The Future Impact of Rice Diseases

Robert S. Zeigler
Director General Emeritus

Hei Leung
Plant Pathologist
International Rice Research Institute

Building on the past

The past four decades have seen the publication of a very large number of reports in every area of research on rice diseases. These have appeared as monographs, books, articles, or proceedings, addressing individual rice diseases, or broader subjects related to rice diseases in general. However, up to now, the seminal work on rice diseases (Ou 1972, 1985) has been the most comprehensive and detailed document on rice diseases and a key and unique reference source for researchers, students, and extension specialists.

In order to assess the future impact of rice diseases, the authors of this collection of sections and chapters in this unique online resource attempt to retain the factual information provided by Ou (1985) but, at the same time, update the profile of diseases causing yield and quality loss in rice in changing production systems. The threats of diseases are expected to be exacerbated by changing socioeconomic conditions and climate changes (see further below). However, advances in science and technologies also present opportunities to provide new solutions for new problems as well as for old ones. Because of the global nature of disease problems, international collaboration must be organized to develop a program integrating host resistance, disease pathogen monitoring, and ecological management. Such a program can facilitate sharing of resistant germplasm data on disease outbreaks, and sharing of successful technologies in managing diseases on a regional and global scale.

If not a global assessment—what then?

Developing a global view of the impact of any single rice disease is a monumental challenge as it must be derived from a breakdown of different production scenarios, varying environments, pathosystem-specific characteristics, prevalent cultivar characteristics, and management practices. Many of the sections and chapters in Parts II and III of this online resource cover each of these areas in some detail. However, attempting to develop a global assessment of the impact of the rice disease universe, while an intriguing prospect, is unlikely to yield anything of practical use.

What could be of use, though, is a perspective on how rice production systems vary across the world, how production practices are likely to change over the coming decades, how the drivers of change themselves may impact on the severity and expression of diseases in rice, and what these circumstances and changes might mean in terms of research challenges for managing plant diseases. In this general introduction, the major rice production scenarios around the world are briefly described by region. Then major changes that have occurred in the last 20 years are introduced together with an estimate of the impact these changes have had on rice diseases. Our brief analysis of the drivers of change attempts to predict the directions rice production practices may take in different regions.

Demand for rice will continue to grow

If we look at the global rice equation, as far as we can tell, the demand for rice is going to continue to grow for many decades to come. Every prediction that the demand for rice is going to taper off has proven to be incorrect. If we look at the population trends for the next several decades, the world is going to be adding about a billion people every 12 to 15 years. So, an additional 2 billion mouths will have to be fed around mid-century, when the world reaches the 9 billion mark, and this is projected to exceed 10 billion by the end of the century (Mohanty 2013). If global per capita rice consumption follows the trend in the past two decades, then total consumption will grow at the rate of population growth. A billion people translate into 100 million tons of additional paddy (produced rice) to feed them. So, just in order to keep pace with population growth, we'll have to add 100 million tons of paddy (produced rice) or 65 million tons of milled rice every decade and a half—a major challenge!

Diversity of rice production systems

The most significant first split among rice production systems is whether or not the water supply is controlled and managed (table below). As will be seen in the next section, continuous flooding has important implications for potential disease regimes. We generally refer to systems with an assured and manageable water supply as "irrigated rice" systems. These lands are highly productive, often intensively cropped (two or more crops per year), with farmers typically applying significant fertilizer and crop-protecting chemical inputs. These systems cover about 50% of rice production area yet produce around 75% of rice globally. They are the predominant systems in eastern Asia and many of the great river deltas where rice is grown.

Likewise, irrigation schemes have been developed around the world in areas where relatively flat topography and abundant water permit them. In most irrigation schemes, even those managed wholly by individual farmers, the extremities of the systems suffer occasional water shortages at some time. Where irrigation schemes are poorly maintained, water shortages, stagnation, and/or salinity problems can have a serious negative impact on the crop, with associated increases in disease pressure. In areas where intermittent drought occurs, it is likely that blast disease incidence and severity will increase.

