

The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics

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Abstract Knowing pests and diseases that may cause injuries and are likely to affect plant health and quality is critical to minimizing the gap between attainable yield and actual yield. In this paper, we highlight concepts and strategies aimed at controlling major biotic constraints affecting wheat in intensive production systems and present emerging challenges, with a special attention to the developing world. Disease epidemics result from the combination of inoculum, favorable environment, and host susceptibility. Changes in cropping systems as a result of adoption of conservation agriculture may have serious implications. Necrotrophic pathogens such as those responsible for tan spot or septorias are likely to emerge, and *Fusarium* head blight may increase. However, resistance breeding combined with rotations, timely sowing, and irrigation or even fungicide utilization, if affordable, are part of integrated crop management practices that can minimize losses. In South Asia, the effect of spot blotch, a devastating foliar disease caused by *Cochliobolus sativus*, can be minimized by reducing physiological stress through timely sowing and

adequate use of fertilizers, which demonstrates the complex relationships among crop physiology, disease resistance, and yield. Although some root rots that induce premature death of tillers in cooler high-yielding humid environments can be important, the dryland crown rot (*Fusarium* spp.), common root rot (*C. sativus*), and the cereal nematode (*Heterodera* spp. and *Pratylenchus* spp.) should not be ignored. These are all known to be much more damaging under suboptimal moisture (rainfed or supplementary irrigation), particularly where plant growth is stressed. Climate change is likely to modify the wheat disease spectrum in some regions, and pathogens or pests considered unimportant today may turn out to be potential new threats in future.

Keywords Yield · Rusts · Foliar blights · *Fusarium* · Root rots · Climate change

Introduction

With world population increasing and food security projected to become more critical, increasing wheat yield potential in the developing world remains a high priority. High-production irrigated areas will continue to play a major role in reaching this objective. However, whereas absolute yields are determined by genetic potential, the level of diseases, pests, and other threats

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determines actual yields (Cook and Veseth 1991). Light reducers, tissue consumers, stand reducers, assimilate sappers, as well as senescence accelerators are all ready to take advantage of the situation (Gaunt 1995). Thus, knowing the pathogens, their ecology, distribution, virulence patterns, and variability is important in minimizing diseases and the gap between actual and attainable yields. In environments characterized by dense stands and high tiller density, foliar diseases caused by obligate or semi-biotrophic pathogens with a high evolutionary rate (McDonald and Linde 2002) are the most important yield constraints. This is mainly because some airborne parasites can migrate over long distances and are more likely to overcome genetic resistance than pathogen populations with a low evolutionary potential, which are confined to fields, i.e. soil-borne pathogens. Their direct effect on grain-fill, particularly after anthesis via reduced light interception and radiation use efficiency, logically results in lower yields (Dubin 1996).

In this paper, we highlight efforts toward minimizing yield losses due to biotic constraints and revise concepts and strategies for controlling diseases and pests mostly relevant to intensive irrigated wheat systems in the developing world. Although soilborne pathogens are more frequently found in rainfed systems, they should not be overlooked because water availability may not always be satisfactory. Similarly, viruses are often overlooked. An exhaustive list of various wheat diseases commonly found in most agricultural systems along with details for their identification and control can be found in specialized compendia (Wiese 1987; Wilcoxson and Saari 1996; Duveiller et al. 1997). Taking a long-term perspective, we also draw attention to emerging challenges resulting from environmental and climate change.

Actual yield losses

Research papers on wheat diseases frequently report impressively high potential yield losses and suggest that sizable areas of wheat are at risk to specific diseases or pests. High yield loss figures are often obtained in trials conducted on

