing directly to China, but also to the distant northern Japan, where WBPH caused unusual economic damages to rice in the 1980s (Takano et al. 1984; Murai et al. 1986; Araya et al. 1989).

In addition, the prevalence of WBPH, a new virus disease, southern rice black-streaked dwarf virus, which is transmitted persistently by WBPH, became epidemic in the hybrid rice areas in China and Vietnam since 2008 (Zhang et al. 2008). Prevalence of WBPH and new virus disease are attributed to the nationwide extension of WBPH-susceptible hybrid rice with heavy inputs of insecticides and nitrogenous fertilizers in the WBPH-dominated insect migration areas.

5. Ovicidal resistance in *japonica* rice

It has been well known the WBPH immigrants produce conspicuous necrotic symptoms to the leaf sheaths of newly transplanted rice seedlings by intensive oviposition. *Indica* rice oviposited by WBPH does not exhibit such symptoms. The necrosis is one of the damages to deter the initial plant growth, but at the same time, it is a sign of unique self-defense mechanism against the rice planthoppers in *japonica* rice. The WBPH eggs deposited in the rice plants suffer high mortality by an ovicidal substance, benzyl benzoate, which is induced in situ in the plants laid eggs within 1–2 days after oviposition (Suzuki et al. 1996; Seino et al. 1996). Egg mortality due to the ovicidal response increases as host plants grow during the tillering stage, but decreases after the heading stage and declined to negligible levels in the ripening stage (Suzuki et al. 1993; Kiyonaga and Suzuki 1998).

Because *japonica* rice in Japan commonly has the ovicidal trait, it has been remained unaware until recently. Also, it has long been ignored because in the routine breeding process, it is an invisible and neutral trait. The ovicidal trait was discovered as an "hyper-susceptibility" to WBPH in the *japonica*/*indica* hybridized lines that lost the ovicidal trait intrinsic in the *japonica* parent due to a cryptic erosion during the breeding process (Sogawa 1991). *Japonica* varieties "Musashikogane" and "Asahinoyume" lost the ovicidal trait insidiously during the breeding process to incorporate rice stripe virus (RSV) resistance gene from a Pakistani *indica* rice "Modan" to *japonica* rice. As the result, "Musashikogane" and "Asahinoyume" became highly susceptible to WBPH, though it was highly resistant to RSV (Hara and Saito 1984; Murakami and Kanda 1984; Nakamura et al. 2009). Likewise, WBPH populations increase easily on some forage rice varieties, which lost the ovicidal resistance during the process of *japonica/indica* hybridization breeding (Sogawa 1991; Matsumura 2006).

The ovicidal resistance to WBPH was found restrictedly in the *japonica* rice germplasm. Almost recent Japanese *japonica* paddy rices have distinct ovicidal resistance (Suzuku 1996), but some upland rice varieties lack the ovicidal resistance (Sogawa 2007). About 24 % of *japonica* rice improved in China also shows the ovicidal response to the WBPH eggs. Similar ovicidal response was found in the landraces of native *japonica* in Zhejaing Province, East China (Sogawa et al. 2003c). Those landraces show continuous variations in the level of ovicidal activities. For example, "Sanqianhuang" and "Changhongdao" show strong ovicidal response, while "Laohudao" and "Jijiaohuang" entirely lack it. Furthermore, the ovicidal response is induced in a strain of perennial wild rice, *O. rufipogon*, when oviposited by WBPH (Sogawa 2007). On the other hand, the ovicidal resistance to WBPH does not distributed among the *indica* and tropical *japonica* (*javanica*) varieties (Sogawa et al. 2003c). A strain of annual wild rice, *Oryza nivara,* has no ovicidal function (Sogawa 2007). A single dominant gene *Ovc* on chromosome 6 mainly governs the ovicidal trait in *japonica* rice (Yamasaki et al. 1999a, b; Sogawa et al. 2003a, d).

The ovicidal response is an important component of field resistance or self-defense mechanism to protect *japonica* rice from sudden massive overseas immigrations of rice planthoppers in the temperate Asia, where the paddy ecosystems exist only in the summer season and natural enemies are not enough to cope with the massive immigrant planthoppers in the newly prepared paddy fields. The ovicidal response explains why WBPH is not so destructive to the rice plants as is BPH in Japan, in spite of its 100 or higher immigration density than that of BPH and high intrinsic fecundity as an typical *r*-strategist. The ovicidal resistance has no other antibiosis to the planthopper nymphs and adults. Therefore, the *japonica* rice plants allow WBPH to establish a low density of populations from the eggs that escaped from the ovicidal reaction, but vegetative growth of host plants usually compensates such limited infestations with WBPH. The ovicidal response is also found to be effective against the BPH eggs to some extent, which may contribute to suppress the population buildup of BPH on *japonica* rice plants during the vegetative growth stage (Kiyonaga et al. 1997; Yamasaki et al. 2000).

If *japonica* rice had not ovicidal resistance, WBPH could be a much greater threat to traditional rice farming in Japan. This is an typical example of field resistance to WBPH in *japonica* rice, which cannot be evaluated by the SSST.

2.6 Rice Planthoppers: A Health Barometer of Paddy Ecosystem

High reproductive potential of rice monophagous and *r*-strategic BPH and WBPH evolved in order to balance with defensive traits of rice plants and intensive biotic pressure by natural enemies. Thus, field resistance in rice plants and natural enemies are essential ecological and genetic components to keep balance of tritrophic interactions among the rice plants, planthoppers, and natural enemies in the paddy ecosystems (Verkerk et al. 1998).

Depending on the paddy ecosystem conditions and crop management practices, the planthoppers perform two distinct population trends, namely the endemic and epidemic patterns. IPM is an ecological approach to keep the population density of planthoppers to the endemic level, where natural enemies and indigenous field resistance in rice plants play key roles. Mismanagement of paddy ecosystem by prophylactic sprays of insecticides induces resurgence of the planthoppers. We have to recall to our mind why the BPH outbreak prevailed over the tropical rice areas during the process of “green revolution,” which was embarked with easy adoption of insecticides as an essential high-yielding input.

At the same time, the *r*-strategic planthoppers have a potential to reproduce beyond endemic level escaping biological control by natural enemies on the highly susceptible HYVs, which lost field resistance traits due to genetic erosions during breeding process. Field resistance in rice plants is an intrinsic self-defense mechanism to suppress the planthopper populations to the levels that natural enemies are controllable and host plants enable to compensate. Therefore, field resistance in rice plants and natural enemies are the basic components to ensure the sustainable management of *r*-strategic rice planthoppers. A concept of the preventive breeding has been proposed so as to prevent the epidemic boom of indigenous endemic pests and pathogens already present in the crop ecosystem in the tropics (Buddenhagen and Ponti 1983). In the preventive breeding for the endemic pests, the significance of durable field resistance was anticipated to be the basic foundation of sustainable crop and pest managements. The use of temporary (transient) vertical resistance conferred by the monogenic factors isolated by the SSST should be tried to avoid against highly mobile *r*-strategic insect pests such as BPH and WBPH in the tropical rice areas, which only encouraged the biotype shifts of the planthoppers. In this connection, the SSST-based resistance breeding should be redressed, because the SSST cannot evaluate field resistance mediated in the various phases of post-feeding interactions between the host plants and planthoppers, which commits a great risk of insidious erosion of useful field resistance traits from breeding materials.

Both the rice monophagous BPH and WBPH are a sensitive barometer to alert paddy ecosystem crisis. Recent revival of BPH outbreaks and unusual population upsurges of WBPH are warning the crisis of paddy ecosystems due to misuse of insecticides, misdeployment of host plant resistance, and mismanagement of farm environment.

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Chapter 3
Addressing Planthopper Threats to Asian Rice Farming and Food Security: Fixing Insecticide Misuse

Kong Luen Heong, Larry Wong and Joy Hasmin Delos Reyes

Abstract Planthopper outbreaks in rice production are induced by insecticides that destroy natural control mechanisms. In Asia, excessive insecticide use is fueled by market promotions in the manner of fast-moving consumer goods (FMCG) where pesticide marketing regulatory frameworks are weak or nonexisting. Thus, a large proportion of the insecticides farmers use are misuses and unnecessary. Unknowingly, farmers and consumers are also exposed to health risks posed by insecticides, which include autism, Alzheimer's disease and Parkinson's disease. Field research has also shown that there is little or no productivity gain from farmers' insecticide use. Instead, they increase crop vulnerability to planthopper outbreaks. The paper discusses the threats of rampant insecticide misuse in Asia and emphasizes the urgent need to reform and professionalize plant protection services and improve pesticide marketing regulations. Ecological engineering methods to increase ecosystem services and reduce insecticide use may be introduced to increase ecosystem resistance and resilience to pest outbreaks and to promote sustainable production systems for food security.

Keywords Planthopper outbreaks · Insecticide marketing · Supply chain · Health and environmental costs · Ecological services

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3.1 Introduction

Preharvest losses caused by pests[1] can threaten rice production, food security, and rural livelihoods. This is especially so when massive pest outbreaks occur at later crop stages. Affected farmers suffer heavy financial losses, fall into debt, and even commit suicide (OAE 2010). Such pest outbreaks can have devastating effects on rice production as rice ecosystems continue to remain vulnerable. A large variety of chemicals collectively known as pesticides are used by rice farmers in Asia to control pests. Insecticides are used to control insects, fungicides to control diseases, herbicides to control weeds, and molluscicides to control snails. In many countries, farmers often respond to insect pest threats by increasing insecticide use as prophylactic applications to protect their crops. Oftentimes, the sprays do not work as most farmers tend to overestimate the pest damages and losses and thus apply more pesticides than necessary. Paradoxically, excessive use of insecticides does not help control pest outbreaks but seems to even induce their numbers. Further, farmers increasingly rely on insecticides that are toxic and have adverse health implications. This paper examines the link between insecticide use and insect outbreaks, and what this means in terms of maintaining ecosystem services. The paper also asks why there has been a significant use of insecticides, including those that are banned for health reasons, and finally analyzes if there are merits to the use of insecticides in terms of yield improvement. The flow of the paper is as follows: Sect. 3.2 discusses the relationship between pest outbreaks and insecticide use. Section 3.3 presents recent studies on the supply chains of insecticides and pest management information. The section shows how insecticide use by farmers is driven by marketing strategies rather than by the rationale of yield protection. Section 3.4 briefly examines recent data and arguments of economists that productivity gains from insecticide application are insignificant and are further eroded when externalities such as health and environmental costs are considered. Section 3.5 summarizes and concludes the discussion with policy options for structural reform to fix insecticide misuse—the root cause of the threats of pest outbreaks in rice production.

3.2 Planthopper Pest Outbreaks and Insecticide Use

3.2.1 Planthopper Outbreaks and Crop Losses

Most rice-producing countries in East and Southeast Asia have incurred losses due to rice planthopper outbreaks over the last 10 years. The rice bowl of Thailand in the central plains suffered from persistent planthopper outbreaks for 10 consecutive

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[1] Pests refer to all organisms that can cause economic loss in rice production. These pests include arthropods, pathogens, viruses, weeds, mollusks, and vertebrates.

seasons from 2008 to 2012. The Office of Agricultural Economics in the Ministry of Agriculture and Cooperatives of Thailand reported that the outbreaks caused losses worth $52 million or equivalent to about 173,000 t during the dry season of 2010. In the Mekong Delta of Vietnam, the loss of around 1 million tons of rice was reported in 2007, which resulted in a government freeze on the export of rice. In Indonesia, rice production in the island of Java lost 0.9 million tons in 2011 due to these pests. Likewise, the Peoples Republic of China (PRC) lost about 2.5 million tons of rice in 2005 and is continuously losing an average of 1 million tons of paddy annually. In early 2012, the PRC's southwestern provinces lost about 10 million tons of rice due to heavy planthopper outbreaks. Rice planthopper outbreaks have also been reported, albeit at lower scales, in Bangladesh, Cambodia, India, Malaysia, Myanmar, and the Philippines. As these nations continue to face the same planthopper problem, the farm practices on dealing with pests were systematically observed to test whether planthopper outbreaks have been induced by insecticide misuse.

3.2.2 Insecticides and Pest Outbreaks

Planthoppers are typically r-strategists[2] that live and breed only in rice and are completely adapted to the rice ecosystem. They normally exist in rice fields in very low numbers of less than five planthoppers per plant and do not damage the rice plants or cause yield loss (Heong et al. 1992). However, they can destroy crops in 2 weeks if their populations increase exponentially. The data from light traps (insect-recording devices to monitor planthopper adults and their migration patterns) from Chainat Province in Thailand indicate that this may have been the case as shown in Fig. 3.1. The graph indicates the sudden increase of brown planthopper (BPH) populations from 2008 to 2012. In 2009, the BPH count in January was less than 1,000. The number surged to 100,000 in March. This was much higher than the BPH migration peak that was recorded in 2008, which was then 300.

Under normal circumstances, the rice ecosystem has a rich biodiversity of arthropod predator and parasitoid species that provide pest regulation ecosystem services, which keep planthopper numbers at bay. It is when this rich biodiversity is destroyed that the planthopper population becomes out of control, growing exponentially into outbreak proportions.

Scientific studies (Way and Heong 1994; Bottrell and Schoenly 2012) have shown that planthopper outbreaks can be traced to the misuse of insecticides. Farmers in most Asian countries spray insecticide in the early crop stages (Heong and Escalada 1997). Early insecticide spraying has the effect of reducing the food

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[2] r-strategists are organisms with high biotic potential that are able to rapidly colonize a habitat and utilize the resources. They tend to be small with short life cycles and are able to multiply quickly and often exploit unstable environments. Normally, their populations are constrained by natural forces such as biological control.

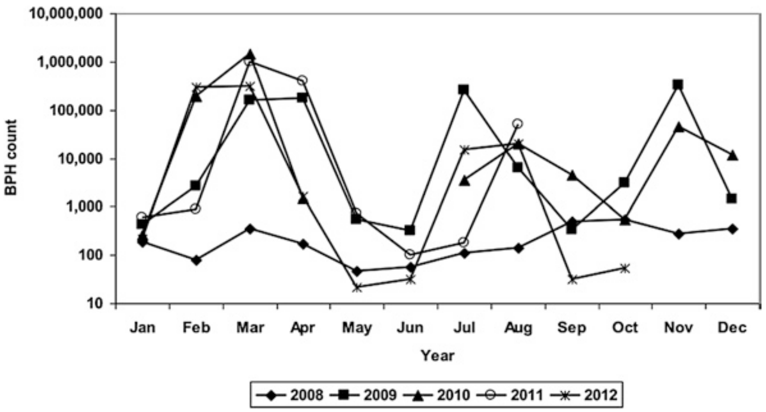

Fig. 3.1 Monthly brown planthopper brown planthopper (BPH) light trap catches in Chainat, Thailand. *BPH* brown planthopper. *Note* X-axis = monthly totals of BPH count recorded in log scale, Y-axis = months of the year. The cumulative BPH monthly total of the year showed that populations developed rapidly in the months of February to April, July to August, and in November. *Source* Data from Chainat Rice Research Center, Chainat, Thailand. Courtesy of Chairat Chanoo

chain length[3] from three links (rice–pests–enemies) to two links (rice–pests), rendering the crop vulnerable to the exponential growth of the invading planthoppers (Heong and Schoenly 1998). Figure 3.2 shows the differences in the mean food chain length between the unsprayed and sprayed fields. The vertical lines depict range in food chain length for sprayed and unsprayed food chains on each

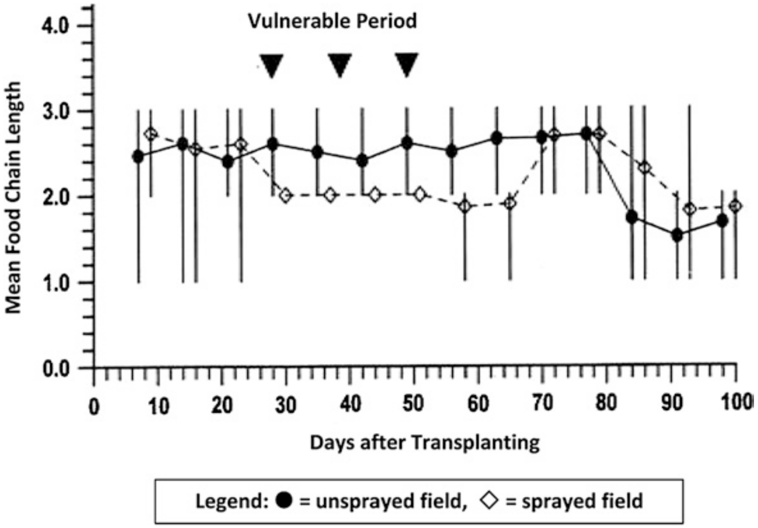

Fig. 3.2 Impact of insecticides on the mean food chain lengths in rice ecosystems. *Source* Heong and Schoenly (1998)

sampling date. On prespray days, food chains had up to three links (rice–pests–enemies). However, after the first deltamethrin spray on the 29th day after transplanting, the mean food chain length decreased from 2.6 to 2.0, which resulted in a web containing two-linked chains only (rice–pests).

In addition, the early sprays also disorganized the predator–prey links and made biological control functions ineffective. Settle et al. (1996) noted that insecticides reduced natural enemy populations, which resulted in resurgence of pest populations, particularly Brown planthopper (BPH), which is the “vulnerable period” as shown in Fig. 3.2.

Insecticides, especially pyrethroids[4] and organophosphates,[5] have disproportionate killing effects on the predators and parasitoids, which are often smaller in size, are aquatic, have soft bodies, and move about in prey search. The spray equipment of Asian rice farmers is generally of low quality, resulting in more than 80 % missing the pest targets and instead ending up in the water, thus destroying the natural predators. With the natural predators gone, insects flourish and increase in number unhampered.

3.3 Insecticide Marketing and Information Supply Chains

Scientists also showed that planthopper outbreaks are due to excessive insecticide use (Way and Heong 1994; Bottrell and Schoenly 2012). In most cases, the rice crop requires no insecticide use (FAOSTAT 2012) or just one application in the entire crop season (Heong and Schoenly 1998). Insecticide imports of the member states of the Association of Southeast Asian Nations (ASEAN)[6] have been on a significant uptrend in the last 5 years. Figure 3.3 shows the dramatic rise in insecticide imports relative to the fairly stable growth in rice production in Indonesia in the last 20 years.

In Southeast Asia, the sharp increase in imports and the use of insecticides can be attributed to the aggressive marketing strategies of agricultural insecticide companies, similar to those used in the promotion of FMCG. Insecticides being sold in this manner are not consistent with the principles of integrated pest management (IPM) and the International Code of Conduct on the Distribution and Use of Pesticide of the Food and Agriculture Organization (FAO) of the United Nations.[7]

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[4] Pyrethroids are a group of synthetic insecticides with chemical structures similar to natural pyrethrins produced by flowers of pyrethrums (Chrysanthemum cinerariaefolium). Most of these compounds are less toxic to mammals and less persistent in the environment as they are easily broken down by sunlight.

[5] Organophosphates are a group of organic insecticides that are generally esters of phosphoric acid. These compounds tend to have acute toxicity to mammals and are persistent in the environment.

[6] The Association of Southeast Asian Nations is composed of 10 member states: Brunei Darussalam, Cambodia, Indonesia, the Lao People’s Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam.

[7] See http://www.fao.org/docrep/005/Y4544E/y4544e00.htm.

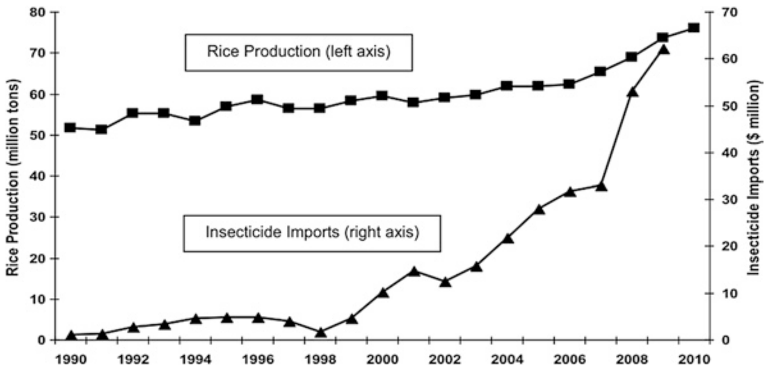

Fig. 3.3 Rice production and insecticide imports in Indonesia, 1990–2010. *Source* Data from FAOSTAT (2012)

For instance, insecticide marketing is driven by attractive product packaging and brand names, while IPM requires knowledge-based choices and rational decision making. Calendar-based applications are promoted by insecticide marketing, which appeal to farmers as less thought needs to go into it, whereas IPM requires a good understanding of the local environment and the ecosystems, the biological cycles of pests, the relations of natural enemies and ecosystems, and their services in pest control. IPM promotes scientific rationality based on technical knowledge of ecosystems when deciding on insecticide use; insecticide marketing strategies focus on mass-scale consumer use to maximize returns.

The International Code of Conduct on the Distribution and Use of Pesticide is a voluntary code of conduct in support of food security, and protection of human health and the environment. It was developed by FAO and endorsed by 191 United Nations member states, the pesticide industry, trade unions, and nongovernment organizations (NGOs). Article 11.2 is commonly violated.[8] For instance, Article 11.2.18 states that “advertisements and promotional activities should not include inappropriate incentives or gifts to encourage the purchase of insecticides.” However, in Indonesia and Thailand, raffle tickets, free vacations, and electric household appliances are offered to promote the sale of insecticides.

At a workshop sponsored by the Asian Development Bank, FAO, and the International Rice Research Institute in May 2011 involving eight ASEAN member states, it was confirmed that insecticides, which are toxic to humans when not used properly, are sold as FMCG in most of the ASEAN countries, except in Malaysia. Most insecticides are neurotoxins that can cause irreversible impairment of the human nervous system. They also contribute to chronic neurodegenerative disorders such as Parkinson’s disease (Costa et al. 2008) and Alzheimer’s disease

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[8] Article 11 is about pesticide advertising and Article 11.1 outlines the government’s role in establishing pesticide marketing regulations, while Article 11.2 outlines what the pesticide industry should ensure.

(Casida and Durkin 2013), as well as autism, attention deficit hyperactivity disorder (ADHD), and low IQ in children through prenatal exposures (Bouchard et al. 2010). Since insecticides are nonspecific, they are also toxic to nontarget species such as birds, amphibians, fish, and arthropods. In sharp contrast, in developed countries, insecticide sales and marketing are regulated, including the control of advertisements and promotional schemes.

To better understand excessive insecticide use and misuse, a study was conducted on insecticides and insecticide information supply chainsInformation supply chains Supply chainsin Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam. The study examined the flow of both insecticides and insecticide information, such as advice to farmers, to effectively control pests. This was augmented by a farm-level survey to track and quantify farmers' practices with respect to insecticide (mis)use and (mis)information.

The study found that 50–99 % of insecticides in these countries were supplied by rural retailers, who sell insecticide along with food, clothing, and other general merchandise. The retailers in these small convenience stores also act as extension workers who provide the farmers advice on appropriate dosage. This practice, coupled with the adoption of the sales and marketing strategies akin to FMCG, constituted the "push" side of insecticide promotion. Sales schemes to entice farmers to buy insecticide included cash rewards, lottery tickets, bonus points, free holiday trips and trips to Mecca, free gifts, credit schemes, and multilevel marketing.

Mapping of the insecticide information supply chainSupply chains showed that between 20 and 80 % of the farmers in the eight ASEAN member states surveyed relied on the local insecticide dealers for pest management information, advice, and insecticide recommendations. This overt reliance on dealers or the dominance of dealers, coupled with the latter's common recommendations of calendar sprays and use of insecticide "cocktails," constituted the "pull" side of insecticide promotion. Figure 3.4 shows the insecticide information supply chain in Indonesia, wherein 70 % of the insecticide information comes from insecticide companies and resellers. Both the government and private sector conduct their own farmer field schools, training, and media campaigns; however, the private sector appears to have more influence on farmers not only because retailers outnumber agriculture extension workers but also because they provide farmers with credit and incentives.

There is also evidence that some government workers are earning extra cash from chemical companies by promoting the use of their insecticides. For instance, agricultural extension agents in the PRC generate most of their salaries and office operating costs through pesticide sales (Hamburger 2002). In Vietnam, extension staff often earn extra money by selling inputs to farmers and thus tend to bias the information they provide (McCann 2005). The interplay of all these factors in an environment of inadequate regulation and poor enforcement has invariably led to the perpetuation and escalation of insecticide overuse and misuse.

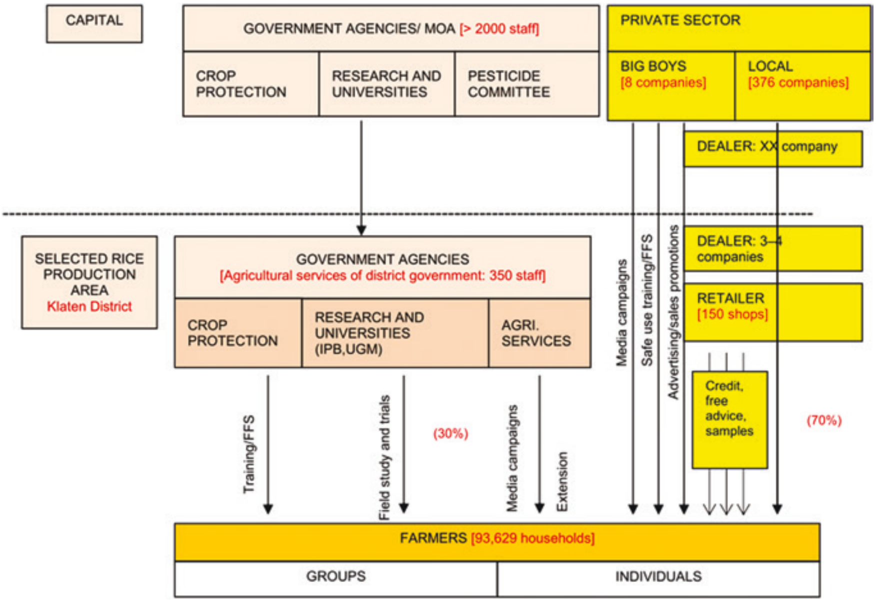

Fig. 3.4 Rice insecticide information supply chain in Indonesia. *FFS* Farmer field school, *IPB* Institute Pertanian Bogor (Bogor Agricultural University), *MOA* Ministry of Agriculture, *UGM* Universitas Gadjah Mada (Gadjah Mada University). *Source* Authors

3.4 Insecticide Application and Productivity Gains

Economists have suggested that there are little or negative productivity gains from insecticide applications in rice production (Herdt et al. 1984; Pingali et al. 1997). Since the spray equipment of farmers in Asia is generally inefficient and applications are made based on lack of appropriate information and knowledge, most insecticide applications are misuses. Misuse is defined as improper or incorrect use. Thus, when an insecticide is used for the wrong target pest or at the wrong time, or both, it is considered misuse. A study on farmers' insecticide use was conducted in Leyte, Philippines, and results showed that more than 80 % of the sprays applied were considered misuse. Among the 300 farmers interviewed, 78 % started spraying insecticides in the first 30 days after transplanting. As for the sprays used, only 19 % of the 841 sprays had chemicals intended to prevent pests and yield loss (Heong and Escalada 1994).

Regression analyses of correlating yields and insecticide sprays from eight surveys of 5,410 farmers in the Mekong Delta in Vietnam revealed that the regression was not significant (meaning no relation) in five cases, negative and significant (implying high yield with less use of insecticides) in two cases, and there was only one case with a positive correlation, with a coefficient of 0.123 (Table 3.1).

Table 3.1 Regression analyses of yield–insecticide applications of farmers in the Mekong Delta, Vietnam

Area/Year	*F* value	Probability	Significance	Regression coefficient
Tien Giang/2003	8.54	<0.01	Highly significant	+0.123
Tien Giang/2004	2.43	0.12	Not significant	−0.062
Tien Giang/2010	0.04	0.84	Not significant	+0.009
Tien Giang/2011	1.35	0.25	Not significant	+0.055
Can Tho/2002	4.23	0.04	Not significant	+0.073
Can Tho/2003	8.81	<0.01	Highly significant	−0.098
An Giang/2011	20.24	<0.01	Highly significant	−0.135
An Giang/2012	0.21	0.65	Not significant	−0.020

Source Data from Escalada et al. (2009)

When input and labor costs were considered, productivity gains were negligible (Pingali et al. 1997). Economists have also argued that when externalities such as health and environment costs are considered, insecticide applications often outweigh the limited productivity gains (Herdt et al. 1984; Antle and Pingali 1994; Pingali et al. 1997).

3.5 Conclusions

3.5.1 Insecticides Marketed as Fast-Moving Consumer Goods

In summary, most insecticide sprays that farmers apply in rice crops are unnecessary. Hence, insecticide misuse is the main reason planthopper outbreaks continue to spread across the ASEAN region. Aggressive marketing of insecticides without commensurate proper advisory services exacerbate the situation. As shown in Fig. 3.4, pest management advice and information is mainly supplied by the private sector, which promotes their own products in their extension work. A study in Thailand also showed that pesticide retailers are often the only or main source of pesticide recommendations and information (Jungbluth 1996).

These outbreaks have caused huge losses not only in monetary terms of production but also, in extreme cases, in the lives of farmers. Farmers continue to become the victims of the marketing strategy to entice insecticide buying and usage. As shown by research, rice ecosystems, when left undisturbed by unnecessary insecticide sprays, can regulate themselves and rice can grow to full harvest without the occurrence of planthopper outbreaks. The adoption of such sustainable techniques does not require a lot of resources. In fact, it saves farmers from incurring huge debts and losses.

In recent years, spending in the agriculture sector in most Asian countries has declined. Lowder and Carisma (2011) noted that expenditures on agriculture as a share of total public expenditure decreased in all regions except Europe and Central Asia from 1980 to 2007. The 2010 data from the International Food Policy Research Institute showed that Indonesia's agricultural spending dropped from 10 to 3 %. Among the agricultural expenditures, investment on agricultural extension services has been most affected. On the other hand, the insecticide industry has strengthened its marketing networks, penetrating into local villages.

Cognizant of the extent of insecticide misuse and misinformation, there is a need to prioritize the strengthening of insecticide marketing regulations and enforcement as well as to regulate insecticide information through structured certification programs for retailers, dealers, and plant protection service providers. The dangers of insecticide misuse and misinformation should also be mainstreamed, especially into the consciousness of farmers, to ensure the sustainable development of Asian rice farming and food security and to restore ecological resilience. There is also a need to develop an analytical framework incorporating supply chain and full-cost accounting to better understand and present the socioeconomic impact of planthopper outbreaks, especially toward enhancing policy discussions.

Plant protection services in Asia have been designed like a fire brigade service to hunt and kill pests. The Millennium Ecosystem Assessment (2005), on the other hand, clearly demonstrates the value of ecosystem services and their conservation for sustainable pest management. To build ecosystem services, structural transformation and professionalization of plant protection services are needed. These should include information databases, diagnostics, and accreditation programs to correct insecticide misuse and to generate informed and well-balanced recommendations for farmers. There is also a need to implement a policy requiring insecticide sellers to be certified and licensed, similar to doctors and pharmacists who prescribe and sell medicine. In that way, farmers can be assured that they receive the proper information on insecticide use.

3.5.2 Ecological Engineering as an Enabler to Fix Insecticide Misuse

In parallel with policy and structural reforms in plant protection services, the ecological engineering approach can be usefully employed to build ecosystem services. This approach involves three ecological strategies to improve pest suppression (Gurr et al. 2012). The first is to reduce mortality of beneficial arthropods by reducing insecticide use, especially in the early crop stages. The second is to provide alternative food sources in some arthropod species for the predators in the early crop stages. Avoiding early-season insecticide use in the first 40 days after sowing will also enhance this second strategy. The third is to enhance hymenopteran parasitoids by habitat manipulation like growing nectar-rich flowering plants on the bunds. A huge diversity of pest parasitoids can benefit from the bund flowers as they provide nectar for food (Gurr et al. 2011). Egg parasitoids of planthoppers, for instance, increase their attack capacities when they feed on sesame flowers (Zhu et al. 2013). Thus, there is a huge potential to adopt ecological engineering and reduce insecticides to conserve biodiversity and ecosystem services for sustainable pest management in rice production. In addition, growing flowers on bunds can also be a communication tool to motivate farmers to reduce insecticides despite the strong insecticide marketing and advertising influences (Escalada and Heong 2012). Pest-tolerant varieties developed through traditional breeding or biotechnology grown under ecologically sustainable environments will also be more durable (Gallagher et al. 1994).

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Chapter 4
Rice Planthoppers in Tropics and Temperate East Asia: Difference in Their Biology

Takashi Wada

Abstract Differences in population growth and physiological characters of *Nilaparvata lugens* between the populations of the tropics and of temperate East Asia are discussed. Fundamental differences in population dynamics seem to be related to the origin of initial immigrants and activity of natural enemies. In tropical fields, initial immigrants originate from nearby paddy fields, resulting usually in high immigrant densities. On the other hand, few immigrants after seasonal long-distance migration initiate population in temperate paddy fields. In the tropics, *N. lugens* exhibit various population growth patterns depending on the interaction with the natural enemies. While in the temperate areas, populations tend to increase gradually due to paucity of natural enemies probably due to collapse of natural enemies during cold winter. *N. lugens* in subtropical and temperate East Asia, compared to tropical Asia, produce more macropters, and have longer pre-ovipositional period and more starvation tolerance. Thus, the East Asian population of *N. lugens* is more adapted to migration, while tropical populations in southeast Asia are adapted to multiplication. Biotype compositions and insecticide resistance in *N. lugens* populations in time and space are quite similar within East Asia (subtropical and temperate areas), while they tended to slightly differ depending on locations in the tropics. It is considered that these characters in East Asian *N. lugens* population are genetically maintained by a migration system mediated by seasonal monsoon wind. Strong population suppression by natural enemies in the tropics implies the possibility that escape from natural enemies was a driving force for evolution of migration in *N. lugens.*

Keywords Brown planthopper · Initial immigrants · Population dynamic · Natural enemy · Evolution of migration

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4.1 Introduction

Status of planthoppers as rice pests have changed depending on time in the tropics. Before the Green Revolution, the brown planthopper (BPH), *Nilaparvata lugens*, was one of the minor insect pests in the tropical paddy fields (Dyck and Thomas 1979; Heinrichs and Mochida 1984). International Rice Research Institute (IRRI) was founded in the Philippines in 1960. In fact, little description of *N. lugens* was found in IRRI Reports published in early 1960s (Kisimoto 1981). The first outbreak of BPH was observed at IRRI fields in 1964 (Iida 1972). In 1966, IR8, a miracle rice, was released, and the green revolution began. In early 1970s, BPH outbreaks frequently occurred in the Southeast Asian countries where high-yielding rice varieties originated from IRRI were introduced (Dyck and Thomas 1979; Kisimoto 1981). IRRI released the varieties such as IR26 and IR32, which were resistant to BPH. However, the BPH overcome the resistance soon by the appearances of new biotypes (Saxena and Barrion 1985). Repeating events of releasing resistant varieties and overcoming their resistance by the appearances of new BPH biotypes have continued until now. Another problem with the BPH management is the development of insecticide resistance in BPH populations. Reduction of susceptibility to organophosphorus or carbamate insecticides appeared in late 1970s (Nagata et al. 1979; Kilin et al. 1981). Recently, the BPH populations showing high resistance to chloronicotinyl insecticides is a serious problem in Asian paddy fields (Matsumura et al. 2008).

The causes for BPH outbreaks in tropical paddy fields after the late 1960s are generally considered to be: (i) introduction of nitrogen responsive high-yielding varieties, which favors BPH multiplication through increased fecundity and low mortality; (ii) improvement of irrigation system, which facilitated intensive and successive rice planting throughout the year favored generation continuity of *N. lugens*; (iii) resurgence induced by abuse of insecticide applications: non-selective insecticide sprays destroy natural enemy fauna and possibly also increase *N. lugens* fecundity to a certain extent.

On the other hand, rice planthoppers, *N. lugens* and *Sogatella furcifera*, were serious pests of rice in East Asia from long time. The oldest record of planthopper outbreak was in 697 AD in Japan (Mochida and Okada 1979). Korean records show planthopper outbreaks since eighteenth century. During the early modern period of Edo era (1600–1867) in Japan, many records are found describing serious famines caused by planthopper damage together with cool and longtime rainy summer (Nagata 1982; Miyashita 1961). One of the great famines occurred in West Japan in 1732, when rice yields were decreased to only 10 % of normal yields. Recent advancements in understanding of wind-assisted long-distance planthopper migration into West Japan (Kisimoto 1976; Seino et al. 1987) explain why serious outbreaks occurred in cool rainy summers. There were many guardian deities of children (jizo), which console dead people on great famines of Edo era in all over Japan (Fig. 4.1a). In Amakusa, Kyushu, West Japan, where planthopper immigrant density is usually higher, farmers have performed an annual festival since Edo era in mid-July (“mushi-oi sai” that means driving away insects) in which they imagine control

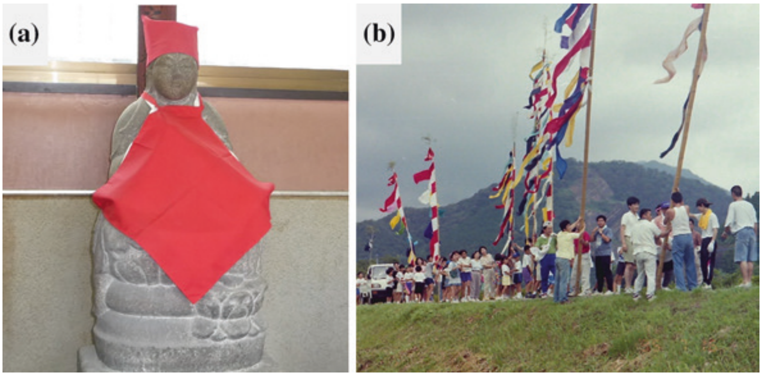

Fig. 4.1 **a** A guardian deity of children (Uenin-Jizo) at downtown of Fukuoka, Japan, which console dead people on great famines in Edo era. **b** Yearly festival of "Mushi-oi sai" in Amakusa, Kumamoto, which is to drive away of rice insect pests

of rice insect pests (Fig. 4.1b). These outbreak events of planthoppers in Japan happened in the periods much before creations of modern high-yielding varieties and synthetic insecticides. In Edo era, farmers sometimes used whale oil or rape seed oil to control planthoppers (Nagata 1982; Tateishi 1981). They tapped or immersed plants and dropped planthoppers onto oil-spread water surface. Planthoppers died from drowning or asphyxiation. Unlike in the tropics, *N. lugens* have been a serious insect pest of rice since history in the temperate regions.

Historically, why is there difference in pest status of *N. lugens* between tropical Asia and temperate East Asia? In order to understand the reason, differences in biology of *N. lugens* between the tropics and temperate East Asia are focused on in this chapter.

4.2 Population Dynamic

Several reports (Kuno and Dyck 1985; Perfect and Cook 1994; Sawada et al. 1993; Wada and Nik 1992) focused on the difference in population dynamic of *N. lugens* between tropical regions and temperate East Asia. Detailed population study was first done in temperate paddy fields in South Japan by Kuno (1968), and Kuno and Hokyo (1970), followed by Watanabe (1996). In temperate Japan, where *N. lugens* cannot overwinter, population dynamics are generally characterized by low initial immigrant population which invades from overseas with the assist of monsoon wind, and high-population growth rate throughout the crop season, resulting in rather monotonous increase through three consecutive generations. Populations of the initial densities finally reach 1,500 times on average (Kuno 1968). The populations in tropical fields, however, show entirely different features. Populations in tropical paddy fields are generally characterized by (i) high initial immigrant density, (ii) low population growth rate, (iii) earlier population peak: The peak occurs in the 2nd

Table 4.1 Differences in general population growth features between tropical and temperate *N. lugens* populations

	Tropical population[a]	Temperate population[a]
Population growth in field		
Initial immigrant density	(High)	Low
Seasonality of immigration	None	Rainy season
Population growth rate	(Low)	high
Population peak in a crop season	(2nd generation)	(3rd generation)
Population predictivity from initial density	(No)	Yes
Population growth pattern	Various patterns	(monotonous increase)
Physiological characters		
Wing form	More brachypters	More macropters
Pre-ovipositional period	Short	Long
Starvation tolerance of macropter	Weak	Strong

[a] A parenthesis indicates that there are many exceptions

generation as compared to the 3rd in temperate Japan, (iv) difficult to predict latter population density from the initial population. General feature of the both temperate and the tropical populations is summarized in Table 4.1.