In systems where water supply is not assured, or "rainfed rice" systems, the crop depends entirely on rainfall for water. On relatively flat, often lowland, topography, or where fields have been leveled, farmers normally construct bunds to capture and hold rainwater. In years with abundant well-distributed rainfall, rainfed lowlands may approach irrigated yield potential. However, in most years the crops may suffer from drought, or flooding, or

Global rice production systems: proportion, average yield, and contribution to rice production.[1]

Production system	Area (million hectare)	Average yield level (t/ha)	Contribution to global rice production (%)
Irrigated lowland	80	5.4 as high as 8-10	75
Rainfed lowland	60	Variable, 3-4	20
Rainfed upland	14	1.0	4
Total	154	-	-

[1]Source: Rice Almanac. 2013. 4th ed. Global Rice Science Partnership.

both. On sloping lands, or "rainfed upland" systems, bunding is generally not practiced. Standing water rarely, if ever, accumulates in the fields and yields are typically very low. The risk of crop failure is so high under both rainfed lowland and upland conditions that farmers are often unwilling to invest much in fertilizer applications. Yields therefore tend to be low, and as will be seen in some chapters, disease pressure also tends to be lower. Rainfed upland systems were more common in the past and increasingly are now found only in areas with limited market access or where lands are being opened for other ultimate purposes.

Most rice in the world–that is, in Asia–is transplanted. Typically, seedlings are grown in high density in a "nursery" until they are anywhere from 15 to 30 days, or more, old. As the seedlings grow and depending on the availability of water, labor, and draft animals or machinery, farmers will prepare the land accordingly. Ideally, they will puddle the soil, completely destroying its structure such that the settled clay particles seal the soil and prevent water form percolating down into the soil profile. Once the soil is prepared, the seedlings are up rooted from the nursery and transplanted into the main field. In Korea and Japan, this is almost exclusively done by machines, while in the rest of Asia and Africa, it is done by the farmers' families and/or hired labor. Transplanting in puddled soils and maintaining standing water in the field combine to help control weeds. How the land is prepared, with adequate water or not, may affect soilborne diseases. For example, when practicing aerobic rice production as a water conserving management approach, farmers face more soilborne problems than under traditional irrigation regimes.

Where water is abundant in the dry season, a farmer can get two or even three rice crops per year. In cases where there are multiple crops per year and where developmental stages of the crop in different fields may be asynchronous, pathogen propagules and/or vectors may move from field to field and build up in large numbers. Irrigation water also serves as a dispersal medium for sclerotia of the sheath blight causal agent, ***Rhizoctonia solani***.

In some parts of Asia and in most of the Western Hemisphere, rice is direct seeded into the field. Direct seeding is almost always found where labor is scarce or very costly. If the soil is flooded and/or puddled at planting time, farmers will plant "pregerminated seed." This is seed that has been thoroughly soaked in water and allowed to begin the germination process for at least 24 hours. For planting in relatively dry soils, dry seed is broadcast or drilled into the soil. Rainfed uplands are almost exclusively direct dry seeded. Weed control is very difficult in direct-seeded rice, especially dry direct-seeded rice, so herbicides are increasingly being used for weed management. Because of weed problems and irregularities in stand establishment that are so common with direct-seeded rice, seeding rates tend to be very high (150–200 kg or more of seed per hectare) creating very dense canopies early in the season. This has implications because it may create a microclimate favorable to certain diseases

Water

All rice land receives 35–45% of all the world's irrigation water (which itself uses some 70% of all the world's developed water resources (Bouman 2013). Water supply and its management are without doubt the greatest determinants in the performance of rice cultivation. Because of the aerenchyma in its roots, the rice plant is able to grow in soils that are completely submerged and essentially anoxic. The reducing environment in the soil solubilizes nutrients, such as phosphorus, that might otherwise be deficient. Likewise, the anaerobic environment is highly suitable for microorganisms capable of fixing atmospheric nitrogen. Crops grown under conditions of continuous or near-continuous flooding generally are in a more favorable nutrient status than crops without continuous flooding. The unique chemistry of flooded rice soils probably is a major determinant of the sustainability of irrigated rice systems. Some paddies have been continuously cropped for over 1,000 years with little nitrogen added and no sign of a deterioration of soil quality. Such performance would be impossible for crops such as wheat or maize that are grown under nonflooded conditions. The flooded conditions also serve to reduce many soilborne pathogens, such as nematodes, common in dryland crops.

Because systems with reliable standing water have a much lower risk of crop failure, farmers are more likely to apply inputs such as mineral fertilizers and pest control products. The relationship between plant nutritional status and disease incidence is not straightforward. However, those areas where inputs are the greatest and production intensity the highest tend to be those areas where losses to disease are greatest.