experiment stations or under controlled conditions, generally using as a check, a commercial cultivar that has become susceptible. Although risks are not undermined and must be properly calculated, crop health and actual losses in farmers' fields are significantly different, particularly when modern and broadly adapted resistant cultivars are cultivated, as is generally the case in intensive production systems. Oerke et al. (1994) suggested that the global average of actual yield losses caused by all wheat diseases, including developed and developing countries, was about 12.4% on an annual basis. Unfortunately, in developing countries, precise data on actual yield losses caused by diseases in farmers' fields are often unavailable or are difficult to assess. In Kansas, a study covering 1976–2000 and including a total of 18 diseases reported annual losses of 10–22% (Bockus et al. 2001). During this period, leaf rust caused by *Puccinia triticina* was by far the most important disease, causing on average 3.48% losses annually, followed by wheat streak mosaic virus (1.88%), and the *Septoria* complex (1.6%). In the same study, with the exception of leaf rust and outstanding outbreaks of *Septorias* (causing 5.8%, 3.5%, and 7.4% losses in 1983, 1984, and 1995, respectively), barley yellow dwarf virus (BYDV) (4.5% and 3.5% losses in 1976 and 1987, respectively) or tan spot (3.5% losses in 1980 and 1987), all diseases taken individually caused less than 3% losses annually, and in general not more than 0.1–2% (Bockus et al. 2001). An estimate calculated on 22 developing countries growing more than 100,000 ha of wheat indicated an area-weighted average yield loss over 10 years due to leaf rust of around 3.7% (Marasas et al. 2004) which is in agreement with above data. Spot blotch caused by *Cochliobolus sativus* is reported to prevail on about nine million hectares of wheat grown after rice in the Indo-Gangetic Plains and yield losses of 20% have been observed (Duveiller 2004a). However, most likely only 40% of this area is actually suffering losses in the range of 5–15% every year, depending on the level and duration of dew and heat stress (Sharma and Duveiller 2004). It should be underlined that a disease only occurs if inoculum is present, environment (climate,

soil, and cropping system) favorable, and the host susceptible. Also, the relationship between diseased leaf area or any disease scoring scale and yield is not straightforward because the physiological implication of symptom assessment and effect on yield is not always proportional or linear. The extent of damage may vary significantly according to the host physiological growth stage at the onset of an epidemic and often depends more on the green leaf area duration than the amount of disease area estimated with the help of a visual scale.

Obligate parasites with high evolutionary potential

The wheat rusts

The rust diseases of wheat have historically been one of the major biotic production constraints worldwide (Saari and Prescott 1985). Stem (or black) rust caused by *Puccinia graminis* has been under control since the semidwarf spring wheats of the Green Revolution came to occupy most of South and West Asia in the 1960s. Leaf (or brown) rust caused by *P. triticina* and stripe (or yellow) rust (Chen 2005) caused by *Puccinia striiformis* continue to pose a major threat to wheat production over large areas, particularly in Asia. In this continent, leaf and stripe rust could affect production on approximately 60 (63%) and 43 (46%) million hectares, respectively, if susceptible cultivars are grown (Singh et al. 2005).

Rust fungi are obligate parasites and only survive on living plants. High-input, irrigated agriculture and the existence of a cool off-season location where wheat or accessory hosts are found, promote the carryover of inoculum between seasons. Numerous races are now known to occur worldwide. The presence of races capable of overcoming different resistance genes, or their combinations, has been demonstrated for all three rust fungi. New races may arise through sexual recombination (not known for *P. striiformis*), mutation, or somatic hybridization followed by selection if a new race has a selective advantage (Singh et al. 2002).

The strategies to limit damages caused by wheat rusts, especially in the last decades, followed the principles of a coordinated anticipatory breeding approach (McIntosh and Brown 1997; Singh and Rajaram 2002; Singh et al. 2002). The methodology has been particularly successful against leaf and yellow rusts and is summarized hereafter. Pathogen monitoring through scouting of commercial fields and observing trap nurseries at relevant hot spot or favorable locations along with limited sampling for race analysis allows the early detection of new races and confirms the prevalence of major existing races. Enhanced information about the effectiveness and genetic basis of resistance in important wheat cultivars is obtained together with the testing of new wheat germplasm developed by International Agricultural Research Centers (IARCs), National Agricultural Research Systems (NARS) and Advanced Research Institutes (ARIs) at relevant hot spot sites. Diverse resistance sources are used for germplasm enhancement. Breeding for durable resistance based on the accumulation of additive minor genes through use of race nonspecific (slow rusting) resistance is emphasized. As defined by Caldwell (1968), slow rusting is a type of resistance in which disease progresses at a retarded rate. It results in intermediate to low disease levels against all pathotypes of a pathogen. It is also characterized by adult plant resistance despite compatible infection type at seedling stage. In the process, DNA marker-assisted selection (MAS) should be utilized when feasible. Seed multiplication and distribution of diverse resistant improved genotypes are to be promoted through meaningful and efficient seed production programs also. However, participatory variety selection schemes may prove useful in rapidly replacing old varieties in farmers' fields. As a rule, only rust resistant cultivars should be recommended in rust-prone areas. Lastly, resources for research, training, and infrastructure are of primary importance.

