Part I. General Introduction

Section 2. The "Shifty Enemies" of Rice Production in Asia

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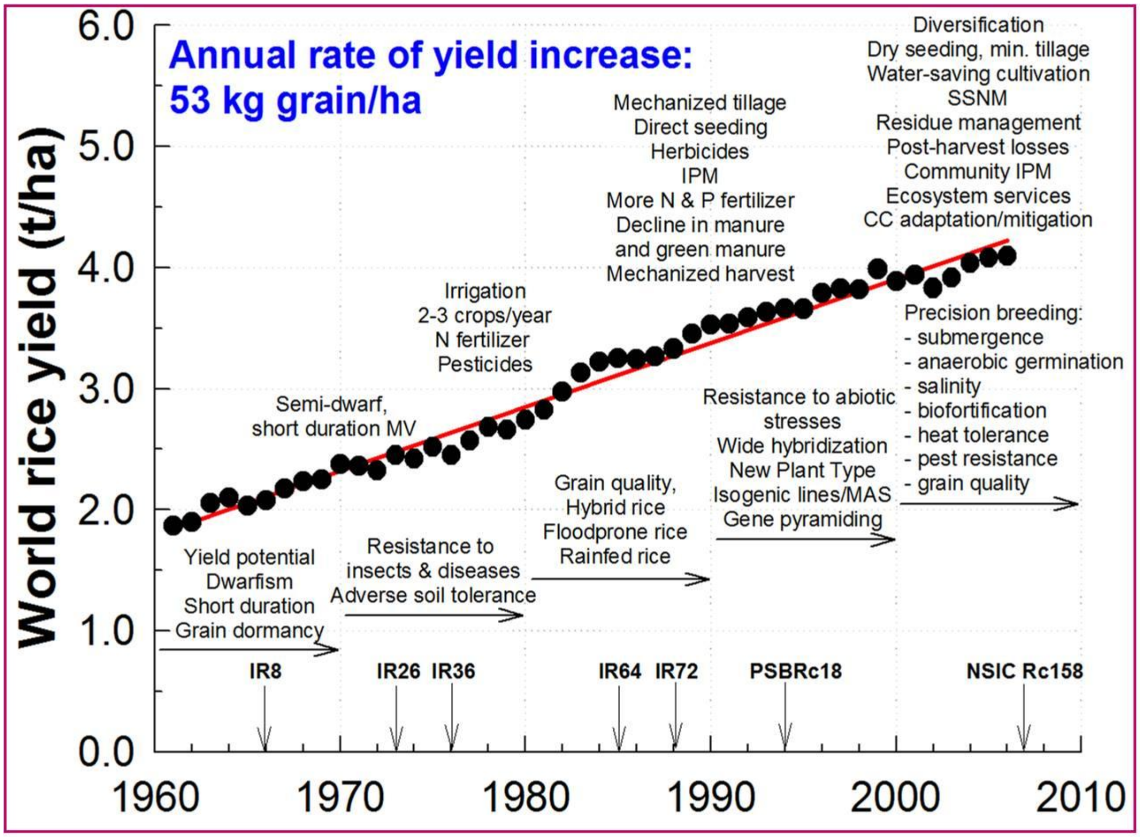
1. More rice needed for Asia's growing population

Rice is the staple food in Asia, which comprises around 4.3 billion people or 60% of the world's population. Immediately after World War II and continued regional conflicts in the 1950s, there was a threat that population growth would grow at the rapid rate of more than 2% while food production using traditional rice varieties would grow at less than 1%. National and international economic planners feared that a large-scale famine was almost inevitable in developing countries of Asia (GRiSP 2013).

To look into raising rice yields to ease the pressure of population growth, the International Rice Research Institute (IRRI) was funded and established in 1960 to conduct all aspects of research on rice production, especially varietal improvement. In just a few years, IRRI developed semidwarf, input-responsive rice varieties for the tropics that began the Green Revolution in rice and modernized rice production with high-yielding rice varieties (HYVs) in most of the rice-producing areas of tropical Asia. These varieties revolutionized rice production by doubling, or even tripling, the yields the tall, traditional rice varieties got.

However, the initial success was short-lived. Progress was hampered mainly by the emergence of new biological constraints. The new HYVs brought new sets of production constraints, including pest and disease outbreaks that occurred unexpectedly more frequently than when traditional varieties were planted. Nonetheless, the new venture created a new model for international agricultural research organized to tackle successfully food production competing against the rapid population growth. New rice varieties, which are more productive and responsive to inputs such as fertilizers and good water management, have been continuously developed to safeguard food security of Asia's developing countries. In strong partnerships and collaboration with the national agricultural research and extension systems, IRRI has been successful in improving rice and rice production in developing countries at an annual grain yield increase rate of 53 kg/ha as shown in **SE Figure 1**.

Many changes have occurred since the introduction of HYVs to the rice farmers in Asia. Some of these changes are consequences of deployment of HYVs while others occurred in parallel with new cultivation methods. Global climate change has been another factor. Also, new sets of rice diseases have arisen due to the dense canopy of the HYVs, creating an environment that is very conducive to disease development that scientists failed to anticipate when the modern



SE Fig. 1. Factors involved in the successful improvement of rice and rice production in developing countries. Source: IRRI.

After analyzing survey data, Savary et al (2011) and Reddy et al (2011) found that rice disease occurrence was greatly influenced by planting certain types of rice and/or the shortage of natural resources required in rice production. plant types were developed.

False smut, for instance, was found to be closely associated with areas of wide-scale cultivation of hybrid rice while brown spot occurred more frequently in areas afflicted with drought or water shortage. The studies associated the injury profile caused by different pests and diseases on various rice varieties in the field and rice crop production practices due to rice variety changes. The studies further confirmed previous observations related to changes in rice crop varieties and changes in global climate. The findings also pointed out the importance of field surveys and monitoring as an aid to understanding the occurrence of rice diseases.

Unfortunately, most of these surveys and other studies, previously conducted in national programs, have since ceased due to a shortage of funds and, more importantly, to the erroneous belief that rice production had reached its pinnacle, hence no further need for rice research as a national priority. Nevertheless, the war against rice diseases, or these “shifty enemies” as Stakman (1947) called them, is a war that we must continuously wage.