However, the situations are rather complicated in the tropical fields. For examples, as for initial immigrants, the densities were low in the fields of the specific conditions such as rain-fed fields in the Philippine, where rice were planted more synchronously (Cook and Perfect 1989), the first crop of the wet season after the fallow period in Indonesia (Sawada et al. 1993), and the fields just after the fallow period, which was settled in the dry season in Malaysia (Wada and Nik 1992). Additionally, in these fields, populations tended to increase gradually with high-population growth rates, showing rather "temperate type." Thus, various population growth patterns seem to exist in the tropical fields (Cook and Perfect 1989; Wada and Nik 1992).

What are the fundamental differences between temperate and tropics? According to vigorous studies since the 1970s (Kisimoto 1976; Kisimoto and Sogawa 1995; Otuka et al. 2006), the source of immigrants of *N. lugens* and *S. furcifera* in temperate fields is long-distance (over 1,500 km) migrants, thus the densities of initial immigrants are usually very low. However, *N. lugens* in the tropic are considered to be much less mobile (Riley et al. 1987; Perfect and Cook 1987). Origins of initial immigrants were estimated less than from 30 km. Therefore, immigrant densities are usually high in the tropics where rice is more or less staggered planted. But the densities are low even in tropical fields around which there are no or very few paddy fields in the later growth stages from which planthoppers are expected to emigrate (Kisimoto and Rosenberg 1994). In fact, after the fallow period, initial immigrant densities were very low but populations increased gradually as of temperate areas (Wada and Nik 1992; Sawada et al. 1993).

The other fundamental difference seems to lie in the factor, which determines the population growth pattern. In temperate fields, populations basically increase through generations although the situation is not so simple due to variation in the proportions of macropters to brachypters in the population (Suzuki 2002). Thus, the later populations are predictable from initial immigrant densities. On the other hand, tropical *N. lugens* exhibit various population growth patterns. Some determinants, probably within-field factors, regulate population growth. One of the important determinants, which many authors pointed out, is natural enemy activity. Kuno and Dyck (1985) described importance of *Microvelia*, due to the close relationship between population change rates of *N. lugens* and *Microvelia* densities. Cook and Perfect (1989) suggested abundance of natural enemies over the first 20 days after transplant was a critical factor in determining later population size. Kenmore et al. (1984) showed physical exclusion of predators or reduction of predators, in particular, spiders and veliids, caused outbreak of *N. lugens*. Sawada et al. (1993) concluded that high *N. lugens* densities in synchronous planting areas were caused by paucity of natural enemy activity. Wada and Nick (1992) concluded that interaction between planthopper and natural enemies was a major factor, which determines population growth patterns of planthoppers. Thus, natural enemy activity fluctuates by specific situations in the tropics, which seems to cause the variation in population growth patterns. Importance of natural enemy activity as a factor, which regulates *N. lugens* population in the tropics, has been verified by frequent occurrences of hopperburns (resurgence) caused by abuse of insecticides (Heinrichs and Mochida 1984; Heong 2009).

Determinants other than natural enemy interaction, Sawada et al. (1993) pointed out water availability in the field causing big fluctuation of population growth rates in dry season in Indonesia. Kuno and Dyck (1985) suggested climate and rice varieties also influence population growth of *N. lugens*.

4.3 Natural Enemy Abundance

Difference in the *N. lugens* population growth in fields between temperate and tropics is mainly attributed to natural enemy activities. Since *N. lugens* are not able to overwinter in temperate regions, specific natural enemies hardly exist. In addition, cold winter is thought to significantly destroy natural enemy fauna. Immigrants, which invade young paddy fields, are able to increase their populations through a few generations with advantage of paucity of natural enemies. Although some predators (*Cyrtorhinus*) and parasitoids (Drynids) invade fields, accompanying planthopper migration (Kisimoto and Rosenberg 1994; Kitamura and Nishikata 1987), there is likely to be an establishment time lag that often precludes their effectiveness (Perfect and Cook 1994). In other word, *N. lugens* succeed to escape from natural enemies by long-distance migration and explode their population in temperate habitats.

On the other hand, natural enemy activities in the tropics without winter seem to be maintained, more or less, continuously throughout the year. Before the green revolution, *N. lugens* populations were effectively suppressed into low level by local natural enemies. However, after the green revolution, introduction of high-yielding varieties favored multiplication of *N. lugens* (Lu and Heong 2009) and resulted in an environmental shift. When natural enemy activities are disturbed by some reasons, outbreaks of *N. lugens* quickly occur. Abuse of insecticides is a typical case in which natural enemy activities are disturbed. Insecticide applications disorganize predator–prey interaction and the food web structure, thus favoring *N. lugens*, an r-strategist pest with high fecundity and short life span (Heong 2009). There are factors besides insecticide applications, which disturb natural enemy activities in the tropics. The dry season allowing most insects living in paddy fields to face shortage of hosts seems one of them. The crop-free fallow period is sometimes considered for planthopper management (Nozaki et al. 1984). However, *N. lugens* population levels were ironically higher in the cops after the fallow period than in the other crop season with asynchronous plantings (Wada and Nik 1992; Sawada et al. 1993; Way and Heong 1994). It is quite probable that eradication of *N. lugens* in a certain area by the fallow period destroys residential natural enemies and favors a few new planthopper immigrants from other areas or possibly within the area. The crop-free fallow period in the dry seasons sometimes provided more serious impact on biodiversity. Hopperburn frequencies relative to planting area were extremely high in the paddy fields, which were seeded just after the fallow period in the Muda Area of Malaysia in 1990 (Wada and Nik 1992). Climate and farmer practices profoundly influence predator–prey interactions, and thus, *N. lugens* seem to exhibit various population growth patterns in the tropics.

4.4 Physiological Characters

Nagata and Masuda (1980) first found the genetic difference of the physiological character between tropical and temperate *N. lugens*. They found that Japanese BPH populations produce higher proportion of female macropters compared to tropical population (Thailand and Philippine), which dominates brachypters at same rearing densities. Iwanaga et al. (1985, 1987) reported that majority of the populations collected from various locations of Japan and coastal areas of China produced more female macropters as compared to the populations collected in tropical Philippine, Indonesia, and Malaysia. However, they found that a few populations in Japan exhibited a similar trend of the wing-form production as tropical populations. This was explained by the difference in the sources of immigrants, i.e., Japanese *N. lugens* were originated from South China in most cases, but sometimes also from other tropical countries.

Wada et al. (2007) demonstrated that *N. lugens* populations collected from subtropical and temperate East Asia (Northern Vietnam, Central China, and Kyushu, Japan) had longer adult immature stage before oviposition, compared to tropical populations (Southern Vietnam, Thailand, and Malaysia). The periods required for 50 % female to begin oviposition at 25 °C were 4.7 days for tropical populations

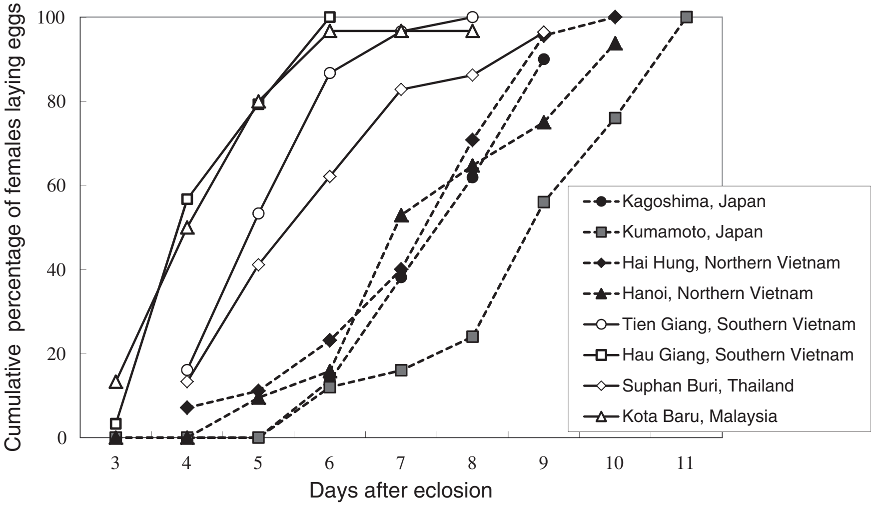

Fig. 4.2 Difference in pre-ovipositional periods among *N. lugens* populations originated from temperate, subtropical, and tropical Asia (*solid lines* indicate populations from tropical Southeast Asia, and *dotted lines* indicate populations from temperate and subtropical East Asia)

and 7.6 days for East Asian populations (Fig. 4.2). Further, Wada et al. (2009) reported that macropters originated from East Asia were more tolerant to starvation than those from tropical countries. Macropters feed actively on rice for the first 2 or 3 days after eclosion (Tanaka 1999). Macropters of East Asia populations possess increased starvation tolerance after the post-eclosion feeding (live 2.6 times longer without feeding than newly emerged adults) relative to the tropical populations (1.7 times). Accordingly, the periods required for 50 % macropters to die without feeding after 2-day post-eclosion feeding were 11.5 days for East Asia populations and 7.0 for topical populations. These results also suggest the timing of takeoff by *N. lugens*: macropters emigrate from a paddy field after two- or three-day post-eclosion feeding when they maximize starvation tolerance. Figure 4.3 illustrates a typical example showing the difference in longevity of macropters between temperate and tropical populations, in relation to post-eclosion feeding. Taken pre-ovipositional periods into consideration, Wada et al. (2009) suggested the difference in resource allocation (vitellogenesis or stored resources) between East Asia and tropical populations: Macropters of East Asia populations invest energy intake from feeding mainly on reserves, which enhance starvation tolerance, while those of tropical populations invest on ovary development as well as stored reserves.

These differences in characters, which are closely related to dispersal or migration, provide the evidence that *N. lugens* populations which are adapted to pre-ovipositional migration are distributed in subtropical and temperate East Asia. On the other hand, *N. lugens* populations in the tropics are adapted to multiplications with higher brachypter production and shorter pre-oviposition period. These differences

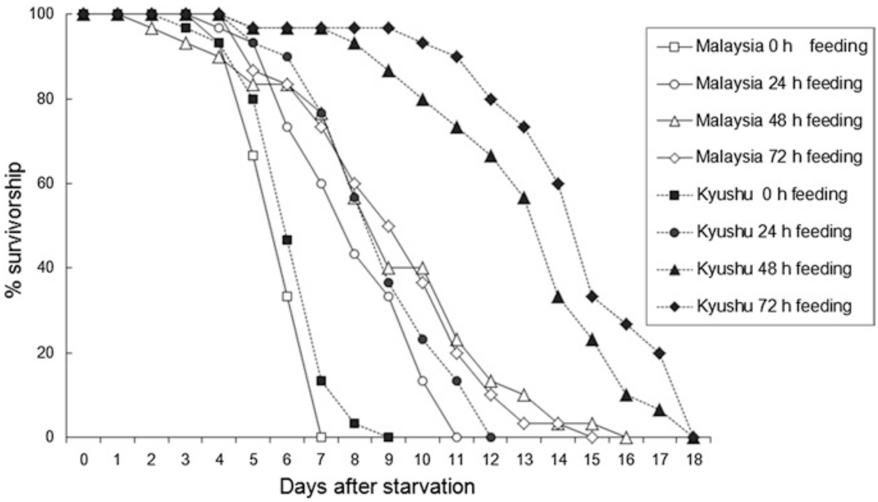

Fig. 4.3 Increase in starvation tolerance after feeding on rice for 0, 24, 47, and 72 h after adult molt in the tropical Malaysia population and the temperate Kyushu population in 1994 (*solid lines* indicate the progenies of Malaysia populations, and *dotted lines* indicate the progenies of Kyushu populations)

influence population dynamic in fields, in particular, numbers of eggs laid relative to adult density. But information on the difference in oviposition performance between populations in tropics and East Asia is not yet available.

Other characters that are not directly related to migration also indicate genetic difference between *N. lugens* populations in East Asia and in the tropics. The study of biotypes (individual or population that shows virulence to different cultivars) was widely carried out in Asia (Saxena and Barrion 1985). Sogawa (1992) suggested that the change from biotype 1 to biotype 2 capable of feeding on rice with Bph 1 resistance gene had simultaneously occurred in Northern Vietnam, China, and South Japan. Due to the capability of feeding on ASD7 with bph2 resistance gene, similarity of the biotype composition in local populations throughout subtropical and temperate East Asia again reported by Wada et al. (1994) and Takahashi et al. (1994). Tanaka and Matsumura (2000) reported that increase of *N. lugens* capable of feeding on ASD7 in Japan occurred after wide spread of varieties with bph2 gene in China and Northern Vietnam. As a whole, biotype compositions in time and space are quite similar within East Asia, while they tended to slightly differ depending on locations in the tropics.

Development of chloronicotinyl insecticide resistance in *N. lugens* which appeared from the mid-2000s in Asian countries has been a serious problem until now. Geographical differences in resistance development against various insecticides also suggest genetic similarity of *N. lugens* in East Asia. *N. lugens* in Northern Vietnam, China, and Japan had high resistance to imidacloprid (Matsumura et al. 2008; Matsumura and Sanada-Morimura 2010). The populations in Southern Vietnam also exhibited high resistance, but the populations in the Philippines were still susceptible to this chemical. This fact suggests insecticide resistance occurred simultaneously over the countries in East Asia, but the status of resistance depended on the local situations in the tropics.

4.5 Some Implications of Evolution for Planthopper Migration

Studies of physiological characters demonstrated that there is a so-called East Asian population of *N. lugens* (Sogawa 1993), which are migratory and are isolated to some extent from tropical populations. Studies of long-distance migration have indicated genetic exchange within East Asia. *N. lugens* overwinter in subtropical East Asia (Northern Vietnam and southern end of China) (Chen et al. 1982; Cheng et al. 1979). In spring, the first northeastward migration occurs from overwintering sites to early crops in South China (Otuka et al. 2008). After population multiplications through one or two generations in South China, another step of northeastward migrations occur, which led to initial immigrants in newly planted rice in Japan, Korea, and Central China (Sogawa and Watanabe 1992; Otuka et al. 2006). Although migration events are not clearly observed compared to early summer migration (Kisimoto and Rosenberg 1994), southwestward return migration from temperate regions toward overwintering sites has been demonstrated (Cheng et al. 1979; Riley et al. 1994; Qi et al. 2010). Destinations of *N. lugens* migration depend entirely on wind directions. Wind-dependent migration simulations can predict long-distance immigrations (Seino et al. 1987; Watanabe et al. 1991; Otuka et al. 2005). So, the migration system of *N. lugens* in East Asia is mediated by seasonal monsoon winds, allowing northeastward expansion during spring and early summer, and southwestward return movement in autumn. This system maintains *N. lugens* having longer adult immaturity genetically for long years in spite of disadvantage of prolonged oviposition for multiplication.

Rice cultivation began about 10,000 years ago in Central China and about 4–8000 years ago in Japan (Sato 2008). Because rice is the only host plant of *N. lugens,* East Asian population must be evolved after northern expansion of rice by mankind in East Asia. In the process of forming East Asian population, yearly seasonal monsoon is considered to favor mobile *N. lugens* and cause differentiation of the East Asian population probably from tropical populations.

The phenomenon of the effective population suppression by natural enemies in the tropics together with successful escape from natural enemies in temperate regions implies significance of migration as one of the strategies for the rice planthoppers. Evolution of migration has often been discussed in relation to heterogeneous or ephemeral environments in time and space (Roff and Fairbairn 2007). Migration is a strategy to avoid impending unfavorable habitat caused by climate or inter- and intraspecific competitions. Seasonal fluctuation and heterogeneous distribution of food resource should be a typical example causing insect migration.

But escape from predators and parasites is also a factor, which may favor evolution of migration (Southwood 1978; Pulido 2007).

In the tropics, planthopper populations usually collapse within a crop period, partially due to predation and parasitism by natural enemies. However, the extinction of the populations in a paddy field does not occur only by the function of natural enemy activities. It is partially caused by the appearance of macropters, which emigrate from the paddy field (Kuno and Hokyo 1970). Appearance of macropters increases with advancement of rice growth (Kisimoto and Rosenberg 1994). In addition, the natural enemy pressure on the planthopper population was also the factor, which increases with the advancement of rice plant growth stages (Wada and Nik 1992): egg mortality due to egg parasitoids (Watanabe et al. 1992) and young nymph mortality caused by predators (Wada and Nik 1992) increases with plant ages and planthopper generations in a crop period. Therefore, staying in a field for a few generations seems to lead the planthopper population to take a risk of the high natural enemy pressure and finally to become extinct. The simplest way to avoid natural enemy pressure for planthoppers seems to take off the field even before deterioration of quality of the host plant. Rice planthoppers migrate from field to field, otherwise they may not be able to survive in the tropics. This idea seems to be probable if we consider *S. furcifera*, which produce high proportions of macropters even in early rice (Kuno 1968; Watanabe 1996). In addition, because *N. lugens* populations were always low in ancient tropical paddy fields, a risk of population decline caused by natural enemies seems to be more critical than deterioration of rice damaged by planthoppers themselves. The similar causal aspect of migratory flight escaping from natural enemy attacks was demonstrated in the other important migratory agricultural pest, *Spodoptera litura* (Tojo et al. 2008). Rice planthoppers migrate from fields to fields to escape from natural enemies, exploring new habitats in the tropics, which may be the preadaptation of long-distance migration of East Asian *N. lugens.*

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Chapter 5
Herbivore-Induced Defenses in Rice and Their Potential Application in Rice Planthopper Management

Yonggen Lou, Lingfei Hu and Jiancai Li

Abstract Upon attacked by insect herbivores, plants can activate a range of defenses that result in direct and/or indirect resistance to subsequent challenge by a herbivore. Significant development in understanding of the physiological and molecular basis of these herbivore-induced plant defense responses has been achieved over the past decade. Our understanding of these defense responses has led to new ideas of herbivore management methods that can be environmental friendly and safer. We studied the responses of rice, one of the most important food crops of the world, to infestation by insect herbivores, including rice planthoppers. In this review, we first briefly summarize the fundamentals and molecular basis of herbivore-induced rice defense responses. We then introduce the methods of planthopper management in rice that could be exploited. These methods include using herbivore-induced plant volatiles (HIPVs) as attractants of the natural enemies, the application of chemical elicitors, and the genetic modification of crop variety. Finally, some insights are given about the directions of future research and how to tap this opportunity of herbivore-induced plant defense response in rice pest management.

Keywords Rice planthoppers · Herbivore-induced plant defense response · Herbivore-induced plant volatiles · Chemical elicitors · Tritrophic interactions

5.1 Introduction

In nature, plants suffer from various biotic stresses, such as herbivores and pathogens. In order to protect themselves, plants have evolved a series of defense mechanisms (Wu and Baldwin 2010; Arimura et al. 2011; Bonaventure et al. 2011;

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Hilker and Meiners 2011; Erb et al. 2012). These strategies include constitutive defenses, which exist in plants before pest attack, and induced defenses, which are activated following attack.

Plant-induced defenses, which can be elicited by feeding or oviposition of herbivores, are known to be triggered by elicitors derived from herbivores and/or the interaction between plants and herbivores (Mithöfer and Boland 2008; Heil 2009; Wu and Baldwin 2010; Arimura et al. 2011; Bonaventure et al. 2011; Hilker and Meiners 2011; Erb et al. 2012). Induced plant defenses may positively or negatively influence the performance of subsequent herbivores directly or indirectly by influencing the effectiveness of the natural enemies of the herbivores (Bostock 2005; Howe and Jander 2008; Baldwin 2010; Heil and Karban 2010; War et al. 2011; Mithofer and Boland 2012; Clavijo McCormick et al. 2012). For example, herbivore infestation induces some plants to release volatiles and/or produce extrafloral nectar, both of which can influence the behavior and performance of the predators and parasitoids of herbivores (Baldwin 2010; Erb et al. 2012; Peñaflor and Bento 2013). Moreover, these plant-mediated interactions may occur not only among above-ground herbivores but also between above-ground herbivores and below-ground herbivores (Erb et al. 2012). Thus, herbivore-induced plant defense responses play an important role in modulating the composition of the arthropod community and structure in an ecosystem (Kessler et al. 2007; Zheng and Dicke 2008). Some of these plant defense traits, such as volatiles attracting natural enemies of herbivores and elicitors inducing plant defense, can enhance the efficiency of natural enemies and/or reducing the performance of herbivores; these could be exploited for new measures for managing herbivores (War et al. 2011; Peñaflor and Bento 2013).

Rice is one of the most important food crops of the world. It suffers from many insect pests. In China, the main rice insect pests include rice planthoppers—brown planthopper (BPH) *Nilaparvata lugens* (Stål), white-backed planthopper (WBPH) *Sogatella furcifera* (Horváth), and small brown planthopper (SBPH) *Laodelphax striatellus* (Fallen); rice borers—striped stem borer (SSB) *Chilo suppressalis* (Walker) and *Scircophaga incertulas* (Walker); and rice leaf folder (LF) *Cnaphalocrocis medinalis* Guenee. In some regions, the water weevil *Lissorhoptrus oryzophilus* Kuschel, the gall midge *Orseoia oryzae* (Wood-Mason), and the thrip *Chloethrips oryzae* (Wil.) also heavily infest rice. To prevent rice plants from herbivore infestation, some control methods have been tried. The major control methods include resistant varieties, cultural controls, biological controls, and chemical controls (Lou et al. 2013). However, since the number of rice varieties resistant to herbivores is small, and cultural and biological controls are labor consuming and less efficient, the major control measure for rice insect pests is the use of insecticides. These not only cause severe environmental pollution but also lead eventually to the resurgence of herbivores and reduce populations of the natural enemies. Therefore, developing safe and effective methods for managing rice insect pests is essential.

Rice plants have also been reported to produce defense responses following attack by insect pests, including rice planthoppers (Lou et al. 2005a, b, 2006; Zhou et al. 2009, 2011; Lu et al. 2011; Qi et al. 2011). These defense responses may influence the performance of the subsequent conspecific and non-conspecific herbivores directly and/or indirectly by regulating the third trophic level (Lou et al. 2005a, b, 2006; Zhao et al. 2001, 2009, 2011; Lu et al. 2011; Qi et al. 2011). Moreover, a few studies have revealed that induced rice defense responses are able to modulate the arthropod community composition and the population densities of insect pests in the field (Xiao et al. 2012). Therefore, appropriately inducing rice defense traits may decrease the population densities of rice insect pests, in turn reducing the amount of chemical insecticides.

In this review, we first summarize the fundamentals and molecular basis of herbivore-induced rice defense responses. Then, we introduce methods of managing rice insect pests, especially rice planthoppers, that could be exploited based on these defense responses. Finally, future research directions are proposed.

5.2 Herbivore-Induced Rice Defenses

Like many other plant species, such as Arabidopsis, tomato, and tobacco, rice produces defense responses when attacked by insect herbivores; these responses can influence the behavior and performance of subsequent herbivores directly and/or indirectly by attracting the natural enemies of herbivores (Chen et al. 2002; Lou et al. 2005a, b, 2006). Striped stem borer larvae fed on SSB larvae-infested plants grow slowly compared to those fed on non-manipulated plants (Zhou et al. 2009). In response to BPH infestation, rice plants release volatiles that attracts egg parasitoid *Anugrus nilaparvatae* (Lou et al. 2005a) and enhance the susceptibility of rice to WBPH (Zhao et al. 2001). Prior feeding by *Spodoptera frugiperda* or jasmonic acid (JA) treatment increases resistance in rice to the water weevil, *Lissorhoptrus oryzophilus,* a root-damaging herbivore (Hamm et al. 2010). Moreover, plants treated with JA significantly reduce number of immature *L. oryzophilus* relative to untreated plants. Like the other plant species, herbivore-induced rice defense responses also change with rice variety (Lou and Cheng 2003, 2006) and plant growth stage (Ma et al. 2004; Wang et al. 2011), herbivore species (Zhou et al. 2009; Lu et al. 2011), density, and infestation time (Ma et al. 2004; Xiang et al. 2008), and with abiotic factors, such as nitrogen levels (Lou and Cheng 2003). The information suggests that herbivore-induced rice defenses have strong plasticity and play an important role in shaping the composition of the arthropod community and structure in rice ecosystem.

The process by which herbivore attack induces a plant's defensive response is complicated. First, the plant has to recognize herbivore-associated molecular patterns (HAMPs); subsequently, these activate early events and multiple signaling pathways, such as a change in the plasma transmembrane potential (Vm), calcium flux, calcium-dependent protein kinase (CDPK), and mitogen-activated protein kinase (MAPK) cascades, and JA-, salicylic acid (SA)-, ethylene-, and H_2O_2-mediated pathways (Wu and Baldwin 2010; Arimura et al. 2011; Erb et al.

2012). The activated signals and pathways increase the levels of defense-related gene transcripts and defense-related compounds, and this increase causes plants to become resistant to subsequently attacking herbivores (Howe and Jander 2008; Wu and Baldwin 2010; Arimura et al. 2011; Bonaventure et al. 2011; Erb et al. 2012).

Thus far, several HAMPs, such as fatty acid–amino acid conjugates (FACs) (Alborn et al. 1997; Halitschke et al. 2001; Yoshinaga et al. 2007), β-glucosidase (Mattiacci et al. 1995), inceptin (Schmelz et al. 2007), caeliferins (Alborn et al. 2007), bruchins (Doss et al. 2000), and benzyl cyanide (Fatouros et al. 2008), have been identified. Like herbivore infestation, some of these HAMPs have been found to induce Vm change and calcium flux (Maffei et al. 2004; Arimura et al. 2011), as well as the activation of MAPKs and JA, and ethylene biosynthesis and signaling (Halitschke et al. 2001; Giri et al. 2006; Wu et al. 2007; Skibbe et al. 2008). Moreover, calcium flux, protein kinase (such as CDPK and MAPK) cascades, and JA-, SA-, ethylene-, and H_2O_2-mediated signaling pathways have been confirmed to play a central role in shaping the specificity of herbivore-induced plant defense responses (Wu et al. 2007; Howe and Jander 2008; Wu and Baldwin 2010; Heinrich et al. 2011; Meldau et al. 2012; Mithofer and Boland 2012). However, nothing was known about plant receptors that perceive HAMPs. So far, only two possible receptors, lectin receptor kinase 1 (Gilardoni et al. 2011) and BAK1 (Yang et al. 2011), have been reported.

Studies on the mechanism underlying herbivore-induced rice defense also revealed that the process by which rice responds defensively is complex and involves changes in the transcript levels of many genes that belong to 18 functional groups and the reconfiguration of a wide variety of metabolic, physiological, and biochemical processes (Zhang et al. 2004; Hua et al. 2007; Zhou et al. 2011). An integrated signaling network consisting of phytohormones, especially JA, SA, and ethylene, and secondary signal transduction components, such as Ca^{2+} signaling, reactive oxygen species, G protein signaling, and protein kinases, underlies the entire process (Lu et al. 2006; Wang et al. 2008; Zhou et al. 2009, 2011; Lu et al. 2011; Qi et al. 2011). This signaling network alters the transcript levels of many genes by activating many transcription factors; the activation of these factors has many biological consequences, including the accumulation of defense chemicals and decreases in photosynthetic activity (Zhou et al. 2011).

Recently, several early components that regulate signaling pathways in rice have been identified. OsERF3, for example, has been found to function upstream of OsMPK3, JA, SA, ethylene, and H_2O_2 pathways, and to positively regulate the biosynthesis of JA, SA, and ethylene but negatively modulate H_2O_2 production (Lu et al. 2011). OsPLDα4 and α5 were reported to influence the production of JA and green leaf volatiles (GLVs), the products of the hydroperoxide lyase (HPL) branch of the oxylipin pathway (Qi et al. 2011). Bph14, a coiled-coil, nucleotide-binding, and leucine-rich repeat (CC-NB-LRR) protein predominantly expressed in vascular bundles, was found to confer resistance to BPH by activating an SA signaling pathway, inducing callose deposition in phloem cells and enhancing the activity of trypsin protease inhibitors (TrypPIs) after planthopper infestation (Du et al. 2009). OsMPK3 positively mediates the production of elicited JA, which subsequently affects levels of herbivore-induced TrypPIs and decreases the performance of SSB larvae (Wang et al. 2013). These findings suggest that the herbivore-elicited rice defense responses are regulated by a set of signaling networks (Fig. 5.1).

Plants' defense responses to different herbivores are modulated by the different signaling pathways that they elicit (Howe and Jander 2008; Wu and Baldwin 2010; Meldau et al. 2012; Mithofer and Boland 2012). Various signaling pathways in rice were found to play different roles in modulating resistance to herbivores with different feeding habits. The resistance of rice to lepidopteran caterpillars, such as the larvae of SSB and LF, is mainly positively mediated by JA and ethylene signaling pathways, whereas resistance to piercing and sucking herbivores, such as BPHs, is modulated negatively by JA but positively by H_2O_2 and SA pathways (Zhou et al. 2009; Lu et al. 2011) (Fig. 5.1).

Research with numerous plant species has revealed that a great variety of constitutive and inducible chemicals, such as terpenoids, phenolics, alkaloids, glucosinolates, and cyanogenic glycosides, and defensive proteins, such as proteinase inhibitors (PIs), cysteine proteases, lectins, chitinases, and polyphenol oxidases (PPOs), have toxic or antifeedant effects on insect herbivores (Ryan 1990; Peumans et al. 1995; Wang and Constable 2004; Aharoni et al. 2005; Mohan et al. 2006; Howe and Jander 2008; Gill et al. 2010). Moreover, herbivore-induced plant volatiles (HIPVs) and GLVs have been reported to influence the behavior and/or performance of the subsequent herbivores directly and/or indirectly by attracting the predators and parasitoids (Kessler and Baldwin 2001; Degenhardt et al. 2003; Dicke and Baldwin 2010; Snoeren et al. 2010). In rice, the levels of some defense-related compounds, including PIs, phytoalexins, pathogenesis-related proteins, and terpenoids, were observed to be enhanced when plants were infested by herbivores or treated with defense-related signals, such as JA (Rakwal and Komatsu 2000; Zhou et al. 2009). In addition, the TrypPI activity, which was positively regulated by JA and ethylene signaling pathways (Zhou et al. 2009; Lu et al. 2011), negatively affected the performance of lepidopteran caterpillars, such as the larvae of SSB and LF (Zhou et al. 2009; Lu et al. 2011). Volatiles emitted from rice plants infested by herbivores or treated with JA can attract parasitoids and enhance the parasitism of herbivores (Lou et al. 2005a, b, 2006). Some volatiles, such as linalool and (*E*)-β-caryophyllene (Xiao et al. 2012), as well as GLVs (Qi et al. 2011; Tong et al. 2012), were found to not only influence the efficiency of the natural enemies but also to affect the performance of herbivores, including BPHs, SSBs, and LFs (Fig. 5.1). Callose deposition in phloem cells, which could be induced by BPH infestation, was regarded as one of the resistance mechanisms of rice plants to BPH (Hao et al. 2008). Moreover, benzyl benzoate, a chemical that is elicited by WBPH egg deposition has been shown to increase ovicidal activity against WBPH (Seino et al. 1996). In general, defense compounds used against insect herbivores in rice were less well understood (Horgan 2009).

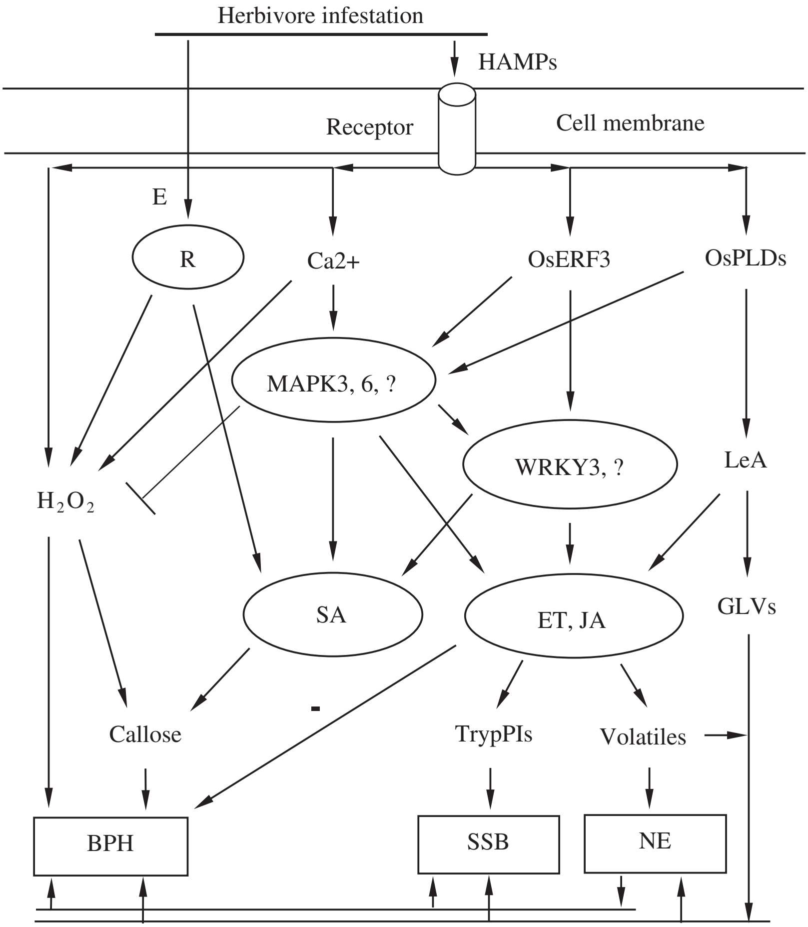

Fig. 5.1 Current information on mechanisms responsible for herbivore-induced defense responses in rice. Rice plants recognize herbivore-associated molecular patterns (HAMPs) derived from herbivores or interaction with the plant and then activate components, such as calcium influx, OsERF3 and OsPLDs. These activated early components will elicit MAPK cascades, jasmonic acid (JA)-, salicylic acid (SA)-, ethylene (ET)-, and H_2O_2-mediated signaling pathways, which in turn enhance levels of defense-related gene transcripts and defense compounds. This increases resistance to herbivores. Some herbivores may secrete effectors (E) which suppress the plant's defenses. However, for resistant varieties, plants possess resistance genes (R), such as BPH14, that will recognize the herbivore's effectors and activate the second layer of defense responses; this is known as effector-triggered immunity. Among these compounds, herbivore-induced plant volatiles (HIPVs), including green leaf volatiles (GLVs), which are mainly regulated by JA and ET pathways, can influence the behavior and performance of both chewing herbivores and piercing and sucking herbivores, such as striped stem borers (SSBs) and brown planthoppers (BPHs), directly and indirectly by the natural enemies of the herbivores. Trypsin proteinase inhibitors (TrypPIs) are also positively modulated by both JA and ET signaling pathways and negatively affect the performance of chewing herbivores, such as SSBs. Both callose deposition that may be mediated by H_2O_2 and SA pathways, and H_2O_2 itself, have a negative effect on BPH performance. JA- and ET-mediated pathways negatively modulate resistance in rice to BPHs

5.3 Potential of Herbivore-Induced Defense in Rice Planthopper Management

Many studies have demonstrated that herbivore-induced plant direct and indirect defenses can influence the population dynamics of herbivores in the field (Karban and Baldwin 1997; Baldwin 1998; Halitschke et al. 2008; Degenhardt et al. 2009; Allmann and Baldwin 2010; Xiao et al. 2012). Moreover, these defenses can enhance plant fitness (Baldwin 1998; Steppuhn et al. 2004; Schuman et al. 2012). For example, Baldwin (1998) found that MeJA treatment increases resistance in tobacco (*Nicotiana attenuate*) to herbivores and enhances the plant's fitness in nature. Field studies revealed that HIPVs emitted from tobacco and maize can reduce herbivore populations from 24 % to more than 90 %, via enhancing the predation and parasitism of herbivores (Kessler and Baldwin 2001; Rasmann et al. 2005; Halitschke et al. 2008; Degenhardt et al. 2009; Allmann and Baldwin 2010) and deterring herbivores from egg deposition (Kessler and Baldwin 2001). Thus, appropriately using and/or regulating these defense traits might reduce densities of herbivores and hence decrease the amount of pesticides applied.

5.3.1 Influence of Synthetic HIPVs in Attracting Natural Enemies

Based on the biosynthesis pathways or their known within-plant functions HIPVs mainly include three chemical groups (Holopainen and Gershenzon 2010). The first group, the terpenoids, is generally the dominant group of HIPVs in many plant species and is produced by two separate pathways, one active in plastids (MEP) and the other one (MVA) in cytosol (Loreto and Schnitzler 2010; Maffei 2010). The second group includes fatty acid derivatives, including the C6 lipoxygenase products, so-called GLVs. The third group is the volatile aromatic compounds, such as methyl salicylate and indole. In addition, there are a multitude of other volatile compounds, such as the volatile plant hormone ethylene and volatile amino acid derivatives (Dicke and Baldwin 2010; Holopainen and Blande 2013; Peñaflor and Bento 2013).