The combination of minor genes with additive effects has been particularly effective in reducing disease severity for leaf and yellow rust during the last three decades, and the methodology has proven very cost effective for leaf rust (Smale et al. 1998). The South American cultivar Frontana is

considered to be one of the best sources of durable resistance to leaf rust. Genetic analysis of Frontana and several CIMMYT wheats possessing excellent slow rusting resistance to leaf rust worldwide has indicated that such adult plant resistance is based on the additive interaction of *Lr34* and two or three additional slow rusting genes (Singh and Rajaram 1992). Leaf rust severity observed in Mexico on most slow rusting cultivars is related to the number of minor genes they carry. Slow rusting resistance to leaf rust is common in spring wheat germplasm. Studies have shown that at least 10–12 slow rusting genes are involved in the adult plant resistance of CIMMYT wheats. Thus, obtaining durable resistance is feasible even in the absence of *Lr34*, as in the case of Pavon 76, in which a new gene for slow rusting, *Lr46*, on chromosome 1B has been identified. The close association of *Lr34* and *Lr46* with *Yr18* and *Yr29*, respectively, which have shown to be very effective against yellow rust, is of particular interest (Singh 1992; William et al. 2003; Rosewarne et al. 2006).

Since airborne rust urediniospores are able to travel over long distances, new races may readily migrate to other countries. Movement of the *Yr9*-virulent race of *P. striiformis* from the East African highlands to the Indian subcontinent between 1985 and 1997, when it eventually reached Nepal, is a classic example of the spread of the disease believed to be associated with the weather system called the “Western Disturbance.” Earlier, virulence for the *Yr2* gene, first recorded in Turkey, had been traced over time from Turkey to Pakistan. (Singh et al. 2002, 2005). These examples suggest that Asia’s entire wheat area, except China, may comprise a single epidemiologic zone, a point of even greater concern when considering that “megacultivars” cover most of the area grown to wheat in some individual countries or that genotypes with the same genetic background are widely released under different names in several countries. This increased probability for selecting a new virulent race is shown by cultivars PBW343 and Inqualab 91, grown on seven and six million hectares in India and Pakistan, respectively, and under different names in other countries. Growing fewer cultivars that carry race-specific resistance genes leads to

greater genetic uniformity and, consequently, greater disease vulnerability. Therefore, if a new race arises anywhere in this area, given time it could spread throughout the epidemiologic region. Recent reports confirm this principle since both cultivars are protected from stripe rust by the same resistance gene, *Yr27*, for which virulence was detected recently in Afghanistan, Iran, Kyrgyzstan, Tajikistan, Pakistan, and India. Thus, the virulence to *Yr27* is an emerging threat in Asia. The new race appears to have originated in the region and has not followed the same distribution pathway as races virulent to *Yr2* and *Yr9* in the past. The stripe rust epidemic became very severe in late sown materials in 2005 in North West Frontier Province (NWFP) of Pakistan. After considering the positive effect of precipitation on early sown rainfed wheat that had already escaped the epidemic, it may still have cost up to US\$ 100 million based on a rapid average total losses estimate of 3–4%. Incorporation of high levels of durable (slow rusting) resistance to yellow and leaf rusts in PBW343 and Inqualab-91 through a single backcross-selected bulk breeding approach has been very economical when incorporating additional resistance while maintaining the high yield potential of broadly adapted commercial cultivars popular with farmers.

Another threat emerged in Africa with the outbreak of stem rust race Ug99, initially detected in Uganda in 1999, then in Kenya in 2002–2003, and now Ethiopia in 2003–2004 (Expert Panel on the Stem Rust Outbreak in Eastern Africa 2005). Although reported on *Sr31* and *Sr38*, the race combines virulence to many other important resistant genes. Because most leading cultivars and breeding lines tested in 2005 in Njoro (Kenya) and in Ethiopia are susceptible, the present situation could turn into a disaster should the new race migrate through the “Western Disturbance” or be accidentally introduced to a new area through international travel. Although stem rust, a disease known to cause very severe losses in warmer wheat growing areas, has been controlled and thus was virtually ignored for several decades, it could well reappear and wreak havoc if rapid action is not taken. Damages could total US\$ 1–2 billion in Asia alone, based on a

10% yield loss estimate and depending on market price. In response, a Global Rust Initiative has been launched, which includes massive testing of advanced lines in East Africa accompanied by an emergency crossing program to pyramid effective resistance genes (Jin and Singh 2006).