The most important direct impact of water regime on rice diseases, however, is the suppression of most soilborne pathogens that are aerobics. Root-feeding nematodes are among the worst problems in nonflooded continuously cropped tropical soils. However, they are nonexistent under flooded conditions as nematodes cannot survive in the low-oxygen environment. Similarly, almost all soilborne root- and vascular system-affecting fungi and bacteria that plague upland crops are not problems for rice grown in flooded soils. However, this may change as we move towards using less water.

Standing water may also serve as a buffering system for temperature regulation, thus reducing temperature fluctuations. The differential temperature between air and soil surface determining the dew period could reduce the duration of dew period, which likewise could reduce the incidence of leaf-infecting pathogens like the blast fungus, which requires a dew period of 6 hours for effective infection, a situation rarely occurring in the tropical lowlands (Ou 1985). On the other hand, the high relative humidity experienced in the lower regions of the fully irrigated rice canopy may be a very favorable environment for the development of leafhoppers and planthoppers that transmit a number of rice-infecting viruses.

Changes in the way rice is grown

The forces that are transforming the global economy and the societies of many rice-producing countries are also having a major effect on how rice is and will be grown. First, even though populations continue to increase, more and more people are leaving the countryside for a chance at a better life in the city. Thus, labor is becoming increasingly scarce for transplanting and hand weeding. As cities grow and as more and more industries demand more water, there is increasing competition for fresh water. Large areas of peri-urban land are being transformed from rice production to urban uses. So, the world will have to meet the increasing demand for rice using less land, less labor, and less water. This leads to the inescapable conclusion that rice cultivation will have to become more intensive. It is also quite likely that there will be a transition to direct seeding, both wet and dry, to save on labor costs.

With increasing water scarcity, there will be a trend for farmers to reduce their water usage. Dry direct seeding into nonpuddled soils will be an attractive option. Likewise, there will likely be increased adoption of some kind of alternate wetting and drying schemes as opposed to maintaining permanent standing water. In these cases we can expect that the severity of damage from soilborne pathogens and nematodes would increase.

A harbinger of the kinds of changes that we could expect to see is the introduction and spread of "crinkling" disease of rice, or ***entorchamiento*** (Morales et al 1999). It is caused by the rice stripe necrotic virus (RSNV) and transmitted by the obligate root parasitic fungus ***Polymyxa graiminis***. It may have been introduced into Colombia from West

Africa sometime before 1991. It was first reported in Africa in the late 1970s and there was considerable importation of rice seed from West Africa into Colombia during the 1980s. It has subsequently spread throughout Colombia and into Panama. In both countries, there are considerable plantings of favorable rainfed lowland and upland rice that are ideal for plant-to-plant transmission via motile zoospores.

Labor, water, and land issues combined with increasing demand for animal feeds may also serve to be drivers of cropping system diversification. Experiments at the International Rice Research Institute (IRRI) have shown that switching from continuous irrigated rice cultivation to a rice–maize rotation results in a marked decrease in soil organic matter after only 10 years. If this results in a significant change in crop nutritional status, it could have important implications for the long-term health of the rice crop.

Intensification of rice systems in Latin America has apparently led to an increase in another soil-associated pathogen ***Gaeumannomyces graminis***, the causal agent of crown sheath rot. This pathogen, which can be so devastating on wheat, is associated with continuously cropped rainfed rice in Latin America.

Adoption of hybrid rice

A major change will also most likely occur in the utilization of hybrid rice in tropical regions. Hybrids dominate production in China but are still in the very early developmental stages over most of the remaining rice-growing areas of the world. However, over the last decade, the large multinational seed companies have begun investing in hybrid rice development. Smaller companies are also moving into hybrid rice development and marketing. Because of the high price of seed and higher yield potential, hybrids will most likely be planted at wider spacings, receive higher fertilizer applications, and have crop-protection products applied more frequently.