HIPVs are known to have multiple functions: Some signal within a plant to activate systemic defenses, priming and activating defenses in neighboring plants; some influence the behavior or performance of herbivores and pollinators; and some attract natural enemies of herbivores (Dicke and Baldwin 2010; Holopainen and Blande 2013; Peñaflor and Bento 2013). These functions may be helpful for controlling insect pests, as more than 20 single compounds or mixtures, including GLVs, terpenoids, and aromatics, have been found to attract the natural enemies of herbivores in the field (James 2003a, 2005a, b; Yu et al. 2008; Lee 2010; Orre et al. 2010); methyl salicylate and GLVs are strong candidate chemicals for this purpose (Table 5.1). Methyl salicylate (MeSA), for example, has been reported to

Table 5.1 Summary of positive responses from beneficial insects to synthetic HIPVs in the field

Compound	Natural enemies	Crops	References
Cis-3-hexen-1-ol	*Stethorus punctum picipes*, *Orius tristicolor*, *Anagrus daanei*	Hop yard	James (2005a)
	Orius similis, *Paragus quadrifasciatus*	Cotton	Yu et al. (2008)
Trans-2-Hexen-1-al	*Geocoris pallens*	Hop yard	James (2005a)
Cis-3-Hexenal	*Anagrus nilarpavatae*	Rice	Wang and Lou (2013)
Cis-3-Hexenyl acetate	Braconidae	Hop yard	James (2005a)
	Anaphes iole	Cotton	Williams et al. (2008)
	Deraeocoris brevis, *Stethorus punctum picipes*	Hop yard	James (2003b)
	Coccinella septempunctata, *Orius similis*	Cotton	Yu et al. (2008)
	Metaphycus spp., *Anagrus* spp.	Grapes	James (2003b)
	Anagrus nilarpavatae	Rice	Wang and Lou (2013)
Nonanal	Sarcophagidae	Hop yard	James (2005a)
	Erigonidium graminicolum, *Orius similis*	Cotton	Yu et al. (2008)
Octanal	*Deraeocoris punctulatus*, *Paragus quadrifasciatus*	Cotton	Yu et al. (2008)
Dimethyl octatriene	*Paragus quadrifasciatus*	Cotton	Yu et al. (2008)
Octylaldehyde	*Orius tristicolor*, *Anagrus daanei*	Hop yard	James (2005a)
Linalool	*Geocoris pallens*	Tobacco	Kessler and Baldwin (2001)
	Anagrus nilarpavatae	Rice	Wang and Lou (2013)
α-farnesene	*Anagrus daanei*	Hop yard	James (2005a)
	Anaphes iole	Cotton	Williams et al. (2008)
3,7-dimethyl-1,3,6-octatriene	*Orius similis*	Cotton	Yu et al. (2008)
Geraniol	Sarcophagidae	Hop yard	James (2003a)
Squalene	Male *Chrysoperla nigricornis*	Apple orchard	Jones et al. (2011)
Benzaldehyde	*Stethorus punctum picipes*, *Orius tristicolor*, Tachinidae	Hop yard	James (2005a)
	Chrysoperla plorabunda	Apple orchard	Jones et al. (2011)

(continued)

Table 5.1 (continued)

Compound	Natural enemies	Crops	References
Indole	*Geocoris pallens*, Micro-Hymenoptera	Hop yard	James (2003a)
2-phenylethanol	*Chrysoperla carnea*	Soybean	Zhu and Park (2005)
Methyl anthranilate	*Thaumatomyia glabra*, Braconidae	Hop yard	James (2003a)
	Thaumatomyia glabra	Field with a mowed grass lawn and a pear orchard	Landolt (2000)
	Ceranisus menes	Field with vegetables and trees	Murai et al. (2000)
Methyl salicylate	*Stethorus punctum picipes, Orius tristicolor*, etc.	Hop yard	James (2003a)
	Chrysopa nigricornis	Hop yard	James (2003a)
	Coccinella septempunctata	Soybean	Zhu and Park (2005)
	Geocoris pallens, Syrphidae, *Stethorus punctum picipes*	Hop yard	James (2003b)
	Chrysopidae, *Orius tristicolor*	Strawberry	Lee (2010)
	Erigonidium graminicolum, *Orius similis,*	Cotton	Yu et al. (2008)
	Chrysopa nigricornis, *Deraeocoris brevis*, *Empididae*, etc.	Grapes	James and Price (2004)
	Metaphycus spp., *Anagrus* spp.	Grapes	James (2003b)
	Diadegma semiclausum, *Anacharis zealandica*	Turnip	Orre et al. (2010)
Methyl jasmonate	Braconidae	Hop yard	James (2005a)
	Metaphycus spp.	Grapes	James (2003b)
Cis-jasmone	Braconidae, Sarcophagidae	Hop yard	James (2003a)
Dimethyl disulfide	*Aleochara bilineata*, *Aleochara bipustulata*	Cabbage	Ferry et al. (2007)
MeSA, cis-3-Hexenal, cis-3-hexenyl acetate and linalool	*Anagrus nilarpavatae*	Rice	Wang and Lou (2013)

attract many species of the natural enemies of herbivores, such as *Stethorus punctum picipes, Orius tristicolor*, *Erigonidium graminicolum*, *Orius similis, Chrysopa nigricornis*, *Deraeocoris brevis,* and *Anagrus* spp. (Table 5.1). In addition, MeSA was found to actually enhance the efficiency of the natural enemies and thus to dramatically reduce the population densities of the main pests, spider mites, and aphids (James and Price 2004). However, HIPVs may also attract herbivores and the fourth trophic level, the natural enemies of parasitoids and predators, or repel the natural enemies of the herbivores (Dicke and Baldwin 2010; Holopainen and Blande 2013; Peñaflor and Bento 2013). For example, the parasitoid *Diadegma semiclausum* is repelled by MeSA (Snoeren et al. 2010; Braasch et al. 2012). Thus, the synthetic HIPVs that attract natural enemies but not herbivores and/or hyperparasitoids should be screened (Kaplan 2012).

In rice, previous studies have shown that herbivore infestation or jasmonic acid (JA) treatment alters the volatile profiles of rice plants (Lou et al. 2005a, b, 2006; Yan et al. 2010; Zhou et al. 2011). These volatiles mainly include fatty acid derivatives and terpenoids (Lou et al. 2006; Zhou et al. 2011; Xiao et al. 2012). *N. lugens*-induced or JA-elicited rice volatiles are strongly attractive to the egg parasitoid *A. nilaparvatae*, a major natural enemy of the rice planthopper (Lou et al. 2005a, b). Moreover, the parasitism of *N. lugens* eggs by *A. nilaparvatae* on plants that were surrounded by JA-treated plants is more than twofold higher than on control plants in the greenhouse and in the field (Lou et al. 2005a, 2006), implying that augmenting the release of rice-produced attractants has the potential to enhance the effectiveness of the parasitoid in the control of *N. lugens*. Recently, Wang and Lou (2013) found that five compounds—Z-3-hexenyl acetate, 1-penten-3-ol, Z-3-hexenal, linalool, and MeSA—attract the parasitoid. Moreover, *A. nilapareatae* were strongly attracted by the mixtures of MeSA plus Z-3-hexenal, one containing Z-3-hexenal, Z-3-hexenyl acetate and linalool, and one containing MeSA, Z-3-hexenal, Z-3-hexenyl acetate, and linalool. Field experiments demonstrated that the parasitism of BPH eggs was significantly increased on plants that received a septa containing one of the three chemicals (Z-3-hexenal, Z-3-hexenyl acetate, and linalool) or the mixture containing MeSA, Z-3-hexenal, Z-3-hexenyl acetate, and linalool. The findings may contribute to improving or may help improve the biological control of *N. lugens* in the future.

5.3.2 *Effects of Exogenous Application of Chemical Elicitors*

Chemical elicitors are defined as chemicals that trigger resistance or enhance a plant's ability to mobilize induced defense responses (priming agents) to pests and are themselves not directly toxic to the pest (Kessmann et al. 1994; Pare et al. 2005; Beckers and Conrath 2007; Kim and Felton 2013). Thus far, many such natural and synthetic elicitors, especially elicitors that induce plant defense responses to pathogens, have been identified and/or synthesized. These elicitors include microbe-associated molecular patterns (MAMPs), such as bacterial flagellin, lipopolysaccharides (LPSs), and peptidoglycan (PGN) as well as fungi chitin and β-glucan, HAMPs, phytohormones and their analogs, such as JA and its analogs, SA and its analogs, and other chemicals, such as terpenoids and BABA (Pare et al. 2005; Silipo et al. 2010; Hilker and Meiners 2011; Newman et al. 2013). These elicitors can activate defense-related signaling pathways (Schmelz et al. 2009; Silipo et al. 2010; Newman et al. 2013) or increase the sensitivity in triggering defense responses (Pare et al. 2005; Kim and Felton 2013), which subsequently makes plants able to resist pathogens or insect herbivores. Up to now, several of these chemical elicitors, such as benzo-(1,2,3) thiadiazole-7-carbothioic acid S-methyl ester (BTH), 2,6-dichloroisonicotinic acid (INA), and β-aminobutyric acid (BABA), have been commercialized for plant disease control (Vallad and Goodman 2004; Beckers and Conrath 2007; Knoth et al. 2009).

There are more than 20 chemical elicitors, mainly including HAMPs, phytohormones and their analogs, that induce or prime plant defense against insect herbivores (Table 5.2). For example, HAMPs and JA have been reported to activate defense-related signaling pathways and thus increase direct and indirect resistance in plants to herbivores (Table 5.2). Terpenoids, GLVs, and two inorganic chemicals, copper and silicon, can prime plants and enhance their ability to defend themselves against subsequent invaders (Table 5.2). In general, JA and elicitors that induce the JA signaling pathway mainly trigger resistance to necrotrophic pathogens and chewing herbivores, whereas SA and SA-inducing elicitors mainly elicit resistance in plants to biotrophic pathogens and piercing/sucking insects (Thaler et al. 2002; Arimura et al. 2005). However, Turlings and his research group recently found that BTH and laminarin, both of which elicit the SA signaling pathway, reduced the emission of herbivore-induced volatiles but increased direct and indirect resistance (attraction of the parasitoids) to the herbivores (Rostas and Turlings 2008; Sobhy et al. 2012), suggesting the complexity of induced plant defense responses.

Like elicitors that induce plant defense to pathogens, some of elicitors that elicit defenses to insect herbivores have also been proven to enhance the resistance of plants to herbivores in the field. For example, Baldwin (1998) found that MeJA treatment increases resistance in *N. attenuata* to herbivores and enhances its fitness in nature. The exogenous application of JA can elicit direct and indirect defense responses of plants to herbivores in the field (Thaler 1999; Thaler et al. 2002). Wheat plants in the field sprayed with low levels of *cis*-jasmone as an aqueous emulsion have been found to have lower aphid infestations (Moraes et al. 2008). Recently, Bingham et al. (2013) found that the application of microencapsulated *cis*-jasmone combined with piperonyl butoxide, a synergistic agent of pesticide, on tomato plants in the field resulted in a nearly 90 % reduction in the number of the tobacco whitefly, *Bemisia tabaci*. Moreover, plant seeds treated with elicitors have been found to enhance plant defense responses to herbivores. For example, tomato plants whose seeds were treated with JA showed enhanced responsiveness of defense-related genes and increased resistance to the tobacco hornworm *Manduca sexta*, green peach aphids *Myzus persicae*, and spider mites *Tetranychus urticae* (Worrall et al. 2012). Sobhy et al. (2014) reported that treating maize seeds with either BTH or laminarin increased the attractiveness of herbivore-infested plants to all three tested parasitoid species, *Microplitis rufiventris* v

Table 5.2 Summary of elicitors that induce defense responses in plants to herbivorous arthropods

Elicitor	Source	Sensitive plants	Plant defense responses	References
HAMPS				
Fatty acid–amino acid conjugates (FACs)	Regurgitant of *Teleogryllus taiwanemma*, *Drosophila melanogaster*, *Spodoptera exigua*, *Manduca sexta*, and other lepidoptera	Maize, tobacco, eggplant, *Solanum nigrum*	Membrane depolarization, Ca^{2+} influx, JA burst, ethylene burst, change of transcription of numerous genes; release of volatiles attracting carnivores	Yoshinaga et al. 2007, Mithofer and Boland 2008, Schmelz et al. 2009, Yoshinaga et al. 2010, Bonaventure et al. 2011
Caeliferins	Grasshopper regurgitant	Maize, Arabidopsis	Release of volatiles attracting carnivores; JA and ethylene burst	Alborn et al. 2007, Schmelz et al. 2009
Inceptins	Lepidopteran larval regurgitant	Cowpea	Increases in levels of JA, SA and ET; the release of volatiles attracting carnivores	Schmelz et al. 2007, 2009, 2012
β-glucosidase	Regurgitant of *Pieris brassicae* larvae	Lima bean, cabbage, maize	Release of volatiles attracting carnivores	Hopke et al. 1994, Mattiacci et al. 1995
Bruchins	Bruchid females	Pea and other legumes	Growth of neoplasms; change of transcription of several genes	Cooper et al. 2005, Doss et al. 2000, Doss 2005
Benzyl cyanide	*Pieris* eggs	Brussels sprouts, Arabidopsis	Change in leaf surface that attracts egg parasitoids; change of transcription of numerous genes	Fatouros et al. 2005, 2008, Little et al. 2007
Secreted proteins	Eggs of sawfly D. pini and the elm leaf beetle *X. luteola*	Pine	Volatiles release; reduction of photosynthetic activity; change of transcription of terpene synthases	Hilker et al. 2005, Schrŏder et al. 2005, 2007, Koepke et al. 2008, Hilker and Meiners 2011

(continued)

Table 5.2 (continued)

Elicitor	Source	Sensitive plants	Plant defense responses	References
Phytohormones and their analogs				
JA, MeJA, JA-Ile	Plants	Arabidopsis, tomato, tobacco, rice, maize, etc.	Accumulation of defense-related compounds; release of volatiles; change of transcription of numerous genes	Baldwin 1998, Bostock 2005, Howe and Jander 2008, Mithöfer and Boland 2012, Erb et al. 2012
Cis-jasmone	Plants	Arabidopsis, wheat, tomato, tobacco, cotton, sweet pepper, soybean, etc.	Accumulation of defense-related compounds; release of volatiles; change of transcription of numerous genes; priming plants	Pickett et al. 2001, Bruce et al. 2008, Moraes et al. 2008, Bingham et al. 2013, Oluwafemi et al. 2013
Coronatine	Bacterial phytotoxin	Tomato, tobacco, soybean, Arabidopsis, etc.	Accumulation of defense-related compounds; release of volatiles; change of transcription of some specific genes	Schüler et al. 2004, Svoboda and Boland 2010
Coronalon	Synthetic	Tomato, tobacco, soybean, barley, lima bean, Arabidopsis	Accumulation of defense-related compounds; release of volatiles; change of transcription of some specific genes	Schüler et al. 2004, Svoboda and Boland 2010
BTH	Synthetic	Maize	Accumulation of phytoalexins and pathogenesis-related (PR) proteins; decreases in elicited volatiles but enhance the attractiveness to carnivores	Rostas and Turlings 2008, Sobhy et al. 2012
2,4-D	Synthetic	Rice	Increases in the levels of JA, SA, ethylene and volatiles	Xin et al. 2012

(continued)

Table 5.2 (continued)

Elicitor	Source	Sensitive plants	Plant defense responses	References
Other chemicals				
Laminarin	algal β-1,3-glucan	Maize	Accumulation of phytoalexins and pathogenesis-related (PR) proteins; decreases in elicited volatiles but enhance the attractiveness to carnivores	Rostas and Turlings 2008, Sobhy et al. 2012
GLVs	Plant volatiles	Maize, hybrid poplar Arabidopsis, tobacco	Priming plants and thus enhance defense responses	Engelberth et al. 2004, Kessler et al. 2006, Frost et al. 2008, Hirao et al. 2012
Terpenoids	Plant volatiles	lima bean, Maize, Arabidopsis, tobacco	Priming plants and thus enhance defense responses	Arimura et al. 2010, 2011, 2012, Godard et al. 2008
Copper (Cu)	Soil	Maize	Priming plants and thus enhance defense responses	Winter et al. 2012
Silicon	Fertilizer and soil	Rice	Priming plants and thus enhance defense responses	Ye et al. 2013

Note JA jasmonic acid; *MeJA* methyl jasmonate; *JA-Ile* JA-isoleucine conjugate; *BTH* benzo-(1,2,3) thiadiazole-7-carbothioic acid S-methyl ester; *2,4-D* 2,4-dicholorophenoxyacetic acid; *GLVs* Green leaf volatiles

Kok., *Cotesia marginiventris* (Cresson), and *Campoletis sonorensis* (Cameron). These works suggest that the appropriate application of chemical elicitors could effectively reduce the population densities of herbivores.

In rice, it has been reported that *N. lugens*-induced or JA-elicited rice volatiles are strongly attractive to the parasitoid *A. nilaparvatae*, and the parasitism of *N. lugens* eggs by *A. nilaparvatae* on plants that were surrounded by JA-treated plants is more than twofold higher than on control plants in the greenhouse and field (Lou et al. 2005a, 2006). Recently, by developing a high-throughput chemical genetics screening system, Xin et al. (2012) found that 2,4-dicholorophenoxyacetic acid (2,4-D) induced a strong defensive reaction and a significant increase in volatile production. Induced plants were more resistant to SSB but became highly attractive to BPH, as well as its parasitoid, *A. nilaparvatae*. In a subsequent field experiment, 2,4-D application were able to draw away BPH from non-treated plants and turn the treated plants into deadly traps by also attracting large numbers of parasitoids. Such a chemical elicitor, combined with push-pull management strategy (Cook et al. 2007), may improve our ability to manage BPH. When rice plants at the edge of a field, for example, are sprayed with 2,4-D, a trapping zone is created that reduces pest damage in the inner parts of the field. This may also lead to higher numbers of egg parasitoids in these zones, keeping pest reproduction to a minimum and creating a source of parasitoids that can attack the next generation of the pest in the untreated parts of the fields (Xin et al. 2012).

5.3.3 Genetic Modification of Rice Variety

As our understanding of the molecular mechanisms responsible for herbivore-induced plant defense responses increases, the genetic engineering of plants may offer a means to enhance resistance in plants to herbivores (Degenhardt et al. 2003; War et al. 2011; Peñaflor and Bento 2013). By overexpressing or knocking down one or more genes, including those responsible for defense-related signaling pathways, volatile emission, and defense compound synthesis, genetically modified plants have been made in many plant species, such as Arabidopsis, maize, rice, tomato, and tobacco, and some have been proven to enhance the direct and indirect resistance of plants to herbivorous insects in the field (Degenhardt et al. 2009; Schuman et al. 2012; Xiao et al. 2012). For example, when the ability of American corn varieties to emit (*E*)-β-caryophyllene (an important signal used by entomopathogenic nematodes to find hosts) was restored (expressing a (*E*)-β-caryophyllene synthase gene in plants), transgenic corn plants were damaged much less by western corn rootworm than were corn plants lacking the enzyme (Degenhardt et al. 2009). The larvae of *Manduca sexta* grew faster on and preferred plants of *N. attenuata* whose nicotine levels had been reduced by 95 % via genetic engineering (Steppuhn et al. 2004). When planted in their native habitat, plants whose nicotine production had been impaired were attacked more frequently and, compared to wild-type plants, lost threefold more leaf area from a variety of native herbivores, suggesting that nicotine functions as an efficient defense in nature and that plants with high levels of nicotine will resist herbivore damage. Recently, a 2-year field study by Schuman et al. (2012) has shown that plants that emit GLVs produce twice as many buds and flowers—a measure of fitness—as plants that have been genetically engineered not to emit GLVs; GLVs only increased plants' fitness when various species of Geocoris (a bug that preys on *Manduca sexta)* reduced the number of herbivores.

Xiao et al. (2012) found that rice lines impaired in emissions of *S*-linalool, a compound that is strongly induced by BPH infestation, were less attractive to the egg parasitoid of rice planthoppers, *A. nilaparvatae,* as well as to predatory spiders but more attractive to BPH than were wild-type plants. On the other hand, lines with low levels of (*E*)-β-caryophyllene, a constitutively emitted volatile that is not inducible by BPH, attracted both BPH and its natural enemies less often than did WT plants. Both of the lines resulted in an increase in the BPH population in the field (Xiao et al. 2012). Thus, such transgenic lines may be used in combination with control BPH: Rice plants that produce (*E*)-β-caryophyllene but not *S*-linalool could be sown at the edges of the field to attract both BPH and its natural enemies, and other plants could be engineered to produce high amounts of *S*-linalool but not (*E*)-β-caryophyllene in order to attract egg parasitoids and avoid BPH colonization (Xiao et al. 2012).

Although there are some successful cases of reducing population densities of herbivores by using transgenic plants, developing a transgenic variety that constitutively expresses some defense-related genes should be avoided. The continuous production of defense chemicals may decrease plant fitness as the production of defense compounds is expensive (Steppuhn et al. 2004; Zavala et al. 2004), and herbivores adapt quickly to plants because selection pressure is high. Moreover, if the defense chemicals that constitutively produced are volatiles, such a variety will lose its attractiveness to natural enemies because the attracted natural enemies have no rewards (neither hosts nor prey) (Turlings and Ton 2006; Khan et al. 2008), and may attract pathogens and herbivores (Carroll et al. 2006; Halitschke et al. 2008). Therefore, a better approach to enhancing resistance in plants would be to develop lines whose defenses could be stronger and more rapidly induced by herbivores (Degenhardt et al. 2003; Turlings and Ton 2006).

5.4 Conclusions and Perspectives

In this review, we summarize recent advances in the understanding of herbivore-induced plant defense response and their application in pest management. With the accumulation of knowledge about genomics, proteomics, and metabolomes, much progress has been made over the past 10 years in understanding the molecular basis of herbivore-induced defense responses in rice. Moreover, based on this knowledge, some methods for insect pest control, mainly including HIPV-based attractants for the natural enemies of herbivores, the application of chemical elicitors and the genetic manipulation of crop variety, are being exploited. These methods have been shown to increase not only the foraging efficiency of the natural enemies of herbivores but also the resistance in plants to herbivores, and their use often decreases the population densities of and the damage by herbivores; in the end, fewer pesticides are applied. More importantly, in crops, especially in annual cropping systems, natural enemies are always one step behind the pest, which generally reduces the foraging efficiency of the natural enemies. Using methods such as HIPV-based attractants or elicitors, natural enemies may be attracted to crops earlier. In rice, such methods also show great potential, especially in the management of planthoppers (Lou et al. 2005a, b, 2006; Xiao et al. 2012; Xin et al. 2012; Wang and Lou 2013). Because these methods are environmentally friendly and can redistribute herbivores and their natural enemies in space and time, they are promising for pest management.

Like all measures for pest management, such as pesticides, however, the herbivore-induced plant defense-based methods also have weaknesses. First, HIPVs have been proven to mediate multiple functions in ecosystems. In addition to repelling herbivores (De Moraes et al. 2001; Bruinsma et al. 2007; Szendrei and Rodriguez-Saona 2010) and attracting their natural enemies, HIPVs can also provide signals with which parasitic plants (Runyon et al. 2006) or herbivores (Bolter et al. 1997; Kalberer et al. 2001; Carroll et al. 2006; Halitschke et al. 2008) can locate their hosts. Therefore, the inappropriate application of synthetic HIPVs may enhance the probability of infestation by other herbivores. Second, some parasitoid species use HIPVs to locate their hosts, relying on associative learning (Meiners et al. 2003). The diffuse application of synthetic HIPVs might attract the natural enemies but no "rewards" (hosts or prey), which will thus decrease the foraging efficiency of the parasitoids (Turlings and Ton 2006; Khan et al. 2008). Third, a chemical that is an elicitor for some pests may become a suppressor for others. For example, treatment with 2,4-D induces resistance in rice to SSB but induces susceptibility to the brown planthopper, *Nilarpavata lugens* (Xin et al. 2012). The application of JA makes plants resistant to herbivores, but at the same time, the SA-mediated pathway might be inhibited and plants could become more susceptible to pathogens (Stout et al. 1998; Thaler et al. 1999). Moreover, some elicitors, especially those analogous to plant hormones, may influence the growth and reproduction of plants. In addition, plants that constitutively enhance levels of defense-related compounds may decrease the efficiency in controlling herbivores as stated above. Therefore, it is important to investigate the main species of herbivores and their natural enemies in different locations of each crop system, as well as the interactions mediated by the induced defenses in the context of agroecosystem. Moreover, appropriate defense-related compounds that repress herbivore populations directly or indirectly and adapt to specific herbivores and areas of each crop system, various elicitors that induce different resistance mechanisms of plants to herbivores and have no harmful effect on plants, and crop varieties in which defense responses could be rapidly and strongly elicited by herbivore infestation should be exploited. Based on these results, effective methods of herbivore management that adapt to various areas and crop systems may be developed. Furthermore, various elicitors that induce different resistance mechanisms in plants could be used in combination so that herbivores cannot adapt to resistance traits induced by elicitors.

These herbivore management methods could also be combined with other management strategies, such as push-pull (Cook et al. 2007) and an ecological engineering program (Gurr et al. 2011), which may greatly reduce the damage by herbivores. For example, if rice plants that produce (*E*)-β-caryophyllene but not *S*-linalool are sown at the edges of the field, both BPH and its natural enemies could be strongly attracted. If the rest of the plants are engineered to produce high amounts of *S*-linalool but not (*E*)-β-caryophyllene, they will likely remain pest free (Xiao et al. 2012). Combined with an ecological engineering program, such methods, for example, HIPV-based attractants for natural enemies and the application of chemical elicitors, will further enhance the effect of natural enemies by helping them to locate their hosts/prey, an effect that neither of the two measures can achieve alone (Gurr et al. 2011).

In rice, defense compounds, especially non-volatile defense compounds against insect herbivores, including rice planthoppers, are largely unknown. Thus, to effectively exploit herbivore-induced defense responses, we should first identify the main defense chemicals in rice. Once the genes that regulate these chemicals as molecular markers are found, appropriate chemical elicitors and rice varieties could be exploited. Recently, an ecological engineering program that focuses on vegetation diversity and aims to enhance the population density and efficiency of natural enemies of insect pests has been established, and the results have shown that this program can effectively augment the effect of natural enemies, decreasing the frequency of outbreaks of insect pests, including planthoppers, and the need for pesticides in rice (Gurr et al. 2011). Therefore, the use of management methods developed from herbivore-induced rice defense responses and an ecological engineering program will further enhance population densities and the effectiveness of employing the natural enemies of insect pests (Gurr et al. 2011). By decreasing the population levels of rice insect pests, we can reduce the amount of insecticides and environmental pollution.

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Chapter 6
Mechanisms of Rice Planthopper Resistance to Insecticides

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Abstract History of insecticidal control of rice planthoppers in Asia and associated resistance development is summarized. Rice planthoppers have developed resistance against all the insecticides that were commonly used. Experiences of past 30 years of chemical control of the rice planthoppers in many parts of Asia confirm that the use of any kind of insecticide for long time leads to the development of resistance. Overseas migration of rice planthoppers may markedly affect the status of insecticide resistance in populations over long distances, and the effects of migration can be maintained at least until the following year. It is possible that insecticide resistance may spread as a result of intercrossing between resistant immigrant and susceptible domestic populations. When insecticides are used against major pest, such planthoppers also produce selection pressure on the potential pests. It is believed that the resistance of small brown planthopper (SBPH) to insecticides is one of the important factors behind the recent outbreaks of smaller BPH in China. Pesticide-induced resurgence involves ecological and physiological factors. Many of the pesticides stimulate the reproduction of the brown planthopper (BPH), and sublethal dosages increase its reproduction. Decimation of natural enemy by pesticides is an important ecological factor for the induction of BPH resurgence, but stimulation of reproduction by pesticides is more responsible for the occurrence of resurgence. Insecticide resistance and pest resurgence caused by insecticides and their outcome result in occurrence of outbreak or resurgence of pests. Pesticides also affect physiology and biochemistry of rice plant in different ways. Insecticide resistance and insecticide-induced resurgence are closely related, and resultant outcome is pest outbreak or resurgence.

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6.1 Introduction

Chemical control was the most popular ways for rice planthoppers control and will likely to continue to remain as the important strategy in near future (Lima et al. 2012). Almost all kinds of insecticides such as organochlorine (Nagata et al. 2002; Davies et al. 2007), organophosphate (Kimura 1965; Zibaee et al. 2009), carbamate (Nagata et al. 2002), pyrethroid (Sun and Dai 1984), buprofezin (Su et al. 2013), neonicotinoid (Gorman et al. 2008), fipronil (Zhao et al. 2011), and pymetrozine (Gorman et al. 2010) were used to control rice planthoppers in Asia. With the use of these insecticides, insecticide resistance appeared as a major problem in planthoppers management. The traditional definition of insecticide resistance proposed by the Insecticide Resistance Action Committee (IRAC) is "the selection of a heritable characteristic in an insect population that results in the repeated failure of an insecticide product to provide the intended level of control when used as recommended (Kasai et al. 2011)." This definition considers the interaction between insects and insecticides only. However, in reality, some other factors are also involved with the failure of an insecticide to control target pest. These factors include the plant host, the natural enemies, and other nontarget insect species present in the ecosystem. So, from the ecosystem-based control, perspective insecticide resistance should also consider the insecticide tolerance induced by insecticide applications, the reduced effects of natural enemies against target insects, the negative effects on host plant resistance against insect pests, and the effects on the biological diversity and ecosystem balance. In this chapter, we focus our discussions on the development of insecticidal resistance in rice planthoppers and associated other factors, i.e., the mechanisms of rice planthoppers resistance to insecticides.

6.2 Insecticide Resistance Development in Rice Planthoppers

6.2.1 History of Chemical Control of Rice Planthoppers

Insecticide resistance is a major worldwide problem for the effective control of insect pests (Georghiou 1983). Resistance has emerged in field populations of insect pests to all major insecticide classes such as organochlorines, organophosphates, carbamates, pyrethroids, buprofezin, neonicotinoids, fipronil, and pymetrozine (Nagata et al. 2002; Davies et al. 2007; Kimura 1965; Zibaee et al. 2009; Nagata et al. 2002; Sun and Dai 1984; Su et al. 2013; Gorman et al. 2008; Zhao et al. 2011; Gorman et al. 2010).

The rice planthoppers are the most important insect pests of rice in Asia. Initially, control of rice planthoppers depended on the chemical method. Organochlorines were extensively used to control rice planthoppers in 1940s and 1950s (Nagata et al. 1979; Kilin et al. 1981), which were replaced by organophosphorus (OPs) and carbamate insecticides in 1960s. The application of these insecticides was relatively small at the beginning due to their higher price. However, OPs and carbamates became the main insecticides to control rice planthoppers and had been used extensively since 1960s (Kiritani 1979). Pyrethroids were toxic to fish and easily to lead to the resurgence, which were rarely used in controlling the brown planthoppers (BPH). However, some pyrethroids, such as permethrin and deltamethrin, were also used to control rice planthoppers in a few countries and areas (Ozaki and Kassai 1984). Since the 1980s, buprofezin and imidacloprid had been applied and became the most important insecticides to control BPH due to its excellent effects and low price. Fipronil, the first member of the phenylpyrazole insecticide, shows novel mode of action. It has high effects against many insect pests and is safe to nontarget organisms (Wang et al. 2008a, b, 2009a, b, c). Pymetrozine is the first and only substance from the group of azomethine pyridines, a novel class of insecticides (Ling et al. 2011). In 2005, when high resistance to neonicotinoid insecticide was observed, fipronil and pymetrozine were widely used to control brown planthoppers (BPH) in China.

6.2.2 *Insecticide Resistance Development*

6.2.2.1 Organochlorines Resistance

Organochlorines, such as BHC and DDT, were the first insecticide used to control the BPH. Organochlorine insecticides were began to apply in Japan against the BPH in 1949. After 5 years continuous use, low levels of resistance to BHC and lindane were reported (Nagata et al. 1979; Kilin et al. 1981). In China, field populations from Dongyang, Zhejiang Province, had developed a medium-level resistance (RR: 11.5-fold) to lindane. DDT was introduced against BPH in Japan in 1969. Due to a large number of organochlorine insecticides were restricted to use in 1970s, and the increased use of organophosphates and carbamates, sensitivity of BPH to organochlorines was restored (Wang et al. 1996).

6.2.2.2 Organophosphates and Carbamates Resistance

As a result of the widespread use of organophosphate and carbamate insecticides in rice, resistance development against these two groups of insecticides was relatively fast. The resistance levels were significantly different among insecticides, because of the differences of pharmacological and toxicological characters between varieties of these two types of insecticides.

In Philippines, carbamates resistance was reported firstly in 1977. After using carbofuran for 3 years, it failed to control BPH at IRRI fields in 1977. Studies indicated a sevenfold increase in topical LD_{50} value of carbofuran in BPH field populations compared to the greenhouse cultures. In Japan, insecticide susceptibility of the immigrant generation of BPH collected from the 6 prefectures of Kyushu was estimated in 1979 (Kilin et al. 1981). Comparison of the data with those obtained in 1967 revealed the obvious development of carbamate resistance with an increase of LD_{50} by approximately 10 times to MTMC (3-tolyl N-methyl carbamate), carbaryl and MIPC (2-isopropylphenyl N-methyl carbamate).

Higher levels of resistance with a 10–30 times increase of LD_{50} were observed for the OPs tested. During 8 years of monitoring, from 1980 to 1987, the insecticide susceptibility of the Ono population (Hyogo Prefecture, Japan) of the BPH to carbamates and OPs fluctuated greatly, suggesting the development of certain degree of resistance (Hirai 1993). Data of the other prefectures showed similar fluctuations. The BPH collected in 1984 and 1985 showed extremely high LD_{50} values to both carbamates and OPs. In the years 1984 and 1985, there was a remarkably high resistance of the BPH to carbamates and OPs in the whole country, and in 1986 and 1987, the susceptibility seemed to recover as the LD_{50} values fell to the 1980/1981 levels. Annual changes in insecticide susceptibility of white-backed planthopper (WBPH) were monitored from 1967 to 1983. The WBPH showed no obvious change until 1984 when marked increase in LD_{50}, especially for the organophosphates, was observed. These studies revealed that the resistance occurred and gradually increased. WBPH from Vietnam, Thailand, and Malaysia showed remarkable increase in LD_{50} during the last two decades (Nagata 2002).

In China, the resistance monitoring began in late 1970s. Initially, resistance to OPs and carbamates in BPH developed slowly and had been maintained at the low levels for sometime. OPs and carbamate insecticide resistance were not found in 1977 in Zhejiang Province (Tang et al. 1982). In 1985 and 1986, the BPH collected from Nanning (Guangxi Province) showed medium-level resistance to malathion (RR: 23.5-fold). The BPH collected from Yangzhou (Jiangsu Province) showed low- to medium-level resistance to methyl parathion, parathion, and carbaryl with resistance ratios of 12.7-, 11.1-, and 7.1-fold, respectively. In 1990, the susceptibility seemed to recover as the RR values fell to six-fold (Gao et al. 1987; Mao and Liang 1992). During 8-year resistance monitoring of 12 insecticides, from 1988 to 1995, the results also indicated the resistance in BPH collected from Anqing (Anhui Province) increased slowly or remained stable. In 1995, the resistances of methamidophos, isoprocarb, carbaryl, and xylyl-N-methyl-carbamates were at medium levels with RR of 13.1-, 14.5-, 18.3- and 12.8-fold, respectively (Wang et al. 1996). Differences of MTMC and MIPC susceptibility in BPH were also found by field survey in Taiwan (Lin et al. 1979). However, recent survey (2010) results showed that BPH populations in both Vietnam and China are moderately to highly resistant to isoprocarb (Ling et al. 2011).

6.2.2.3 Pyrethroids Resistance

Pyrethroids, such as permethrin and deltamethrin, were used to prevent BPH only in a few countries and areas, because they were toxic to fish and can easily lead to the resurgence. It was reported that some pyrethroids showed cross-resistance with organochlorines, OPs, and carbamates (Ozaki and Kassai 1984). As a result, the susceptibility of BPH decreased. BPH field populations with resistance to OPs and carbamate insecticides developed high resistances to non-α-cyano group pyrethroids. BPH showed 89-, 115-, and 377-fold resistance to permethrin, phenothrin, and fenpropathrin, but only 51-, 7- and 56-fold resistance to cypermethrin, deltamethrin, and fenvalerate (Dai and Sun 1984). The pyrethroid resistance in BPH was monitored since 1985 in China mainland. During 1987–1995, low-level resistance to deltamethrin was detected, and the resistance ratio reached 13.5-fold in 1998. The RR of fenvalerate maintained around ten-fold at the same period, except 25.3-fold in 1991 (Ling et al. 2011).

6.2.2.4 Buprofezin Resistance

Buprofezin is an insect growth regulator, which was commercialized in 1984 to control BPH. After 10 years of wide scale use, the sensitivity of BPH to buprofezin began to decline. The monitoring data from China showed that all the populations from 6 provinces of the Yangtze River Delta and the back-migration populations in Shaoguan and Shenzhen (Guangdong, China) showed low-level resistance to buprofezin (3.0- to 11.9-fold) during 2006–2008 (Liu et al. 2010b; Shao et al. 2011). The medium resistance was found in Huzhou of Zhejiang, China, in 2009 (Liu et al. 2010a). In 2010, BPH populations from China and Vietnam showed medium- to high-level resistances to buprofezin with RR of 6.20- to 66.71-fold (Ling et al. 2011).

6.2.2.5 Neonicotinoids Resistance

Imidacloprid is a nicotinic acetylcholine receptor (nAChR) agonist with potent insecticidal activity. It was the first member of the neonicotinoid insecticides to be commercialized (in 1991) and used extensively for both crop and animal health protection. Although the resistance to imidacloprid emerged slowly since its introduction, a number of important insect pests have become resistant recently. In 2003, the development of neonicotinoids resistance in the BPH was first observed in Thailand and has since been found in other Asian countries such as Vietnam, China, and Japan (Matsumura et al. 2008). Since 2005, outbreaks of BPH have occurred in East Asian countries such as Vietnam, China, and Japan, which were closely related to the development of insecticide resistance. The susceptibilities of BPH populations from Japan, China, Vietnam, and Philippines to four insecticides were evaluated in 2006. Topical LD_{50} values for imidacloprid in the BPH populations from East Asia (Japan and China) and Vietnam were significantly higher than those from the Philippines, suggesting that resistance to imidacloprid has developed in BPH in East Asia and Indochina, but not yet in the Philippines (Matsumura et al. 2008; Matsumura and Sanada-Morimura 2010).

All the 10 immigration populations collected during 2006–2008 from 6 provinces in the Yangtze River Delta and the back-migration populations in Shaoguan and Shenzhen of Guangdong, China, showed high or extremely high level of resistance to imidacloprid. Resistance levels of 13 populations from 8 provinces in 2008 were 210.1- to 381.7-fold, though the resistance level dropped slightly in the following 3 years compared with the extremely high level in 2005 (277- to 811-fold). Resistance ratios for other neonicotinoid insecticides such as thiamethoxam, nitenpyram, and dinotefuran were in the range of 2.0- to 15.8-fold, 0.7- to 4.8-fold, and 0.6- to 2.8-fold, respectively (Liu et al. 2010b; Shao et al. 2011).

In recent years, field populations of BPH in China had developed variable levels of resistance to neonicotinoids, with a high resistance level to imidacloprid (RR: 135.3- to 301.3-fold), a medium resistance level to imidaclothiz (RR: 35- to 41.2-fold), a low resistance level to thiamethoxam (up to 9.9-fold), and no resistance to dinotefuran, nitenpyram, and thiacloprid (RR < 3-fold). BPH populations in Huzhou of Zhejiang, China, had strong resistance to imidacloprid (RR: 422.2-fold) and were still susceptible to nitenpyram and chlorpyrifos (RR < 3-fold) in 2009 (Liu et al. 2010a). Different BPH populations from China and Vietnam showed high to extremely high resistance to imidacloprid (RR: 105.87–518.87) in 2010 (Ling et al. 2011).

6.2.2.6 Fipronil Resistance

Since 2005, when high resistance to neonicotinoid (imidacloprid) was found generally in China, fipronil was widely used to control BPH, and soon medium-level resistance has been detected in field populations (Wang et al. 2008a, b, 2009a, b, c). The resistances to fipronil in BPH monitored during 2006 to 2008 showed that BPH rapidly developed resistance to fipronil following its immigration route. The levels of fipronil resistance in 10 immigration populations from 6 provinces in the Yangtze River Delta and the back-migration populations in Shaoguan and Shenzhen of Guangdong, China, were moderate (resistance ratio 15.0- to 32.5-fold) and high (66.9- to 73.7-fold), respectively, higher than those of all 6 field populations from 5 provinces in 2006 (2.6- to 5.8-fold) and 11 populations from 9 provinces in 2007 (3.2- to 8.4-fold). The above results suggested that by 2009–2010, BPH has developed a high level of resistance to fipronil in most rice-growing areas in China (Liu et al. 2010b; Shao et al. 2011). However, BPH populations in Huzhou showed low resistance to butylene-fipronil (3.7-fold) in 2009 (Liu et al. 2010a). But in 2010, LC_{50} values of fipronil of BPH populations from China and Vietnam were 0.7–8.4 mg/L, and the resistance ratios were 25.17–215.60, 0.17–6.56, and 3.63–48.24 (Ling et al. 2011).

Cross-resistances to two fipronil analogs, butene-fipronil and ethiprole, were detected in fipronil-resistant field populations of BPH, although the two analogs have not been used widely in rice in China. The results showed that 6 field populations with 23.8- to 43.3-fold resistance to fipronil also had the high level of cross-resistance to ethiprole (RR: 47.1- to 100.9-fold) and had the low level of cross-resistance (RR: 3.4- to 8.1-fold) to butene-fipronil (Zhao et al. 2011).

WBPH populations collected from Japan, China, Vietnam, and Philippines in 2006 had extremely large LD_{50} values for fipronil, suggesting that resistance to this insecticide is widespread in WBPH populations throughout East and Southeast Asia (Matsumura et al. 2008; Matsumura and Sanada-Morimura 2010). In China, a field population of WBPH was collected with 50.5-fold resistance to fipronil, which increased to 137.5-fold after continuous selection for 11 generations (Tang et al. 2010).

6.2.2.7 Pymetrozine Resistance

Pymetrozine is the first and only substance from the group of azomethine pyridines, a novel class of insecticides. It's spectrum of activity covers sucking pests such as aphids, whiteflies, and planthoppers. Recently, pymetrozine has been widely used in rice fields in China because of the prohibition of highly toxic organophosphate insecticides and its high efficacy on BPH). BPH populations from China and Vietnam were sensitive or slightly resistant to pymetrozine (RR: 0.17–6.56) in 2010 (Ling et al. 2011).