2. Changes in rice cultivation

Rice diseases are dynamic and their occurrence is influenced by the host genotypes and the microclimates created by the host crop environment. The rice production environment is manifested by replacement planting of HYVs and also by new methods of rice cultivation. Changes in cultivation methods, most frequently over the last 3 to 4 decades, were prompted by cropping intensity and a shortage of natural resources. The changes included every aspect of rice production, from varietal development to rice crop cultivation.

In plant breeding, for instance, the concept of a new and productive plant type for the tropics, conceptualized in early 1960s, was to shorten the tall stature of the traditional varieties and significantly increase the number of tillers to more than 30. The prototype was IR8, which launched the Green Revolution of large-scale planting by farmers in the late 1960s. In the 1990s, a new plant type (NPT), with fewer but more productive tillers than that of IR36, led to a second generation of modern rice varieties for the tropics. This NPT aimed to have 25% higher yield than that of existing varieties, with a yield of 12 t/ha. It would have a thick culm and fewer but more productive tillers and would be taller than IR36 and IR72 (semidwarf plants with many tillers).

2.1. Changes in varieties

As rice varieties planted by farmers continued to be improved, yields were increased from an average 2.0 t/ha at start of the Green Revolution in the 1960s to 4.0 t/ha by 2000. The new HYVs and technologies developed since then have increased yields in the same areas from 6 to 10.0 t/ha (GRiSP 2013). All of the new features of the new rice varieties would no doubt affect the profile of rice diseases in the field. The NPT concept has a central role in today's rice improvement and production in the tropics that have resulted in today's grain yield gains. Rice improvement is a continually evolving process as is the evolution of the diseases that afflict the new varieties.

The most significant change in rice production has been the introduction of hybrid rice, first developed by Chinese scientists for temperate regions in the 1960s and 70s. Hybrid rice increased yields from 15 to 25% over those of inbred varieties. The hybrid technology has, in recent years, expanded beyond China to the rice-growing regions of tropical Asia. Today, hybrid rice constitutes more than 50%, perhaps as high as 70%, of all the rice grown in China. In other rice-growing countries, the potential of hybrid rice has gradually received more attention and, in many cases, has been viewed as the best chance to increase rice yields. How this production system might affect rice diseases was evident immediately when hybrid rice was planted on a large scale. Lack of resistance made hybrid rice varieties susceptible to bacterial blight (Lee et al 1989). Reports on the occurrence of false smut and kernel smut also appear to be closely associated with hybrid rice planting (Savary et al 2011, T.W. Mew, International Rice Research Institute, unpubl. data).

When the first generation of hybrid rice was released in China, susceptibility to diseases, notably bacterial blight, was one of the main biological constraints encountered. Fortunately, most of the disease resistance genes are dominant in nature and expressed fully in F_1 hybrids, which can be exploited by hybrid rice development where the resistance genes can be incorporated into various combinations to overcome major diseases such as bacterial blight or blast (for references, go to the various chapters in **Part II, Biology of rice diseases** in this online resource). The deployment of the resulting hybrid rice varieties is even more efficient and effective if the pathogen population structures are documented, i.e., monitored periodically. For some of the other widespread diseases, such as false smut, identification of the resistance source remains a great challenge because of the lack of research on false smut until just very recently.

As the effect of global climate change impinges on rice cultivation, the shortage of natural resources, such as water, is increasingly affecting crop production. To mitigate the shortage of the agricultural water supply, "**aerobic rice**", a new type of rainfed rice, has been developed. It can be seeded like any other dryland crop under unsaturated soil conditions. When rain comes, it grows like other rainfed rice varieties. However, the disease situation is also similar to other dryland crops. When seedlings are established in a nonflooded system, the rice plant is predisposed to root pathogens such as *Pythium* sp., root knot nematodes (RKN), such as *Meloidogyne graminicola,* and other soilborne fungal pathogens, which can further worsen the effects of other abiotic factors such as nutrient deficiency.

The utility of the HYVs in increasing food production is their high responsiveness to crop management, specifically regarding nutrient supply. Traditional rice varieties may be as productive as the modern ones, but addition of nitrogen fertilizer often results in lodging (Yoshida 1981). Lodging near crop maturity can reduce grain yield by more than 1 t/ha in irrigated systems (Yoshida 1981). Because of their short stature and sturdy culm, HYVs can withstand lodging. However, at the maximum tillering stage, most HYVs produce a thick canopy, which sustains high temperatures and humidity that favor infestation and infection of insect pests and diseases.

2.2. Changes in cultivation methods

Planting methods may affect occurrence of some diseases but have no effect on others. For instance, direct-seeded HYVs may have less sheath blight than those that are transplanted (Willocquet et al 2004).

It was common to use wider spacing in traditional varieties to reduce lodging, but probably, transplanting was usually random and not in rows (David Mackill, University of California, Davis, per. comm.). For instance, in the dry season, traditional tall and leafy, heavy-tillering varieties, such as Peta, were spaced 25×25 cm in relatively poor soils and 30×30 cm in fertile soils. In the wet season, tall varieties were spaced 30×30 cm in poor soils but 35×35 cm in fertile soils. Studies at IRRI suggested that the optimum spacing for lodging-susceptible tall varieties is 50×50 cm, whereas the optimum spacing for nonlodging short varieties is 30×30 cm in the wet season (De Datta 1981).

Even in China, wider spacing was used before the 1960s for the traditional varieties because they were tall and would lodge under high density. In the

1970s when China promoted double-season rice, density was very high with spacing of 10x15 cm with five seedlings per hill. After that, when hybrid rice was being commercialized, plant density was reduced gradually because hybrid rice has large panicles and the cost of hybrid rice seed is high. In recent years, planting density has been reduced to 20x30 cm with two seedlings per hill because super hybrid rice has larger panicles and the seeds are more expensive. Labor shortages are also a driving force to lower the plant density for manually transplanted rice (S.B. Peng, Huazhong Agricultural University, pers. comm.).

Thus, the planting densities of HYVs, such as IR8, IR36, IR42, and IR50, because of their short stature, lodging-resistance, and photoperiod-insensitivity were spaced 20×25 cm in the wet season, regardless of soil fertility. In the Philippines, the planting space of today's rice is 22x22 cm with 5 to 10 seedlings per hill. So, the planting population ranges from 103,000 to 206,000 plants/ha (Teodoro Correo, Jr., International Rice Research Institute, pers. comm.).