The widespread adoption of hybrid rice is offering great opportunity as well as potential risk. If the new hybrids are developed using the tremendous knowledge base on pathogen resistance and management accumulated over the last 50 years, then even early on in their adoption, they should be attractive to farmers. By their very nature, they offer unprecedented opportunities to combine and deploy resistance genes in heretofore impossible ways. For example, in modern inbred varieties, breeders can only use one allele of a particular gene. By carefully designing the parents, a hybrid can actually carry two alternate alleles, perhaps dramatically extending the breadth or durability of the resistance gene. If, on the other hand, in the pursuit of quick profits, poorly adapted hybrids are introduced, farmers could find themselves confronted with disease epidemics that have not been seen for decades.

The biology of flowering in rice hybrids may also make them more vulnerable to certain pathogens. The most obvious risk is false smut caused by ***Ustilaginoides virescens***. This pathogen was, until very recently, seen rarely and was considered simply to be a nuisance. There is anecdotal evidence that hybrids tend to be more susceptible than inbred varieties (Mew et al 1986). High incidence of false smut was observed on a number of hybrids introduced into tropical Southeast Asia from China. And incidence of the disease has also increased in the southern United States where hybrid rice cultivation has been increasing in recent years. The suggestive correlation between high incidence of false smut and hybrid rice must be validated by rigorous experimentation. Part of this research should focus on the fate of the mycotoxins produced by the pathogen to determine if they remain in clean, milled, and polished grain.

Climate change

A changing climate will have an effect on the distribution and possibly the impact of rice diseases. A warmer and wetter climate, especially in the higher latitudes, will most likely result in a broader range of pathogens better adapted to tropical and subtropical conditions. We have already seen a northward migration of rice production in China (Villano et al 2014). As yet, it is uncertain whether this is primarily a climate effect as temperatures rise in the higher latitudes, a change in preference for rice over other staples in these regions, or the development of rice cultivars that are more tolerant of lower temperatures. A number of studies combining plant growth models, disease incidence and epidemic models, and climate projections have clearly shown that the impact on disease management will be significant and negative (Garrett et al 2006). It is unlikely that disease problems will become less severe as the pathogens move into regions in which farmers are not accustomed to dealing with them.

For example, warmer temperatures and higher humidity will certainly favor the development of sheath blight (Ou 1985, Gautam et al 2013). High levels of nitrogen will also exacerbate the disease (Savary et al 1995, Cu et al 1996). Likewise, warmer nighttime temperatures have been associated with bacterial panicle blight in the Americas (Ham and Groth 2011). The seedborne complex of fluorescent ***Pseudomonas*** spp. and ***Burkholdia*** spp. have been known for decades to be causal agents of discolored grain. However, they were considered to be minor pathogens until the 1990s. Now, severe outbreaks of ***Burkholdia glumae*** (formerly ***Pseudomonas glumae***) have been reported in Colombia and Panama. This pathogen could become a serious threat to tropical rice production.

Increased frequency of drought may well occur and exacerbate disease problems. More severe tropical storms may result in more local spread of bacterial blight and bacterial leaf streak. More severe and more frequent cyclones (typhoons, hurricanes) may also transport viruliferous insect vectors to regions where they normally are absent. Combined with warmer winters, areas that did not formerly allow overwintering of the insects could become habitable year round. In China, there are already reports that suggest the relationship between higher temperature and more frequent brown planthopper outbreaks, which may increase the spread of rice viruses (Hu et al 2010, 2011). This could fundamentally change the rice virus disease outlook for areas such as Japan and the southern United States.

New science and technologies for disease management

Rapid advances in high throughput sequencing have changed the way we understand the genomic diversity of organisms, offering new insights on rice pathosystems. The Rockefeller Foundation launched an international rice biotechnology program in the mid-1980s (Khush and Toenniessen 1991). That endeavor led to significant discoveries in rice genetics and interactions with rice pathogens and insect pests at the molecular level. Their impact on germplasm development has carried rice improvement to a new plateau. This is also an important impetus for research on molecular plant pathology, in which rice and its pathogens have become model systems for host-pathogen interactions. Work during the early phase of rice disease research has provided a better understanding of the population biology and genetics of rice pathogens.

The phylogenies of resistance and virulence yielded useful information on the co-evolution of host resistance genes and pathogen virulence. More importantly, however, this information has guided resistance breeding to determine which resistance genes could be combined into a single variety and deployed in a rice production environment to make the system more durable. This information serves to connect basic research to resistance-gene management or deployment based on information on changes in pathogen population structure in farmers' fields. Starting in the 1990s and continuing until now is the era of genomics.