Looking over the past 30 years of chemical control of the rice planthopper in many parts of Asia confirms that the use of any kind of insecticides for long time leads to the development of resistance and can also develop cross-resistance to other insecticides.

6.3 Indirect Selection of Insecticide Resistance

6.3.1 Indirect Selection from Insecticides Used Against Rice Planthoppers

During the recent years, both imidacloprid and fipronil are commonly used to control rice planthoppers in rice fields in the western Japan. On the other hand, imidacloprid but not fipronil has been used more widely for controlling outbreaks of the small brown planthopper (SBPH), *Laodelphax striatellus,* and rice stripe virus in China because of its lower price (Sogawa 2005).

The long-distance migrating rice planthoppers believed to migrate to Japan from southern China or northern Vietnam (Sogawa 1992) for which exchange of the populations between tropical and temperate Asia is highly plausible. In June 2008, a large migration of SBPH from overseas was reported in western Japan. By backward trajectory analysis, the source population was estimated to be Jiangsu Province in China. Large differences in LD_{50} values of imidacloprid and fipronil were found between immigrant and domestic populations of SBPH in Japan. The LD_{50} values of imidacloprid against the immigrant populations were 5- to 88-fold larger than those of domestic populations. In contrast, LD_{50} values of domestic populations exposed to fipronil were 70- to 442-fold larger than those of immigrant populations (Otuka et al. 2010).

Immigration of SBPH affected only the western parts of Japan, but not the eastern or northern parts (Otuka et al. 2010). Insecticide resistances to imidacloprid, fipronil, and BPMC were compared among the local populations in these western regions after migration and also in other areas of northern and eastern parts of Japan, several sites in China, and the northern parts of Vietnam (Table 6.1) (Sanada et al. 2011). SBPH migrated from eastern China, where it was resistant to imidacloprid, to western Japan, where it was susceptible in early June 2008 (Otuka et al. 2010). Until this migration event, the LD_{50} values of imidacloprid have not increased for a long period in the western parts of Japan (Endo and Tsurumachi 2000; Sone et al. 1995); however, the LD_{50} values have increased after 2008. Study showed that the overwintering populations maintained the resistance traits present in the previous year in the western parts of Japan, which suggested that insecticide susceptibility had been strongly affected by immigrant populations (Tables 6.2 and 6.3). The populations in northern and eastern parts of Japan were resistance to fipronil, but the LD_{50} values were much lower for imidacloprid and BPMC than in western parts of Japan and were the same as the baseline data (Table 6.4).

High LD_{50} values for BPMC but low values for imidacloprid and fipronil were found at all sites in Taiwan, China, in 2006 and 2007; however, between 2006 and 2009, the LD_{50} values increased slightly for imidacloprid and fipronil at two sites in the eastern parts of Taiwan. Unlike in Japan, farmers in China do not use nursery box insecticidal treatment to protect and control insect pests in the early season. SBPH is not currently a serious pest in Taiwan, China. However, it might be affected by the sprays of insecticides against *N. lugens* and the rice leaffolder (*Cnaphalocrocis medinalis* Guene´e) (Table 6.5). In the early 1990s, the LD_{50} values for imidacloprid and BPMC were very low in northern Vietnam (Endo et al. 2002) and were the same as the baseline data. However, insecticide susceptibility to these compounds has decreased greatly in northern Vietnam. Furthermore, susceptibility to fipronil decreased gradually from 2007 to 2009 (Table 6.5).

Before the migration of SBPH from overseas to western Japan, the LD_{50} value for fipronil was high, but not that of imidacloprid. Susceptibility of source area (Jiangsu, China) populations to imidacloprid but not fipronil was low (Otuka et al. 2010). This pattern of resistance of SBPH is clearly different from BPH and WBPH, which developed species-specific insecticide resistance to imidacloprid and fipronil in East and Southeast Asia (Matsumura et al. 2008). Overseas migration of SBPH, however, can occur when a large outbreak of insects coincides with the timing of the harvest and strong monsoon winds. Such a combination of events occurred on June 5, 2008 (Otuka et al. 2010). Overseas migration might markedly affect the status of insecticide resistance in populations over long distances, and the effects of migration can be maintained at least until the following year. It

Table 6.1 Location and collection date of tested populations of *L. striatellus* (Sanada et al. 2011)

No.	Population	Location	Lat/Long	Collection date			
				2006	2007	2008	2009
1	Japan-YM	Aburatani, Nagato, Yamaguchi, Japan	N 34.43, E 130.98			Aug-20	
2	Japan-NGN	Teguma, Nagasaki, Nagasaki, Japan	N 32.78, E 129.80			Aug-29	Mar-12
3	Japan-NGS	Hario, Sasebo, Nagasaki, Japan	N 33.12, E 129.76			Aug-29	Mar-12
4	Japan-FKJ	Joyo, Yame, Fukuoka, Japan	N 33.24, E 130.67			Jun-17	Apr-02
5	Japan-FKY	Yukuhashi, Fukuoka, Japan	N 33.71, E 130.95				Apr-02
6	Japan-FKO	Ochiai, Soeda, Fukuoka, Japan	N 33.49, E 130.87				Apr-02
7	Japan-SGK	Kawazoe, Saga, Japan	N 33.23, E 130.31				Jun-05
8	Japan-KMK	Aioi, Koshi, Kumamoto, Japan	N 32.92, E 130.75				May-21
9	Japan-KMO	Shitamachi, Ozu, Kumamoto, Japan	N 32.86, E 130.86			Sep-05	May-21
10	Japan-KME	Ezu, Kumamoto, Kumamoto, Japan	N 32.76, E 130.74			Sep-05	May-23
11	Japan-KMT	Tomiai, Kumamoto, Kumamoto, Japan	N 32.70, E 130.69			Sep-05	May-23
12	Japan-HKS	Hitsujigaoka, Sapporo, Hokkaido, Japan	N 43.01, E 141.41				Sep-01
13	Japan-HKI	Iwamizawa, Hokkaido, Japan	N 43.24, E 141.72				Sep-02
14	Japan-HKN	Naganuma, Hokkaido, Japan	N 43.05, E 141.76				Sep-02
15	Japan-TGOT	Tonouchi, Ohtawara, Tochigi, Japan	N 36.89, E 140.03				Sep-24
16	Japan-YGOY	Matsunuma, Oyama, Tochigi, Japan	N 36.35, E 139.78				Sep-28
17	China-YLT	Shiluo, Yunlin, Taiwan, China	N 23.86, E 120.48	May-30			

(continued)

Table 6.1 (continued)

No.	Population	Location	Lat/Long	Collection date			
				2006	2007	2008	2009
18	China-HLTA	Fuli, Hualien, Taiwan, China	N 23.19, E 121.28	Oct-18	May-31		
19	China-HLTB	Fuli, Hualien, Taiwan, China	N 23.25, E 121.29				Oct-14
20	China-TTTG	Guanshan, Taitung, Taiwan, China	N 23.02, E 121.18	Oct-18	May-30		Oct-14
21	China-TTTL	Luye, Taitung, Taiwan, China	N 22.95, E 121.16				Oct-14
22	Vietnam-HP	An Lao, Hai Phong, Vietnam	N 20.77, E 106.60		May-04		
23	Vietnam-HD	ThaiDuong, BinhGiang, HaiDuong, Vietnam	N 20.14, E 106.12				Sep-10
24	Vietnam-BN	Tam Son, Tu Son, Bac Ninh, Vietnam	N 21.15, E 105.98				Sep-11

Table 6.2 LD_{50} values (µg/g) of *L. striatellus* populations collected in 2008 in the western part of Japan (Otuka et al. 2010; Endo and Tsurumachi 2000; Sone et al. 1995)

Population	Imidacloprid	Fipronil		BPMC
	LD_{50}	24 h	48 h	LD_{50}
		LD_{50}	LD_{50}	
Japan-YM	7.1 (1.6–15.3)	0.17 (0.15–0.20)	0.08 (0.06–0.10)	169.4 (133–223)
Japan-NGN	23.3 (16.6–33.3)	0.44 (0.34–0.61)	0.42 (0.30–0.76)	321.1 (277–377)
Japan-NGS	6.3 (4.3–9.1)	0.35 (0.27–0.49)	0.19 (0.12–0.30)	180.0 (151–216)
Japan-FKJ	15.8 (10.9–22.6)	81.9 (23.7–2,254)	0.11 (0.08–0.15)	177.9 (151–212)
Japan-KMK	2.1 (1.3–4.6)	39.8 (15.0–184)	2.7 (1.1–5.5)	114.5 (91.3–142)
Japan-KMO	4.0 (2.7–5.7)	193.8 (81.4–802)	8.4 (4.1–15.9)	457.9 (404–522)
Japan-KME	28.3 (20.4–41.0)	187.9 (88.5–589)	0.59 (0.33–0.99)	474.0 (415–547)
Japan-KMT	8.7 (5.3–13.6)	0.31 (0.07–0.76)	8.9 (4.5–16.6)	311.3 (265–375)

LD_{50} value and its 95 % confidence interval in parentheses are shown in µg/g

is possible that insecticide resistance to imidacloprid or fipronil may spread as a result of intercrossing between immigrant and domestic populations in these areas; such intercrossing is common in the laboratory (Sanada-Morimura et al. unpublished data). However, the genetic basis of resistance in SBPH to the insecticides used here is unknown, although some genes that confer resistance to imidacloprid

Table 6.3 LD$_{50}$ values (μg/g) of *L. striatellus* populations collected in 2009 in the western part of Japan (Otuka et al. 2010; Endo and Tsurumachi 2000; Sone et al. 1995)

Population	Imidacloprid	Fipronil	
	LD$_{50}$	24 h	48 h
		LD$_{50}$	LD$_{50}$
Japan-NGN	16.4 (11.4–25.1)	0.46 (0.34–0.70)	0.32 (0.24–0.46)
Japan-NGS	13.9 (10.4–18.4)	0.22 (0.18–0.27)	0.11 (0.09–0.14)
Japan-FKJ	13.6 (9.9–19.1)	282.6 (89.2–4,418)	2.1 (0.93–3.9)
Japan-FKY	6.2 (3.9–10.1)	24.8 (14.1–56.8)	10.4 (5.7–23.2)
Japan-FKO	1.9 (1.2–2.8)	–^{c}	–^{c}
Japan-SGK	4.1 (2.7–7.8)	7.5 (3.0–14.3)	0.3 (0.07–0.8)
Japan-KMK	4.0 (2.4–7.3)	12.4 (7.3–22.9)	3.4 (2.2–5.0)
Japan-KMO	3.9 (1.8–7.6)	956.3 (121–)	16.2 (7.7–37.5)
Japan-KME	9.2 (6.3–17.8)	18.3 (10.2–40.6)	2.7 (1.8–4.1)
Japan-KMT	6.5 (4.6–9.1)	14.1 (7.3–32.3)	3.2 (1.4–6.1)

$^{LD}{}_{50}$ value and its 95 % confidence interval in parentheses are shown in μg/g

^{c} Not observed

Table 6.4 LD$_{50}$ values (μg/g) of *L. striatellus* populations collected in 2009 in the eastern and northern parts of Japan (Otuka et al. 2010; Endo and Tsurumachi 2000; Sone et al. 1995)

Population	Imidacloprid	Fipronil		BPMC
	LD$_{50}$	24 h	48 h	LD$_{50}$
		LD$_{50}$	LD$_{50}$	
Japan-HKS	0.18 (0.16–0.22)	0.05 (0.04–0.06)	–^{b}	24.9 (18.8–33.7)
Japan-HKI	0.29 (0.2–0.3)	0.06 (0.05–0.07)	–^{b}	13.7 (9.7–17.8)
Japan-HKN	0.21 (0.2–0.3)	0.05 (0.04–0.06)	–^{b}	26.6 (21.3–33.0)
Japan-TGOT	0.27 (0.21–0.35)	49.3 (33.5–72.5)	5.4 (1.9–9.0)	20.1 (17.5–25.9)
Japan-TGOY	0.57 (0.46–0.71)	493.8 (196–2,265)	1.1 (0.2–3.2)	29.9 (24.7–36.9)

$^{LD}{}_{50}$ value and its 95 % confidence interval in parentheses are shown in μg/g

^{b} Not observed

have been reported in BPH (Liu et al. 2005; Liu and Han 2006; Wang et al. 2009a, b, c). It will be necessary to investigate the genetic systems of insecticide resistance to imidacloprid and fipronil and to determine their exact status to aid the control of SBPH in East and Southeast Asia. The long-distance migrating rice planthoppers migrate to China from northern Vietnam, and the extensive use of imidacloprid in China and Vietnam may result in high resistance in the rice planthoppers in China.

Table 6.5 LD$_{50}$ values (μg/g) of *L. striatellus* populations collected in 2006–2009 in Asia (Endo et al. 2002)

Population	Collection Year	Imidacloprid	Fipronil		BPMC
		LD$_{50}$	24 h	48 h	LD$_{50}$
			LD$_{50}$	LD$_{50}$	
China-YLT	2006	0.40 (0.05–0.87)	<0.28^{b}	_^{c}	176.6 (85.3–442)
China-HLTa	2006	1.4 (1.08–1.95)	0.06 (0.04–0.09)	_^{c}	227.9 (186–288)
China-HLTa	2007	0.40 (0.31–0.52)	0.24 (0.18–0.31)	_^{c}	128.9 (101–159)
China-HLTb	2009	10.9 (6.8–18.6)	4.7 (2.8–9.1)	1.7 (1.0–2.8)	507.6 (428–603)
China-TTTg	2006	1.9 (1.41–2.75)	0.11 (0.04–0.23)	_^{c}	441.7 (323–563)
China-TTTg	2007	2.2 (1.85–2.73)	0.32 (0.22–0.46)	_^{c}	307.1 (173–777)
China-TTTg	2009	4.8 (3.0–705)	3.2 (2.1–5.8)	7.6 (1.1–)	305.6 (247–377)
China-TTTl	2009	8.2 (5.3–13.2)	1.1 (0.8–1.7)	0.5 (0.3–4.8)	293.7 (247–349)
Vietnam-HP	2007	3.0 (1.94–4.44)	0.11 (0.09–0.12)	_^{c}	128.7 (102–163)
Vietnam-HD	2009	10.2 (7.5–13.5)	98.3 (48.5–314)	2.2 (0.97–3.9)	262.2 (218–319)
Vietnam-BN	2009	2.2 (1.4–6.0)	171.2 (75.7–192)	2.6 (0.71–5.5)	163.5 (136–192)

$^{LD}{}_{50}$ value and its 95 % confidence interval in parentheses are shown with μg/g

[c] Not observed

6.3.2 *Indirect Selection Pressure of Insecticides*

When insecticides were applied against a target pest, several other insect pests are also present in the field. Thus, the use of insecticides may bring another problem, i.e., fight against major pests may also produce selection pressure to potential pests. In this situation, the potential pests may become the major pests. For example, WBPH and BPH often occur together in the rice field, so insecticides resistance also selected in WBPH when insecticides were applied to control BPH. Brown planthopper in the tropics (Vietnam, Thailand, and Malaysia) shows apparent insecticide resistance with remarkable increase in LD$_{50}$ as compared to the late 1970s. WBPH from those tropical zones also showed remarkable increase in LD$_{50}$ during the last two decades (Nagata et al. 2002). Fipronil was widely used to control BPH since 2005. Although only medium level of resistance was detected in BPH field populations, almost all the WBPH populations from Japan, China, Vietnam, and the Philippines also showed large LD$_{50}$ values (19.7–239 μg g^{-1} or more) for fipronil (Matsumura et al. 2008). In China, fipronil has been used commonly to control the rice leaffolder and the rice stem borers in the early growth stages of rice (Jiang et al. 2005). Application of fipronil early in the season may have more effect on WBPH than on BPH, because WBPH increases earlier than BPH in the rice-growing season. Thus, high fipronil resistance was found in WBPH (Tang et al. 2010).

The rice planthoppers that has caused significant yield loss are BPH and WBPH. Although SBPH exists in the field, but the population density is relatively low and stable (Cheng et al. 2008). Since SBPH was a secondary pest over a very long time, no special prevention or treatment was taken against it. The decrease of SBPH sensitivity to insecticide may be due to indirect selection in the process of controlling BPH and WBPH (Wang et al. 2008a, b).

Neonicotinoid insecticides, such as imidacloprid, have been used to control BPH widely. At the same time, the selection pressure also resulted in the development of resistance in SBPH. In the early 1990s, the efficiency of the control dosage 30 g/hm^2 is 96 % at 19 d after application of imidacloprid to SBPH (Fang et al. 1998), but after 10 year, the efficiency at the three times higher dosage (90 g/hm^2) was only 70 % (Wang et al. 2005). SBPH collected from Jiangsu, China, showed the highest resistance to imidacloprid among the field strains collected from 6 provinces of China with RR ranged from 66- to 108-fold (Gao et al. 2008). Wuxi and Huzhou populations also developed high level of resistance to imidacloprid (79.6- and 44.6-fold) (Ma et al. 2007).

Field populations of SBPH in 2007, which collected from Jurong, Tongzhou, Chuzhou, Dafeng, Nanjing and Suzhou of Jiangsu, China, and Lujiang of Anhui, China, showed very high resistance to buprofezin with the resistance ratio over 200-fold and medium or high resistance to alpha-cypermethrin with the resistance ratio of 7.8- to 108.8-fold (Wang et al. 2008a, b).

Susceptibility to fipronil in SBPH population from Wuxi of Jiangsu, China, was reduced with a rate of 2.0-fold, LC_{50} from 0.246 mg/L up to 0.514 mg/L, compared with those to the insecticide in 2007 (Peng et al. 2009). The efficiency of buprofezin to SBPH in Huai'an of Jiangsu, China, was reported to be very poor. The efficiency at the dosage of 50 g/hm^2 (25 % wettable powder) was only 16.15 % after 6 d application (Sun and Wang 2005).

In recent years, abundance of SBPH increased significantly, and there were even large outbreaks in many places in China in 2004 and 2007–2008 and were difficult to control (Sun et al. 2005; Zhang et al. 2005; Hang et al. 2008; Hui et al. 2008). It is believed that the resistance of SBPH to insecticides is one of the important factors behind this increase (Liu et al. 2006). There is a need to conduct research on the indirect selection of resistance.

6.4 Insecticide-induced Resurgence of Rice Planthoppers

Resurgence of pests is defined as an increase in target arthropod pest species abundance to a level that exceeds that of a control or untreated population after the application of an insecticide (acaricide) (Hardin et al. 1995). Pesticide-induced resurgence involves ecological and physiological factors. The former includes the collapse of natural enemy population and substitution of competitive species due to application of pesticides; the later includes pesticide-induced reproduction stimulation of pests. Some herbicides (butachlor and bentazone) and fungicide (jinggangmycin) stimulate reproduction of the BPH besides insecticides (Wu et al. 2001a, b; Jiang et al. 2012). Therefore, resurgence of pests can be defined as a significant increase of pest population that exceeds a control population due to application of pesticides. BPH is a classical, resurgent rice pest induced by pesticides (Chelliah and Heinrichs 1980; Ressig et al. 1982; Gao et al. 1988; Wang et al. 1994; Yin et al. 2008; Azzam et al. 2009; Ge et al. 2010a, b; Wang et al. 2010; Jiang et al. 2012). Variety of pesticide induces resurgence of BPH, which mainly includes organophosphates (diazinon, chlorazolphosphorus, methyl parathion, monocrotophos, pyridaphenthion, quinalphos, methamidophos), pyrethroids (fenvalerate and deltamethrin), and carbamates (isoprocarb, metolcarb, and trimethacarb) insecticides. Recent studies demonstrated that sublethal doses of imidacloprid and buprofezin also stimulate fecundity of BPH, but their high doses suppress fecundity (Azzam et al. 2009). Pesticides may also affect BPH indirectly, through altering rice plant nutrition or resistant substances (e.g., oxalic acid), and lead to resurgence (Wu et al. 2002, 2003, 2004).

6.4.1 *Effects of Sublethal Dose*

BPH is a classical resurgent pest, which induces by pesticides. Many of pesticides stimulate reproduction of BPH, of which organophosphates (triazophos) and pyrethroids (deltemethrin) are typically induced resurgent pesticides (Yin et al. 2008; Azzam et al. 2009; Ge et al. 2010a, b, 2011; Wang et al. 2010). However, triazophos and deltemethrin not only stimulate fecundity but also stimulate reproduction of adult males (Ge et al. 2010a, b; Wang et al. 2010; Yu et al. 2012). Mating pair of triazophos-treated male with untreated female significantly enhanced fecundity of female compared to the pair of untreated male with untreated female (Wang et al. 2010). Recent study has demonstrated that treated male transferred more accessory protein to adult female through mating, which stimulates fecundity of adult female (Wang et al. 2010; Yu et al. 2012) (Fig. 6.1). Other biological traits of treated female significantly influence, for example, preoviposition duration shorten, oviposition period and longevity, and hatchability of egg increase (Azzam et al. 2009). Fungicide jinggangmycin, an antibiotic compound developed in China, is a pesticide that is mainly used in controlling the rice sheath blight *Rhizoctonia solani* and stimulates fecundity of BPH (Wu et al. 2001a, b; Jiang et al. 2012). Studies indicated that the way of reproduction stimulation of the fungicide is mainly works through the alteration of nutriment in rice plant which is beneficial for feeding of BPH. Therefore, effect of foliar spray on reproduction stimulation is more obvious than topical application of the fungicide (Jiang et al. 2012).

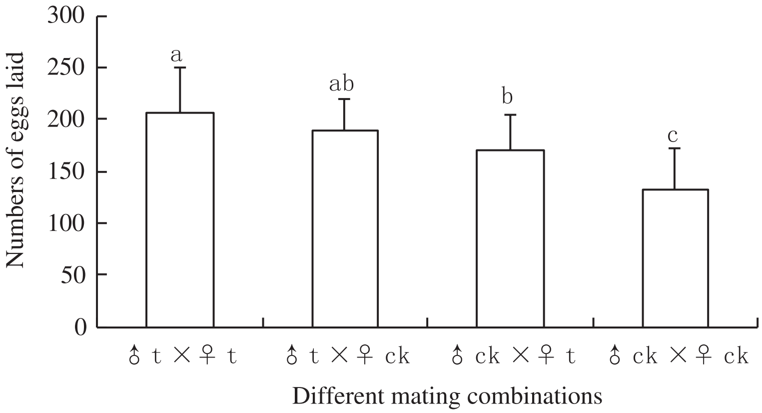

Fig. 6.1 Effect of different mating pairs of triazophos-treated males and/or females on the fecundity of the females (♂$_{t}$ × ♀$_{t,}$ ♂$_{t}$ × ♀$_{ck,}$ ♂$_{ck}$ × ♀$_{t,}$ and ♂$_{ck}$ × ♀$_{ck}$ are mating pairs of treated males with females, treated males with untreated females, untreated males with treated females and untreated males with females, respectively; bars with different letters indicate that means differ significantly at the $P < 0.05$ level (from Wang et al. 2010))

6.4.2 *Pesticide-induced Resurgence via Decimating of Natural Enemy*

Natural enemy community in rice ecosystem is a key ecological factor for suppression of BPH population growth. However, many pesticides of organophosphate, pyrethroid, and carbamate groups have a serious decimating effect to natural enemies; as a result cause BPH resurgence (Ressig et al. 1982; Gao et al. 1988; Wang et al. 1994). Some herbicides such as butachlor, bentazone, metalachlor, pretilachlor, oxyfluorfen, and oxadiazon also decimate natural enemies (Table 6.6) (Li et al. 2000).

Some insecticides such as bisultap paralyze spiders rather than decimating them; as a result, predation function is lost during paralysis. Wu et al. (1997) suggested estimation of function decrease rate of predators, total function decrease rate, and function decrease rate of natural enemy group as follows:

Function decrease rate

$$(\mathrm{FD}_t):\ \mathrm{FD}_t = (\mathrm{F_{ck}} - \mathrm{F}_R/\mathrm{F_{ck}}) \times 100$$

where $\mathrm{F_{ck}}$ is predation function of untreated natural enemy and F_R is predation function of treated natural enemy.

Total function decrease rate of a natural enemy species

$$(\mathrm{FD}) := (\Sigma(\mathrm{D}_t + \mathrm{S}_t \times \mathrm{FD}_t))/\mathrm{TR} \times 100$$

where S_t is survival rate of the natural enemy species at t time and TR is necessary time for recovery of predation function.

Table 6.6 Mortality of spiderlings of *Pirata subpiratiucus* Boes et Str following herbicide treatments (Li et al. 2000)

Herbicide	Concentration (mg/kg)	Days after treatment (DAT)	
		1	2
Oxyfluorfen	143	100	100
Oxadiazon	432	100	100
Metalachlor	216	20	100
Acetochlor	240	40	60
Bentazone	355.2	10	40
CK	0	0	0

Function decrease rate of natural enemy group

$$(\mathrm{FD}) = \Sigma \mathrm{a}_i \times \mathrm{FD}_t$$

where a_i is ratio of predation number for *i* species to total predation number of the group.

Wolf spiders (e.g., *P. subpiraticus*) are an important predator for planthoppers. Triazophos and pymetrozine have a serious negative effect to egg development of the *P. subpiraticus*. Yolk granules in eggs of the spider treated with triazophos and pymetrozine showed a loose arrangement, and some eggs remain empty (Fig. 6.2) (Xu et al. unpublished data).

Parasitoids in rice ecosystem are more sensitive to pesticides. Pesticides not only kill parasitoids but also decrease parasitism rate of survivors via behavior response (Liu et al. 2010c, 2012). For example, the sublethal concentrations (LC_{20} and LC_{10}) of triazophos and deltamethrin disrupted the ability of *Anagrus nilaparvatae* (Pang and Wang) to perceive host plant odor cues. After exposure to sublethal concentrations of triazophos and deltamethrin, some surviving parasitoids showed no response to volatiles from *N. lugens*-infested plants, and responsive

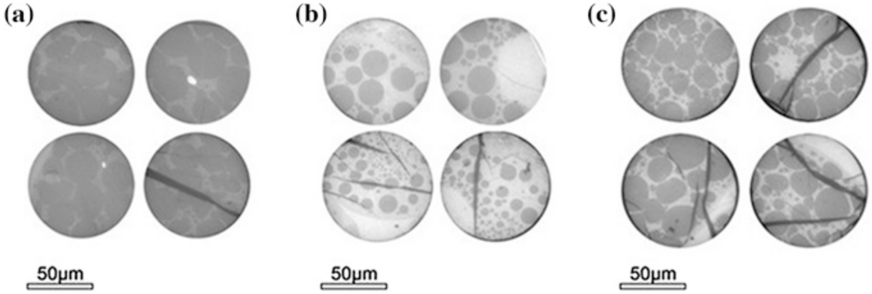

Fig. 6.2 Comparisons of arrangement of yolk granules of egg of *P. subpiraticus* treated with triazophos and pymetrozine. **a** is untreated control, **b** is pymetrozine, **c** is triazophos-treated eggs

Table 6.7 Behavioral responses of surviving *A. nilaparvatae* treated with sublethal concentrations of imidacloprid to volatiles from *N. lugens*-infested rice plants

Exposure route	Concentration of imidacloprid	No. of tested parasitoids	No. of no response parasitoids	No. of the parasitoid to the odor		χ^2 value
				Odor 1	Odor 2	
Contact	Control	32	0	25	7	9.03**
	LC_{10}	40	14	13	13	0.04
	LC_{20}	40	22	13	5	2.72
Oral ingestion	Control	40	0	31	9	11.03**
	LC_{10}	40	0	20	20	0.03
	LC_{20}	40	17	15	8	1.57

Note The degree of freedom for χ^2 test was uniformly equal to one
**indicated significant difference at $\alpha = 0.01$ level, df = 1, $\chi^2_{0.01} = 6.63$. Control means *A. nilaparvatae* exposed to 80 % (v/v) acetone only. LC_{10} and LC_{20} were 100 and 200 μg a.i./l in the contact toxicity and were 10 and 20 mg a.i./l in the oral toxicity, respectively. Odor 1 means rice plants infested by *N. lugens*, and Odor 2 means healthy rice plants

survivors were equally attracted to volatiles emitted from *N. lugens*-infested plants and those from healthy plants. However, sublethal concentrations (the recommended field rate and half the recommended field rate) of chlorantraniliprole and pymetrozine had little impact on the foraging ability of *A. nilaparvatae* (Liu et al. 2012). In addition, selective insecticides such as imidacloprid at sublethal concentrations (LC_{20} and LC_{10}) disrupted the foraging ability of *A. nilaparvatae.* Some survivors did not respond to volatiles from *N. lugens*-infested plants (Table 6.7) (Liu et al. 2010c). Parasitism of *N. lugens* eggs in high concentration of imidacloprid-treated rice plants by *A. nilaparvatae* decreased significantly (Fig. 6.3) (Liu et al. 2010c).

Decimating of natural enemy by pesticides is an important ecological factor for induction of BPH resurgence but not the only factor. Stimulation of reproduction by pesticides is more responsible for the occurrence of resurgence.

6.4.3 Alteration of Biochemical Substances of Rice Plant by Pesticides

Pesticides affect physiology and biochemistry of rice plant in different ways. Buprofezin, imidacloprid, and jinggangmycin reduce oxalic acid content in rice plants, increase amount of chlorophyll and photosynthetic rate in leaf, and reduce sugar content in rice leaf sheath (Wu et al. 2003). Isotope labeling experiments demonstrated that export rate of assimilate in rice leaf treated with triazophos,

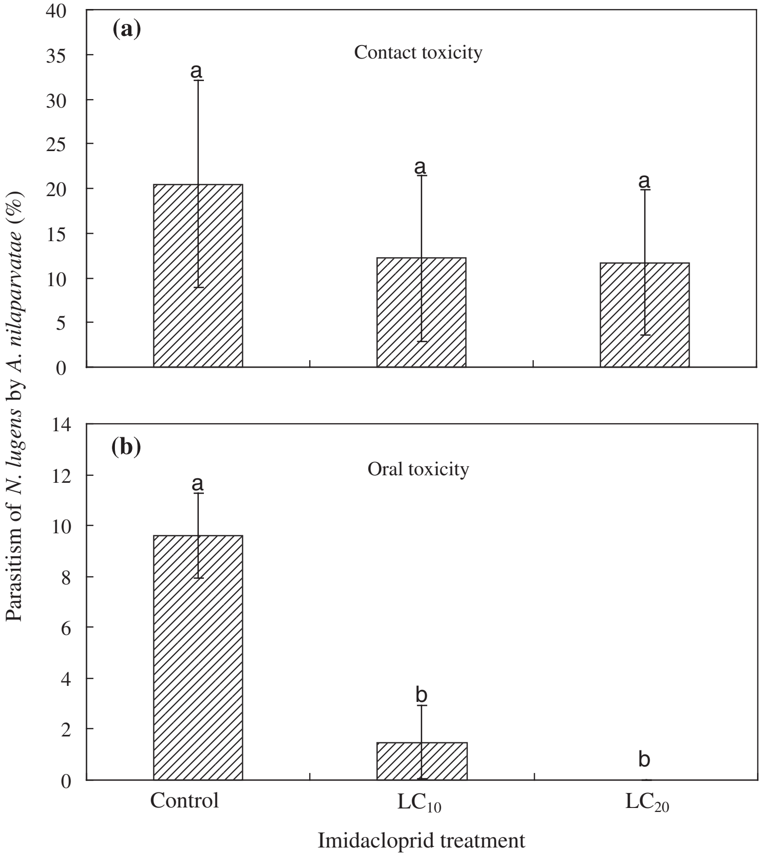

Fig. 6.3 Parasitism (mean ± SD) of *N. lugens* by surviving *A. nilaparvatae* treated with imidacloprid (Liu et al. 2010c) **a** Contact toxicity, **b** Oral toxicity

jinggangmycin, and bisultap is blocked (Luo et al. 2002). Imidacloprid and jinggangmycin reduce grain filling rate and grain weight, especially at high dose (Wu et al. 2004; Qiu et al. 2004a, b). In addition, pesticides influence level of plant hormones which play a vital regulation role in growth, development, physiology, and biochemistry of rice plant. For example, zeatin riboside content in rice leaves decreases significantly 3 days after foliar sprays with 150–300 ppm buprofezin, 30–60 ppm imidacloprid, 200 ppm jinggangmycin, and 480 ppm triazophos (Qiu et al. 2004a, b). Wu et al. (2001a, b) suggest a pioneer concept of pesticide-induced susceptibility (PIS) of rice to planthoppers. PIS is an important way of pesticide-induced resurgence of BPH. Effective duration of PIS of jinggangmycin and herbicide butachlor is 7–14 days, respectively (Wu et al. 2004). In effect, ecological and physiological mechanisms of resurgence induced by each pesticide may be different. For example, jinggangmycin or butachlor stimulates fecundity

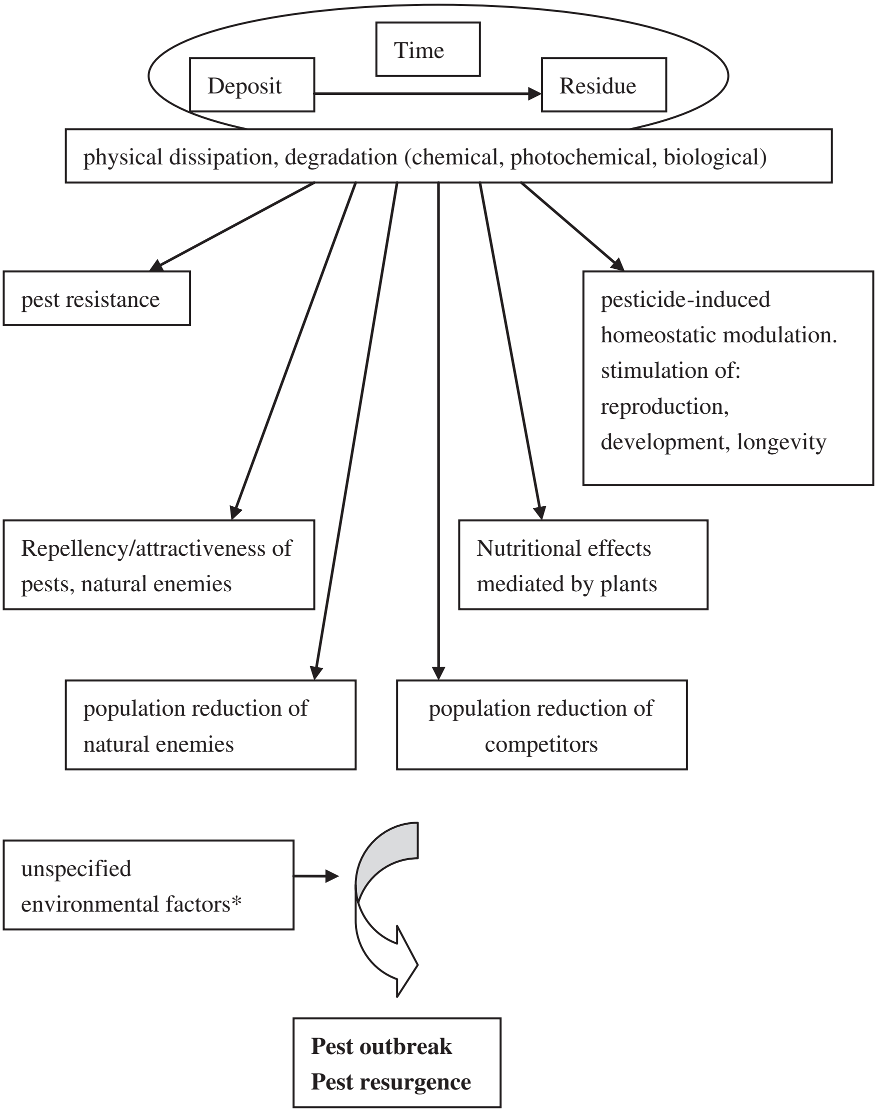

Fig. 6.4 Mechanisms for possible destabilization of pest populations as mediated by direct pesticide application or pesticide residues

via effect on physiology and biochemistry of rice plant rather than decimating effect on natural enemy; triazophos or other organophosphates induces resurgence of BPH via both stimulation effect of fecundity and decimating effect of natural enemy, while imidacloprid and buprofezin stimulate fecundity at low concentration and suppress fecundity at high concentration (Azzam et al. 2009).

6.4.4 Effects of Pesticides on the Ecosystem Balance

Insecticide resistance and pest resurgence are caused by insecticides. Their outcome results in occurrence of outbreak or resurgence of pests. Thus, resistance and resurgence are closely correlated, and there are some common biological characteristics such as population number increase. Insecticide resistance is one of causes of pesticide-induced resurgence of pests (Cohen 2006). Ecotoxicology process of pest resurgence or outbreak can be outlined as in Fig. 6.4. Increases in pest populations have frequently been attributed to mechanisms that act in tandem, in concert or even in synergy (Cohen 2006). Furthermore, there are two hypotheses for fitness of resistant population: reproductive disadvantage (fitness cost) and reproductive advantage. For BPH, fitness changes of imidacloprid resistant and susceptible populations treated with triazophos and deltamethrin show no significant fitness cost. In contrast, relative fitness of resistant population is significantly higher than that of susceptible population (Wang et al. 2009a, b, c), indicating that a specific insecticide resistant population has fitness advantage under other stressors, which may be an evolutional phenomenon. From this, we infer that fitness advantage of resistant population more easily results in occurrence of natural population resurgence. Therefore, insecticide resistance and insecticide-induced resurgence are closely related, and resultant outcome is pest outbreak or resurgence.

6.5 Conclusion

Planthoppers are most important insect pests of rice and cause big losses in each year. So far, insecticide applications have been the important means of control efforts farmers made. However, insecticide application causes some negative effects on planthopper populations and also on paddy field ecosystem, which decrease the control effects of insecticide and disrupte the natural balance. Based on the side effects, the insecticide resistance in rice planthoppers can come from the insecticide tolerance and from the disruption of ecological balance mechanisms. Insecticide application has dual characters, which provides quick control of rice planthoppers, but also causes some side effects, which fade such control effects. Application of non-chemical control measures is becoming more important and should be considered in the integrated pest management strategy.

Firstly, a balance should be established between the chemical controls and biological controls against rice planthoppers, because many insecticides showed high toxicities against natural enemies. Among insecticides in the control of rice planthoppers and leafhoppers, OPs, carbamate, and neonicotinoid insecticides showed low toxicities against natural spiders, but pyrethroid and phenylpyrazole insecticides were highly toxic to the spiders. Most chemical insecticides show high toxicities against the miribug, the most important natural enemy against rice planthoppers. So, when chemical insecticides are used, the safety to natural enemies should be always kept in mind to balance the two different control strategies.

More importantly, chemical controls could significantly increase vulnerability of rice ecosystems through stimulating fecundity of planthoppers and destroying arthropod community and natural regulation Natural regulation functions. Therefore, the short-term effects on pests resulted from chemical control might resulted in the long-term losses from pest frequent outbreaks in vulnerable rice ecosystems as we have seen the development of planthopper problems partially caused by unappropriate chemical control in the past half century. The ecological mechanism of planthopper resurgence caused by pesticides provides us typical examples for developing new approaches to reform the chemical control.

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Chapter 7

The Big Picture: Prospects for Ecological Engineering to Guide the Delivery of Ecosystem Services in Global Agriculture

Geoff M. Gurr, Zeng-Rong Zhu and Minsheng You

Abstract Feeding an estimated nine billion people by the year 2050 will be challenging. Though controversy surrounds the extent to which food production needs to increase, versus a focus on distributional issues and reduced waste, there is a need to reduce the environmental impacts of current farming practices and to avoid further depletion of biodiversity. Over the last century, biodiversity loss has accompanied agricultural intensification so a business-as-usual scenario gives little cause for optimism. In the last decade, studies in many countries have demonstrated the benefits of "alternative" agricultural systems that can be as productive as conventional agriculture on a per-hectare basis, despite requiring fewer pesticides and fertilizers. These systems employ ecological intensification whereby ecosystem services such as nutrient provisioning, natural pest control, and enhanced pollination replace anthropogenic inputs. Enhancement of biodiversity in these systems is not confined to planned diversity such as multiple crops but includes many other taxa to the extent that farmlands can be important complements to nature reserves and other protected areas. Ecological engineering is one approach that can guide the diversification of farmlands to deliver multiple ecosystem services agricultural intensification based on an ecological evidence base offers significant scope for a win–win scenario whereby future food production needs are more strongly supported by ecosystem services whilst simultaneously motivating farmers to accommodate biodiversity.