Some of the new cultural practices have forced Asian farmers to find new methods of raising seedlings, which, in turn, have triggered the occurrence of new diseases, especially seedling diseases previously unobserved in the traditional wet bed nurseries. The indoor seedling box technique, for example, has replaced the traditional outdoor nursery in response to mechanized rice production. This change in seedling production has induced the seedling diseases that had not been experienced before when conventional field nurseries were used.

The inoculum of seedling diseases may originate from either the soil or carried by seeds harvested from a previously infected field crop. The new seedling diseases are caused by both bacterial and fungal pathogens, some of which were formerly classified only as "minor" diseases and others not reported at all. Often, these seedling diseases are imposing production constraints in this man-made seedling production environment. The disease incidences increase costs of seeds and labor and delay planting time.

These diseases, now common, include **bakanae** caused by *Fusarium fujikuroi* (formerly known as *Fusarium moniliforme*), seedling blight caused by *Sclerotia rolfii*, some **bacterial seedling diseases**, such as bacterial brown stripe and seedling diseases caused by *Rhizopus* spp., *Pythium* spp., and *Trichoderma viride.*

For details, see the chapters on **fungal** and **bacterial** seedling diseases in this online resource.

2.3. Increase in fertilizer use

Traditional rice varieties are not responsive to added nutrients. Addition of more nutrients results in lodging when the plants are near maturity, which reduces yield. Tall traditional varieties can yield more when supported to prevent lodging (Yoshida 1981). However, the use of such support is an added cost in rice production, hence, unpopular among farmers. In reality, most farmers are not aware of such a practice.

Due to the responsiveness of the new semidwarf HYVs to nutrient inputs and boosted by government subsidies to purchase fertilizer, the rate of fertilizer application increased throughout the 1970s and 80s. Farmers then were convinced that more fertilizer would significantly increase their rice production. However, the new varieties' short stature and dense crop canopy were conducive to disease development. The number of reported disease outbreaks all seemed to be due to a lack of host resistance and to uncontrolled high fertilizer use (Mew 1991, 1992). Most farmers were not aware of the concept of input use efficiency in those days.

Moving from the use of organic compost to inorganic chemical fertilizers was common in the 1970s and '80s. However, the rate of fertilizer application eventually decreased in some countries as subsidies were removed and farm credit systems were still lacking. And, since the 1990s, because of increasing awareness of food safety and pesticide contamination in food production, organic rice farming has reappeared since it has been promoted and become popular among urban rice consumers.

3. HYVs and rice diseases

Currently, HYVs cover more than 80% of where rice is grown in Asia. Several rice diseases have appeared as a result of their introduction. From scattered information in the literature, these diseases were really "not new" but occurred on such a grand scale that they were thought of as "new." The diseases reported occurring on HYVs had been previously reported as "minor" diseases in specific rice-producing environments or regions. Some have been "upgraded" from "minor" to "major" status (Ou 1985). This has been attributed to intensive cropping during the introduction of the HYVs since the 1960s and a lack of host plant resistance among the first generation of HYVs for both regular and hybrid rice.

The first-generation HYVs, such as TN1 and IR8, were very susceptible to bacterial blight caused by *Xanthomonas oryzae* pv. *oryzae* and virus diseases. There was very little knowledge on these diseases at that time in tropical Asia. Large-scale planting of these HYVs resulted in immediate development of these "new" diseases in many countries. It showcased a serious threat to rice production that farmers had never experienced before. Subsequently, there was a major effort by rice breeders to improve disease resistance of the HYVs. However, new forms of the pathogens, such as that of *X. oryzae* pv. *oryzae,* also evolved. This scenario had been recognized in Japan half a century earlier, confirming E.C. Stakman's observation that plant disease is agriculture's "shifty enemy" (Stakman 1947). The threatening behavior of plant pathogens is exposed only when the host genotypes lack the needed resistance. With increased plant density and cropping intensity, it is a lesson that all plant pathologists and breeders have learned, sometimes too late.

The "infection window" of the pathogens causing these diseases may be broad or narrow, but they all occur during critical stage of rice growth, causing serious damage, thus hindering rice production. "Infection window" is defined as the most vulnerable crop growth stage during which a pathogen attacks. The infection window of some selected pathogens and the diseases they cause in relation to rice crop growth are listed in **SE Table 1**. Once an infection is initiated

SE Table 1. Rice growth stages most vulnerable for invasion by microbial pathogens.*

Disease	Pathogen(s)	Growth Stage							
		Germinated seeds	Seedling	Tillering	Maximum tillering	Booting	Flowering	Filling	Ripening
Yellow syndrome	Ragged Stunt and Grassy Stunt Virus								
Tungro	Rice Tungro Bacilliform Virus and Rice Tungro Spherical Virus								
Seedling blight	*Burkholderia plantarii*								
Seedling/ grain rot	*Burkholderia glumae*								
Bacterial blight	*Xanthomonas oryzae* pv. *oryzae*								
Grain discoloration	Opportunistic fungal and bacterial pathogens								
False smut	*Ustilaginoidea virens*								
Sheath blight	*Rhizoctonia solani* AGI-IA								
Brown spot	*Bipolaris oryzae*								
Blast	*Magnaporthe oryzae*								
Bakanae	*Gibberella fujikuroi*								

*Black-shaded areas indicate rice stage most vulnerable to pathogen invasion while the gray-shaded areas indicate doubt as to whether invasion actually happens during the corresponding rice growth stage.

by any of these pathogens, the diseases can develop rapidly and hinder crop growth, lowering yield. Occasionally, some researchers have claimed that the pathogens causing these newly observed diseases were introduced from other countries due to seed movement. From a plant quarantine point-of-view, whether or not a pathogen is indigenous or introduced via seed movement must be carefully studied and established before any such claim can be made (Ou 1985).

3.1. Changing the balance of the host-pathogen relationship

The triangular relationship in plant disease development illustrates the importance of the target host plant, the attacking pathogen, and the prevailing environmental conditions. Although all three components are equally important and need to be present for disease development, the host’s resistance or susceptibility and the crop’s population density play crucial roles in disease occurrence and intensity.

Favorable environmental conditions can exacerbate disease development. The disease has to occur on a host plant that is susceptible to the infection caused by a pathogen. If a new disease is reported, the question often asked is has the pathogen been introduced via seed importation from outside the region? The absence of a disease in a particular host environment or ecosystem may be due to resistance of the host plant. It is also possible that a particular disease was always around but had never been full blown enough to be observed by farmers or researchers.