Powdery mildew

Powdery mildew, caused by *Blumeria graminis* f. sp. *tritici*, is an important disease of wheat worldwide, especially in highly productive areas with a maritime or semicontinental climate (Cunfer 2002). Compared to rusts, powdery mildew conidia do not spread over very long distances, but the fungus' evolutionary rate is high. Powdery mildew is important in China, where at least 12 million hectares can be affected, and in South America (Costamilan 2005). It may also be cause for concern in Pakistan and western India should susceptible varieties be grown and the weather be favorable. Since natural epidemics of powdery mildew do not occur in Mexico, where CIMMYT has its main breeding operations, most of the breeding materials sent from Mexico to the regions are susceptible when grown in areas prone to the disease (Wang et al. 2005).

Utilization of resistant cultivars is the most economical and environmentally safe means of controlling powdery mildew. To date, 48 *Pm* genes or alleles at 32 loci are known to confer race-specific resistance in wheat. Knowing the virulence pattern of isolates collected over large areas is useful when combining race-specific resistance genes (Wang et al. 2005). However, since race-specific genes result in a rapid build-up of the pathogen population possessing matching virulence genes, this approach is not sufficient. A more sustainable objective is to find adult plant resistance such as that in North America's cultivar Knox 62 and its derivatives which have shown durable resistance over a long period. Lillemo et al. (2006) demonstrated that the bread wheat cultivar Saar exhibited a high level of this type of resistance in the fields and that it was controlled by at least three genes. Lillemo et al. (2005) also found that genes *Lr34/Yr18* and *Lr46/Yr29* contributed to reduced levels of powdery mildew. Understanding the reaction mechanism against

obligated parasitic fungi controlled by genes against different diseases such as the leaf and yellow rusts and powdery mildew represents a new research challenge to unravel the basis of race nonspecific adult plant resistance against obligated parasites.

Residue borne and non-obligate semi-biotrophic pathogens

Tan spot

Tan spot caused by *Pyrenophora tritici-repentis* has a wide distribution; it is found in South and North America, Europe, Central and South Asia (Friesen et al. 2005). The disease is seed-borne and favored in wheat grown after wheat under zero tillage (Bockus and Shroyer 1998). The fungus survives on crop residues at the soil surface where the sexual stage (pseudothecia containing ascospores) develops. Tan spot incidence and severity has been linked with the change in the variety composition and expansion of zero tillage cultivation, especially in Brazil, Paraguay, and Argentina where it is recognized as a major leaf blight responsible for potential yield losses of 10–20% (Annone 1998). Tan spot is common in Central Asia where long winters do not allow fast stubble decomposition and where monocropping is common. Damages result mainly from destruction of the flag leaf, so the plant is robbed of assimilates or photosynthesis products otherwise destined to fill the grain. Tan spot can kill the leaves after heading, resulting in premature death of the infected plants.

Although the practical importance in breeding for resistance to this disease has not been clearly shown, at least eight races of *P. tritici-repentis* have been established based on virulence patterns induced by three host specific toxins on a set of three effective wheat differentials (genotypes Glenlea, 6B662, and 6B365) (Stelkov and Lamari 2003). Races 1 and 2 are present in Mexico; races 1, 2, and 8 in South America; race 1 dominates in the steppes of Kazakhstan in Central Asia, and races 1, 2, 3, and 4 are found in Tajikistan, where the disease can be severe. Good resistance sources in spring wheat include Milan and M-3 = Cando/

R143//Mexi’’S’’/3/*T. tauschii* (CI18). Crop rotation and genetic resistance can control the disease under conservation tillage systems.

Septorias

Septoria tritici blotch (STB), caused by *Mycosphaerella graminicola* (anamorph *Septoria tritici*), is currently the most serious foliar disease of wheat grown under temperate (15–20°C) and humid climates in Europe, South America, North Africa, and Central Asia. Resistant cultivars reduce the use of costly fungicide treatments. Useful sources of resistance include Bobwhite, Kavkaz-K4500, Corydon, Catbird, and Milan (Singh and Rajaram 2002). The population of *M. graminicola* is highly diverse genetically (McDonald and Linde 2002) and the fungus reproduces sexually several times during the wheat growing season, which increases the risk that the pathogen overcomes host resistance (Zadoks 2003). Likewise, this high evolutionary rate probably explains the widespread failure of strobilurin fungicides after most *M. graminicola* isolates appeared to spread the mutation G143A in a very few years in the United Kingdom (Lucas 2003).