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7.1 Introduction

Despite the United Nations Millennium Development Goal (MDG) addressing extreme poverty and hunger, it is estimated that between 0.75 and 1 billion of the current population of 7 billion humans currently have insufficient access to food (Godfray et al. 2010a). Grim as this situation is, our population continues to grow and is likely to reach nine or even 10 billion by the middle of the century. The United Nations considers that even if the MDG is achieved in 2015, 600 million people will remain undernourished. Much remains to be done to improve food distribution equity across geographical areas and social groupings and make better use of available resources including reducing food wastage (estimated to be 30–40 %) (Stuart 2009). Progress in each of these areas could bring rapid improvement to the way in which current global crop resources are used to meet human needs including addressing high rates of obesity in developed countries. Notwithstanding the importance of these distributional issues, there is also a need to increase agricultural production. The need for more food to be produced is compounded by rising living standards increasing the desired level of diet variability. Indeed, there are tight correlations between per capita income and both calorific intake and protein demand (Stuart 2009). This is significant because livestock for meat and dairy products is often fed plant products that might otherwise be consumed by humans. A detailed analysis of the magnitude of increase in global crop production required by 2050 put the figure at 100–110 % of current levels (Tilman et al. 2011). Somehow, this goal needs to be met despite the fact that the area of land available for agricultural production can be increased only at the expense of other uses such as biodiversity protection. Further, current agricultural lands are shrinking qualitatively and quantitatively as a result of urbanization, industrialization, desertification, soil erosion, and salinization. In significant parts of the world, it is likely that the impacts of climate change will exacerbate such phenomena over coming decades and add issues such as sea level rises inundating low-lying farmland and reduced rainfall reliability. There are also supply-side stressors relating to the inputs upon which conventional agriculture heavily depends on. Most importantly, water and energy are certain to rise in cost. The fact that current energy sources are largely from non-renewable resources has spurred interest in biofuels. These have the advantage of being renewable but require land for their production and, when crops such as maize are used, compete directly with human dietary needs. Although only 1 % of agricultural land is used in the production of biofuels (Gregory and George 2011), this figure is likely to increase.

At the same time, the planet is facing high levels of biodiversity loss, estimated to be between several hundred and 10,000 times the natural, background rate (Chappell and LaValle 2011). Much of the environmental impact, for example,

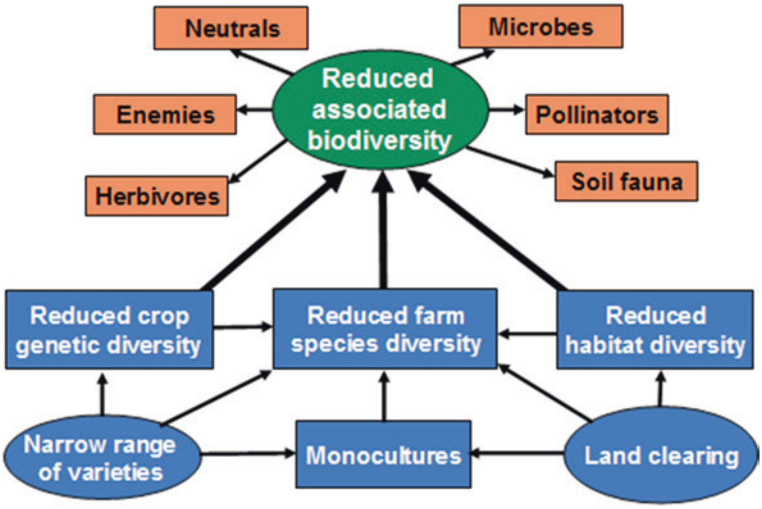

Fig. 7.1 Conventional agriculture erodes biodiversity at the genetic, species, and habitat levels of ecological organization. Expansion of crop monocultures at the expense of natural vegetation has adverse effects on various guilds of associated biodiversity

“dead zones” of eutrophication from fertilizer run-off (Diaz and Rosenberg 2008), off-target impacts of pesticides (Ehrlich and Pringle 2008), forest clearing (Rands et al. 2010), and greenhouse gas emissions (Tilman et al. 2011) are linked to agriculture. Biodiversity is also reduced by agriculture at the genetic, species, and habitat levels via land clearing and the use of monocultures of few crop species and limited numbers of cultivars of each crop (Fig. 7.1). This leads to adverse effects for the biodiversity associated with agriculture (Vandermeer et al. 2002). Reflecting the current severity of this overall situation, another MDG is aimed at sustainable development to reduce the rate of loss of biodiversity (Food and Agriculture Organization of the United Nations (FAO) 2012). But given that agricultural intensification (increased inputs to provide increased output per unit area) and land clearing have been major causes of biodiversity loss and environmental impact (Tilman et al. 2011), how can the goals of achieving food security and protecting biodiversity be reconciled?

7.2 Options to Double Crop Production

Since the “world food crisis” of 2006–2009 in which food price volatility contributed to an 8 % increase in numbers of malnourished Africans between 2007 and 2008, (Food and Agriculture Organization of the United Nations (FAO) 2012) there has been much attention focused on food security. Despite the importance of social and economic factors, the contribution of biologists is to increase agricultural production. In the past, this has mostly been done by expanding agriculture into new areas but significant intensification has also occurred, especially in developed countries. For example, in the last 50 years, grain production has more than doubled although the area of arable land increased by just 9 % (Pretty 2008). Such intensification will be important because the possibility of expanding agriculture is constrained bio-climatically, since large areas are mountainous or desert unsuitable for agriculture. In fact, only 3 billion ha of the world's 13.4 billion ha of land area is considered suitable for agriculture and around half of that is already cultivated (Gregory and George 2011). About double this area is used for grazing so that agriculture overall accounts for about 26 % of the planet's ice-free land area (Foley et al. 2011). Other major uses include human habitation and natural and semi-natural ecosystems although only ~12 % of land has any level of legislative protection for conservation purposes and only half of this is within IUCN categories I–IV (Brooks et al. 2004). Whilst current agricultural land area is being eroded by urbanization and industrialization, it is continuing to extend into formerly uncleared areas. This phenomenon is most marked in the tropics (Foley et al. 2011) because of now widespread recognition in developed countries of the practical and aesthetic value of biodiversity. Reflecting this, Godfray et al. (2010b) warned against further depleting biodiversity by clearing land for agriculture. Amongst the important ecosystem services (ES) provided by non-agricultural biodiversity is sequestering atmospheric carbon whilst clearing for agriculture is a major cause of greenhouse gas emissions (Tilman et al. 2011). But if food production is to be doubled without substantial clearing, yield from existing farmlands must be dramatically increased (Fig. 7.2). Much of the academic discussion about the feasibility and merits of these opposing strategies have been framed as land sparing and land sharing.

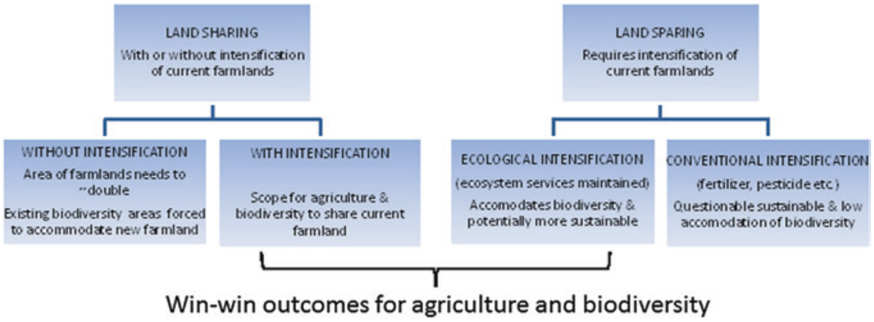

Fig. 7.2 Possible scenarios for doubling food production. The outermost branches have negative outcomes for biodiversity (*left*) or agricultural sustainability (*right*) whilst the *centre* most branches offer biodiversity and agricultural benefits if the ecosystem services provided to agriculture by biodiversity can be adequately harnessed

7.3 Land Sparing and Land Sharing: Between a Rock and a Hard Place

Land sharing is the notion that biodiversity should be conserved on farm lands whilst land sparing is essentially partitioning land uses such that non-agricultural land should be spared from clearing and cultivation; this made possible by intensifying production on the area that is farmed so that this is able to meet human needs. Such a simple dichotomy is, however, too simplistic. Land sharing has been said to constitute a scenario characterized by less intense cultivation and "sacrificing" crop yields; (Godfray 2011) that being the price to pay for conservation of biodiversity on the same land. But given the need to double crop production by 2050, the area of land cultivated would need to at least double under this scenario (Fig. 7.2, left branch). Thus, the benefit of conserving biodiversity by land sharing comes at the cost of massive land clearing which would have catastrophic impacts for biodiversity, especially for mobile species that could not survive in shared landscapes, for ES and greenhouse gas emissions. The opposite strategy (Fig. 7.2, right branch) is not without hazards. Doubling food production on existing farmlands in order to spare land from clearing will require high levels of intensification. Achieving this using the technologies that characterize conventional, industrialized agriculture come with elevated levels of pollution from fossil fuel, fertilizer, and pesticide use as well as increased energy needs to manufacture and distribute these inputs and to irrigate crops. The sustainability of this route is questionable in terms of environmental and human health impact and because of reliance on non-renewable resources. Further, this land sparing scenario is vulnerable to abuse (Ewers et al. 2009). Spared land may be subject to various forms of degradation such as those arising from edge effects where it borders farmland or urban zones. As these land uses encroach on biodiversity areas, patch sizes decline and fragmentation increases leading to adverse effects, especially on higher trophic level species. This reduces the value of the spared land to biodiversity and human perceptions of its conservation value making it more likely to be cleared. Compounding this issue, the intensification that might facilitate land sparing by increasing productivity also serve to make clearing more attractive; especially for the poor in developing countries who would clear land to farm in pursuit of higher incomes (Chappell and LaValle 2011). These risks illustrate the importance of policy in realizing the potential for harmonizing biodiversity conservation in agricultural lands.

The unattractive scenarios outlined above demand that other options are considered. The remainder of this review assesses scope for ecological intensification, the redesign of agricultural systems to better exploit the ecosystem services that are provided by strategically enhanced biodiversity in farm landscapes and, thereby, lessen reliance on external inputs and the attendant environmental impacts (Bommarco et al. 2013). Potentially, such an approach could provide sufficiently increased levels of production from agricultural land that land sparing is realistic whilst simultaneously allowing farm landscapes to be shared with many forms of biodiversity (Fig. 7.2, centre).

7.4 Agricultural Intensification and Biodiversity

Gregory and George (2011) suggest that only 20 % of future yield increases will be met by expanding agriculture into new areas. A much higher proportion (67 %) is predicted to result from increased yield and a further 12 % from cropping intensity (growing crops more frequently on a given area of land). If these projected proportions are even remotely accurate, there is a clear need to focus research efforts on achieving the best possible forms of intensification. Public investment in agricultural research has fallen significantly over recent decades in many developed countries. Whilst private investment has increased, this has been concentrated on agricultural biotechnology, reflecting business decisions to pursue technologies that can be protected by patent and marketed to generate economic return to investors. Whilst this is entirely rational from an economic perspective, it may not steer research investment to address the most important needs (Evans 1998). Although the last two decades have witnessed high levels of activity in areas such as novel pesticide development and agricultural biotechnology (Varshney et al. 2011), research into ecologically based solutions for agricultural issues such as insect pest, weed, and plant disease problems have been the subject of less investment. Research investment in China has increased over recent years with the aim of promoting sustainable development of agriculture although ecological, rather than molecular, approaches remain a minor proportion. This is unfortunate because ecology could help deliver an alternative to the unattractive extremes sketched out above by allowing agricultural land to be shared without lowering crop yields.

Current forms of conventional agriculture have high levels of intensity as measured by output per unit of labour but achieve this only by heavy dependence on external inputs that lead to “dis-services” (Fig. 7.3). Water pollution by nitrates and phosphorus from fertilizers, widespread pollution of habitats by pesticide residues including off-target effects on wildlife, and threats to pollinators are amongst these. Agriculture is also a large contributor to greenhouse gases, particularly during land clearing. Such disservices affect humans negatively, either directly or indirectly via their impact on biodiversity. In contrast, the ES provided by biodiversity can directly benefit the human population (e.g. fixing carbon dioxide, stabilizing soil to prevent erosion, and helping provide clean water) whilst others benefit humans via agriculture. Costanza et al. (1997) highlighted the value of such ES, estimated to be $16–54 trillion per annum globally. For example, biological control of pests was estimated to provide $0.47 trillion per annum globally. More detailed recent studies of biological control in specific regions reinforce the importance of natural enemies. For example, the value of biological control in the USA is estimated to be $57 billion per annum (Losey and Vaughan 2006). The need for effective biological control of pests, weeds, and plant diseases will increase in the future because of the development of pesticide resistance and the spread of invasive species into new areas (Godfray et al. 2010b). Yet, life table analyses suggest that natural pest control can be dependent on multiple links in complex food webs (Hawkins et al. 1999) so promoted by biodiversity. Thus, if biodiversity on farmlands was preserved and ES such as natural pest control were

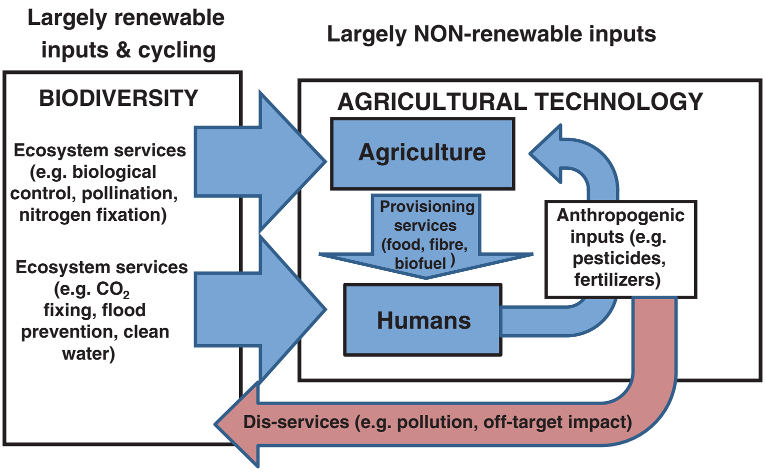

Fig. 7.3 Modern agricultural systems provide humans with products but are heavily dependent on inputs such as pesticides and fertilizers that also cause disservices such as pollution. If the ecosystem services from biodiversity, including natural pest control and nutrient provisioning, were more fully harnessed, agriculture could be sustainably intensified

better harnessed, they could replace many of the non-renewable inputs and reduce the impact of those that remain essential.

Scope for yields to be increased by intensification is evident from considering the “yield gap” between what is typically realized in a region and the best that is possible using current technologies and crop varieties. This gap is estimated to be 50–80 % depending on which crop system is studied (Gregory and George 2011). For example, in the important rice systems of south-east Asia, the potential is considered to be 8.5 t/ha yet the average is only about 60 % of this (Cassman 1999). Godfray et al. (2010a) summarize data that illustrate in a contrasting manner the scope to increase food production. Despite its well-known population growth, China’s per capita food production has increased by almost 3.5-fold over the last 50 years, yet the situation in Africa is radically different. Current production there fell after peaking in the 1970s and has only recently recovered to those levels. If appropriate technologies could be implemented widely in Africa, contingent of course on political stability, there would be huge scope to boost agricultural productivity. Significant controversy surrounding attempts to assess the merits of different agricultural systems has obstructed technological change.

7.5 “Alternative” Agricultural Systems

Farming systems in current use around the world are highly varied and this has created problems for those analysing the merits of each. A frequently applied dichotomy is the “conventional” systems versus a raft of “alternative” systems.

Amongst the alternative systems reviewed by Badgley et al. (2007)—bio-intensive vegetable gardens, multilayer tree gardens, incorporation of trees and animals into cropping systems [e.g. rice-fish coculture (Xie et al. 2011)], cover crops, and IPM—all have proven value and some more recent studies have shown scope to successfully combine high yields and aspects of biodiversity (Clough et al. 2011). The largest scale evaluation of such alternative systems focused on developing countries and considered 286 cases of "resource-conserving" methods being implemented in 57 countries covering 37 million hectare and 12.6 million farms (Pretty et al. 2006). Though only successful studies were selected, thus illustrating the potential of these alternative technologies rather than being broadly representative, yield increases following interventions were considerable, ranging from 22–146 % with an overall increase for all projects of 80 %. Moreover, many of the projects involved strategies to suppress pests and in these cases, pesticide-use data revealed that 77 % of projects reduced usage. In more recent work, the same types of alternative systems were assessed under the umbrella term of "sustainable intensification". Reviewing 40 projects in 20 African countries extending over 12.75 million hectare, a range of benefits to farmers, their families, and communities were identified in addition to average yield increases of over 100 % achieved without harm to the environment (Pretty 2009).

A key factor of the alternative agricultural systems discussed above is that they have a low level of reliance on synthetic, external inputs and instead rely heavily on appropriately managed biodiversity to provide ecosystem services such a pest control, disease suppression, and nutrient provisioning to crops. The remainder of this review considers whether this eco-centric approach can guide agricultural intensification and if broader components of biodiversity (those that do not provide ES directly to agriculture) might be enhanced in alternative agricultural systems where there is an attempt to have shared use by biodiversity.

7.6 Biodiversity and Ecosystem Services

A recent study focusing on tropical forested areas (Phalan et al. 2011a) aimed to assess the relative merits of land sparing versus land sharing on wildlife in tropical systems. The resulting diversity–yield relationships showed that sparing benefitted more species than did sharing, especially for species with a narrow geographical range whilst some species were favoured by intermediate farming intensities. Further studies of this type are required to determine whether the results apply in other settings such as temperate forests, and grassland. Phalan et al. (2011a) recognized the limitations of their analysis to the wider land sharing versus sparing debate, such as the need to consider factors such as the value of the ES provided under a land sharing scenario, a point reinforced by Godfray (2011). An example is pollination by domesticated and wild pollinator species which can be threatened by industrialized agricultural intensification (Klein et al. 2007). Similarly, the movement of the natural enemies that provide natural suppression of pests can be adversely affected by intensification (Tscharntke et al. 2005). As a consequence, pollination and pest management are dependent heavily on seasonal relocation of domesticated bees (the health of which is under worldwide threat from poorly understood factors) and synthetic pesticide use, respectively. There is, however, a scope to use management practices in a targeted manner to preserve specific aspects of biodiversity and the ES they provide in intense agricultural systems. For example, to protect a tree species or a guild of animals associated with a type of vegetation, particular woody plant species could be selected for use in shelterbelts, woodlots, or hedgerows on farms. Such management to provide the "right kinds" of habitat diversity is known as ecological engineering, an approach that could be a powerful way to orchestrate land sharing so that biodiversity conservation is maximized in manners that simultaneously deliver ES to farming.

7.7 Ecological Engineering in Agriculture

Ecological engineering can be considered the design of human systems in a manner consistent with ecological principles so that the role of natural processes is maximized and the need for human inputs is reduced (Mitsch and Jørgensen 1989; Parrott 2002). In China, this broad "design with nature" philosophy has a long history (Ma 1985). In the agricultural context, ecological engineering involves encouraging biodiversity in farm landscapes to restore ecosystem function whilst simultaneously providing land area for flora and fauna conservation that is in addition to that in protected reserves. It is an approach that has been especially pursued for natural pest control where its success is underpinned by two key ecological processes. First, herbivores tend to be less abundant in mixed vegetation than in monocultures because, especially in the case of specialist herbivores, it is more difficult to locate and remain upon suitable plants in mixed stands where confusing and sometimes repellent visual and chemical cues are present. Second, the activity of pest natural enemies is usually greater in mixed vegetation because resources such as nectar, pollen, and alternative hosts and prey are available along with moderated microclimates. Both these effects can operate simultaneously and even apply at the landscape scale (Tscharntke et al. 2005).

Additional aspects of ecology that offer scope for practical use in ecological engineering against pests are still emerging. For example, recent studies have illustrated the significance of two effects that could have profound ramifications for the way in which biodiversity might be harnessed to best effect in agriculture.

First, community evenness of natural enemies (the relative abundance of species) has been largely neglected in comparison with studies of species richness (the number of species present). Having plenty of natural enemy species present in a given crop can be advantageous, constituting "insurance" (Crowder et al. 2010) that whatever pests arrive or whatever abiotic conditions prevail, there is a good chance that one of the enemy species present will be suited and able to provide pest control. Yet it is also intuitive that a community with relatively even numbers of each natural enemy species will be better able to provide suppression of pests than a community in which, say, all but one natural enemy species was rare. Field enclosure experiments with differing levels of evenness in natural enemy communities showed that the strongest pest control and largest potato plants resulted from even communities of predatory and pathogenic natural enemies (Crowder et al. 2010). Notably, higher pest densities and lower potato plant biomass under conditions of lower evenness resulted independently of which natural enemy species was numerically dominant, thus illustrating the effect of evenness itself. Though strategies to promote community evenness generally are not well understood, natural enemy evenness in agriculture seems to be promoted under organic production conditions (Crowder et al. 2010), an effect consistent with a meta-analysis of the effects of organic agriculture on species diversity and abundance (Bengtsson et al. 2005). Research to identify the ecological mechanisms operating in organic systems would be valuable so that they might be exploited in the wider intensification of agricultural systems by ecological engineering.

A second effect reported recently was uncovered in an Australian study of the landscape scale patterns of vegetation types and how these influenced natural enemy numbers in cotton crops (Perović et al. 2010). This showed that for at least some natural enemies, the level of connectivity in the landscape was more important than was the composition of the landscape. It was well known that composition (for example, a high proportion of woody vegetation in the landscape) can influence in-crop densities of natural enemies but connectivity can vary independently of composition (for example, woody vegetation existing solely as a patch-located remote from the crop, versus the presence of “stepping stones” or “corridors” linking crops to source vegetation). The cost-distance modelling approach used in that study had previously been applied to conservation biology but the significance of connectivity to dispersal of natural enemies through landscapes up to 3 km into crops had not been recognized.

Advances such as those outlined above illustrate that there are increasingly good prospects for ecological engineering to play a major role in future pest management strategies within intensified agriculture. Further, because they are based on the active use of aspects of biodiversity such as non-crop vegetation, even species that are not providing direct ecosystem services to agriculture stand to benefit. In the case of agricultural landscapes that might, in the future, be designed with the aid of cost-distance modelling and other GIS approaches, there is scope to explicitly integrate the needs of wildlife conservation.

7.8 Ecological Engineering Agricultural Systems for Multiple Ecosystem Services

The most widely adopted example of ecological engineering for pest management is the push–pull system introduced initially to suppress stem borer pests of maize in Africa (Khan et al. 2012). This employs intercropping cereals with *Melinis* *minutifolia* or *Desmodium* species that are repellent to gravid stem borer moths but attractive to parasitoid wasps. This makes the crop selectively more attractive to natural enemies over pests. Simultaneously, the crop is bordered by *Pennisetum purpureum* that is attractive to ovipositing stem borers but does not allow their larvae to complete development. Thus, pests are either pushed from the crop or face high levels of attack by parasitoids, plus are pulled to grasses that kill progeny. It took 6 years from the inception of this push–pull system in 1999 for its adoption to exceed 2,000 farmers but uptake boomed in the following six years to almost 50,000 farmer households in 2011. Yields of maize were increased from 1 to 3.5 t ha^{-1}, sorghum from 0.8 to 2 t ha^{-1} and millet from 0.4 to 0.8 t ha^{-1}. Whilst these yield levels may be modest compared to those in industrialized agricultural systems, the magnitude of increase is at least equivalent to the doubling in global production that is reported to be necessary by 2050 (Tillman et al. 2012). At the local scale, the benefits to individual farmers are complemented by reduced weeding and cultivation costs plus the intercrops, which are perennial, are valuable fodder crops that are used by the farmer's own dairy cow or sold for cash.

An important factor in the positive outlook for ecological engineering strategies such as push–pull is the fact that the vegetation used to suppress pests can have additional benefits. This "multifunction agricultural biodiversity" (Gurr et al. 2003) is apparent in push–pull's non-pest-related benefits that include suppressing parasitic stiga weeds, fixing nitrogen, controlling erosion, and improving the soil's physical properties including water holding capacity, providing fodder for livestock and reducing labour requirements (Khan et al. 2012).

Another well-known form of ecological engineering for pest suppression is the creation of beetle banks (Thomas et al. 1991). These are used on approximately 1 % of English farms as well as elsewhere in Europe, the USA, and New Zealand (Tillman et al. 2012). This level of uptake is despite the limited current value of beetle banks in pest management because aphids have recently been minor pests in Britain and, for the time being at least, are susceptible to cheap insecticides. The use of beetle banks is, however, encouraged by government payments to farmers under the Environmental Stewardship agri-environmental scheme. The payments reflect the value of beetle banks in conservation of wildlife including small mammals and birds. Invertebrates are also encouraged and this further promotes adoption as these are important in the diet of game birds, the target of recreational shooting. Similarly, the use of conservation tillage together with cover crops in the important cotton growing state of Georgia, USA has been promoted by multiple benefits. As well as enhancing natural pest control of lepidopteran pests, this form of ecological engineering fixes nitrogen, improves soil structure, improves water infiltration, and thereby reduces erosion (Tillman et al. 2012).

The foregoing examples illustrate that ecological engineering strategies for pest control are most likely to be adopted when they have additional benefits. This is promoted when native rather than exotic plant species are employed. In a survey of farmers, reasons for adoption of insectary hedgerows in the USA included attraction of beneficial insects (the intended function), dust control (a nuisance that can impair crop growth, quality, and the activity of predatory mites), increased shade for livestock, and the provision of wildlife habitat (Brodt et al. 2009).

Another multifunction ecological engineering strategy used native ground cover plants in the Waipara region of New Zealand (Landis et al. 2012) where the need to encourage biodiversity is especially great because much has been lost since white settlement. In the Waipara system, biodiversity and suppression of lepidopteran pests benefits were complemented by marketing the aesthetic appeal of engineered vineyards for ecotourism, erosion management, filtration of winery effluent (Landis et al. 2012), and potentially improved fungus disease control via infected prunings being more readily decomposed in vines with a mulch (Jacometti et al. 2007). The cases of uptake outlined above illustrate the importance of there being multiple benefits from the ecological engineering. In contrast, uptake is limited when vegetation is manipulated solely for pest control (Griffiths et al. 2008).

Ecological engineering of farmlands will not lead to a utopian situation where biodiversity in all its forms will be enhanced and agriculture will be intensified; there will be trade-offs between biodiversity and crop yields in many cases of land sharing (Phalan et al. 2011b). Recent work in cacao production has, however, shown that biodiversity of invertebrates, trees, fungi, and vertebrates did not decline with yield, suggesting "substantial opportunities" for combining high biodiversity and high yields (Clough et al. 2011). What ecological engineering can offer is a means to maximize the frequency and extent of meeting the dual goals of biodiversity and production in shared lands and thereby contribute to sparing land for the conservation of other forms of biodiversity. Figure 7.4 shows an eastern Chinese landscape (Hejia Village, Sanmen County, Zhejiang Province) in which high yields of rice have been produced without the need for insecticide use in the

Fig. 7.4 An eastern Chinese mixed use landscape (Hejia Village, Sanmen County, Zhejiang Province) in which high yields of rice have been produced without the need for insecticide use in the last decade (Yu et al. 2011); the agricultural area has a network of diverse crop and non-crop vegetation whilst adjoining forest prevents landslides whilst harbouring biodiversity including enemies of pests (Rands et al. 2010)

last decade (Yu et al. 2011). This agricultural area has a network of diverse crop and non-crop vegetation including perennial species on the bunds surrounding each area of crop. Amongst the vegetation growing on the bunds are species that are allowed to flower and so provide nectar and pollen to parasitoids and predators of pests. This network of vegetation links the crop area with adjoining forest which serves as source habitat for many species of natural enemies of pests (Zhu et al. 2012). It also provides other ecosystem goods and services including stabilization of the soil to prevent landslides, water purification, timber and fuel, aesthetic, and recreational value.

7.9 Conclusions

The current decline in global biodiversity is chiefly a threat to humans; whilst we depend upon it, our activities erode biodiversity. Conversely, biodiversity can get along just fine without us. Biodiversity waxed and waned for many millions of years before the advent of humans. Means must be found to achieve food security whilst avoiding the problems associated with either land sharing without intensification (Fig. 7.2, left) or land sparing using only conventional forms of intensification (Fig. 7.2, right). A blended approach will be necessary whereby as much land as possible is spared to preserve the ES it provides whilst intensification of agricultural land is achieved by ecological engineering to strive for win–win outcomes for production and biodiversity (Fig. 7.2, centre). Potentially, such intensification could even allow some of the area now used for agriculture to be returned to its original land use (Zhang et al. 2012).

Ecologically intensive forms of agriculture do exist (Pretty et al. 2006; Reganold et al. 2011). However, having them adapted for and introduced over wider areas to deliver multiple ES and biodiversity conservation will require breaking down the barriers between fields (Godfray et al. 2010b). This challenge extends well beyond scientific disciplines. Structural, policy, and social aspects dominated the seven key requirements for scaling-up sustainable intensification identified by Pretty et al. (2011). Non-technical reasons were also behind the slow adoption of innovative farming systems in the USA where policy and market failure were said to be as significant as scientific reasons (Reganold et al. 2011). Undeniably, conserving global biodiversity would be easier with a declining rather than a growing human population. But until politicians and policy makers are able to resolve issues surrounding population growth, poverty, and inequity, the role of life scientists is to find ways to balance the need for more food with biodiversity conservation. Human dependence upon biodiversity for many ES including global atmospheric carbon regulation means that significant areas of land need to be spared from clearing (Rands et al. 2010). For thousands of years, agriculture relied upon biodiversity ranging from soil microbes to trees for ES including nutrient provision, pest suppression, and pollination. Attempts over the last handful of generations to intensify production by use of synthetic, non-renewable inputs such as fertilizers and pesticides are inherently unsustainable and will do nothing to address the projected decline in global biodiversity over the twenty-first century (Pereira et al. 2010). Rather than entrenching dependence on synthetic, non-renewable inputs, intensification of agriculture should be based on ecological principles that have been responsible for sustaining biodiversity and associated ecosystem services for millennia (Zhu et al. 2012).

Tilman et al. (2011) concluded that technology transfer to elevate crop yields in under-performing areas, especially in Africa, could meet most of the needs for extra food. Further, such intensification would allow significant land sparing to take place and dramatically cut the levels of associated greenhouse gas emissions. If this intensification was accomplished using mainstream technologies, it would require significant additional synthetic nitrogen fertilizer but alternative agriculture technologies could be employed. For example, maize yield in China has been increased by 90 % in studies of integrated soil and crop management (Chen et al. 2011) and has reached 15 t/ha (Zhang et al. 2012). More broadly, the use of sustainable intensification approaches including integrated pest management practices, mulches and cover crops, and other forms of vegetation manipulation can yield more food per unit area whilst simultaneously reducing environmental impacts (Godfray et al. 2010b). Chappell and LaValle (Gregory and George 2011) stress the interdependency of agriculture and biodiversity and posit that we can have both if appropriate alternative practices are used. Incentives paid to farmers to encourage biodiversity on farms are part of the solution and various forms of agri-environmental schemes have been implemented, many of which have production as well as environmental benefits (Wade et al. 2008) so there is significant scope for restoration of farmlands to enhance ecosystem function (Pywell et al. 2011). Ecological engineering may prove to be the mechanism by which intensification is orchestrated to deliver benefits for both biodiversity and agriculture (Fig. 7.5).

Research into alternative agricultural systems that will allow intensification of production per unit of land based on ecological principles is a promising direction. Evidence suggests that such forms of agriculture can enjoy both high productivity and conserve many forms of biodiversity. This view of the benefits of harnessing biodiversity's ES is consistent with a recent assessment of world agriculture that pointed to the need for sustainable practices based on ecological approaches (McIntyre et al. 2009). A separate report for the United Nations Environment Programme concluded that ecologically based farming practices

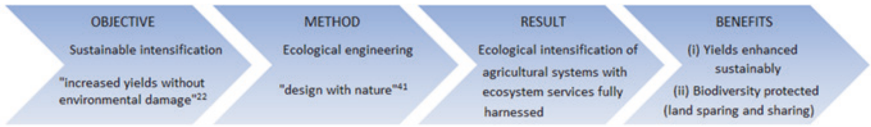

Fig. 7.5 Sustainable intensification of agriculture could employ the principles of ecological engineering to integrate biodiversity into production systems. The increase in ecosystem services could sustainably boost production whilst preserving biodiversity on- and off-farms

could double food production in a decade (De Schutter 2010). If biodiversity was fully harnessed so that ES to agriculture were maximized, it would be a strong contributor to agricultural intensification rather than being, as if often conceived, a burden to be accommodated on farmlands. Moreover, agriculture based on ES and less dependent upon non-renewable inputs would have fewer attendant disservices and be more sustainable. Intensification achieved mostly by ES would be a double win for biodiversity because much of it could be conserved in shared land and other forms of biodiversity preserved in land spared from clearing via successful intensification.

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Chapter 8
Rice Pest Management by Ecological Engineering: A Pioneering Attempt in China

Zhongxian Lv, Pingyang Zhu, Geoff M. Gurr, Xusong Zheng, Guihua Chen and Kong Luen Heong

Abstract Ecological engineering is a relatively new concept of environmental manipulation for the benefit of man and the environment. Recently, a pioneering attempt was made in China to see if rice insect pest problems could be solved through ecological engineering. Five years of experimentation at Jinhua, Zhejiang Province in eastern China involved habitat manipulation based on growing nectar producing flowering plants (preferably sesame) combined with trap plants on the rice bounds, reducing the intensity of pesticide use and nitrogenous fertilizers, and managing the vegetation in non-rice habitats including the rice-free season. These practices increased biodiversity in the ecosystem, significantly increased biological control of rice pests, and provided biological stability in the ecosystem. Experimentation with ecological engineering in China indicated that it offers immense opportunities to rice pest management using non-chemical methods leading to economic and environmental benefits. Ecological engineering is not a "high-tech" approach so is simple and practical for rice farmers to implement. Having witnessed the benefits and utility of ecological engineering, the National Agriculture Technology Extension and Service Centre (NATESC) of Ministry of Agriculture has recommended it as the national rice pest management strategy in China.

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Keywords Rice planthoppers · Ecological engineering · Rice pest · Trap plant · Nectar crop · Biological control

8.1 Introduction

Initial use of the term “ecological engineering” referred to the “environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources.” (Odum 1962). The term subsequently developed when Mitsch (2012) defined it as the “design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both.” Ecological engineering functions include designing an ecosystem to: reduce a pollution problem; reduce a resource problem; restore an area after a significant disturbance; bring stability to an area in an ecologically sound way; and improve the functionally of the system for human benefit (Mitsch and Jørgensen 2004). Gurr (2009) stressed that the characteristics of ecological engineering are: to have low dependence on external and synthetic inputs and high a reliance on natural processes; to be based on ecological principles; and to have scope for refinement by ecological experimentation. The goals of ecological engineering as defined by Mitsch and Jørgensen (2004) and Mitsch (1996) are the restoration of ecosystems that have been substantially disturbed by human activities, and the development of new sustainable ecosystems has both human and ecological value.

The application of ecological engineering for pest management includes use of cultural practices, usually based on vegetation management, to enhance biological control or the “bottom-up” effects that act directly on pests (Gurr et al. 2004a). The latter include methods such as trap crops that divert pests away from crops and changing monocultures to polycultures to reduce pest immigration or residency. Providing resources such as nectar and pollen to natural enemies promotes biological control.

Rice is the most important staple food worldwide, especially in China (Peng and Hardy 2001; Zeigler and Barclay 2008; Yuan 2014). Recent outbreaks of delphacid pests [brown planthopper (*Nilaparvata lugens*), white-backed planthopper (*Sogatella furcifera*), and small brown planthopper (*Laodelphax striatellus*)] have been very destructive in Asia (Cheng 2009; Savary et al. 2012). In China, 26.7 million hectares was damaged by delphacids between 2005 and 2007 (Xia 2008). Changes in cropping systems, including an increase in the use of susceptible hybrid rice varieties, high use of fertilizers and pesticides, combined with higher temperatures, created rice ecosystems that were more vulnerable to planthoppers, promoted population growth rates, and resulted in high population sizes and increased frequency of outbreaks (Cheng 2009). The impact of rice planthoppers is now so severe that they have been cited a threat to global food security (Lou and Cheng 2011).

Rice cropping systems are characterized by high levels of disturbance including aggressive soil tillage, seasonal wetting and drying, transplanting, and harvesting as well as high inputs of synthetic pesticides and fertilizers. While the pesticides reduce populations of natural enemies resulting in impaired biological control (Heong 2009), high rates of nitrogenous fertilizers directly promote planthopper nutrition and population growth rate (Lu and Heong 2009). Habitat manipulation/management to enhance biological control has been explored in a wide range of crop systems (Landis et al. 2000). This approach is intended to promote natural enemy activity by providing resources to enhance their performance. These resources include alternate foods when prey or hosts are temporarily unavailable (Gurr 2009). The availability of resources such as nectar has been shown to improve longevity, searching efficiency, and realized parasitism of many parasitoid species (Mitsunaga et al. 2004, 2006; Rivero and Casas 1999; Shearer and Atanassov 2004; Jervis et al. 2004; Zhu et al. 2013a; Lu et al. 2014). Ecological engineering for pest management is a targeted approach to habitat manipulation where the attributes of a number of candidate plants are assessed to determine optimal ones to introduce into a farming system (Gurr et al. 2004b). This contrasts with the "hit and miss" approach to habitat manipulation used in the 1990s which was based on the simple premise that increased vegetation diversity would promote pest suppression.

Ecological engineering for rice pest management was led by the International Rice Research Institute (IRRI) and initiated in China, Vietnam, and Thailand in 2008. Recently, in Vietnamese field studies, it was demonstrated that growing nectar plants on the bunds beside rice crops significantly increased the number and impact of natural enemies on rice planthopper*s* (Lan et al. 2010). In this chapter, we discuss the parallel development and evaluation of ecological engineering in rice ecosystems in China.

8.2 Influence of Flowing Plants on the Biological Control

Increasing in the area of agricultural production and improving crop yields was thought to guarantee the adequate provision of food with an increasing world population. These changes have reduced the area of non-crop habitat and simplified farming landscapes. This sharp decline in farmland biodiversity reduces the number of flowering plants, which natural enemies depend on (Lu et al. 2014). In this context, ecological engineering aims to protect crops from pest damage by maximizing natural mortality by strategic introduction of plant diversity (Gurr et al. 2004a; Cullen et al. 2008). A key consideration is the identification of plants that selectively favor natural enemies over pests. Ideally, these are then included in agro-environmental schemes so as to provide pest suppression at the seam time as delivering other ecosystem services such as pollination and biodiversity conservation.

8.2.1 Influence of Sesame Flowers and Alternative Prey on Planthopper Egg Parasitoids Anagrus *spp.*

Anagrus spp. are egg parasitoids that are important in the management of leaf- and planthoppers in Asia (Gurr et al. 2011). In China where *A. nilaparvatae* dominates, parasitism rates in rice fields are between 10 and 70 % (Yu et al. 2001). The same species is also important in Cambodia, India, and Philippines (Chandra 1979; Kalode 1983; Preap et al. 2001). Ecological engineering strategies in rice-based ecosystems that target this natural enemy are twofold. First, providing alternative hosts for the parasitoid during periods of rice planthopper unavailability. In eastern China, a perennial vegetable crop *Zizania caduciflora*, which is attacked by the green slender planthopper *Saccharosydne procerus*, is often grown in fields to rice. The parasitoid *A. optabilis* attacks *S. procerus* during the winter period and then moves to rice crops in spring to parasitize rice planthoppers (Lu 2003; Zheng et al. 2003). A second, and complementary, approach is the use of flowering plants to provide nectar to parasitoids.