If a pathogen has never been present in the host environment, then most likely it has been newly introduced. The occurrence of a particular disease may be associated with a change of host plant varieties planted by farmers and/or an increase in host plant's population density. Farmers changing methods of cultivation or cultural practices can also be a factor. In the context of the changing scenario of rice diseases due to HYV introduction in Asia, we need to keep all of these factors in mind. Otherwise, any report of a “new disease” may seem to be just a “new” introduction. While introduction of new pathogens through seed movement is not uncommon, reports claiming a new disease need to be treated cautiously and proven with good science.

3.2. Classifying the emerging diseases

How are emerging rice diseases classified in terms of their importance? In the context of this online resource, to set research priorities on resistance breeding, rice diseases are perceived as either “major” or “minor.” This must be based on long-term field observations on their occurrence and their potential damage imposed on the rice crop in farmers' fields. So, it is the “experience” of rice plant pathologists that is crucial. The diseases are also grouped according to the parts of the rice plant they attack. They are called “emerging diseases” if they have appeared exclusively and widespread after HYV introduction. The term “emerging” provides a “hidden sense” of the disease spreading but provides no quantitative sense of its association with the production system. However, this classification may provide an indication, and sometimes a description, of the relationship of the disease to cropping intensity and management priority.

In the literature, however, plant diseases are delineated as ”endemic” or ”epidemic,” which are roughly defined as occurring frequency and spreading potentially in spatial and temporal scales within a crop population, respectively, thus resulting in crop damage intensity. Nonetheless, whether plant diseases are classified as “major or minor” and “endemic or epidemic”, they are descriptions that indicate the degree of their importance and their potential to seriously damage the crop.

Following the terms used in medical science, Savary et al (2011) proposed placing plant diseases into three broad categories: chronic, acute, and emerging. Chronic disease is defined as one that “occurs over large areas, causing regular attrition in system performance, including reduction in crop yields.” Acute disease “occurs irregularly, both temporally and spatially, and which, when occurring, may cause massive disruptions.” An emerging disease is “one whose range is expanding to new areas.” While chronic diseases have some similarities to the term “endemic” and acute diseases have similarities to “epidemic”, the descriptions of these new terms provide a sense of their “arising and threatening” aspects.

A chronic disease may be widespread and the degree of crop damage it causes, on a damage scale, may be spread over time. So, it seems to be less than an acute disease at the point of occurrence. An acute disease does not occur often but, once it does, it may totally destroy a crop. In areas where an acute disease is absent, the best option is to prevent it from appearing.

An emerging disease may be present but it may be ignored if it imposes no threat to crop production with existing varieties and cultivation methods. However, once a new crop variety, which is susceptible, is planted on a large scale, the disease's potential is likely to be exposed. A disease's spread on a spatial scale will be a function of the expansion of the new variety. In this online resource, "emerging rice disease" simply means a disease that has arisen and expanded to a level higher than its previous status in distribution and in causing crop damage. This suggests that the disease occurrence is related to cropping changes, and/or new rice genotypes.

The purpose of documentation is to emphasize the importance of setting resistance breeding and disease management as priorities in rice crop improvement and production. It also shows the importance of field observations and subsequent reporting. Because of their "shifty" nature, recorded descriptions of new diseases are useful references for future generations of rice scientists.

The scope of this short review is limited to the planting of the new HYVs, genotypes, and cultivation methods. For detailed information on each disease, go to where they are discussed in detail in this online resource. The following summarizes their occurrence. Because HYV introduction began in the 1960s, their descriptions are based on field observation reports, some of which have been published in the literature.

3.3. Five groups of rice diseases

Whether rice diseases are chronic or acute, major or minor, there are five groups into which some existing ones have changed and some others have emerged since the introduction of the first generation of HYVs.

- Group 1 is composed of those diseases that were called "major" or "chronic" prior to HYV introduction. During the initial large-scale HYV planting, coupled with new technologies for crop production such as seed treatment, they became "minor". But after a period of "quiet retreat" for two decades, they re-emerged to be "major" again. Bakanae and brown spot, **Part II, Section 1, Chapters 1** and **2**, respectively, are examples of group 1 diseases.
- Group 2 is composed of those diseases that have never been "quiet" from the past up until now. Actually, the fungal disease, rice blast (**Part 12 of Part II, Section 1, Chapter 2**), may be the only true example. It is a major and acute disease.
- Group 3 is composed of those diseases that are closely related to the introduction of the HYVs. They may have been there before but were not noticed or reported by farmers or researchers. After introduction of the HYVs, they "emerged" to show their "true colors". Bacterial blight (**Part II, Section 2, Chapter 2**), rice tungro (**Part II, Section 3, Chapter 1**), and grassy stunt and ragged stunt (**Part II, Section 3, Chapter 2**) are in this group. They initially occurred or were observed as acute types. Their occurrence was related to large-scale planting of the new rice genotypes that lacked host plant resistance to them and the HYVs' asynchronic planting, especially where tungro was concerned. Increased inputs for the HYVs also played a role.
- Group 4 is composed of those diseases that were considered minor problems prior to HYV introduction until production systems to

accommodate the HYVs became more intensified with more nutrient inputs. Sheath blight and other sheath and culm diseases (**Part II, Section 1, Chapter 3**), caused by sclerotium-producing pathogens, and false smut and grain-related diseases (**Part II, Section 1, Chapter 4**) fall in this group. Red stripe (**Part II, Section 1, Chapter 2**) may also fit into this group. Relatively new in the literature, its occurrence seems to be related to the deficiency of certain mineral nutrients due to crop intensification. So far, its distribution is restricted. In Vietnam, it was a serious problem for a few years then gradually decreased to very minor in importance.

- Group 5 diseases are more related to changes in cultivation methods, especially using seedling boxes in nurseries to raise seedlings indoors in screen or vinyl houses when machine transplanting is involved. These are the seedling diseases caused by pathogens that are either fungal (**Part II, Section 1, Chapter 4**) or bacterial (**Part II, Section 2, Chapter 4**). However, their occurrence may not necessarily be related to planting HYVs, but more to planting methods. The fungal diseases have been reported in the literature prior to the introduction of HYVs but some of the bacterial seedling diseases may have not. The bacterial pathogens are seedborne and have been detected in rice seeds.