We can now decipher both pathogen and host genomes at relatively low cost. Sequencing of thousands of rice genomes has provided a platform to extract new resistance genes from the deep diversity of rice maintained in the IRRI Genebank (Alexandrov et al 2014, GigaScience 2014). Advances in molecular analysis of pathogens have also revealed pathogen genes that are responsible for triggering or evading recognition by the host. Such diagnostic gene markers can be used to monitor evolution of pathogens in the field, enabling disease resistance breeding to stay one step ahead of pathogen evolution. The combined knowledge of the pathogen and the host can offer prediction of the effectiveness and even durability of resistance genes, a long-sought goal in disease resistance breeding.

How about the role of transgenic technology in future disease resistance breeding? Can transgenic technology be used to expand the gene pool for resistance? It has been long observed that rice does not have any rust diseases, and wheat potentially has broad spectrum disease resistance genes that may be useful in rice (Ayliffe et al 2011). Can gene transfer technology connect the genomes of plant species to take advantage of resistance available across different species?

So far, transgenic approaches in controlling diseases have not been practiced in most parts of the world. The costs and extensive regulatory policies associated with transgenic technology have made it a prohibitive technology for small breeding programs and research institutions to develop transgenic products. However, the emergence of genome editing technologies (Xiong et al 2015) has enabled precise manipulation of genomes without interspecific gene or promoter transfer. Significantly, there is growing consensus among scientists and some regulatory agencies that genome-edited products may not be classified as transgenic. This will open new approaches to use transgenic tools to produce nontransgenic products as a means to address some disease problems.

Besides germplasm improvement, genomic technology can be used to quantitatively characterize the microbial communities in different cropping systems. Microbiomes is an emerging field that applies low-cost sequencing technologies to quantify microbial diversity and how the microbes interact with plant roots. Such an analysis may reveal the factors contributing to soil health, a largely neglected area that has implications for managing soilborne diseases.

New technologies are either available or emerging to address the problems associated with new environments impacted by climatic changes. The challenge is to have the right mix of technologies to manage diseases sustainably. We must take advantage of the large amount of data generated from the characterization of genotypes, phenotypes, and microbiomes in a pathosystem. The data can be organized in a user-friendly database, providing real-time information to enable rapid response to emerging disease problems.

Additional perspectives

Rice production has changed over the past three to four decades in almost every aspect. Change has taken place from varietal development to crop cultivation. In plant breeding, the concept of a plant type for the tropics that produced IR8 represented the basis of the Green Revolution in the 1960s. The more recent concept of "new plant type", with fewer, but more productive tillers aims to break the yield ceiling created by the first and second generations of modern rice varieties in the tropics. The target yield is 25% higher than that of the latest varieties developed and we hope to reach a yield of 12 to 15 tons/ha.

The plant type of the first and second generations of modern tropical rice exemplified by IR8, IR36, and IR72 is a semidwarf plant with many (more than 20) tillers. This has multiple implications in terms of disease conduciveness and vulnerability. The new plant type (NPT) has fewer but more productive tillers and also a thick culm. It is taller than IR36 and IR72 and, very likely, will have multiple consequences on diseases. The NPT concept was launched in the early 1990s. It is likely to play a central role in future rice production in the tropics. However, the most significant change in rice production has been, as already mentioned, the introduction of hybrid rice, which exploits hybrid vigor and is expected to achieve increased, disease-free, attainable yields significantly more than modern popular high-yielding varieties.

The adoption of new varieties carrying resistance genes and new crop establishment methods are major changes in farmers' cultural practices. Simultaneously, the amount of fertilizer use considerably increased over the 1970s to '90s, partly because of government subsidies and policies. Eventually, fertilizer input decreased in some countries as the subsidies were removed and farm credit was lacking. Production practices went from increased use of organic compost to inorganic chemical fertilizers in the 1970s and '80s to a situation where promotion of "organic rice farming" encourages some farmers to try to rely solely on organic matter for soil improving plant nutrition. In addition, the seeding rate rose from the standard 25 kg/ha as recommended for tropical irrigated rice (as transplanted seedlings) to more than four times this rate in the 1980s and '90s. This rate has increased since the 1980s in many tropical countries, not because of change in rice genetic potential, but because of poor seed quality and the desire to suppress weeds in direct seeded crops. Direct seeding, a pervasive change in cropping practice, is a reflection of the many facets of global change–in this case, the dramatic reduction of labor available to agriculture and the absolute necessity to increase the crop-output/labor-input ratio as mentioned above.