Laboratory screening experiments were conducted to select plant flowers that best enhance *Anagrus* spp. parasitoids (Zhu et al. 2013a). Findings indicated that *A. optabilis* is attracted by volatiles of *Sesamum indicum*, *Impatiens balsamen*, *Emilia sonchifolia*, *Hibiscus coccineus*, *Trida procumbens,* and *Hibiscus esulentus* (Table 8.1). Of these, *S indicum, E. sonchifolia*, and *I. balsamena* were also attractive to *A. nilaparvatae*. Sesame was selected for further study that discovered that *A. nilaparvatae* and *A. optabilis* female life span was enhanced by sesame flowers. Realized parasitism by *A. nilaparvatae* was also enhanced by sesame flowers as was that of *A. optabilis* (Table 8.1). This indicated that sesame promotes key aspects of *Anagrus* spp. performance and justified its use in field studies. Field experiments also indicated that egg parasitisms by *A. nilaparvatae* and *A. optabilis* could be significantly enhanced by sesame flowers in field conditions (Fig. 8.1).

Table 8.1 Percentage of food-deprived parasitoid adults choosing flower odors or clean air in a Y-tube olfactometer

Plant flowers	*Anagrus nilaparvate*		*Anagrus optabilis*	
	Choosing flower odor (%)	Choosing clear air (%)	Choosing flower odor (%)	Choosing clear air (%)
Sesamum indicum	70.0*	30.0	67.5*	32.5
Impatiens balsamena	72.5*	27.5	77.5*	22.5
Emilia sonchifolia	67.5*	32.5	70.0*	30.0
Hibiscus coccineus	45.0	55.0	77.5*	22.5
Tagetes patula	30.0	70.0	70.0*	25.0
Hibiscus esulentus	55.0	45.0	70.0*	27.5
Vernonia cinerea	85.0*	15.0	50.0	50.0
Luffa cylindrica	70.0*	30.0	/	/

(continued)

Table 8.1 (continued)

Plant flowers	*Anagrus nilaparvate*		*Anagrus optabilis*	
	Choosing flower odor (%)	Choosing clear air (%)	Choosing flower odor (%)	Choosing clear air (%)
Tagetes erecta	65.0	35.0	/	/
Rosa chinensis	72.5*	25.0	/	/
Largeleaf Hydrangea	42.5	55.0	/	/
Gazania rigens	37.5	62.5	/	/
Glycine max	60.0	40.0	/	/
Canna indica	37.5	60.0	/	/
Ageratum conyzoides	55.0	40.0	/	/
Trida procumbens	60.0	37.5	/	/
Mazus japonicus	80.0*	17.5	/	/
Erigeron annuus	45.0	52.5	/	/
Portulaca grandiflora	47.5	52.5	/	/
Cosmos sulphureus	37.5	52.5	/	/
Ipomoea nil	65.0	35.0	/	/
Herba Ecliptae Eclipta prostrala	50.0	50.0	/	/

From Zhu et al. (2013a)

*indicate a significant deviation from random choice (preference or repellency) (test on two-tail binomial distribution; $p < 0.05$)

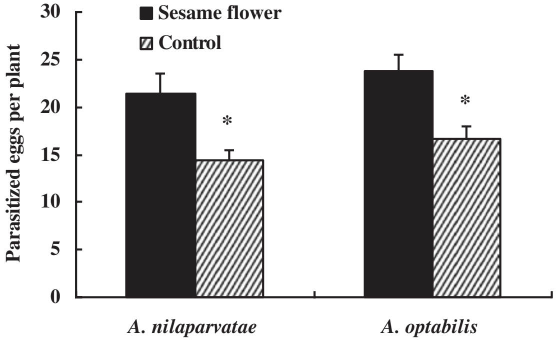


Fig. 8.1 Effects of sesame flowers on realized parasitism of *Anagrus* spp. Asterisks indicate a significant at $p < 0.05$. From Zhu et al. (2013a)

8.2.2 *Influence of Flowering Plants on Planthopper Predator* Cyrtorhinus Lividipennis

The mirid bug, *Cyrtorhinus lividipennis* (Heteroptera: Miridae), is an important zoophytophagous predator, preferring leaf- and planthopper eggs and young nymphs (Zhu and Chen 1981; Chen et al. 1985; Katti et al. 2007; Shepard et al. 1987). It tends to be highly correlated with planthopper density and plays a key

Table 8.2 Predatory capacity of *Cyrtorhinus lividipennis* offspring after feeding the parental adults with different plant flowers

Plant flowers fed on parental adults	*S. indicum*	*T. erecta*	*T. procumbens*	*E. sonchifolia*	Control
4th instar nymph	19.07 ± 0.72a	14.23 ± 0.80b	13.29 ± 1.02b	10.15 ± 0.50c	7.92 ± 0.33d
Female adult	24.03 ± 0.61b	29.71 ± 0.86a	22.14 ± 1.07b	23.56 ± 0.87b	21.57 ± 0.92b

From Zhu et al. (2013b)
Values are mean ± SE. Means within a row followed by differing letters are differ significantly at $p < 0.05$. Tukey's test was used

role in suppressing planthopper populations (Heong et al. 1991; Laba and Heong 1996). Predation of *N. lugens* eggs by *C. lividipennis* in the field can average 30 % and reach up to 70 % (Zhou and Chen 1986). Laboratory studies have shown that individual *C. lividipennis* nymphs and adults can consume up to 7.5 and 10.2 *N. lugens* daily (Reyes and Gabriel 1975). Whether the life history parameters and predation performance of *C. lividipennis* could be improved by access to nectar was uncertain until recently. It had been suggested that *C. lividipennis* may benefit from plant foods (Shepard et al. 1987) and can survive in the crop even when prey is scarce or totally absent (Ingegno et al. 2011).

Recent laboratory studies examined the growth and predatory capacity of *C. lividipennis* progeny after feeding by the parents on the flowers of four plant species *Sesamun indicum*, *Tagetes erecta*, *Trida procumbens,* and *Emilia sonchifolia* (Zhu et al. 2013b). The findings indicated that the offspring nymphal period duration of *C. lividipennis* was shortened after the parent adults had feed on the four candidate flowering plants, and the male nymph duration was significantly reduced by parental adults feeding on the flower of *S. indicum.* The 4th instar nymph's predation on BPH eggs was significantly increased after parental adults feed on *T. procumbens*, *E. sonchifolia*, *T. erecta,* and *S. indicum* flowering plants. Among the flowering plant treatments, *S. indicum* was the most favorable, followed by *T. erecta* and *T. procumbens* (Table 8.2). The adult's predation on BPH eggs was greatly enhanced after the parental adults feed on *E. sonchifolia*, *T. erecta,* and *S. indicum* flowering plants (Table 8.2). Among the flowering plant treatments, *T. erecta* was the most favorable. These results show that suitable flowering plants can significantly improve the predation ability of offspring *C. lividipennis* and can shorten the nymph duration period in progeny.

8.3 Development and Demonstration of Ecological Engineering Practices in Jinhua, China

Rice is a very important crop in China with cultivation dating back for thousands of years. The green revolution in 1960s was aimed at meeting the increasing demand for food with the rapid population growth. Rice production increased greatly, with the wide-scale adaptation of high-yielding varieties, extensive use of pesticides and chemical fertilizers. The resulting production system was dependent on high inputs of agrochemicals resulting in a serious threat to the ecological safety of rice, environmental health, and the rice grain quality (Heong 2009). Although rice yields in China continuously increased in recent decades, the outbreak of rice pests has become one of the main obstacles to sustainable production. Large-scale outbreaks of rice planthoppers and the viral diseases they transmit become common in the first decade of the twenty-first century (Xia 2008). Chemical control has been considered as a key measure to suppress the population of rice planthoppers. The excessive application of chemical pesticides not only led to the development of resistance to insecticides but also negatively affected natural enemies and other beneficial organisms and resulted in unwelcome contamination to the aquatic environment and rice grain (Conway and Pretty 1991). It consequently became essential to minimize the use of chemical pesticides and to guarantee the food safety by developing ecological pest management.

Attempts of rice insect pest management by ecological engineering in Jinhua, China, were initially initiated in 2008 with the funding of ADB and technical support from the IRRI Rice Planthopper Project. To explain and promote ecological engineering concepts, practices were communicated to the professional technicians, policy makers, practitioners, and farmers through a national seminar in 2010 and an international field day in 2012, which was covered by the mass media such as local TV, newspaper, and a farmers' information system. Since 2013, rice insect pest management by ecological engineering has become the national recommended plant protection strategy (NATESC 2013).

8.3.1 History of the Experimental Site

In the recent past outbreaks of pests, rice stem borer, rice brown planthopper, white-backed planthopper, and rice leaffolder were prevalent, resulting in huge losses and great financial cost of insecticides in Jinhua. During 2005 and 2007, the population size of BPH reached the highest level in the history and it seriously threatened rice production. Simultaneously, rice leaffolder populations also reached at high levels. Thus, costs of insecticides used in rice field increased to about 360US$ per hectare for one rice season. Farmers were losing interests in rice production due to the cost of production. Against this backdrop, the Zhejiang Academy of Agricultural Sciences (ZAAS) and the Jinhua Plant Protection Station (JPPS) in collaboration with the IRRI initiated a pioneering attempt to manage rice insect pests by ecological engineering in 2008. A 35 ha experimental site was established to determine and demonstrate the possibility and practicability of sustainable rice pest management by ecological engineering.

The ecological engineering site was located at Si Ping village, set in an area with nearby mountains and high-quality water resources. Although the original ecosystem had not been greatly disturbed, the areas used for rice production had been impacted by intensive cultivation and overuse of chemical fertilizers and pesticides. Using ecological engineering principles and methods, various interventions were made. These included manipulation of vegetation to promote natural enemies specifically planting nectar-rich plants, zero insecticide sprays during first 40 days after transplanting, and stopping overuse of nitrogen fertilizer. The goal was to reduce the usage of chemical pesticide by 60–80 %, to keep yield losses by major pests to less than 3 % and to gradually recover the natural pest control function of the ecosystem.

The 35 ha site was divided into two zones. The small block (8 ha) was assigned to ecological engineering and was made up of 40 rice fields, each of which was managed as a separate crop and subject to arthropod monitoring using sweep nets, yellow sticky traps, and yellow water pan traps. Frog numbers were also monitored by counting at night. The larger block (27 ha), separated from the ecological engineering area by a sealed road, was a control treatment managed under conventional farmer practice including pest management based on repeated insecticide use. It was comprised of 10 separate rice fields in which arthropods and frogs were monitored. Data from the multiple fields in each of the two management regimes were compared by appropriate inferential statistical tests. While this design does not constitute a formal, randomized, replicated design, the scale and reality of the testing conditions do provide a valuable test of the practicability of various ecological engineering methods and a broad indication of the effects on key taxa as well as the ultimate need for insecticide use.

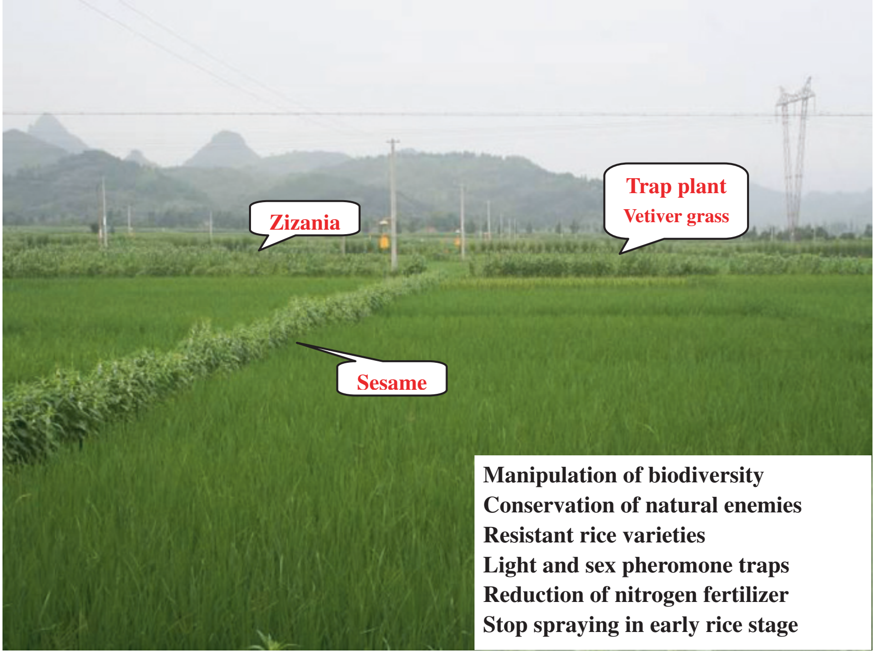
8.3.2 Major Strategies of Ecological Engineering

8.3.2.1 Intervention Conservation and Manipulation of Biodiversity

In the intensified rice-based agricultural production ecosystem, non-crop habitats had been greatly reduced, resulting in the simplified agricultural landscapes and farmland ecosystem. The sharp reduction of biodiversity has weakened the role of natural enemies in pest management. Our primary strategy was to conserve the native arthropod natural enemies by planting with green manure in fields at winter, leaving grasses on the bund and roadsides at other times of the year, growing sesame on the bunds during the rice-cropping season, and inter-planting with *Z. caduciflora* as the overwinter habitat for parasitoid hosts as well as arthropod predators and frogs (Zheng et al. 2003). Sesame was grown on the bunds of rice fields before rice transplanting (Pic. 8.1) and new plantings after 1 month of rice transplanting so as to ensure flowering plants were present at all rice growth stages.

8.3.2.2 Intervention Rational Fertilization

Overuse of chemical fertilizer, especially nitrogen fertilizer, has triggered the outbreak of some rice insect pests and diseases (Lu and Heong 2009). We improved



Pic. 8.1 Design of experimental demonstration of ecological engineering in Jinhua

Table 8.3 Dynamics of rice planthopper population at different rice stages in fields with three controls fertilizer application strategy (per hill rice)

Rice variety	Chunyou 84		Zhejing 88	
Treatments	Three controls	CK (traditional)	Three controls	CK (traditional)
Seedling	0.73	0.95	0.58	0.40
Tillering	0.30	0.18	0.17	0.15
Booting	0	0.15*	0.03	0.73*
Milking	0.15	6.73*	0.65	7.98*

*Significantly high of rice planthopper population at $p < 0.05$

rice tolerance to adverse environmental factors and reduced population growth rate by increasing organic fertilizer and proportion of P and K fertilizers while reducing nitrogenous fertilizer. In fact, we were employing the "Three Controls" (control the amount of fertilizer, control the number of rice seedlings per hill, and control the occurrence of pests) fertilizer application strategy, optimizing total nitrogen amount for improving nitrogen utilization efficiency, and minimizing pest population and pesticide usage (Zhong et al. 2012). Field experiment indicated that the population rice planthoppers can be strongly suppressed after rice booting stages by three control fertilizer application strategy (Table 8.3).

8.3.2.3 Intervention: Management of Stem Borers by Non-pesticide Methods

Striped stem borer (*Chilo suppressalis*) regularly occurs in all rice growing stages in Jinhua and causes dead heart at rice tiller stage and white head at booting stage. Farmers spray with wide-spectrum pesticides to control stem borers in early rice stage; consequentially, spiders and other natural enemies were killed, resulting in frequent planthopper outbreaks. Reduction of pesticides in early growth stages is one of key strategies of sustainable management of rice planthoppers by enhancing biological control (Heong 2009; Gurr 2009). Laboratory and field experiments showed that stem borer *C. suppressalis* adults are strongly attracted to lay eggs on vetiver grass (*Vetiveria zizaniodes*) (Pic. 8.2 and Fig. 8.2), but they cannot complete their life cycle on this plant (Fig. 8.3). Accordingly, we planted vetiver grass as a trap plant on some margins of the rice fields to serve as a trap crop for stem borers. During stem borer adult flight periods, we set up 20 sex pheromone traps and 1 light trap (Pic. 8.1) per hectare to complement the trap plants.

8.3.3 Results

Results indicated that both predators and parasitoids significantly increased in density in the ecological engineering fields (Fig. 8.4). Numbers of *Anagrus*

Pic. 8.2 Trap plant on the rice bund to attract stem borer adult to lay eggs

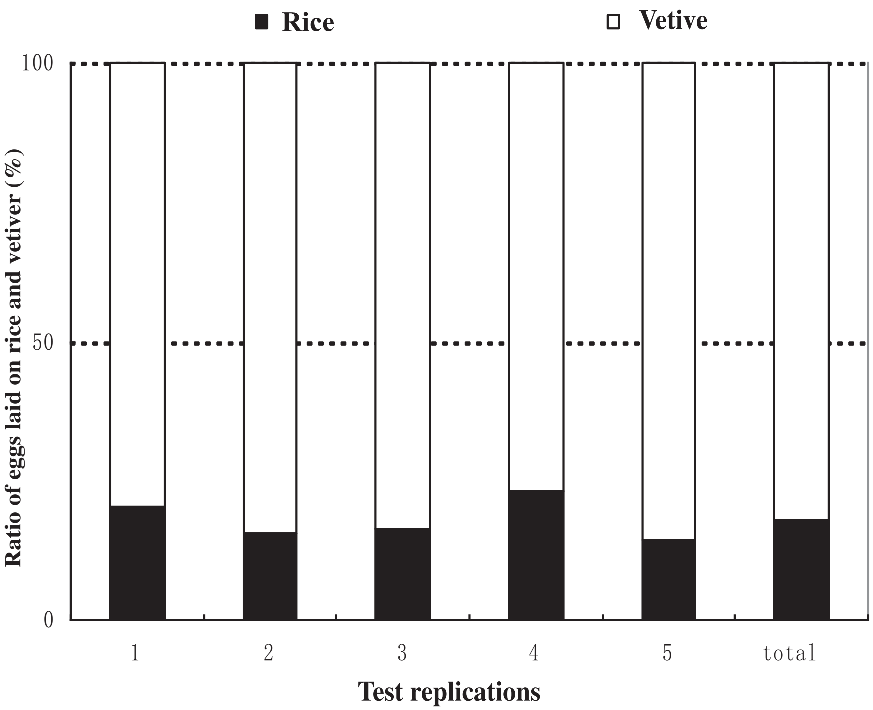


Fig. 8.2 Oviposition selection of *Chilo suppressalis* between rice and vetiver grass. From Zheng et al. (2009)

spp. in the ecological engineering fields were four times higher than in the control fields. Differences were especially great in samples taken after pesticide application in the farmers' fields (Fig. 8.5). The number of invertebrate predators including damselfly was significantly higher in ecological engineering area than the farmers' fields (Fig. 8.6). Frogs too were much more abundant in ecological engineering area than control plots (Table 8.4). In contrast to the ecological engineering fields, conventionally managed fields required several sprays to control escalating numbers of planthoppers, when the number of planthoppers in the ecological engineering fields remained low. For example, the damage by brown planthopper was moderate in 2010, and a pesticide application was made for planthoppers in the ecological engineering fields due to the late immigration, while 4 applications were applied in the farmers' fields (Fig. 8.7). As a result, ecological engineering practices reduced the amount of insecticides by more than 75 %, but the yields in both areas with ecological engineering and farmer practices were above 10 t per ha. There was no significant yield loss in ecological engineering field (10.02 t/ha) compared with yields in farmer fields (10.27 t/ha); meanwhile, famers obtained about 120US$/ha extra income from sesame seeds harvested on the bound and saved about 150US$/ha cost for insecticide

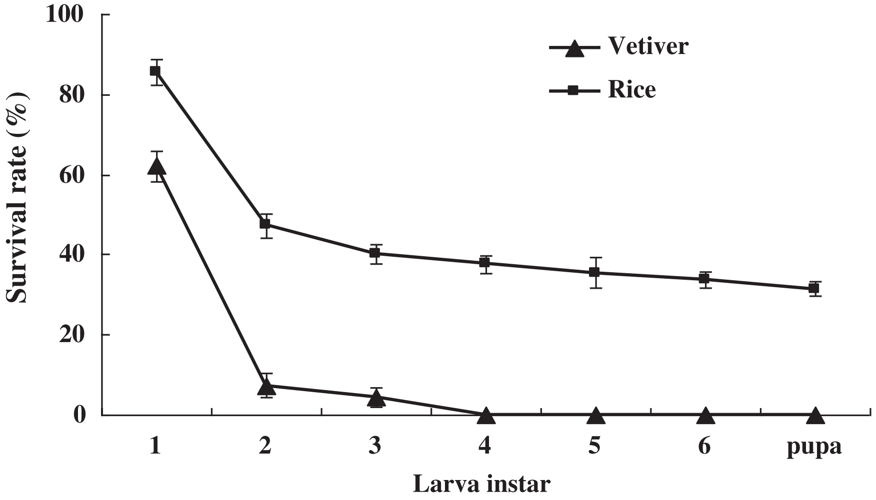


Fig. 8.3 Survival of *Chilo suppressalis* larvae on rice and vetiver grass. From Zheng et al. (2009)

application. Chemical pesticides were not used at all for controlling rice planthoppers in ecological engineering areas in 2009 and 2011. Similar positive results were observed also in similar sites located at Ningbo and Xiaoshan, Zhejiang province, China.

8.4 Opportunities and Prospects for Ecological Engineering in China

Over 100 pest species cause heavy economic losses in China affecting on between 400 and 467 million hectares each year. China initiated integrated pest control in 1953 and in the mid-1970s established a national professional policy for integrated pest management (IPM) (Guo 1998). The key strategy implemented was integrated management with an emphasis on pest prevention and more strategic use of pesticides (Xia 2008), and this developed into the adoption in China of “Green Plant Protection” (Fan 2006). Since 2013, ecological engineering has been recommended as one of the key strategies for sustainable management of rice pests by the National Agriculture Technology Extension and Service Centre (NATESC) of Ministry of Agriculture. It is the time to widely disseminate knowledge and further extend techniques of ecological engineering for substantially minimizing pesticide usage in rice-based ecosystem.

Pest control by ecological engineering practices developed from earlier habitat manipulation and biological control efforts into a rigorous branch

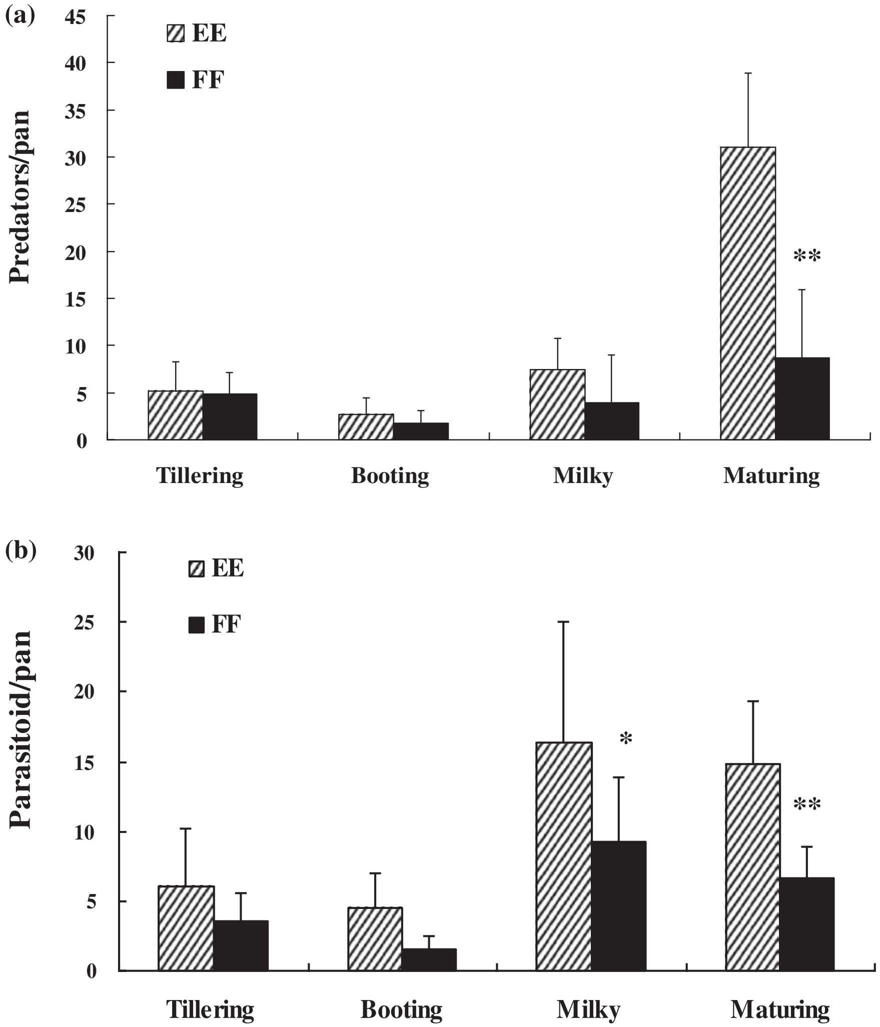


Fig. 8.4 Numbers of predators (**a**) and parasitoids (**b**), sampled by *yellow pan trap* (*EE* = ecological engineering field; *FF* = farmers' field)

of applied ecology (Gurr et al. 2004a, b). Its application has advanced briskly in China, especially in rice production (Gurr 2009; Gurr et al. 2011, 2012a, b; Heong 2011; Heong et al. 2013; Zhu et al. 2013a, b). The experimental demonstration of ecological engineering in Jinhua was a successful case; however, we have to be prepared to adapt the methods that have so far proven effective. Rice varieties will inevitably change, pests may adapt to phenomena such as vetiver grass trap crops, and new pests may emerge. Accordingly, understanding the general principles of ecological

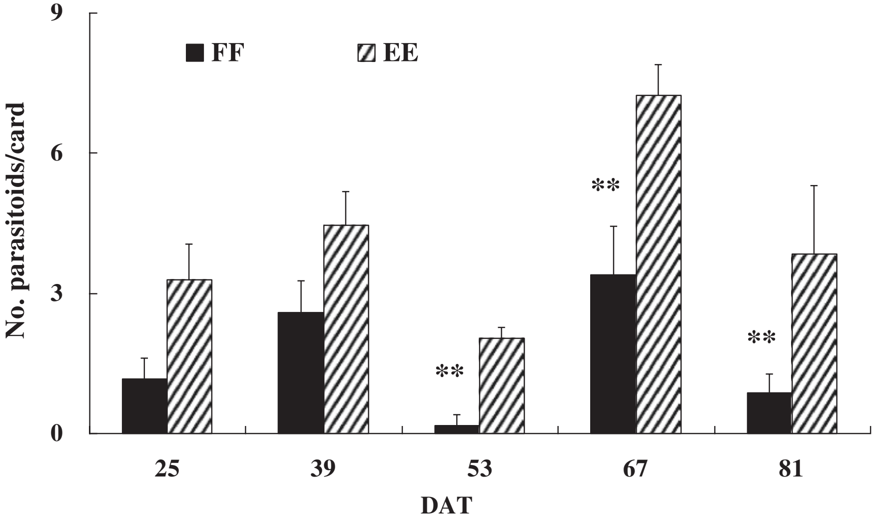


Fig. 8.5 Number of *Anagrus* spp. sampled by yellow sticky board (*EE* = ecological engineering field; *FF* = farmers' field; *DAT* = day after transplanting

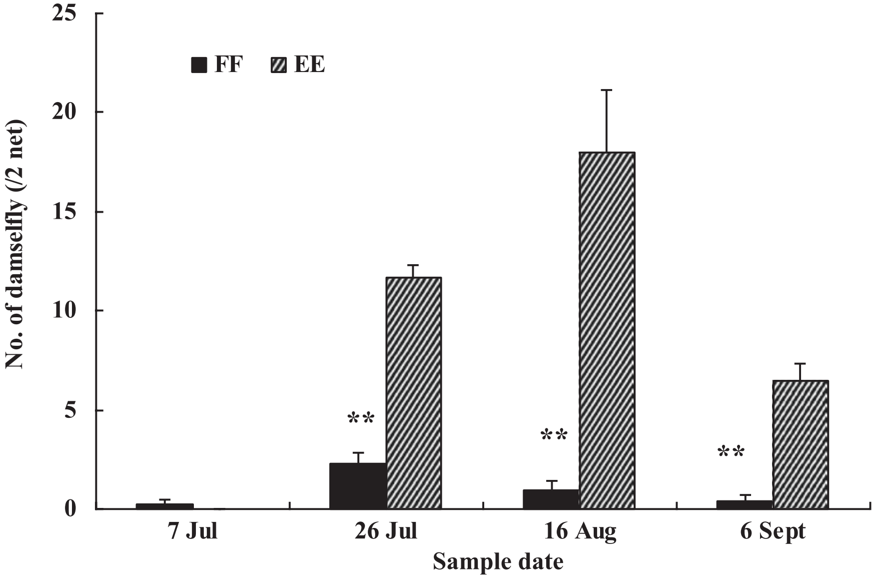


Fig. 8.6 Number of damselfly collected by sweep net (*EE* = ecological engineering field; *FF* = farmers' field)

Table 8.4 Number of frogs at rice booting stage in Jinhua (per 667 m^2)

Rice stage	*Rana limnocharis*		*Rana nigromaculatta*	
	EE fields	Farmer fields	EE fields	Farmer fields
Booting	32.67 ± 3.26a	6.67 ± 2.81b	2.20 ± 0.98	0.67 ± 0.67 ns
Milky	46.33 ± 6.28a	7.35 ± 3.51b	5.32 ± 2.1	2.01 ± 1.43 ns

Values are mean ± SE. Means within a row followed by differing letters are differ significantly at $p < 0.05$. Tukey's test was used

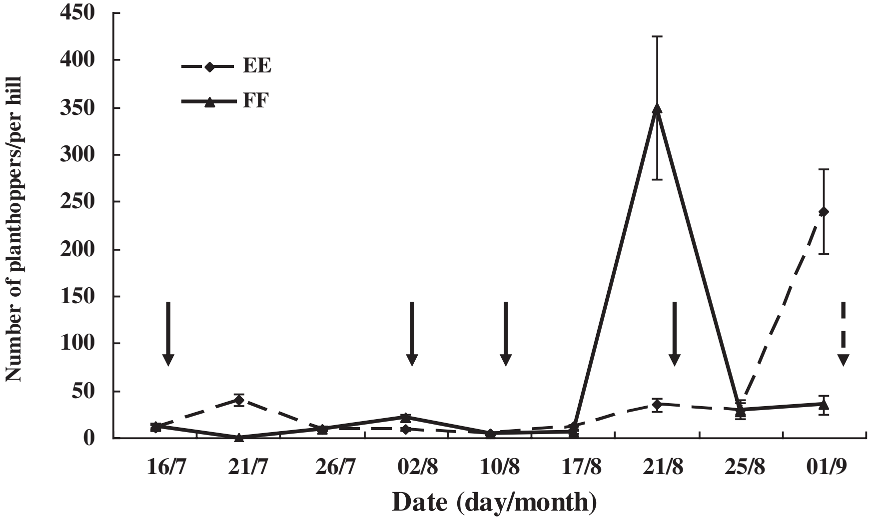


Fig. 8.7 Comparison of population dynamics of rice planthoppers between EE and FF rice fields in 2010 (*EE* = ecological engineering field; *FF* = farmers' field; *solid tips* show the time spraying for rice panthoppers in farmers' fields, and *dotted one* means spraying in ecological engineering fields)

engineering and being prepared to adapt the specifics of nectar plant, trap crop species, and so on are the key to the sustainability of this approach.

Finally, there is excellent scope to build on the initial successes in rice to develop ecological engineering strategies for the pest complexes of other crops such as tea plantations and vegetable gardens. We are certain that, with the Chinese government attaching great importance to the development sustainable agriculture, ecological engineering for pest control will develop rapidly and become a still more prevalent pest management strategy in the future.

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Chapter 9
Are There Productivity Gains from Insecticide Applications in Rice Production?

Kong Luen Heong, Monica M. Escalada, Ho Van Chien and Joy Hasmin Delos Reyes

Abstract Insecticides have always been viewed to be necessary inputs to achieve high rice production. However, this notion has been challenged by ecologists and economists and they have shown that Asian farmers' insecticide use has poor or no productivity gains. Farm surveys of more than 5,000 households in the Mekong, Vietnam, and paired farmer experiments showed that farm yields were not correlated with the number of insecticide sprays used in most cases. In the paired experiments plots, there was no significant correlation between yield and number of sprays in both plots. A survey of farms in a rice planthopper outbreak area showed that farms that had applied insecticides in the early crop stages for leaf folder control had higher probability of heavy planthopper attacks or "hopper burn." The reasons why rice farmers had continued to apply insecticides despite of the poor productivity gain might be due to their misperceptions that lead to overestimate losses caused by insects, the aggressive marketing of pesticides that heightens their loss aversion attitudes thus making them victims of insecticide abuse. Rice farmers appear to be "locked into" circumstances that continue to promote insecticide use despite the lack of productivity gains. With health costs from both acute and chronic long-term impacts and environmental costs especially in causing bee and bird mortalities, scientists and policy makers need to rethink future pesticide management strategies to avoid pesticides becoming a threat to food security instead.

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Keywords Productivity gains · Externality cost · Insecticides · Yield loss · Marketing regulatory frameworks

9.1 Introduction

Pests have been viewed as major yield constraints to rice production and insecticides as necessary inputs. All the herbivores in rice ecosystems are considered undesirable, damaging and contributing to production loss. This thinking is probably derived from the general agronomic view that any reduction in leaf area will affect photosynthesis and production. There are more than 100 herbivore species that feed on rice, and most of them causing slight damages, and probably less than 10 species can occasionally capable of causing sufficient economic loss and only when their populations are high. Yield loss estimates from research range from none to 50 % depending on the conditions the experiments had been carried out. In 117 experiments conducted over 15 years at the International Rice Research Institute (IRRI), Pathak and Khan (1994) found that field plots "protected from insects" which meant sprayed frequently at weekly intervals yielded almost twice as much as the unprotected plots. The data sets were from experiments done when insecticide sprays in IRRI carried out at weekly intervals and rice was planted asynchronously. From 1993, insecticide use in IRRI farm was systematically reduced, and from 2009, insecticide use had reduced by 96 % and no significant yield reductions had been reported (Heong et al. 2007). Instead, the biodiversity of all arthropod functional groups such as the herbivores, predators, parasitoids, and detritivores increased significantly. Pesticide use of farm chemical inputs declined between 1993 and 2006. The amount of pesticide active ingredients (ai) used fell from 6.86 to 0.86 kg ai/ha/year, a reduction of 87.5 %. The analysis also showed that the main pesticides used were insecticides and these declined from 3.79 kg ai/ha/year in 1993 to 0.16 kg ai/ha/year in 2006, a reduction of 95.8 %.

Arthropod biodiversity grouped by guilds in 2005 increased when compared with that of 1989. Species richness of all four guilds was significantly higher. There were twice as many species of herbivores, about 48 more species of predators and parasitoids and greater than 5 times more species of detritivores. There were more species of herbivores such as thrips, plant lice, beetles, and hoppers present in 2005, but not in 1989. Since these were minor pests, they probably function more as food for the generalist predators. Predator species were enriched by a greater diversity of generalists such as spiders, hemipterans, and beetles. There were more hymenopteran species in 2005 than in 1989, particularly trichogrammatids, mymarids, and scelionids. Species richness of detritivores was markedly increased in 2005, especially of dipterans and collembolans. The arthropod composition structure in the two years' samples changed considerably. Proportionately herbivores were more abundant in 1989 (46 %) than in 2005 (12 %), predators were lower than in 1989, 40 % compared to 58 %, and detritivores were also lower in 1989, 8 % compared with 26 %. Parasitoids were, however, slightly higher, 6 % in 1989 compared with 4 % in 2005. The reduction of insecticides in IRRI farm had contributed significantly to the restoration of arthropod biodiversity as well as the community structure to a more "stable" state (Heong and Schoenly 1998).

During the Green Revolution of the 1970s and 1980s, insecticides had been introduced into rice production as a necessary input to achieve optimal yields. Prophylactic spraying campaigns were mounted in rice intensification programs such as the Masagana 99 in the Philippines and BIMAS in Indonesia (Heong and Schoenly 1998). Routine spraying programs were also introduced into China, India, Thailand, Bangladesh, Vietnam, South Korea, and several other Asian countries often with government subsidized pesticides and loan schemes (Conway and Pretty 1991). The pesticide industry with their aggressive advertising and market schemes played a strong role in encouraging farmers to use pesticides.

The notion that insecticides are always needed for high yields in rice production was challenged by Way and Heong (1994), and they argued that "rice pest management should be based on the contention that insecticides are NOT needed rather than they are and only to be used when pests are 'guilty' and only as the last resort." Economists (Herdt et al. 1984; Antle and Pingali 1994; Pingali et al. 1997) have also argued that there were hardly any productivity gains from insecticide applications in rice production. When health cost is factored in, it overwhelmed all gains (Pingali et al. 1997). These conclusions were obtained from experiments carried out in the IRRI experimental farm and in researcher-managed farmer plots, where insecticide applications were carefully administered. When they compared (i) fields with no sprays (or natural control), (ii) farmer practice of two routine sprays, (iii) integrated pest management (IPM) using thresholds, and (iv) maximum protection of six sprays, they found that (i) natural control had higher productivity than all the other practices. IPM had the lowest productivity gains when monitoring cost was factored in. Insecticide application efficiency of farmers is generally poorer because their equipment generally has poor spray droplet delivery and farmers often use the wrong types of chemicals and sprayed at the wrong times. An analysis of Philippines farmers' insecticide sprays showed that 80 % of their sprays were misused and unlikely to be effective (Heong et al. 1995). Instead, the insecticide applications of farmers destroy valuable ecosystem services and render the rice crop more vulnerable to secondary pest outbreaks, such as the rice planthoppers (Heong 2009; Bottrell and Schoenly 2012). This raises the question "Are there productivity gains by farmers using insecticides?" In this chapter, we further explore this question using some farm survey data obtained from the Mekong Delta in Vietnam.

9.2 Insecticide Application–Yield Analyses from 8 Farm Surveys

We used 8 farm survey data sets obtained in three provinces in the Mekong Delta between 2002 and 2012 (data from Escalada et al. 2009) and explored the relationships between farmers' insecticide applications and yields. Yields and insecticide applications from a total of 5,410 farmers were collected using a standard structured pretested questionnaire. Yields from farms with the number of insecticide applications were computed and compared using ANOVA (Table 9.1). There was no significant difference in farm yields in 5 out of the 8 surveys, and 3 had significant difference at 5 % level. In the Tien Giang Province 2003 data, yields of farms with 5 and 6 insecticide applications were significantly higher than that with no application. Similarly, in the Tien Giang Province 2010 survey, farms with 6 applications had the highest average yield which is significantly higher than farms with 7 applications but not significantly higher than farms with no applications. In the An Giang Province 2011 data, farms with zero and 6 insecticide applications had higher average yields than farms that had 7 applications.