3.4. More on both "emerging" and long-time "resilient" rice diseases

3.4.1. *Bacterial diseases.* After the Green Revolution, several bacterial diseases arose to seriously threaten rice production. In the 1960s and 70s, epidemics of **bacterial blight (BB)** occurred after the first HYVs, such as TNI, IR8, and Jaya 8, were released to farmers in South and Southeast Asia. The epidemics revealed BB's threatening nature and the need for host plant resistance. BB resistance became an important trait to incorporate into the new varieties. The first of the new HYVs with BB resistance was IR20. Except for IR24, TKM 6 with the *Xa4* gene had been the source of BB resistance during this period. However, extensive planting of the BB-resistant rice varieties in the 1970s and 80s resulted in repeated BB epidemics due to the emergence of BB races with new virulence. In addition, new rice cultivation methods, such as direct seeding, brought in new bacterial diseases, all having seedborne inoculum.

A number of new seedling diseases were reported after mechanized rice planting began in the 1970s, first in Japan and later elsewhere. Mechanization changed the manner in which seedling production is done, as discussed earlier, now with seedling or nursery boxes in vinyl houses. **Seedling blight (SdB)** was initially reported to occur only in seedling boxes. Also due to the switch to seedling boxes, **seedling rot (SR)**, which shows as grain rot in the field during the grain-filling stage, has also become a serious problem.

Another common seedling disease is bacterial stripe or **bacterial brown stripe (BbS)**, which occurs widely in upland and lowland rice nurseries of most rice-growing countries (Ou 1985). *Pseudomonas fuscovaginae*, which causes **bacterial sheath brown rot (SbR)**, is also reported to infect and cause a soft rotting of seedlings.

In the seedling or nursery box method, prior to germination, seeds are soaked in water for 24-48 hours before sowing in the boxes at a high seeding rate. Thus, if infected seeds are present even at a low percentage, the bacterial inoculum carried by these infected seeds will suspend in the water during seed soaking, which provides inoculum to infect other apparently healthy seeds. So, if any infected seeds are present, this method is actually soaking seeds in a bacterial suspension prior to sowing them in the boxes. Then, all soaked seeds have an equal opportunity to be contaminated. The infected soaked seeds after germination in the seedling box produce seedlings that are killed by the disease. To avoid this, clean and healthy seeds must be used in the process. Currently, chemicals have been used to decontaminate seeds during soaking, but this may not be sustainable. For more information, go to **Part III, Section 2, Improving seed health**.

Climate change may influence the occurrence of rice bacterial diseases in some areas. Bacterial panicle blight in the southern United States, known as **grain rot (GnR)** in Asia, appears to arise when nighttime temperatures increase during flowering (Nandakumar et al 2009). High nighttime temperatures have been found to be associated with recent rice yield declines in tropical Asia (Peng et al 2004). The situation is likely to promote a specific bacterial population that causes a related disease syndrome. The GnR pathogen, *Burkholderia glumae*, is frequently detected on rice seeds and may have been involved with other seedborne bacteria and fungi in causing grain discoloration in tropical environments. The occurrence of GnR in the southern United States and South Korea over the last two decades also seems to be related to the rise in nighttime temperature. For more information, go to on the **introduction on bacterial diseases in Part II, Section 2**.

3.4.2. Fungal diseases. The profile of rice fungal diseases changed after the Green Revolution. Old “minor” diseases, such as **sheath blight (ShB)** and false smut, have become primary concerns to rice farmers in recent years. Some diseases, which have never been before reported, have become a significant concern as a consequence of rice crop intensification. **Red stripe** is “new” because it has never been reported before in the literature. **Brown spot** and **bakanae** may appear to have disappeared in past decades after HYV introduction, but in reality, they are just “waiting” for the opportunity to make a comeback. On the other hand, there are fungal diseases that have never faded away since plant pathology became a scientific discipline. For example, **rice blast** has a long record of staying “one step ahead” of breeders. The new profile for the fungal diseases is expected to be a “full-partner” in the rice disease triangular relationship described earlier.

Most of the frequently reported rice diseases are “old” fungal ones that have been reported prior to introduction of the HYVs. Their continued presence in rice production systems, despite drastic changes in the environment, indicates “longevity and elasticity” of the pathogens that cause them.

Following are some brief summaries of these fungal diseases. For full details, go to the chapters in **Part II, Section 1**.

3.4.2.1 **Bakanae (Bak)**: This is one of the oldest reported rice diseases, as early as 1828 in Japan (Ou 1985). An outbreak in California in 2008 (Carter et al 2008) suggested that rice seed, as an inoculum carrier, plays an important role in the movement of the pathogen in and out of rice production areas. More importantly, however, is the fact that the pathogen, *Fusarium fujikuroi*, can establish a close habitat with aquatic plants around the rice fields to supply inoculum to infect the rice crop. Although Bak has been known to plant pathologists for a long time, its epidemic process remains little understood. Prior to the discovery of seed treatment fungicides, Bak was considered a major problem in rice production. However, extensive use of fungicides in seed treatment has diminished its importance in most places. Even so, in recent years in Japan and some other countries, fungicide-resistant strains of the pathogen have been reported and the disease has re-emerged in seedlings grown in dry-bed nurseries and seedling boxes.

3.4.2.2. Brown spot and blast: Historically speaking, among the rice diseases, the **foliar diseases** have imposed the most serious threats to rice production in Asia. Blast (RBl) and brown spot (BSp) are the two well-recorded and resilient foliar diseases of rice. RBl is well-known and feared by farmers because of its potential to explode to large-scale epidemics, which can destroy even rice crops approaching maturity. A blast epidemic can destabilize a region's food security.

RBl is an old disease, recorded in Chinese rice fields as early as the 16th century. Why and how does the RBl pathogen live for such a long time? Three features of the pathogen provide the relevant answer: high pathogenic variability, reproductive rate, and infection efficiency of its inoculum. All three features combined give RBl its high epidemic potential. The disease also has a broad "infection window." The pathogen can be found during the entire life cycle of the rice plant. Under a favorable environment, it can attack at any time from the seedling stage to the mature crop. The high pathogenic variability makes it very adaptive to the host's changing environment, giving rise to new virulent strains that can spread rapidly when infection occurs.