All these technical evolutions, considered separately, or in combination, are consequences and responses of agriculture to the global changes witnessed at the beginning of the 21st century, whether economic and social globalization, or climate change. These technological evolutions have brought about the emergence of different disease profiles and new thinking and approaches to rice disease management in the tropics. This will be addressed further in this online resource. In the decades to come, a major challenge for the plant pathology community will be to develop appropriate responses to minimize yield losses caused by individual diseases and/or their combination. In an agricultural context, this might be entirely new in their structure and might be different in some of their socioeconomic contexts and even purposes.

Zadoks (2008) provided a historical account of the impact of plant diseases on societies of 19th century in Europe—a century of philosophical, social, political, and economic revolutions, that, in many ways, shaped the world we live in today. The Green Revolution in Asia, which began in the 1960s with the introduction of modern, high-yielding rice varieties, led to rapid increases in both rice yields and overall production. The Green Revolution created a secure rice food supply reliably meeting the rice needs of the general public in both rural and urban areas. The consumer rice price declines resulting from increased supply were equivalent to an increase in income for poorer sectors of society that spent a significant portion of their incomes on rice. It has thus contributed to reduced poverty since late 1960s. Before entering the 21st century, a general feeling prevailed among international donors and policymakers that the supply of rice as food was sufficient and was no longer an issue of concern requiring international aid to support agricultural R&D. To put it simply, in many circles, for several decades, food security has been taken for granted (Zeigler and Barclay 2008, Zeigler and Savary 2010).

Then in early 2008, came the rice price crisis. At first, the world price of Thai rice (5%-broken, a popular export grade) in December 2007 was $362/ton. The price almost doubled to $715 in March 2008. By mid-2008, the price of the commodity had reached

$1,000/ton. The rice price crisis of 2007-08 didn't happen overnight. It had circumstantial causes, as well as deep-rooted origins. As a Chinese saying puts it, "a 3-foot depth of ice cannot be caused by a one day's freezing weather." Actually, one of the important consequences of the Green Revolution was to reduce rice prices, making the key staple food of the poor, urban and rural, affordably available. Since the 1990s, however, many governments developed the belief that enough food is, and will remain, available, grounding this success judgment on low rice prices. Unfortunately, the long-term decline in rice prices ended in 2001, when it started to slowly increase. Since then, the price had continued to rise through 2007 and had sharply increased by the first quarter of 2008 (IRRI 2008).

How will the rice disease situation be affected when there are food crises such as the one in 2007-08? The first thing we need to remember is that much of the rice yield gains relate to our effort in recent years to improve disease resistance in modern varieties in order to lower losses, thus sustaining the gain. Research efforts over the years are only part to the total effort to safeguard yield potential due to genetic improvement of modern varieties. Despite this effort, a large portion of rice production is lost to diseases in the field while the crop is growing and after harvest while it is in storage. The losses amounting to hundreds of millions of tons are enough to feed 100 million people. This is the single most important reason why crops, especially rice, must be protected from damage caused by diseases and other pests so that critical food supplies are not lost during bad times.

This leads to crop loss estimates and predictions. Making estimates relates not only to methodology and conceptual framework, but also to the science behind the undertaking. Making predications needs more information and better analysis to improve our ability to predict. Thus, accuracy in determining crop losses is not only a question of estimates and scale, but also the method and knowledge used to make the estimate. Estimates and the methodology determining crop losses were debated for decades until Savary et al (2006) published results based on surveys and experimentation, which indicated that rice diseases caused about a 10% loss across all rice production situations in Asia. Their assessments were based on results of sound epidemiological research.

Epidemiology is the science that studies the spread of diseases in a crop population. The principles of epidemics are the basis of modern disease management. This provides a framework for how diseases should be managed in the context of rice production systems on available inputs. The progress made in rice disease epidemiology in the last three decades has laid a solid foundation for disease management strategies and tactics. Plant pathologists have gone from a single tactic to a systems approach to the management of the various old and new diseases occurring in farmers' fields. Experience learned and gained from this new thinking and approach deserves to be documented for current and future researchers and students.