The yield–insecticide application relationships were further explored using regression analyses. Table 9.2 shows regression analyses statistics and the

Table 9.1 Farm insecticide applications and summer–autumn season yields (t/ha) in Tien Giang, Can Tho, and An Giang provinces between 2002 and 2012

Province	Tien Giang				Can Tho		An Giang	
Year	2003	2004	2010	2011	2002	2003	2011	2012
Sample size	550	630	504	504	788	904	548	550
Mean sprays	3.03	2.13	1.99	1.75	1.62	2.37	3.32	3.19
0 application	4.34	5.00	7.43	6.40	4.60	6.20	7.43	6.40
1	4.51	5.12	6.69	6.93	4.71	5.76	6.69	6.93
2	4.44	5.08	6.65	6.68	4.67	5.85	6.65	6.68
3	4.49	4.89	6.74	6.83	4.62	5.82	6.74	6.83
4	4.40	5.11	6.58	6.84	4.69	6.09	6.58	6.84
5	5.21	4.84	6.86	6.63	5.06	5.77	6.86	6.63
6	5.04	4.98	8.27	6.75	5.72	6.02	8.27	6.63
7	4.56	5.00	5.50	6.75	–	5.57	5.50	6.75
8 and more	4.93	4.70	–	–	5.50	5.18	–	8.2
F value	1.99	1.43	2.52	1.70	1.22	1.73	2.52	1.70
Probability	0.03*	0.16 ns	0.02*	0.10 ns	0.29 ns	0.08 ns	0.02*	0.10 ns

* means significant at p = 0.05, ns = not significant

Table 9.2 Regression analyses of yield–insecticide application relationships in Tien Giang, Can Tho, and An Giang provinces between 2002 and 2012

	F value	Probability	Significance	Regression coeff.
Tien Giang 2003	8.54	<0.01	Highly significant	+0.123
Tien Giang 2004	2.43	0.12	Not significant	–0.062
Tien Giang 2010	0.04	0.84	Not significant	+0.009
Tien Giang 2011	1.35	0.25	Not significant	+0.055
Can Tho 2002	4.23	0.04	Not significant	+0.073
Can Tho 2003	8.81	<0.01	Highly significant	–0.098
An Giang 2011	20.24	<0.01	Highly significant	–0.135
An Giang 2012	0.21	0.65	Not significant	–0.020

regression coefficients. Three of the 8 data sets had highly significant regression, two had negative coefficients, and one was positive. The positive coefficient of 0.123 predicted an average increase of 123 kg of paddy from each insecticide application. Based on the farm gate paddy price of US$0.22/kg and the average cost of an insecticide application of US$20, the gain would have been US$7/ha. On the other hand, the negative coefficient of 0.135 predicted that there was a loss of 135 kg or US49/ha (US$29 from paddy loss plus US$20 for each application). When labor and health costs were factored in, the gain of US$7/ha in the positive coefficient case would be wiped away and in the negative coefficient case loss would be further exaggerated (loss of > US$50/ha).

The analyses suggested doubtful productivity gains from farmers' insecticide applications. Farmers would be better off if they were to completely avoid insecticides and conserve ecosystem services that will reduce farms' vulnerability to secondary pest outbreaks like the planthoppers that could cause crop failures. The analyses further supports FAO's declaration that "Most tropical rice crops under intensification require NO insecticide use" (FAO 2011 and Way and Heong's 1994) conclusion that rice pest management should be based on the contention that insecticides are NOT needed and only to be used when pests are 'guilty' and only as the last resort.

9.3 Paired Farmer Experiments

During the rice seasons of 2001 and 2002, rice farmers from 35 villages in the Mekong Delta were invited to participate in evaluating practices with reductions in the seed rates for crop establishment, nitrogen rates, and insecticide sprays (Huan et al. 2005). This led to the introduction of the "Three Reductions, Three Gains" (Ba Giam Ba Tang in Vietnamese) program supported by the Ministry of Agriculture and Rural Development that spread to all rice growing areas (Huan et al. 2005; Heong et al. 2010) and had significant impact on farmers' incomes (Huelgas and Templeton 2010). Volunteer participants divided their fields into two portions and implemented "three reductions" practices by reducing (i) seed rates, (ii) nitrogen rates, and (iii) insecticide sprays in one portion (experimental plot). Table 9.3 shows that participating farmers had slightly higher average yields in their experimental plots in both rice seasons. The average difference in yields in the paired plots for the winter–spring (W–S) season was about 0.15 t/ha, in the summer–autumn (S–A) season, yield differences were about 0.08 t/ha,

Table 9.3 Average yields (t/ha) of farmers' experimental and control plots in paired experiments conducted by volunteers in 2001 and 2002 in the Mekong Delta, Vietnam

Seasons	Sample size	Experimental plots	Control plots
Winter–Spring 2001–2002	520	6.46	6.30
Summer–Autumn 2002	431	4.77	4.69

and insecticide use were reduced by 78 % in the W–S season and 77 % in the S–A season. Since these were paired experiments in the same fields using the same varieties and basic agronomic practices, except for those introduced in the "three reductions" program, yield differences can be attributed to these practice modifications. Among the three input modifications, insecticide reductions made the highest contribution to the increase in gross margins (Huan et al. 2005). This supports the notion that insecticides are not necessary inputs to secure yields.

9.4 Insecticides Increase Vulnerability of Rice Crops to Planthopper Pests

A survey of 148 rice farmers in the Mekong Delta, Vietnam, where planthopper outbreaks had occurred was conducted. We found that farms that had received insecticide sprays in the early crop stages were 10 times more vulnerable to crop failures caused by severe planthopper attacks known as "hopperburn" (Fig. 9.1). Farms that used insecticides to control leaf folders had higher probability (86 %) of "hopperburn" than those that did not (8.1 %). Two-thirds (66.9 %) of the farmers reported hopperburn in their fields and had significantly higher insecticide sprays (4.44 sprays) and lower yields (5.45 t/ha) than those with no hopperburn (1.67 sprays and 6.45 t/ha, respectively). Farms that received their first insecticide sprays in the first 40 DAS (54.7 %) were most vulnerable to hopperburn as 91.4 % of these farms had hopperburn.

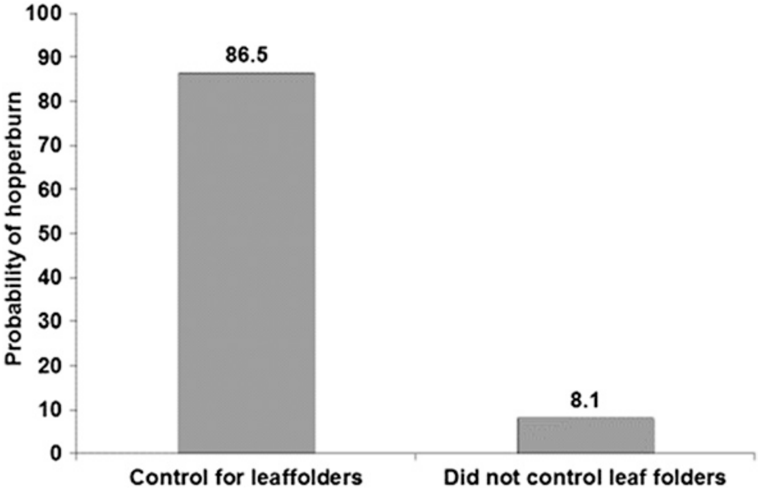

Fig. 9.1 Farms that had sprayed for leaf folders in the early crop season had higher probability to hopperburn than farms that had not sprayed for leaf folders

Those who did spray insecticides in the early crop stages were using insecticides, such as pyrethroids, chlorpyrifos, and other organophosphates. Most of these insecticides have high toxicity to natural enemies and made crops vulnerable to planthopper outbreaks (Heong and Schoenly 1998). Leaf damages caused by these pests although highly visible to farmers had negligible impact on yields because of plant compensation (Graf et al. 1992). Ecological research had shown that arthropod food webs start establishing early in the crop seasons and arthropod biodiversity reached the asymptote at about 40 days after crop establishment (Heong et al. 1991). Insecticide sprays at the early crops stages, disrupt the food web structure by reducing the food chain length from 3 to 2 (Cohen et al. 1994), and disorganized the normal predator–prey relationships. Rice fields under such conditions where biological control ecosystem services have been compromised (Heong 2009) would tend to be more vulnerable to planthopper outbreaks as immigrating adult hoppers would experience lower mortality. Figure 9.2 illustrates the phenomenon that when planthoppers which are typically r-strategists (Southwood and Comins 1976) when released from natural biological control would multiply exponentially to more than a thousand folds as observed by Kenmore et al. (1984).

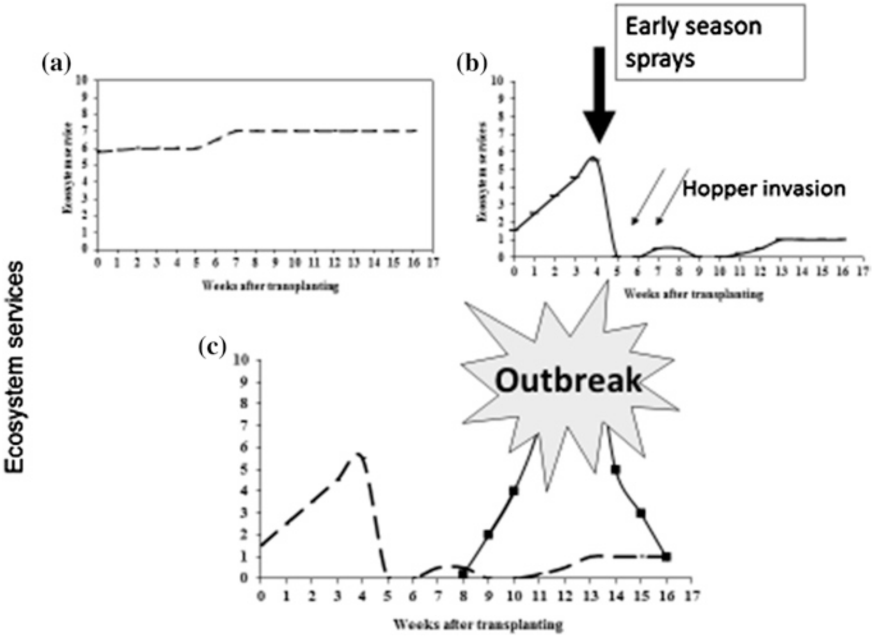

Fig. 9.2 Ecosystem services in rice fields develop normally (**a**). When insecticides are sprayed in the early season, ecosystem services are destroyed, thus making the fields vulnerable to invading planthoppers (**b**). Planthopper populations during the vulnerable period have less constraints and develop into outbreak proportions (**c**)

9.5 Why Farmers Continue to Spray if There Are No Gains?

Insecticides were packaged into Green Revolution technologies introduced as development assistance programs to Asia in the 1970s and 1980s. Rice farmers were urged to spray their crops once a week (often known as “Monday–Monday” or “Seven–Seven” in the Philippines) in the rice intensification programs (Heong and Schoenly 1998). In Indonesia, the government subsidized 80 % of the insecticide cost spending as much as US$150 million per year (Gonzales et al. 1993). It was not until 1986 that the subsidies were gradually removed following a presidential decree InPres 3/87 that banned 57 insecticides (Matteson 2000). Insecticide use in Indonesia dropped primarily because of the subsidy removal resulted in higher costs (Gonzales et al. 1993). IPM was later introduced and millions of farmers were trained to recognize predators and to use insecticide only when necessary. However, insecticide use in Indonesia has escalated in the last 10 years (Heong et al. 2013) and this might be in part due to the aggressive marketing strategies of the pesticide industry to sell pesticides as fast moving consumer goods (FMCG) such as tooth paste and soap.

In examining the paradox that despite the lack of productivity gains and externality costs, farmers had continued to use insecticides (Wilson and Tisdell 2001) had referred to this as “locked-in” circumstances farmers seem to face. Farmers also tend to overemphasize the importance of insects, especially the highly visible ones (Bentley 1989). For instance, leaf damages by leaf folder larvae in the early crop stages with highly visible symptoms and thus high proportion of farmers spray against these leaf feeders (Heong and Escalada 1997). However, these damages inflicted on rice crops at the early stages do not translate into crop loss (Heong 1990; Litsinger 1991). Farmers tend to overestimate losses caused by insect by more than 10 folds (Heong and Escalada 1999). In addition, farmers tend to associate pesticide use with modernism (Kenmore et al. 1985) and thus make them vulnerable victims of pesticide misuse. Furthermore, weak pesticide marketing regulatory frameworks had allowed pesticide companies to entrap farmers by pushing sales through aggressive advertising and promotion to create bias in favor of use (Tisdell et al. 1984). Pesticide companies use sales reward incentives such as electrical appliances, holiday trips, and even trips to Mecca to push sales. These practices violate FAO’s International Code of Conduct for Pesticides Distribution (FAO 2003) but are rampant especially in countries where the regulatory frameworks for pesticide marketing are lacking or weakly implemented (Heong et al. 2013). Insecticides are being sold as fast moving consumer goods under numerous trade names through multi-tier marketing by agents at the village levels in the supply chain. For instance, the insecticide ingredient imidacloprid is sold in more than 500 trade names in China. Such unregulated marketing of pesticides further heightens farmers’ loss aversion attitudes, and they had become victims to insecticide misuse. In some cases, agricultural extension officials were earning extra cash from chemical companies by promoting the use of their insecticides. In some provinces of China, agricultural extension agents were generating most of their salaries and office operating costs through pesticide sales (Hamburger 2002), and in Vietnam, extension staff earned extra money by selling inputs to farmers and thus tend to bias the information they provide (McCann 2005).

At the beginning of the chapter, we raised the question “Are there any productivity gains from farmers’ insecticide use?” Economists showed that gains from insecticide use in rice production are small and with health and environmental costs factored in most of this is wiped out (Pingali et al. 1997). Insecticides impact human health by acute poisoning after direct exposures that might require immediate medical attention and by chronic health problems caused by sub-lethal doses. As insecticides are neurotoxins, they have similar neurotoxic effects on insects, birds, mammals, and humans. While the acute toxicity of insecticides on humans are alarming, chronic effects of insecticides in low dosages are lesser known. Some recent research are now linking pesticides that are neurotoxins with Parkinson’s and Alzheimer’s diseases (Casida and Durkin 2013), autism, attention-deficit hyperactivity disorder (ADHD), and low IQ in children through prenatal exposures (Bouchard et al. 2010). Insecticides are also linked to the decline in bees (Stokstad 2013) and other non-target species such as birds (Caspar et al. 2014), amphibians, fish, and aquatic arthropods (Van Dijk et al. 2013). The work of Antle and Pingali (1994) discussed the health costs related to direct poisoning cases with less attention paid to long-term health effects. Factoring long-term health effects will further raise the negative productivity of farmers’ insecticide use in rice production. Insecticides may even be a threat to food security. A comprehensive assessment of the real productivity gains from farmers’ insecticide use is now needed for scientists and policy makers to rethink and develop pesticide management policies and structures.

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Chapter 10
Social Impacts of Planthopper Outbreaks in Thailand

Monica M. Escalada, Manit Luecha and Kong Luen Heong

Abstract The widespread planthopper outbreaks that had occurred in Asia, especially in central Thailand during the 2010–2012 crop seasons resulted in severe crop losses to rice farmers. Thousands of farmers have been affected by this insecticide-induced pest problem. A study to address the social impacts of pest outbreaks on rice farmers was conducted to better understand the social implications of losses from pests on the rice farming communities. Planthopper outbreaks started in 2007 and had occurred annually in the last 4 years, all the farmers interviewed had had at least one outbreak. Losses were higher in Ang Thong and Suphan Buri, 4.3 t/ha, while farmers in Chainat suffered losses of 3.5 t/ha. Adaptation strategies after the BPH outbreak ranged from replanting their rice farm, planting ahead of their neighbors, planting synchronously with other farmers, pursuing other income sources, and planting a different variety, to borrowing money to pay off debts. Specific household adjustments that farmers did to cope with crop losses included reducing their household expenses, reducing their purchases, giving up recreational activities, and cutting down on household costs such as electricity consumption. Most respondents' adaptation response centered on insecticide use—to look for a more effective insecticide and to borrow money to buy more insecticides. Farmers' coping mechanisms included loan repayment schemes, reduction in household spending, and starting an alternative income source. To help farmers reduce their use of abamectin and cypermethrin, a media campaign was launched with support from the private sector. The campaign had worked in creating awareness and had immediate effects on farmers' newly formed beliefs and practices.

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Keywords Social impacts · Brown planthopper outbreaks · Hopperburn · Coping strategies · Campaign

10.1 Introduction

Planthopper outbreaks have been threatening rice production in Asia in the last 10 years (Cheng, Heong et al., this volume) and is especially heavy in Central Thailand where farmers had been suffering from outbreaks in the last 10 seasons. The direct damages and the virus infections that followed had destroyed about 2 million hectares of paddy. Thousands of farmers have been affected by this insecticide-induced pest problem (Bottrell and Schoenly 2012) and in an attempt to solve this "wicked problem," the Rice Department established the BPH management policy engagement working group to initiate socioeconomic impact assessments of the outbreaks. A study to address the social impacts of pest outbreaks on rice farmers is one of the first attempts to better understand the social implications of losses from pests on the rice farming communities.

In June 2011, the Rice Department working with the Thai Agro Business Association (TABA) launched a media campaign to stop the use of cypermethrin and abamectin in rice as they cause BPH resurgences. In an international panel held in June, the majority of the participants agreed that BPH problems are insecticide-induced and called for immediate actions to control insecticides being marketed as fast-moving consumer goods (FMCGs). The Action Plan developed by IRRI in September 2011 had been presented to senior officials of Ministries of Agriculture of the ASEAN.

From 2008 to 2012, the rice bowl of Thailand in the Central Plains suffered from persistent planthopper outbreaks for 10 consecutive seasons. The Office of Agricultural Economics (OAE) in the Ministry of Agriculture and Cooperatives of Thailand reported that outbreaks causes losses worth $52 million or the equivalent to about 173,000 tons during the dry season of 2010. In 2009, planthopper outbreaks were reported in many countries in Asia. The most seriously damaged areas were the Central Plains of Thailand and northern Vietnam-Yunnan of China. BPH damage in Thailand caused the government to revise its production forecast by 16 % from 8.3 million to 7 million tons. Thousands of farmers lost their crops and the Thai government released 2 billion baht (US$60.5 million) to compensate farmers for their losses. The amount to be given per farm was hardly sufficient to support land preparation for the next crop. In addition, the government also released approximately $1.8 million for free pesticide distribution.

Starting in March 2011, huge populations of the BPH infested rice fields in Ayutthaya, Chai Nat, Suphan Buri, Ang Thong, Sing Buri, and Pathum Thani provinces destroying thousands of hectares. In March 2011, damages reported from 11 provinces affected 104,000 ha and further hopper outbreaks would seem inevitable. Numerous farms in the northern provinces, such as Phitsanulok, were heavily infested. Most rice areas in the Central Plains continue to remain vulnerable to hopperburn because of intensive cropping, continuous planting of a few varieties that BPH has become adapted to, high seed and fertilizer rates, and high use of prophylactic insecticide applications. Perhaps among the vulnerability factors insecticide misuse is the major contributor to the crop yield instability. Most farmers continue to rely on the local pesticide retailer for advice and were told to mix insecticides with BPH resurgence causing properties, such as cypermethrin, abamectin, and chlorpyrifos with herbicide sprays early in the crop season.

To reduce brown planthopper damage, Thailand's Rice Department has developed an integrated pest management initiative by promoting and facilitating best management practices, which includes stopping the use of insecticides such as abamectin and cypermethrin that significantly contribute to brown planthopper outbreaks. The $12.8 million initiative, which is supported by Thailand's Minister of Agriculture and Cooperatives Theera Wongsamut, was announced at Thailand's National Rice Conference. It aimed to:

- Multiply the seed of brown planthopper-resistant rice varieties to 15,000 tons and distribute this seed to Thai rice farmers.
- Establish in 20 provinces giant light traps that attract and catch brown planthoppers.
- Manage 300 brown planthopper community centers and communication campaigns across the country.
- Establish mobile units that will visit villages to promote best management practices to reduce the occurrence of brown planthopper outbreaks.
- Persuade farmers that they should stop using abamectin and cypermethrin because they cause outbreaks.

10.2 The "Stop Abamectin and Cypermethrin" Campaign

In cooperation with TABA, the campaign to stop the use of abamectin and cypermethrin in rice fields was a short-term measure to restore biodiversityBiodiversity and ecosystem services and reduce the outbreaks. Pesticides in Thailand are being sold like FMCGs (fast-moving consumer goods through thousands of detailers and sub-detailers that have shops at the village levels thus promoting misuse. We found that 86.2 % of the farmers purchased their insecticides from these shops. The campaign first launched in Bangkok was repeated in Chainat province with support from the provincial governor, Khun Chamlong Phasuk, to also introduce ecological engineering and "no insecticide use in first 40 days".

10.3 Social Impact of BPH Outbreaks

Most socio-economic impact assessments of crop failures have focused on extreme weather events such as drought and floods. Pandey et al. (2007) did a detailed cross-country analysis of the economic effects of drought and farmers' coping mechanisms.

Their analysis found that production losses varied according to land types which were found to be higher in the upland with a lower moisture-holding capacity. To recoup loss in income, farmers resorted to three main strategies: Selling productive assets, using savings, and borrowing. However, the coping mechanisms used by farmers were found to be inadequate to prevent a decline in income during the drought period.

Del et al. (2001) examined how the 1998 floods affected food security in Bangladesh at the national and household levels. The decline in crop production, losses of other assets, and lower employment opportunities contributed to increased food insecurity. The floods also led to a major deterioration in the quality of households' health environments. Households coped with the floods by reducing expenditures, selling assets, and borrowing. Borrowing was found to be the major coping mechanism of the households studied.

Alston and Kent's (2004) analysis of the social impact of droughts in Australia detailed its social impact on loss of income and high costs, workload issues, impacts on health in men, women and children, social capital, educational access, and employment. Alston (1996) reports that in times of drought, relative deprivation and *psychological poverty* occurs. Psychological poverty includes a lack of access to services, an increase in workloads and a withdrawal from community.

So far, no impact assessment of pest outbreaks in rice-growing environments has been done. To gain insights into the social impact of planthopper outbreaks on farming households, we conducted five focus group discussions and a farmer survey in Central Thailand.

10.4 Household Surveys to Understand Social Impacts

In July 2012, we conducted 5 focus group discussions with 120 farmers in Chainat, Ang Thong, and Suphan Buri provinces in Central Thailand. Focus group results were used to develop and streamline the survey questionnaire. In October 2012, we conducted a survey of 319 farmers n three provinces in Central Thailand—Chainat, Suphan Buri, and Ang Thong. Led by the OAE, the survey looked into details about the planthopper outbreaks—occurrence, perceived causes, magnitude of losses from the worst BPH outbreaks, and value of crop damages. More importantly, it explored farmers' coping mechanisms or adaptation response to outbreaks and household adjustments to cope with crop losses.

A half-day orientation session was held to discuss the purpose of the survey and familiarize the OAE survey team with the questionnaire, particularly, the pest management variables. After the questionnaire review, the OAE survey team pretested the questionnaire. Pretesting results were then used to further refine the Thai translation of technical terms used, particularly the differences between pests and insects, pesticides and insecticides.

Data entry, which was done concurrently with the survey field work, was supervised by two of us (M. Luecha and M. Escalada) to ensure that responses could be clarified while the interviewers were still in the field and to ensure a common understanding of the codes used.

Picture 1. Interviewing

Picture 2. Survey orientation

10.5 Analyses of Farm Household Surveys

10.5.1 Profiles of Farmer Respondents

A total of 319 respondent farmers from three provinces, Chainat, Ang Thong, and Suphan Buri were interviewed by five trained interviewers led by Khun Tiwaporn. The average ages of respondents ranged from 51.1 to 54.3 years with Ang Thong respondents slightly older (54.3) than those in Suphan Buri (52.5) and Chainat (51.1). Survey respondents were fairly distributed by gender, although there were slightly more male respondents from Suphan Buri (36.1 %). In terms of education, the average years of schooling 6.2 years (Table 10.1).

Farming experience reflected the average age of respondents, with a mean of 31.4 years. The overall mean irrigated rice area cultivated by respondents was 5.0 ha.

10.5.2 Crop Losses from the Most Severe BPH Outbreak

Planthopper outbreaks started in 2007 and in the last 4 years, all the farmers interviewed had had at least one outbreak. Most of the outbreaks occurred in 2009 (47 %) and 2010 (38 %). About 32 % of the farmers had two crop losses, 14 % had 3, 4 % had 4, and 13 % had 5 crop losses. Table 10.2 shows that in 2009, farmers lost on average about 3.7 t/ha due to damages by planthoppers. Losses were higher in Ang Thong and Suphan Buri, 4 t/ha and 3.8 t/ha, respectively, while farmers in Chainat suffered losses of 3.3 t/ha.

Table 10.1 Profile of survey respondents, Central Thailand, 2012

	Ang Thong		Chainat		Suphan Buri	
Characteristics	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Sample sizes	100		118		101	
Mean age	54.3		51.1		52.5	
Gender						
Male	57	34.7	49	29.5	60	36.1
Female	43	28.1	69	45.1	41	26.8
Education (years)	6.6		6.1		5.9	
Rice farming experience (years)	31.1		29.9		33.2	
Total irrigated rice area (ha)	4.7		5.1		5.2	

Table 10.2 Farmers' reported crop losses and value of the most severe BPH outbreak, Central Thailand

Variable	Ang Thong	Chainat	Suphan Buri	Overall
Crop loss (t/ha)	4.0	3.3	3.8	3.7
Value of crop lost (USD)	1200.36	906.28	1116.24	1074.29

Box 1. Farmers suffered heavy financial losses from BPH attacks

Mr. Vichian Insawang, 50, has been farming his 50 rai (8 ha) that he inherited for more than 30 years. In the 2010 wet season, he had planted Pathum Tani 1 in 3.7 ha and when he heard about planthopper attacks in the Northern provinces, he started spraying his fields with insecticides hoping to prevent attacks. He had sprayed his crop 10 times applying them in cocktail mixtures of a variety of products including abamectin, cypermethrin, chlorpyrifos, BPMC, and several others as he could not recall their names. These insecticides were recommended to him by the local pesticide shopkeeper. He spent about US$ 320–400 per ha in pesticide purchases and sprayed the fields himself. However, this resulted in losing more than 70 % of his harvest because his crop was badly destroyed by planthoppers and virus diseases. He only grossed about US$1250 which was insufficient to cover his input costs. He had borrowed or US$3100 at 6 % per annum interest and had no means to repay. When the Permanent Secretary of Agriculture who visited the area learned about his predicament, he requested the banks to extend credit, which they did, to farmers who had lost their crops. In addition, the government provided a US$440 per ha compensation grant and free seeds for the next season to allow their virus-infested fields to be plowed under by authorities.

When we asked him what he would do to avoid loss in the next season, Mr. Vichian said that he would be more vigilant which might probably prompt him to begin insecticide applications early in the season. Mr. Vichian's field the following season was similarly attacked by BPH and likely to incur low yields. Mr. Vichian is one of the thousands of rice farmers in Central Thailand in the same predicament. They rely only on pesticides for pest management and use them in a prophylactic manner which predisposes their crop to invading planthoppers. Rice crops sprayed in the early crop periods are generally more vulnerable to hopper attacks. Most farmers depend on the advice and recommendations of the pesticide retail shopkeepers and end up using insecticides that have high visual kill effects and less expensive which are also extremely toxic to natural control agents. The prophylactic sprays destroy ecosystem services and make their crops vulnerable to rapid increase of hopper invaders that often lead to hopperburn.

10.5.3 Nutrient and Insecticide Use Before and After Outbreaks

We compared respondents' seeding rate, nutrient, and insecticide use before the outbreaks became intense in 2009 and after the outbreaks in 2012. Table 10.3 shows that before the outbreak, the mean rice yield was 4.53 t/ha while the yields reported for the wet season 2012 was 5.73 t/ha. In 2009, the mean seeding rate

Table 10.3 Seeding rate, nutrient and insecticide use before and after outbreaks, Central Thailand, 2012

Parameter	Before Outbreak (2009)			After Outbreak (2012)		
	Ang Thong	Chainat	Suphan Buri	Ang Thong	Chainat	Suphan Buri
Rice yield (t/ha)	4.9	4.6	4.1	5.5	5.6	6.1
Seeding rate (kg/ha)	165	162	155	164	157	153
Total N applied (kg/ha)	88.0	85.7	76.5	8.8	7.8	6.9
Insecticide applications	2.3	2.9	2.7	2.2	2.9	2.6

was 161 kg/ha while in 2012, it dropped slightly to 158 t/ha. The average nitrogen fertilizer applied before the outbreak was 83.4 kg/ha and this was drastically reduced to 7.8 kg/ha after the outbreak. Mean insecticide sprays before and after the outbreak was 2.6. However, there appears to be either a recall problem or underreporting of insecticide use before the outbreaks. In focus group discussions we conducted in Chainat province in 2009, we found that the average number of insecticide sprays was 4.2 and in 2012, this was reduced to 3.6, about 14 %.

10.5.4 Most Important Pests and Pest Management

In October 2012, nearly all farmers interviewed in the three provinces reported that the brown planthopper (BPH) was their most important pest. A few others specified the stem borer, rice leaffolder, and rat (Fig. 10.1).

To control their most important pests, the big majority of respondents across the three provinces applied pesticides. Close to two-fifths (37.6 %) of Suphan Buri farmers and less than one-third (32.2 %) of their Chainat counterparts poured an insecticide and diesel oil mixture into the rice field (Table 10.4).

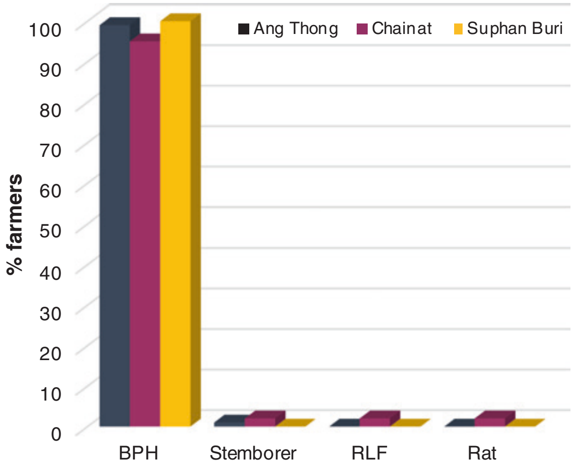

Fig. 10.1 Most important pests of rice farmers in study areas, Central Thailand

Table 10.4 Rice farmers' control measures for most important pests in Central Thailand

Control measure	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Apply pesticide	93	93.0	118	100.0	101	100.0
Pour insecticide and diesel oil mixture in rice field	6	6.0	38	32.2	38	37.6
Electric fence	1	1.0	61	5.28	0	0.0
Plow the field, cut the plant	1	1.0	0	0.0	0	0.0
Drain water	0	0	1	0.8	0	0.0
Other	1	1.0	1	0.8	0	0.0
None	2	2.0	0	0.0	0	0.0

10.6 Social Impact of Outbreaks

10.6.1 Adaptation Response to Crop Losses

Farmers' immediate response to their severe crop losses was emotional. They recalled feeling extremely sad and depressed and unable to discuss the losses with their spouses since many had incurred debts to support their farm operations (Table 10.5). Their adaptation responses to severe crop losses due to the planthopper outbreaks were to find a resistant variety to plant next season (63.6 %), stop planting for a while (46.1 %) or find an insecticide that can effectively control planthoppers (43.6 %) and borrow money to buy more pesticides (26.6 %) (Table 10.6). These responses represent the stages described in the Kübler-Ross (1969) extended grief or loss cycle. The loss cycle consists of these stages: Denial, anger, bargaining, depression, testing, and acceptance.

Table 10.5 Farmers' immediate reaction to crop loss due to BPH outbreaks

Reaction[a]	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Depressed	73	73.0	83	70.3	61	60.4
Worried	71	71.0	93	78.8	68	67.3
Could not discuss loss with family	1	1.0	5	4.2	4	4.0
Stopped planting for a while	23	23.0	24	20.3	33	32.7
Eradicate BPH from field	5	5.0	8	6.8	13	12.9

[a] Multiple response

Table 10.6 Farmers' adaptation response to crop losses from BPH outbreaks

Response[a]	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Find another resistant variety	68	68.0	66	56.4	67	66.3
Find a more effective insecticide	0	0.0	74	63.2	51	23.9
Borrow money to buy more insecticides	43	43.0	31	26.5	22	10.3
Stop planting for a while	38	38.0	49	41.9	59	58.4
Wait for government support	1	1.0	5	4.3	6	5.9
Drain field and irrigate it	9	9.0	11	9.4	8	7.9
Other	1	1.0	1	0.9	0	0.0

[a] Multiple response

10.7 Farmers' Perceptions of Causes of Planthopper Outbreaks

When asked what they thought were the main reasons for the outbreaks farmers provided several: 57 % of them thought that strong winds had brought the hoppers; 47 % believed that they had grown the same variety (Pathum Tani 1) for too long; 39 % thought that the varieties used had grown susceptible and 13 % thought that they had sprayed too much insecticides. This probably accounted for the change in varieties and reduction in insecticide sprays.

10.8 Farmers' Adaptation Responses to the Outbreaks

In their analysis of the economic costs of drought, Pandey et al. (2007) distinguished between adaptive strategies that reduce risk and other strategies that are used to deal with the losses that do occur (Davies 1996). Adaptation responses to livelihood threats or losses such as those resulting from planthopper outbreaks can be classified either as *defensive* or accommodating adaptation. In defensive adaptation, farmers may protect their rice crop from potential pest damage before the outbreak has occurred. Results show that farmers practiced defensive adaptation by following the extension worker's advice (72.2 %), planting rice synchronously with neighbor farmers (68.4 %), applying insecticides (39.6 %), planting a different rice variety (11.9 %), and following the pesticide shopkeeper's advice (3.8 %) (Table 10.7).

Accommodating adaptation, on the other hand, involves confronting the likely outbreak damages through such means as harvesting the crop early, availing themselves of crop insurance, joining a cooperative, planting other crops, leaving the field to fallow, or cultivating another field in another province. In the three provinces, close to three-fourths (74.4 %) of the farmers interviewed resorted to planting rice synchronously with other farmers, followed by almost a third of the

Table 10.7 Defensive adaptation made by farmers before the BPH outbreak

Defensive adaptation[a]	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Planted ahead of my neighbors	3	3.0	4	3.4	3	3.0
Planted rice the same time as other farmers	69	69.0	79	66.9	70	69.3
Followed extension worker's advice	69	69.0	89	75.4	73	72.3
Followed pesticide shopkeeper's advice	1	1.0	10	8.5	2	2.0
Planted a different rice variety	16	16.0	14	11.9	8	7.9
Applied insecticides	34	34.0	58	49.2	36	35.6
Poured vegetable oil in the field then tapped rice plant so BPH to fall into the water	13	13.0	10	8.5	10	9.9
Availed of crop insurance	0	0.0	1	0.8	1	1.0

[a] Multiple response

Table 10.8 Accommodating adaptation farmers made after the BPH outbreak

Accommodating adaptation[a]	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Replanted rice farm/started a new rice crop	12	12.0	5	4.2	18	17.8
Planted ahead of my neighbors	1	1.0	2	1.7	3	3.0
Planted rice the same time as other farmers	71	71.0	92	78.0	75	74.3
Pursued other means to generate additional income	30	30.0	38	32.2	36	35.6
Planted a different rice variety	28	28.0	13	11.0	10	9.9
Reduced insecticide use	24	24.0	28	23.7	18	17.8
Reduced amount of fertilizer applied	18	18.0	19	16.1	11	10.9
Borrowed money to pay debts	10	10.0	20	17.0	7	6.9

farmers (32.6 %) who pursued other means to generate additional income. Other farmers applied the extension recommendation to reduce insecticide use (21.8 %), change variety (16.3 %), and reduce the amount of fertilizer applied (17.3 %), quite similar to the "three reductions, three gains" program in Vietnam Escalada et al. (2009) (Table 10.8).

Box 2. Applying "three reductions" practices to avoid planthopper outbreaks

When we visited Mr. Vichian again in July 2012, two and a half years after our first visit, he was happily enjoying harvests of about 5.6 tons/ha and had not had any BPH outbreaks in his fields for the last four seasons. He had made significant modifications to his inputs, reducing seed and fertilizer rates and insecticide use—similar to the "three reductions" program in Vietnam. The three reduction three gains program locally called Ba Giam Ba Tang was funded and widely promoted by the Ministry of Agriculture and Rural Development in Vietnam through multimedia campaigns, radio dramas, and TV programs. The program helped farmers to reduce insecticide use by as much as 70 %, nitrogen fertilizer by 7 %, and seed rates by 10 % and reduced the vulnerability of subsequent rice crops to planthopper outbreaks. A report by the International Trade Studies Center at the University of the Thai Chamber of Commerce (UTCC) in October 2010 attributed Vietnam rice production success to the implementation of the "three reductions, three gains."

The seed rate he now uses is about 125 kg/ha from 156 kg/ha, a reduction of 20 %. Similarly, he reduced his nitrogen use by 35 % from 240 kg/ha to 156 kg/ha. While he used to spray insecticides 10 times a season at weekly intervals, he now sprays only 3 times at 21, 41, and 61 days after sowing, a reduction of 70 %. He used to plant only one variety, Pathum Tani 1, and now he plants 3 varieties, Chainat 31, 41 and 47. Mr. Vichian and many farmers in the village seem to have learned to cope with the BPH outbreak threat by changing varieties, reducing their seed, fertilizer, and insecticide inputs. After hearing about the "stop cypermethrin and abamectin campaign," they have also refrained from using these products especially since the local pesticide retailer does not carry them anymore. Although Vichian's farm had been free from hopper outbreaks, his three reduction practices can still be modified further to reduce the fields' vulnerability to BPH invasions. For instance, his first insecticide spray on 21 days after sowing can safely be removed and his seed and fertilizer rates can probably be reduced a further 10 %.

10.9 Coping Mechanisms Adopted by Farmers

We asked farmers how they had coped with the crop and financial losses incurred. Most farmers adopted an optimistic attitude that their next crop will not suffer loss (69 %). To reduce the financial burden, farmers had adopted one or more strategies which can be grouped into loan repayment schemes (84.6 %),

Table 10.9 Farmers coping mechanisms for crop losses due to BPH outbreaks

Coping mechanism[a]	Ang Thong		Chainat		Suphan Buri	
	No.	Percentage (%)	No.	Percentage (%)	No.	Percentage (%)
Optimistic that the next crop will be better	79	66.9	79	66.9	62	61.4
Paid pesticide shop by installment	25	25.0	42	35.6	31	30.7
Took loan from farmers' bank or village fund	50	22.0	91	77.1	64	63.4
Borrowed money from relatives to pay debts	10	4.4	15	12.7	17	16.8
Blamed the government for delay in insecticide assistance	1	0.4	1	0.9	4	4.0
Reduced household spending	30	30.0	47	39.8	41	40.6
Pursued other means to generate additional income	29	29.0	37	31.4	26	25.7
Other	3	3.0	4	3.4	4	4.0

[a] Multiple response

reduction in household spending (36.8 %), and embarking on alternative sources of income (28.5 %). Only a few (1.8 %) blamed the government for delay in assistance in providing the insecticides that they needed for their rice crop (Table 10.9).

While many farmers were optimistic that the next crop will be better, they nonetheless made household adjustments that reduced their household expenses such as 1) modifying their daily diet (52.8 %); reducing their meat consumption, using vegetables from the garden and going fishing; 2) reducing purchases (29.2 %) by reducing trips to the market, buying fewer goods, and not buying clothes; 3) giving up recreational activities (5.3 %) by reducing TV viewing hours and drinking; and 4) cutting down on household expenses (12.8 %) by reducing electricity consumption and mobile phone use (Fig. 10.2).