For many decades, efforts to understand the mechanism of RBl's high variability were in vain until advances in molecular biology came along. The new technologies have enabled scientists to look into the organism's genetic makeup to find out how it organizes an attack on the rice plant. Also, with the new techniques, researchers can determine how the rice plant assembles its defenses. With genes identified and gene functions uncovered, in the near future, researchers may be able to develop more durable resistance to turn RBl into just a minor problem for rice farmers.

BSp occurs more frequently on rice being stressed by water shortages or drought. So, it is associated with poor rice production environments, especially fields deficient in nutrients, especially nitrogen. In surveys conducted in the 1990s, BSp may have been responsible for only about 6% of the yield losses across Asia's rice production areas (Savary et al 2000). However, it appears to be coming back due to more drought being induced by global climate change.

3.4.2.3. Red stripe: Red stripe (RS) was first observed in Indonesia in 1988 and was thought to be caused by a bacterial pathogen. Later it was observed in many rice-growing countries in Southeast Asia. Although RS occurs in rice under intensive production systems, it has not been observed in South Asia and in temperate regions. In Vietnam, it occurs widely in the Mekong Delta area only. RS was later established to be a fungal disease with the fungal pathogen belonging to the genus *Gonatophragmium* Deighton (Elasegui et al 2004), which is difficult to isolate and is slow-growing on artificial media. Field observations seem to indicate that RS is associated with nutrient deficiency, specifically potassium in the field.

3.4.2.4. Grain discoloration and false smut: In contrast to the traditional, tall and lodging-prone varieties, popular HYVs lack photoperiod sensitivity and thus can set flowers for grain filling during the rainy season. However, this comes at a cost with increases in grain diseases, often termed by farmers as "dirty panicles" during the wet season crop. This disease syndrome involves both fungal and bacterial pathogens. It occurs more frequently during the rainy season and it is difficult to diagnose. For detailed information, go to the respective chapters for grain diseases caused by fungus pathogens (**Part II, Section 1, Chapter 4**) and bacteria pathogens (Part II, Section 2, **Chapter 4**) and **Part III, Section 2, Improving seed health**).

Various organisms can infect rice grains before or after harvest, causing grain discoloration externally or internally. The extent of discoloration depends on season, location, type of organisms, and the time when the grains are infected in the field or during storage. Some field fungi can infect both the leaf sheath and grains while the crop is still growing in the field. These field fungi may be saprophytes or weak pathogens known as opportunistic pathogens that attack the rice plant when it is already under stress. There are not many reported "true" grain diseases or "diseases of grains and inflorescence" as referred to by Ou (1985) in which the grains are the pathogen's primary target.

Grain discoloration is a complex problem more associated with the HYVs that lack photoperiod sensitivity. It may be due to the presence of opportunistic pathogens that occur after rice infestation by the stink bug (*Oebalus pugnax* F.). Among the various microorganisms isolated from discolored seeds are *Bipolaris oryzae*, *Sarocladium oryzae*, and *Cercospora oryzae*, which primarily target other parts of the rice plant.

False smut (FSm) is not a "true smut", which is caused by the basidiomycetes *Ustilago* or *Tilletia* spp. FSm is caused by an ascomycete and was a minor disease until rice production intensified and with the introduction of hybrid rice. Since then, FSm has increased in incidence and severity, prevailing in irrigated rice ecosystems. The disease is characterized by the formation of "smut balls" in infected grains. FSm has a very narrow "window of infection", which takes place at flowering stage. Because grain is affected and the pathogen produces a toxin, FSm has become an important problem in rice production and, potentially, it may also be related to food safety.

3.4.2.5. Leaf sheath diseases caused by *Rhizoctonia* spp.: A group of rice diseases, singly or in combination, that threaten rice production have emerged during the Green Revolution era. These diseases include those caused by sclerotium-producing fungal pathogens belonging to *Rhizoctonia* spp. and *Sclerotium* spp. Diseases caused by these fungi are widely distributed in various rice ecosystems and are recognized as rice production constraints as rice production intensifies. The primary targets of these pathogens are the leaf sheath and culm, but other plant parts may also be affected. One unique feature of these pathogens is the formation of sclerotia on or in the plant tissues. The shape, size, and color of the sclerotia are used in diagnosis. **Sheath blight (ShB)**, caused by *Rhizoctonia solani*, is one of today's most important diseases in many rice-growing countries.

Where rice was intensively cultivated, such as on research farms, the distribution frequencies of sclerotia in rice fields after harvest were 57, 42, and 0.4% for *R. solani*, *R. oryzae-sativae*, and *R. oryzae*, respectively. The "sheath blight complex" (Banniza et al 1999) is now often used to refer to ShB, sheath spot, and aggregated sheath spot diseases caused by *R. solani* Kuhn AG1-1A, *R. oryzae*, and *R. oryzae-sativae*, respectively. Amplified fragment lengthen polymorphisms (AFLPs) revealed that, among the isolates collected in rice fields in India, *R. solani* AG-1 was by far the most predominant fungus followed by *R. oryzae-sativae. R. oryzae* was not detected in this study (Taheri et al 2007). It seems that factors that determine population distribution of *Rhizcotina* spp. in rice fields vary from one geographic region to another.

We focus on **ShB**, caused by an aerial form of *Rhizoctonia solani* AG1–IA that infects the rice plant near the waterline causing lesions to expand upward. It is unlikely that rice roots are infected in submerged conditions. Likewise, there is no report if roots of upland rice being infected naturally. The ShB pathogen can also infect other crop species including legumes (mungbean, soybean, and cowpea), monocots (maize, sorghum, and wheat), and some gramineous weeds, such as *Echinochloa* spp. On these other host plants, lesion development is similar to that of infected rice, which is an upward lesion expansion after initial infection at the basal leaf sheath.

Most reports describe the pathogen as a "subterranean soilborne" pathogen, which may not be relevant. In reality, the soilborne phase of ShB is only one stage of the epidemics. Field experiments and simulation models show that while the onset of ShB epidemics is determined by initial infection occurring at the base of the leaf sheath, processes occurring in the leaf pathozone strongly determine terminal ShB incidence (Savary et al 1997). The morphological characters, pathogenicity, and restriction fragment length polymorphisms (RFLPs) of AT-rich DNA of isolates from plant debris in the soil were different from the lesions on plants (Banniza et al 1999). The soil isolates were less aggressive than the plant isolates, supporting the view that the soilborne phase may play a less important role than the leafborne phase of ShB epidemics. Likewise, the pathogen population seemed not to be diversified as compared to other fungal pathogens studied. The role of its sexual stage, which is readily observed in the field, is not clear.