References

Alexandrov N, Tai S, Wang W, et al. 2014. SNP-Seek database of SNPs derived from 3000 rice genomes. Nucleic Acids Res 43:D1023–D1027. doi: 10.1093/nar/gku1039.

Ayliffe M, Devilla R, Mago R, White R, Talbot M, Pryor A, Leung H. 2011. Nonhost resistance of rice to rust pathogens. Molecular Plant Microbe Interactions 24: 1143-1155.

Bouman B. 2013. Does rice really use too much water? Bas Bouman's blog. International Rice Research Institute.

Cu RM, Mew TW, Cassman KG, Teng PS. 1996. Effect of sheath blight on yield on tropical, intensive rice production system. Plant Dis. 80: 1103-1108.

Garrett KA, Dendy SP, Frank EE, Rouse MN, Travers SE. 2006. Climate change effects on plant disease: genomes to ecosystems. Ann. Rev. Phytopath. 44:489-509. DOI: 10.1146/annurev.phyto.44.070505.143420.

Gautam HR, Bhardwaj ML, Kumar R. 2013. Climate change and its impact on plant diseases. Cur. Sci. 105:1685-1691.

GigaScience. 2014. The 3,000 rice genomes project. GigaScience 3:7. doi: 10.1186/2047-217X-3-7.

Ham JH, Groth D. 2011. Bacterial panicle blight: an emerging rice disease. Louisiana Agriculture. 3(3):16. LSU AgCent research and Extension.

Hu G, Xie MC, Lin ZX, Xin DY, Huang CY, Chen W, Zhang, Zhai BP. 2010. Are outbreaks of *Nilaparvata lugens* (Stål) associated with global warming? Environ Entomol. 39:1705-14. doi: 10.1603/EN09214.

Hu G, Cheng XN, Qi GJ, Wang FY, Lu F, Zhang, Zhai BP. 2011. Rice planting systems, global warming and outbreaks of ***Nilaparvata lugens*** (Stål). Bull Entomol Res. 101:187-99. doi: 10.1017/S0007485310000313.

IRRI. 2008. The rice price crisis: what needs to be done. Rice Today 7(3):11-12.

Khush GS, Toenniessen GH. 1991. Rice biotechnology. CAB International. 320 p.

Mew TW, Wang FM, Wu JT, Lin KR, Khush GS. 1986. Disease and insect resistance on hybrid rice. **Proceedings** of the International **Symposium** on **Hybrid Rice,** International **Rice** Research Institute, October 6–10,1986, **Changsha**, **Hunan**, **China. pp. 189-200.**

Mohanty S. 2013. Trends in global rice consumption. Rice Today 12(1):44-45.

Morales FJ, Ward E, Castano M, Arroyave JA, Lozano I, Adams MJ. 1999. Emergence and partial characterization of rice stripe necrosis virus and its fungus vector in South America. Eur. J. Plant path. 105:643-650.

Ou SH. 1972. Rice diseases. 1st ed. Commonwealth Mycological Institute, Kew, U.K.

Ou SH.1985. Rice diseases. 2nd ed., Commonwealth Mycological Institute, Kew, U.K.

Savary S, Castilla NP, Elazegui FA, McLaren CG, Ynalvez MA, Teng P. 1995. Direct and indirect effects of nitrogen supply and disease source structure on rice sheath blight spread. Phytopathol. 85:959-965.

Savary S, Teng PS, Willocquet L, Nutter FW. 2006. Quantification and modeling of crop losses: A review of purposes. Annu. Rev. Phytopathol. 44:89-112.

Villano L, Johnson C, Nelson A, Dawe D. 2014. Rice on the move. ***Rice Today*** 13(4):36-37.

Xiong J-S, Ding J, Li Y. 2015. Genome-editing technologies and their potential application in horticultural crop breeding. Horticulture Research 2, 15019; doi:10.1038/hortres.2015.19.

Zadoks JC. 2008. On the political economy of plant disease epidemics. Wageningen Academic Publishers. 250 p. DOI: http://dx.doi.org/10.3920/978-90-8686-653-3.

Zeigler RS, Barclay A. 2008. The relevance of rice. Rice 1(1):3-10.

Zeigler RS, Savary S. 2010. Plant diseases and the world's dependence on rice. In: The role of plant pathology in food safety and food security in the 21st century. Vol. 3, Pt. 1, pp. 3-9. Springer International Publishing AG.