10.10 The Impact of the "Stop Abamectin and Cypermethrin" Campaign on Farmers

At 18 months after the campaign, we conducted a survey in Chainat and neighboring provinces, Ang Thong and Suphan Buri, to determine if the campaign had worked. There was higher awareness, as 90 % of the farmers we interviewed had heard about the campaign—96 % in Chainat, 87 % in Suphan Buri, and 82 % in Ang Thong (Fig. 10.3). We disaggregated the data and found that a significantly

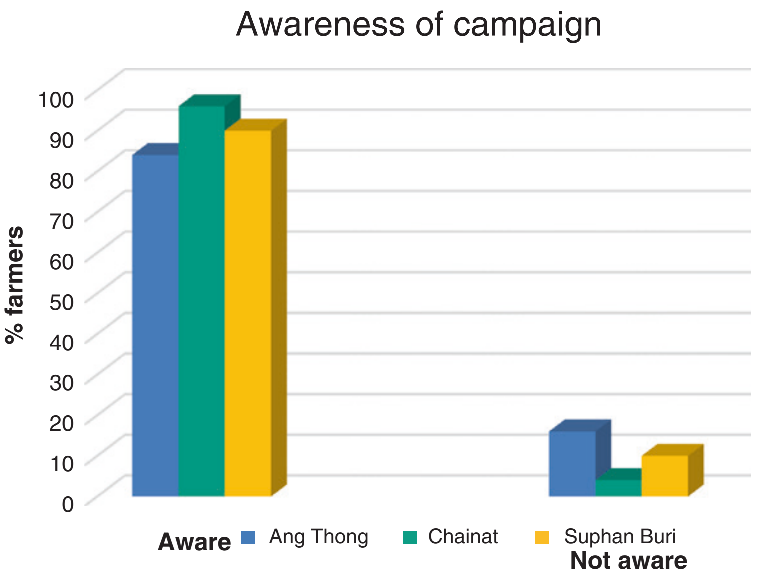

Fig. 10.2 Respondents' awareness of the TABA campaign, Central Thailand

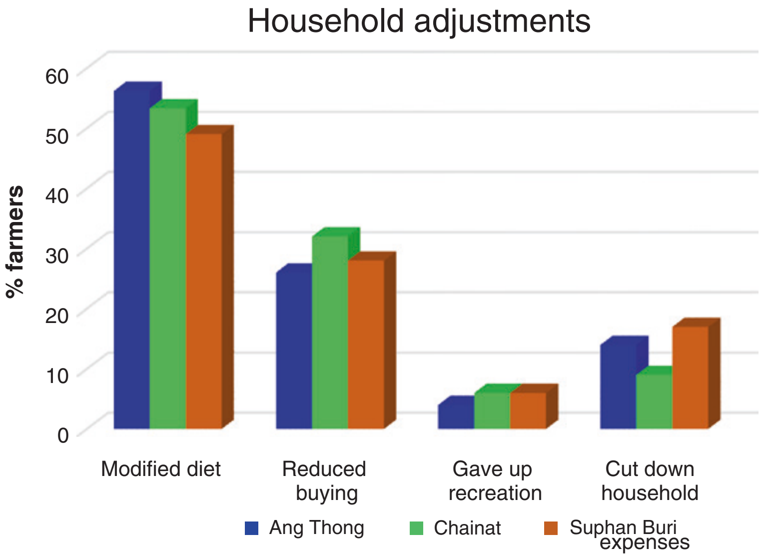

Fig. 10.3 Specific household adjustments respondents made after BPH outbreak

larger proportion of farmers who had heard about the campaign knew why they need to stop using the two insecticides (Table 10.10) than those who had not heard. More farmers who had not heard of the campaign continued to use abamectin and

Table 10.10 Comparison of farmers who had heard about the campaign with farmers who had not heard about the campaign

Proportion of farmers	Farmers who were	
	Aware $n = 283$	Not aware $n = 30$
	90 %	10 %
Percentage of farmers who knew that the 2 insecticides kill natural enemies	42. 7	3.3
Percentage of farmers who know that the 2 insecticides cause pest resurgence	32.2	3.3
Percentage of farmers who know that the 2 insecticides cause BPH outbreaks	31.1	3.3
Percentage of farmers who did not know why	13.4	83.3
Percentage of farmers who continued to use abamectin	24.7	36.7
Percentage of farmers who continued to use cypermethrin	15.5	20.0
Percentage of farmers who used cocktail of abamectin + cypermethrin	5.7	10.0
Percentage of farmers who said they continued to use abamectin or cypermethrin	35.0	70.0

cypermethrin than those who were aware of the campaign. About 70 % of the farmers who had not heard about the campaign would continue to use the two insecticides while only 35 % of the farmers who were aware of the campaign would continue to use them.

There were significant differences in beliefs between farmers who were aware of the campaign and those not aware (Table 10.11). The campaign increased the percentage of farmers who believed that abamectin and cypermethrin can cause planthoppers to increase and felt that farmers should stop using them among those who were aware of the campaign. Proportionately, fewer farmers believed so. However, there were no significant differences in beliefs "the two insecticides are dangerous to rice" and "mixing the two insecticides with herbicide sprays is a bad practice."

10.11 Social Costs to Affected Farmer Households

In this study, we have shown that besides severe crop losses, planthopper outbreaks more importantly, have a social cost to affected farmer households. While farmers' immediate reaction to their crop loss was emotional, the adaptation response focused on searching for another resistant variety, finding a more effective insecticide, and borrowing money to buy more insecticides. Although planthopper outbreaks have been reported to result from excessive insecticide use, farmers continue to use insecticides and see it as a quick fix to their crop losses. The farmers we interviewed in this study reported using a wide range of cocktails or premixed chemicals bought from the pesticide shop or two or more chemicals

Table 10.11 Differences in beliefs about abamectin and cypermethrin between farmers who heard about the campaign and farmers who had not heard about the campaign

Belief statements	Percentage of farmers who said statement always true		Z value #	Probability significance @
	Aware $n = 283$	Not aware $n = 30$		
Abamectin can cause planthopper increase	54.8	23.3	1.8	$P = 0.003$ **
Cypermethrin can cause planthopper increase	56.2	23.3	2.1	$P < 0.001$ **
Farmers should stop using abamectin	67.1	23.3	2.3	$P < 0.001$ **
Farmers should stop using cypermethrin	67.1	20.0	2.5	$P < 0.001$ **
Using abamectin and cypermethrin is dangerous to rice production	35.3	30.0	0.6	$P = 0.8$ ns
Mixing abamectin and cypermethrin with herbicide application is a bad practice	54.8	36.7	0.9	$P = 0.6$ ns

Kolmogorov-Smirnov Z
@ p is probability; ns = not significant; ** highly significant

bought separately and mixed in one spray, such as chlorpyrifos + fipronil, dinotefuran + fipronil, and abamectin + cypermethrin.

One of the factors that exacerbate excessive insecticide use is the intense promotion and marketing of insecticides as a fast-moving consumer good in an unregulated market and information environment. Communication initiatives, such as the “Stop abamectin and cypermethrin” campaign, could help correct this misinformation, change farmer attitudes toward insecticide use, cultivate a new social norm, which hopefully can wean farmers away from chemical dependence.

The sleeper effect is also common with regard to effects of campaigns (Kumkale and Albarracín 2004). Although a campaign may have a very high increase in awareness, beliefs and practices are lower. This might be due to the sleeper effect where new information may take time for some individuals to internalize and result in changes in beliefs and practices. Repetition of the campaign messages will certainly be useful to enhance the process of positive change.

Mass media campaigns can change the behavior of whole populations by targeting the cognitive or emotional responses of the audience. At the societal level, change can also occur when media messages set an agenda for discussion about a particular issue (Wakefield et al. 2010). For instance, public discussion of health, economic, and environmental issues related to insecticide misuse and pest outbreaks can lead to structural changes in government policies. Consequently, for media campaigns to work, policies that support behavior change must be in place.

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Chapter 11
Future Planthopper Management: Increasing the Resilience of Rice Systems

Geoff A. Norton, Kong Luen Heong and Jiaan Cheng

Abstract The problem of planthoppers in rice—the causes of planthopper outbreaks and the ways of reducing the likelihood of this happening—is determined by the dynamic interaction between features of the natural system and decisions made in the human use system. A model of the resilience of the rice planthopper system is used to provide a conceptual framework to explore this complex relationship, involving features at different scales, including the crop, farm, village, country and international level. The way in which various combinations of these various factors can determine the resilience landscape and whether a particular rice planthopper system is more or less resilient are discussed; that is, whether planthopper populations remain at low levels or whether rice crops are subject to frequent planthopper outbreaks. Historically, in a number of countries, a breakdown in resilience and the occurrence of planthopper outbreaks have resulted from intensive rice production associated with the increasing use of pesticides and fertilisers, as well as susceptible high-yielding varieties. In the final section, the threat to the resilience of the rice planthopper system resulting from further rice crop intensification to feed the increasing world population is discussed. A number of recommendations are proposed on how this threat might be avoided, including the use of more sustainable practices as part of a second green revolution, such as maintaining and enhancing ecosystem services through better management practices, including more selective use of pesticides and ecological engineering. An important challenge is how to coordinate the decisions made by various stakeholders in achieving a harmonised and resilient approach to rice planthopper management in the future.

Keywords Human use system · Resilience · Ecosystem service · Stakeholders · Ecological engineering

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11.1 Introduction

Plant protection is part of a complex system, involving the interaction between natural and human use systems (Fig. 11.1). The features of the *human use system* associated with rice production and crop protection are determined by decisions made on public policy issues and regulatory issues; on research, development and commercial technological developments, such as breeding strategy and pesticide development; on marketing and other decisions concerning the distribution and extension of these technologies; and a whole range of decisions made at the crop, farm, village and regional level.

The features of the *natural system* associated with rice include various organisms, such as pest and beneficial species, plant species, alternative host plants and a range of natural events and conditions, such as climate, weather conditions and landscape, which influence the ecological relationships and dynamics of these organisms. It is the dynamic interaction that occurs at the interface between these two systems that has defined the issues and attempted solutions to such pest problems as the rice planthopper system.

This final chapter uses a model of resilience to provide a conceptual template for discussing the main issues concerning the rice planthopper system, many of which have been raised in previous chapters. The first section considers the general history of rice systems and resilience and then introduces the model of resilience for the specific case of the rice planthopper system. In the next section, we review and examine the various factors affecting this rice planthopper resilience profile. We consider factors at the farm/crop level that affect the behaviour of the rice planthopper system, followed by factors at the cropping and landscape level and at a regional and international level that affect rice planthopper resilience. The final section summarises the main features of the rice planthopper system that determine the productivity and resilience of rice production and provides recommendations on actions that need to be considered if increased and sustainable rice production in the future is to be achieved. The main message we would emphasise is that significant progress will only be made where there is collaboration and harmonisation by all stakeholders in improving farmers' appreciation of the main components affecting the risk of planthopper outbreaks on their farm, and in ensuring that research, policy and commercial activities all work towards a more productive and resilient rice planthopper system in the future.

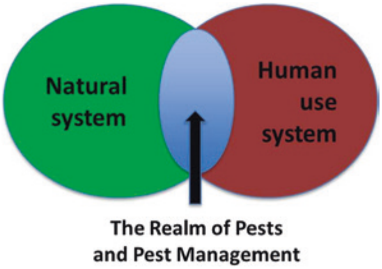


Fig. 11.1 Natural and human use system interactions. Rice-pest system interactions

11.2 The History and Resilience of the Rice Planthopper System

11.2.1 A Brief History of Rice Systems and Resilience

Rice cropping systems date back over 7,000 years and initially "evolved" through natural selection. Only those systems that were resilient and able to cope with pests, diseases and weeds were able to consistently provide subsistence for farm families. Varieties were selected that had high tolerance and were able to compensate for or were resistant to pest attack. Cropping practices, such as irrigation and transplanting, were developed to control weeds and other pests and so added to the resilience of the cropping system. Another resilience feature of these early rice systems was the role that predators and parasites played in limiting the development of insect pest populations, although at various times in the past, rice planthoppers have threatened rice yields in specific areas: one of the earliest recorded outbreaks being in Japan in the seventh century (Sogawa 2014, this volume).

As rice production became more commercial, a change in emphasis occurred, with the focus shifting to increasing crop production and net farm income. The major objective of rice breeding programmes in the Green Revolution was to develop varieties that gave higher yields, with some effort being devoted to selecting or breeding for varieties resistant to specific insect pests and diseases. However, the selection pressure exerted by this strategy often led to pest and disease populations evolving the ability to tolerate and adapt to "resistant" varieties. More recently, white-backed planthopper outbreaks have been the direct result of wide spread use of hybrid rice varieties that favour the pest's development (Sogawa et al. 2009; Cheng 2014, this volume).

The development of synthetic pesticides added a further means of dealing with pest and disease problems, allowing the uncoupling of decisions made on pest/disease management from decisions made on breeding and cropping practices. For many rice farmers, pesticides are seen as quick acting "medicines" that can be used to minimise the potential losses associated with pest and disease problems. However, stakeholder decisions made on the development, regulation, choice and application of pesticides can have other, unintended impacts on the natural system: reducing beneficial organisms and causing secondary planthopper resurgence (Heong and Schoenly 1998; Bottrell and Schoenly 2012) and the development of planthopper populations that are resistant to pesticides (Liu et al. 2014, this volume).

It is the dynamics of such interactions between the natural system and human use system that determine whether developments in crop production and crop protection are increasing or decreasing their resilience. In other words, do the combined actions of the different stakeholders associated with rice systems increase or decrease the "capacity of a system to absorb disturbance and reorganise so as to retain essentially the same functions, structure and feedbacks" (Walker and Salt 2012). It is in this context that this chapter will view the case of rice planthoppers as a specific part of the dynamic interaction between natural and human use systems associated with rice. How are these interacting systems tracking over time and is this development path leading to the rice planthopper system becoming more or less resilient?

Previous chapters in this book have described the history and many features of the dynamic interactions that occur between stakeholder decisions/actions and planthopper outbreaks and damage. Our objectives in this final chapter are to review these previous findings in the context of their contribution to understanding the resilience of rice planthopper systems and how this might help in determining what changes need to be made in the future. An important message is that strategies aiming to increase rice productivity while maintaining or increasing the resilience of rice systems will not be achieved by simple technological change alone but through a harmonised approach whereby decisions on technical, economic, institutional, political and other factors are tuned to achieve this desired result (Norton et al. 1999).

11.2.2 Conceptual Model of the Resilience of Rice Planthopper Systems

The conceptual model shown in Fig. 11.2 provides a graphic framework within which current and future factors affecting the overall resilience of the rice planthopper system can be explored. Any particular rice planthopper system (represented as a ball) can be envisaged as being either in Domain area 1 (low risk of planthopper outbreak) or Domain area 2 (high risk of planthopper outbreak).

The shape of the resilience landscape represented in this model by the blue line will be determined by many biological, ecological, technical, socio-economic, policy and regional factors. For instance, is the "hill" between the two domains high or almost non-existent, which will determine how difficult or easy it is for the planthopper-rice system to move from one Domain to the other, which will depend on many site specific as well as regional, national and even international factors.

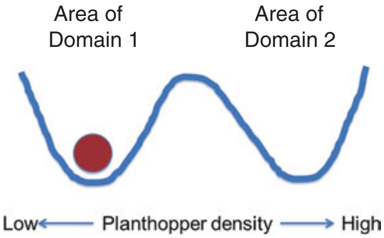


Fig. 11.2 Conceptual model for discussing factors affecting the resilience of rice planthopper systems

The conceptual model in Fig. 11.2 represents the situation for a specific crop in a specific season. However, from season to season, the outcomes of this resilience model can change for two main reasons:

- Short-term variations in such factors as weather conditions, management practices and the level and timing of planthopper migration relative to the growth stage of the "landing" crop in that particular season can affect outcomes.
- Long-term trends in components of the natural and human use system can have more permanent implications for this resilience model. For instance, the development of planthopper resistance to pesticides, changes in the landscape surrounding rice fields that affect natural enemy abundance and changes in pesticide regulation Pesticide regulation and pesticide marketing can all have serious implications for the resilience of the rice planthopper system. On an even longer timescale, global warming and resource depletion can cause even more fundamental changes to the natural and human use elements of the rice planthopper system. Climate change can cause changes in cropping practice and alter the suitability for pest and disease development while increasing scarcity of resources such as land, water, phosphates and nitrogen can be expected to cause further disruption to the rice planthopper system.

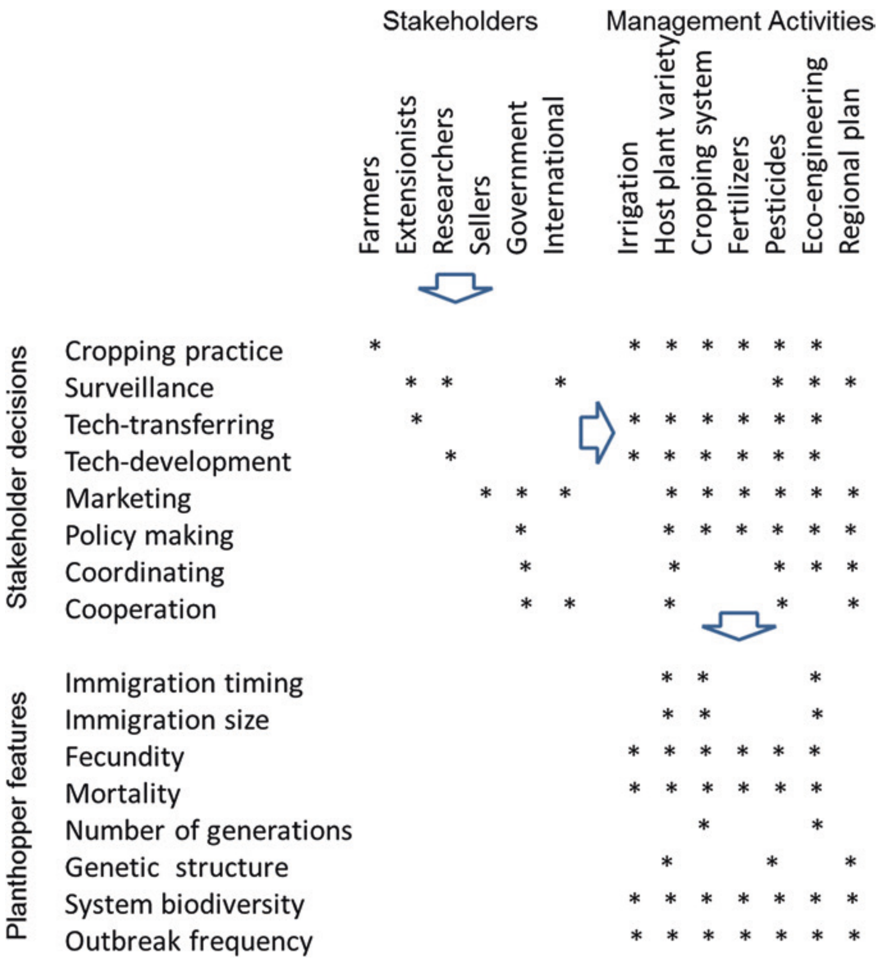
Given this complexity, a major challenge for stakeholders in the future is how to combine public and private decision-making on crop research, development and implementation so that crop productivity is increased, while at the same time maintaining and enhancing the resilience of the rice planthopper system. In meeting this challenge, the first step is to better understand how the driving forces, linkages and interactions between natural and human use system components impact on their productivity and resilience (Norton and Mumford 1993; Walker and Salt 2012).

11.3 Factors Affecting the Resilience of the Rice Planthopper System

The factors influencing rice planthopper resilience occur at three levels (Fig. 11.3): the crop level, the cropping system/landscape level and the region/country/international level.

11.3.1 Crop Level

The main components operating at the crop level, which determine planthopper-rice system productivity and resilience, include the immigration of planthoppers into the rice crop and decisions made on variety, cropping practices and insecticide use.



		Stakeholders						Management Activities						
		Farmers	Extensionists	Researchers	Sellers	Government	International	Irrigation	Host plant variety	Cropping system	Fertilizers	Pesticides	Eco-engineering	Regional plan
Stakeholder decisions	Cropping practice	*						*	*	*	*	*	*	
	Surveillance		*	*			*					*	*	*
	Tech-transferring		*					*	*	*	*	*	*	
	Tech-development			*				*	*	*	*	*	*	
	Marketing				*	*	*		*	*	*	*	*	*
	Policy making					*			*	*	*	*	*	*
	Coordinating					*			*			*	*	*
	Cooperation					*	*		*			*		*
Planthopper features	Immigration timing								*	*			*	
	Immigration size								*	*			*	
	Fecundity							*	*	*	*	*	*	
	Mortality							*	*	*	*	*	*	
	Number of generations									*			*	
	Genetic structure								*			*		*
	System biodiversity							*	*	*	*	*	*	*
	Outbreak frequency							*	*	*	*	*	*	*

Fig. 11.3 Main components of the natural–human use system interaction that determine the status of the rice planthopper systems

11.3.1.1 Planthopper Immigration

The number and timing of planthopper immigrants into a rice crop clearly can have a major influence on the threat they cause to rice yields and revenue particularly in subtropical and temperate Asia. The larger the number of immigrant planthoppers into a crop and the earlier immigration occurs, the greater the risk that the crop will be in Domain 2. The factors affecting immigration include the following:

- Planthopper population size in the source area(s)
- The timing of crop development in the local, regional or international source area, which determines the time at which emigration of macropterous planthoppers occurs

- Wind and temperature profiles at the time of immigration, which determines the direction and speed of movement
- Local weather that can affect the location at which landing occurs
- The timing of local cropping and harvesting schedules in the landing area

The source of immigrants may also affect their genetic make-up, particularly regarding any genetic change that may have taken place in that population enabling it to develop on "resistant" varieties or which gives the immigrant population resistance to pesticides. Both of these factors will, in effect, reduce the height of the hill between Domain 1 and 2, making the transition from domain 1 to 2 much easier.

11.3.1.2 Rice Variety

The decision on which variety to choose will depend on the range of varieties available and the trade-off the farmer is willing to make between each variety's characters, including yield and quality (e.g., millers' and consumer's preference or price) and its resistance to various insect pests and diseases that are likely to challenge the crop. Varieties susceptible to planthoppers or resistant varieties to which planthoppers have become adapted are likely to contribute to higher planthopper densities and potentially push the system to Domain 2. On the other hand, more stable varietal resistance, associated with varieties having durable resistance, such as broader-based IR 64 (Cohen et al. 1997), contributes to longer term ecosystem resilience to planthopper attack and helps to retain the system within Domain 1.

11.3.1.3 Cropping Practice

The application of high levels of Nitrogen fertiliser to increase crop yields, in response to high rice prices and fertiliser subsidies, makes rice plants more nutritious for planthoppers and reduces host resistance, both contributing to reduced ecosystem resilience and pushing the crop system towards Domain 2.

Good irrigation practices can reduce the growth rate of rice planthoppers by managing soil water content and humidity in the rice ecosystem directly. In addition, water scheduling in irrigation schemes can be used to avoid peak immigration peak by adjusting sowing/transplanting times (Cheng et al. 2003).

11.3.1.4 Insecticide Application

Since the damage caused by early season leaf defoliators, such as leaf folders, is very visible, many rice farmers perceive that this early damage could cause significant yield loss, and consequently, they take action by spraying insecticide. However, there is considerable evidence (Way and Heong 1994) that the risk of yield loss resulting from early season defoliation is very low if not insignificant. This is due to the capability of rice plants and the crop to compensate for this damage.

Unfortunately, many farmers have difficulty in assessing the potential damage that pests can cause (Escalada et al. 1999) and, like other decision makers (Kahneman and Tversky 1984), they typically regard potential monetary losses as having a much greater negative impact on their well being compared with the positive impact that an equivalent monetary gain would have. Consequently, many rice farmers try to avoid damage caused by early defoliators by applying pesticides in what they regard as an insurance measure against losses. However, in practice, this invariably has the opposite effect. Rice planthoppers, especially BPH, are migratory "r" pests that have the potential to increase rapidly (Heong 2009); the main natural constraint that limits the increase of planthopper populations in rice is predation and parasitism. As Kenmore et al. (1984) and others (Heong and Schoenly 1998) have shown, such natural biocontrol can be disrupted by early pesticide application in having a much greater impact on mobile predators and parasites compared with much less mobile planthoppers, leading to resurgence of the planthopper population and often to major yield and revenue loss. In this case, early pesticide application reduces rice planthopper resilience and lowers the hill between Domain 1 and 2 for that season, making it easier for the system to move to Domain 2.

Based on these findings, farmer field schools (Matteson 2000), small-scale on-farm experiments to avoid spraying before 30 DAT (Heong and Escalada 1997), multimedia campaigns (Escalada et al. 1999) and entertaining education programmes on radio (Heong et al. 2008) and on TV (Heong et al. 2014) have demonstrated that farmers' perceptions and actions in SE Asia can be modified, increasing the resilience of the rice planthopper system and maintaining or pushing it towards Domain 1.

11.3.2 Cropping System/Landscape Level

The timing, pattern, sequence and number of rice crops per year and the proximity of non-rice plants associated with other crops grown on the farm and with the vegetation on bunds and surrounding landscape can affect rice planthopper resilience in two ways. First, as indicated above, the time at which the crop is sown or transplanted, particularly in temperate situations, can affect the number and time at which planthopper immigrants enter the crop and influence the risk of a planthopper outbreak. Second, the temporal and spatial diversity of rice and non-rice crops and other nearby vegetation can affect rice planthopper resilience through its impact on natural enemies.

The higher diversity found in tropical rice ecosystems means that natural enemy populations are usually high and will generally control planthoppers except where the crop is sprayed or where extremely high and early immigration occurs. The natural enemy populations in these tropical rice crops raise the level of the hill in Fig. 11.2 placing them intrinsically in Domain 1. By contrast, natural enemy populations in subtropical and temperate rice crops, such as those in China, are generally far less abundant, due to climatic factors and to more intensive cropping practices and pesticide usage. These planthopper vulnerable systems, which have a lower dividing hill (Fig. 11.2), will potentially be in Domain 2, immigration being the main factor affecting the potential risk of outbreaks.

Decisions on cropping system design, cropping practices, low pesticide use and the planting of other crops and plants that attract and sustain natural enemy populations can reduce the vulnerability of rice ecosystems to planthopper attack in both tropical and temperate rice crops and raise the hill in Fig. 11.2 to make it more difficult to move from Domain 1 to Domain 2. Ecological engineering approaches discussed in earlier chapters aim to restore natural enemy diversity and abundance and strengthen the biological control ecosystem services.

As well as being affected by the on-farm factors described above, the resilience of the rice planthopper system is affected by a number off-farm decisions and actions, including decisions made in the private as well as the public sector. We review these off-farm influences at increasing spatial and institutional scales, from the village to the national and international level.

11.3.3 Village Level

Area-wide planthopper management strategies are the main options available at this level. In irrigated rice, the management of the time at which water is released to specific irrigation districts can be used to implement synchronous planting strategies and avoiding overlap of planting times, which can lead to the build-up of planthopper populations in the district.

Other strategies that can be implemented at the village or regional level will often require public or private involvement at a national or even international level. These strategies include the following:

- Regional deployment and year-to-year rotation of new and existing planthopper-resistant varieties and pesticides to avoid genetic changes in the planthopper population that lead to reduced efficacy of the control measure. The implementation of these strategies requires the involvement of both public and private organisations.
- Organising villagers in groups to use light trap catches to guide group sowing decisions, known as “Escape Strategy” in the Mekong Delta.
- Local education, training and information strategies to make farmers more aware of the planthopper problem and how to deal with it. As planthopper outbreaks have become more serious and caused serious losses to rice production in affected areas, public agencies have invested in training schemes, such as farmer field schools (Matteson 2000), while the public and private media have been used to improve communication about the problem through radio and TV programmes (Escalada et al. 1999; Heong et al. 2008, 2014). As a result, many farmers have become more aware of the importance of natural enemies and the way in which incorrect pesticide use can cause a reduction in natural enemy populations and cause a resurgence of planthoppers.

- The improvement of advisory services. Surveys of rice farmers have shown that in many areas the principal source of advice on pesticide use is provided by private pesticide dealers, who often operate through the village store (Heong et al. 2014, this volume). These dealers often have limited or no training in this area and often provide bad advice and pesticides. A similar conflict of interest can occur in the public sector where local extension officers receive bonuses according to the amount of pesticide they sell.

11.3.4 National Level

National governments have two roles to play in contributing to the rice planthopper problem. First and foremost, governments can create a policy environment that encourages farmers and other key stakeholders to act in ways, such as those already discussed above, that are consistent with the goal of contributing to a more productive and resilient rice planthopper system that contributes to sustainable development goals. Second, governments can implement or fund other agencies to take appropriate action, such as providing information, training and professional plant protection services. Some of the actions that governments can and have taken are described below:

- Pesticide subsidies have often been provided by rice growing countries as part of a rice intensification package. Since the lower cost of pesticide application obviously encourages pesticide use, this can have a disruptive effect on the rice planthopper system and push it towards Domain 2. Many countries have now reduced or removed direct pesticide subsidies. However, numerous indirect subsidies including favourable foreign exchange and tax relief remain in place (Jungbluth 1996).
- Pesticide marketing and regulation is another important aspect of government policy that can impact on the rice planthopper system, as well as other pest–crop systems. Banning broad spectrum pesticides that are particularly destructive to natural enemy populations have been an important policy tool in some countries in SE Asia. For instance, in Indonesia, the banning of 56 pesticides by a presidential decree markedly reduced planthopper outbreaks (Matteson 2000). To encourage more sustainable rice systems, government will need to revise and implement pesticide marketing and regulations to be in line with the FAO International Code of Conduct (FAO) and avoid pesticides being sold as "fast moving consumer goods" (Heong et al. 2014, this Volume).
- Improving the advice given to farmers by commercial distributors is another crucial role that national governments can play. Heong et al. 2014 (this volume) have called for government policy to address the poor advice being provided in the private sector by professionalising commercial plant protection services. This could be achieved by establishing a compulsory certification schemes

whereby pesticide distributors are trained and only those who have passed an examination and have been certified would be authorised to provide pest management advice and to market pesticides.

- Where national governments provide publicly funded extension services, extension staff need to be properly trained and funded to provide appropriate advice that is in the farmer's best interest. Supplementing the salary of extension agents with bonuses according to the amount of pesticide they sell clearly detracts from this objective and is a policy that needs to be discarded.
- Through its funding of public research and development, governments can influence the trajectory leading to those future practices leading to sustainable intensification of rice production. For example, high-yielding varieties should incorporate broad resistance to planthoppers wherever possible; Nitrogen fertiliser should be used sparingly to reduce ecological fitness of planthoppers, such as survival rates, longevity and fecundity, and at the same time reducing contamination of water resources.
- Government also has a role in establishing and supporting planthopper surveillance and monitoring schemes, to provide advisors and farmers with real-time information on planthopper migration so that farmers can avoid planting during the peak migration periods.

11.3.5 International Level

Planthoppers can migrate from one region and country to another and from tropical rice to temperate rice and vice versa. Long-distance and local migration can not only cause planthopper outbreaks in the receiving region or country but can also introduce migrants with different genotypes that enable them to survive on resistant varieties or confer resistance to certain pesticides. As an example of such an international consequence, an increase in the area growing hybrid varieties, which were introduced from China to Vietnam in the 1990s and susceptible to WBPH, resulted in an increase in WBPH in Vietnam and an outbreak of WBPH in the Red River delta in Vietnam in 2000 (Sogawa et al. 2003, 2009). Because of such possibilities, there is a considerable benefit to all countries involved to strengthen and support international surveillance, information exchange and coordination programmes, to provide advance warning of the likely timing and level of immigration, and to provide information on any new adaptation of planthoppers to resistant varieties and pesticides.

Since pesticides also flow across borders, another area where international cooperation is needed is on policy and regulatory frameworks for pesticides used in rice. Since the destruction of natural enemies through indiscriminate use of broad spectrum pesticides as well as pesticide cocktails is a major cause of pesticide outbreaks, there is an urgent need for harmonisation of the policy and regulation of pesticides and their use in rice.

Since there is much evidence that a major cause of many planthopper outbreaks is due to inappropriate use of pesticides, such as spraying at an early crop stage, there is an important role that the multinational chemical industry could play in supporting efforts to provide better information and training and certification of pesticide distributors, as described above.

11.4 Discussion and Recommendations

As indicated earlier in this chapter, the development of effective synthetic insecticides in the 1950s meant that in planning their cropping practice, farmers could focus on productivity and rely on pesticides to deal with any pest problems that arose. This "fire brigade" approach to fighting pests is still largely intact over 60 years later and the need for a 60 % increase in food production by 2050 to feed the increasing world population, as predicted by OECD and FAO, will continue to put pressure on maintaining this "fire brigade" approach. However, just as the emphasis with fire management has changed from fighting fires to fire prevention, so we need to reform our approach to "pest fighting"—to base it more on preventing pest development through the proactive design of more resilient cropping systems, as characterised by Domain 1 of the resilience model (Fig. 11.2). Clearly, planthopper management is an important component in the development of sustainable and resilient rice intensification systems.

It is clear from earlier discussion and previous chapters in this book that the many differences in rice planthopper systems will need to be taken into account in developing strategies for planthopper management in the future, aimed at keeping the system in Domain 1. Not the least of these differences is that between tropical and temperate rice systems, as indicated in Table 11.1.

Viewed in terms of the resilience profile, initially shown in Fig. 11.2, the history of the rice planthopper system in many parts of Asia seems to have had a

Table 11.1 The main differences between temperate and subtropical and tropical rice planthopper systems

Subtropical and Temperate rice (China)	Tropical rice (SE Asia)
Multiple planthopper species	Predominantly one species—BPH
Complex immigration sources, initially from tropical countries	Initial population usually from local sources
Variable patterns of immigration associated with sources, timing and weather conditions	Relatively simple patterns of immigration associated with local cropping systems
High ecosystem vulnerability associated with low natural enemy populations, high pesticide use, high fertiliser use and other cropping practices aimed at achieving high yields	Low ecosystem vulnerability associated with potentially high natural enemy populations and low pesticide use
Potentially high planthopper population growth rate and outbreak frequency	Potentially low planthopper population growth rate and outbreak frequency

tendency to move from Domain 1 to Domain 2. This has been the result of many factors, particularly the intensification of rice production associated with increased intensification of rice through the technological development of fertilisers and plant breeding, and the increasing use of pesticides as a means of dealing with insect pest problems. The higher value crop (and associated potential loss that can occur due to insects), the perceptions and risk attitude of farmers and aggressive pesticide advertising have meant that signs of pests or pest damage often resulted in pesticide application, which knock out natural enemies, resulting in resurgence of “r” pests such as planthoppers.

The simpler resilience model originally portrayed in Fig. 11.2 is now revisited in Fig. 11.4 to present a more dynamic representation of the problem. While this resilience profile will clearly be very different for specific rice growing sites, nevertheless there are certain key issues that need to be addressed in attempting to increase the zone of resilience (Domain 1) of any specific rice planthopper system. Most importantly, in addressing these issues, the decisions taken by the main stakeholders need to be harmonised to collectively achieve productive and resilient rice planthopper systems.

As indicated in Fig. 11.4, using conventional rice production practices to produce enough food using the limited arable land available is likely to increase vulnerability of rice ecosystems and shift the boundary between the two domains and make the risk of outbreaks worse. Instead, our goal should be to achieve sustainable intensification by establishing a high-yielding and low-vulnerable ecosystem. The results from

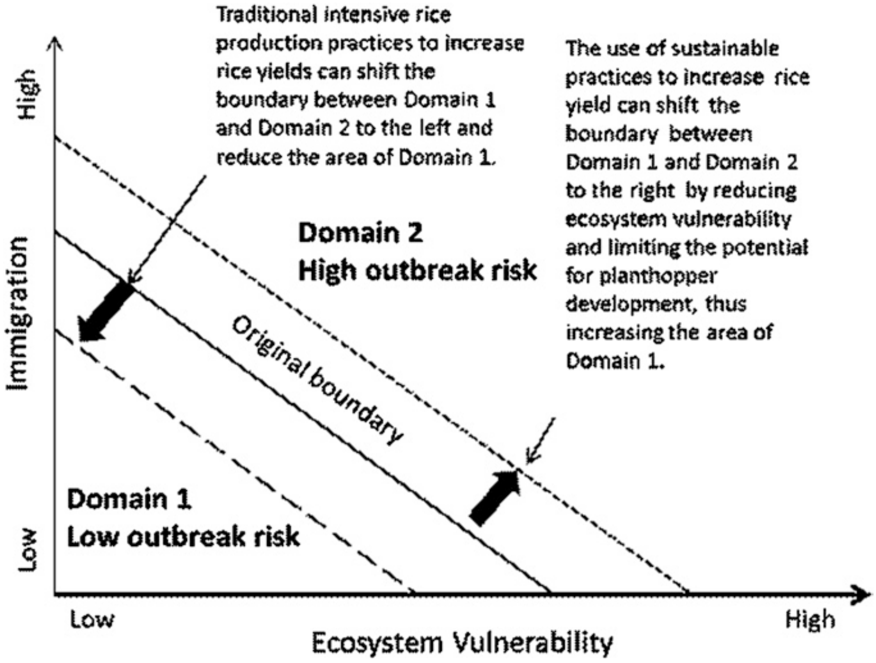


Fig. 11.4 Future scenarios for rice planthopper systems

Jinhua of Zhejiang, China (Lu et al. 2014, this volume) indicates that it is possible to reach sustainable intensification and manage the planthopper problem sustainably by restoring ecosystems and enhancing ecosystem service through ecological engineering in high-yielding systems with a yield of more than 10 t per ha.

However, the difficulty involved in developing a consistent and harmonised approach to integrate the actions of different stakeholders to achieve improved planthopper management and establishing a sustainable intensive production system should not be underestimated. Similar issues have arisen in implementing complex-integrated pest management strategies in Brassica crops, as detailed by Furlong et al. (2011). They conclude—"The technology for sustainable management of diamond-backed moth (DBM) within the context of integrated *Brassica* crop management exists, but current weak extension mechanisms fail to achieve the requisite community-level behavioural changes that are necessary for enduring adoption. In order to succeed, future initiatives will need to target broader community education programmes, be developed on a regional scale, and ensure the active participation of growers, extension officers, pesticide retailers, policy makers, and scientists".

Nevertheless, there are a number of examples where progress in improving planthopper management has been achieved: the best practices that will improve resilience and reduce vulnerability to planthoppper outbreaks include.

At the field and local level

- Design sustainable intensification strategies based on ecological principles that will increase productivity and resilience. Implement ecological engineering programme to restore rice ecosystem by increasing biodiversity and ecosystem service function in the rice landscape. Nectar rich flowering species such as sesame can both provide economic value as well as ecological value as food and shelter resources to natural enemies, particularly parasitoids (Gurr et al. 2011).
- Breed and use high-yielding varieties with durable resistance to rice planthoppers and transmitted viruses.
- Organise campaigns, training and mass media programmes to encourage rice farmers to reduce insecticides by at least 30 % and avoid overuse of chemical fertilisers. Insecticide sprays in the early crop stages (first 30–40 days after planting) should be discouraged. For example Vietnam's "three reductions, three gains" campaign (Huan et al. 2008).
- Conduct community-wide demos through participation from local governments to organise farmers in groups to experiment with sustainable intensification through reducing vulnerability of rice ecosystems (Escalada and Heong 2012).

National and International Level

- Develop new legislation that will favour sustainable agricultural intensification similar to the Environmentally Friendly Agriculture Promotion Act, 1997 in South Korea. The policy objectives of this Act are to stimulate the adoption of sustainable farming practices, cut chemical inputs, encourage the adoption of soil conservation practices and address biodiversity concerns (OECD 2008).

- Develop environmentally friendly agriculture policies, laws and incentives that will promote actions that maximise biodiversity at field levels. Develop nationwide programmes using mass media, such as radio and TV, that will focus on the benefits of biodiversity and the ill effects of pesticides on the environment and on human health.
- Critically review pesticide registration and marketing regulatory frameworks and initiate reforms to restructure so as to minimise pesticide misuse.
- Organise regional harmonisation by exchanging information on varieties and pesticide used, as well as on planthopper occurrences and movement.
- Develop regulations to "professionalise" plant protection services where plant protection advisors and pesticides dealers are accredited.
- A new platform for such a dialogue might need to be established, like the UN Inter country Platform for Biodiversity and Ecosystem Services (IPBES) established in Bonn in 2012. Each country might need to establish a similar platform and request donors and governments to support such efforts.

The history of the first Green Revolution in rice indicates that the vulnerability of rice ecosystems has been increased by intensification using high-yielding varieties combined with high inputs of chemical pesticides and fertilisers. Frequent outbreaks of rice planthoppers are one consequence of this traditional approach to intensification, the result of destroyed ecosystem services.

However, this and previous chapters of this book demonstrate that sustainable intensification of high-yielding rice crops can be achieved in combination with reduced pest problems: this involves enhancing ecosystem services and reducing crop vulnerability to increase the resilience of rice ecosystems. The implementation of this new, second "green" revolution, involving green super rice, more selective use of pesticides and ecological engineering, requires the active involvement of stakeholders at all levels, particularly in constructing favourable policy, economic and social environments.

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