ShB epidemics involve two successive phases: a soilborne phase, which is presumably monocyclic, and a leafborne one, which is polycyclic (Savary et al

1997). In the soilborne phase, the pathozone includes the base of the leaf sheath or the lower layer of the canopy but not the underground parts of the plant. In the leafborne phase, the pathozone is in the upper layer of the canopy. Most diseases caused by soilborne pathogens infect the subterranean plant parts including the roots. However, the ShB fungus does not occur in the "subterranean portion" of the plant. During the first phase of an epidemic, the primary soilborne inoculum, the sclerotium, floats on paddy water after field flooding and then attaches to the base of a plant near the waterline where it usually produces primary lesions.

Kozaka (1961) used the term "vertical spread" to describe post-infection during the soilborne phase. When primary infections are established at the base of the crop canopy near the waterline but above the soil, the leafborne' (Yang et al 1990) or the polycyclic phase can develop in the upper layer of the canopy (Savary et al 1997). The primary lesions expand and often coalesce, giving rise to strands of mycelia that run on the surface of healthy sheaths and leaves where new lesions are established. The second phase involves the spread of the disease.

It should be noted that in rice fields under tropical or temperate conditions, the first phase of infection may not necessarily be initiated from sclerotia in the soil. The inoculum may come from the mycelia and/or sclerotia of plant debris left in the field after harvest or from weed hosts around the rice field levees.

3.4.2.6. Other fungal diseases of importance: There are other fungal diseases important in specific countries or regions, including sheath rot, narrow brown spot, stem rot, among others. For detailed discussions on the fungal diseases, go to the five chapters in **Part II, Section 1**.

*3.4.3. **Virus and phytoplasma diseases of rice**.* Rice viral diseases must have been present ever since humans domesticated *Oryza sativa* for food. Many viral pathogens probably have been in equilibrium with rice as the host for a long time (Hibino 1996). When tungro first occurred in South and Southeast Asia in the 1960s, few would have believed that it was a virus disease (Ou 1985). It was initially thought to be a problem soil disorder tied to plant physiology and many other potential causes, but certainly not an infectious disease of rice caused by a virus.

Indeed, when the HYVs were first widely released to farmers, a score of rice diseases caused by viruses and phytoplasma arose. The first was tungro in the 1960s, followed by grassy stunt in the early 1970s and ragged stunt in the late 1970s. For a short period, viral disease outbreaks, arising one after another, led plant pathologists to wonder when the next one would appear (Ling 1972, Ou 1985). It was an "eye-opening" experience for many plant pathologists working on rice diseases in the tropics. All these "newly discovered" viruses or phytoplasma in the Asian tropics were transmitted by either leafhoppers or planthoppers. This group of diseases is limited in geographic distribution and most have not been reported in rice-growing countries in the high Asian latitudes.

The repeated outbreaks of rice virus diseases from the 1960s up to the 1980s are often attributed to crop intensification through double- or triple-rice cropping systems. Asynchronous planting using HYVs also disrupted the balance in rice production systems. Scientists have been working hard to obtain a more sustainable system in tropical Asia that includes management and resistance breeding. As of this writing, the tungro viruses are apparently endemic and do not cause economic losses. For years, the nature of rice resistance to viruses was not well understood. Recent research has made important breakthroughs especially on resistance to rice tungro viruses. New breeding efforts can use these resistance genes to develop new and durable resistance (I.S. Choi, pers. comm.). For more information, go to **Part II, Section 4, Chapter 3, Molecular genetics of major virus resistance in rice.**

When the rice crop is infected by more than one virus, it becomes clear that substantial efforts to obtain disease resistance in tropical Asia is beyond developing resistance to a single virus disease (Du et al 2007). For years, the so-called “yellowing syndrome” was widely spreading in Mekong River Delta, imposing a serious threat to rice production. The causal agent of the disease had been widely speculated until it became clear that the syndrome is a double-infection by rice grassy stunt virus and rice ragged stunt virus (Du et al 2007). This finding alarmed researchers and farmers alike that the rice crop may be attacked simultaneously by more than one virus if they are transmitted by the same insect vector. Certainly, more research is needed, not only on resistance, but also on the epidemiology of the rice viruses. An effective management strategy must be formulated based on a clear understanding of the disease epidemiology and the feeding behavior and ecology of the insect vectors.

4. Plant diseases, the shifty enemies

Just before the dawn of the 21st century, it was a general belief that the world’s rice supply was abundant; hence, research increasing rice production was no longer to be a main concern. However, in early 2008, a “rice crisis” occurred (IRRI 2008). A crisis of this magnitude could not have been developed overnight. At a fundamental level, the sustained rise in the price over the prior 7-8 years indicated that more rice was being consumed than being produced. This imbalance between demand and production was partly masked by a reduction in rice stockpiles.

Many other factors, both long- and short-term, surely contributed to the 2008 crisis. Specifically, climate change causing prolonged drought in some areas and flooding in others during the main rice cropping seasons had affected and reduced rice production. Major rice exporting countries imposed an export restriction to protect domestic needs, further reducing rice supply in the international market. The real cause of this crisis as noted by IRRI (2008) seemed to stem from complacency of solving rice production problems, including rice diseases.

How could rice diseases exacerbate the food crisis? First, we need to recall that much of the gain in rice yield in the past decades was partly related to the improvement of disease resistance in the HYVs (Figure 1). To lessen the losses caused by rice diseases, planting disease-resistant varieties is an integral component of the total efforts to safeguard yield potential. Despite this effort, a large portion of rice production is lost to diseases in the field while the crop is grown and after harvest during storage. Losses amounting to millions of tons are enough to feed more than 100 million people. This is the single most important reason why the rice crop must be protected from damage caused by diseases and pests to make sure rice food supply is not undermined.

Surveys and studies have estimated that rice diseases cause about 10% losses across all rice production regions in Asia (Savary et al 2000). Individually however, despite the high epidemic potential of RBl and BB, these two diseases cause less than 1% of the yield losses while ShB and BSp each can reduce attainable yield by 6% under different crop production environments. However, these data do not imply that RBl blast and BB are no longer serious threats to rice production. On the bright side, 2nd generation HYVs are now carrying resistance to RBl, BB, and major virus diseases. However, despite the presence of resistance, these diseases can still reduce rice yield by 1% or more. The studies also indicate that BSp and ShB, which used to be considered “less important” when HYVs were first introduced, have emerged since the 1990s. Right behind them are FSm and grain discoloration.

Indeed, some diseases may be temporarily “quiet” but probably will never fade away completely. The shifty nature of rice diseases must not be overlooked. Old pathogens may evolve to new virulent forms that can infect newly developed resistant rice varieties (Mew et al 2004**)**. This is a war in which we need to safeguard our “gained ground” from these shifty enemies.

To again emphasize, rice diseases that initially afflicted the HYVs may not be new. Most of them were either reported as “minor” or unnoticed by farmers and researchers due to their low incidence prior to HYV introduction. Changing the imbalance of the host-pathogen relationship re-enforced the threatening nature of these rice diseases once a susceptible host genotype is released. So, research to fight rice diseases will always be a continuous effort.

References

Banniza, S., Sy A.A., Bridge, P.D., Simons, S.A., Holderness, M. 1999. Characterization of populations of *Rhizoctonia solani* in paddy rice fields in Côte d’Ivoire. Phytopathology 89:414-420.

Carter, L.L.A., Leslie, J.F., Webster, R.K. 2008. Population structure of *Fusarium fujikuroi* from California rice and water grass. Phytopathology 98:992-998.

De Datta, S.K. 1981. Principles and practices of rice production. Wiley-Interscience. Singapore: John Wiley and Sons. 618 p.

Du, P.V., Cabunagan, R.C., Cabauatan, P.Q., Choi, H.S., Choi, I.R., Chien, H.V., Huan, N.H. 2007. Yellowing syndrome of rice: etiology, current status and future challenges. Omonrice 15:94-101.

Elazegui, F.A., Castilla, N.P., Dalisay, T.U., Mew, T.W. 2004. Causal agent of red stripe disease of rice. Plant Dis. 88:1310-1317.

GRiSP (Global Rice Science Partnership). 2013. Rice almanac, 4th edition. International Rice Research Institute, Los Baños, Philippines. 283 p.

Hibino, H. 1996. Biology and epidemiology of rice viruses. Ann. Rev. Phytopathol.34:249-274.

IRRI (International Rice Research Institute). 2008. Background paper: The rice crisis: what needs to be done? Los Baños, Philippines. 12 p.

Kozaka, T. 1961. Ecological studies on sheath bight of rice plant caused by *Pellicularia sasakii* (Shirai) S. Ito and its chemical control. Chugoku Agric. Res. Sta. 20:1-133.

Lee, E.J., Zhang, Q., Mew, T.W. 1989. Durable resistance to rice disease in irrigated environments. In Pp. 93-100, *Progress in Irrigation Rice Research*. International Rice Research Institute, College, Laguna, Philippines.

Ling, K.C. 1972. Rice virus diseases. Manila (Philippines): International Rice Research Institute. 134 p.

Mew, T.W. 1991. Disease management in rice. Pp. 279-299 in: CRC Handbook of Pest Management. 2nd ed. Vol. III. D. Pimental, A. A. Hanson, eds. CRC Press, Boca Raton, FL.

Mew, T.W. 1992. Management of rice diseases: A future prospective. Pp. 54-66 in: Pest Management and the Environment in 2000. A. Aziz, S. A. Kadir, H. Barlow, eds. CAB International, Wallingford, UK.

Mew T.W., Leung H., Savary S., Vera Cruz C.M., Leach J.L. 2004. Looking ahead in rice disease research and management. Crit. Rev. Plant Sci. 23:103-127.

Nandakumar, R., Shahjahan, A.K.M., Yuan, X.L., Dickstein, E.R., Groth, D.E., Clark, C.A., Cartwright, R.D., Rush, M.C. 2009. *Burkholderia glumae* and *B. gladioli* cause bacterial panicle blight in rice in the southern United States. Plant Dis. 93:896-905.

Ou, S.H. 1985. Rice diseases. 2nd ed. CAB International. England.

Peng, S., Huang, J.-L., Sheehy, J., Laza, R.C., Visperas, R.M., Zhong, X.-H., Centeno, G.S., Khush, G.S., Cassman, K.G. 2004. Rice yields decline with higher night temperature from global warming. PNAS 101:9971-9975.

Reddy, C.S., Laha, G.S., Prasad, Krishnaveni, M.S, D., Castilla, N.P., Nelson, A., Savary, S. 2011. Characterizing multiple linkages between individual diseases, crop health syndromes, germplasm deployment, and rice production situations in India. Crop Res. 120:241-253.

Savary, S., Willocquet, L., Teng, P.S. 1997. Modeling sheath blight epidemics on rice tillers. Agric. Sys. 55:359-384.

Savary, S., Willocquet, L., Elazegui, F.A., Castilla, N.P., Teng, P.S. 2000. Rice pest constraints in tropical Asia: Quantification of yield losses due to rice pests in a range of production situations. Plant Dis. 84:357-369.

Savary, S., Nelson, A., Sparks, A.H. Willocquet, L. et al. 2011. International agricultural research tackling the effects of global and climate change on plant diseases in the developing world. Plant Dis. 95(10):1204-16.

Stakman, E.S. 1947. Plant diseases are shifty enemies. Amer. Sci. 33:321-350.

Taheri, P., Gnanamanickam, S., Hofte, M. 2007. Characterization, genetic structure, and pathogenicity of *Rhizoctoni*a spp. associated with rice sheath diseases in India. Phytopathology 97:373-383.

Yang, X.B., Snow, J.P., Berggren, G.T. 1990. Analysis of epidemics of *Rhizoctonia* aerial blight of soybean in Louisiana. Phytopathology 80:386-392.

Yoshida, S. 1981. Fundamentals of rice crop science. International Rice Research Institute, Los Baños. Philippines

Willocquet, L., Elazegui, F.A., Castilla, N., Fernandez, L., Fischer, K.S., Peng, S., Teng, P.S., Srivastava, R.K., Singh, H.M., Zhu, D., Savary, S. 2004. Research priorities for rice pest management in tropical Asia: A simulation analysis of yield losses and management efficiencies. Phytopathology 94:672-682.