Kavkaz-K4500, Veranopolis, and Catbird have isolate-specific resistance. This suggests that several resistance genes can be pyramided in a single cultivar (Chartrain et al. 2004, 2005). Isolate specific resistance is near-complete, oligogenic, and follows a gene for gene relationship, whereas quantitative or partial resistance is incomplete, polygenic, and isolate nonspecific. Twelve genes for resistance to STB have been identified (Chartrain et al. 2004). Specific interactions between cultivars and isolates can easily be assessed by using a detached seedling leaf technique to study resistance in wheat (Arraiano et al. 2001).

Septoria glume blotch caused by *Phaeosphaeria nodorum* (anamorph *Stagonospora nodorum*) also has a very high evolutionary rate and is more aggressive at 20–27°C. *Stagonospora nodorum* is seed-borne and can cause seedling infection. The wheat plant is more susceptible to infection by *S. nodorum* at later growth stages, usually during and after heading, whereas *S. tritici* is more common at earlier growth stages, during stem

elongation to flag leaf emergence. The lesions caused by *P. nodorum* on the wheat heads begin as either grayish or brownish spots on the chaff, usually on the upper third of the glume. When nodes are infected, distortion and bending of the straw may be observed, with a possibility of lodging and breakage of the straw at the node, with subsequent yield losses. Septoria glume blotch is common in Central Asia, where a recent study confirmed that MAT-1 and MAT-2 isolates were present in the Kazakh and Russian origins of *P. nodorum*. The presence of both mating type idiomorphs in these populations supports the hypothesis that the sexual stage constitutes an important part of the life cycle of the fungus in this region (Mercado et al. 2006).

Spot blotch

Spot blotch caused by *C. sativus* is the most serious foliar wheat disease in warmer areas, particularly in the Eastern Gangetic Plains of the Indian subcontinent, where high average minimum temperatures during winter, combined with fog or heavy dew stimulate the proliferation of the fungus. The disease is responsible for more annual wheat losses in the subcontinent than leaf rust. Investment in research in the last two decades has produced considerable progress toward understanding and controlling this disease in the plains bordering the Himalayas (Duveiller et al. 2005). Since it is often observed in combination with tan spot, wheat breeders in the region often refer to Helminthosporium leaf blight of HLB (Duveiller and Dubin 2002) to designate foliar blights.

Useful sources of resistance include materials from China (Yangmai #6, SW 89-5193; SW 89-5422, G 162, Ning 8319), South America (Ocepar 7; BH1146; Maringa), derivatives of wide crosses including *T. curvifolium* (Chirya-3, Chyria-7), and to a lesser extent, synthetic hexaploids with *T. tauschii* (Croc 1/*T. tauschii*/Borl 95) (Sharma et al. 2004). Genetic resistance has been incorporated with some success into locally adapted genotypes with high yield potential. On-farm and on-station trials under warm growing conditions confirm progress in breeding wheat for spot blotch resistance (Siddique et al. 2006). However,

resistant cultivars are based on the same resistance sources as 15–20 years ago, thus the main challenge today is the lack of resistance diversity sources.

Another reason for the slow progress in breeding for resistance is the limited effectiveness of the prevalent selection technique to identify multiple genes controlling resistance and to properly assess stable resistance. Resistance is related to host physiology; spot blotch symptoms are highly modulated by abiotic stresses and their effect on source/sink relations after anthesis, which affects senescence. Therefore, understanding the relationships and genetic differences that control resilience to stress is a prerequisite to improving resistance and disease control. Identification of a set of molecular markers linked to spot blotch resistance could accelerate efforts to improve resistance. However, phenotypic data are often difficult to assess, which leads to variable results that can make genetic studies unreliable.

Crop management, timely sowing, and good soil fertility are important components of integrated crop management for spot blotch. In Nepal, it has been shown that an application of 30 kg of K₂O had a similar effect to one fungicide application (Sharma et al. 2005). In the rice–wheat system, wheat residues rapidly decompose after harvest and thus do not play a significant role in inoculum survival. When zero tillage is practiced in the rice–wheat system in South Asia, it is only used for wheat, not for rice, which is planted using puddling. Thus, residues do not play a major role in inoculum survival. Zero tillage can allow sowing of wheat up to 15 days earlier, which has a beneficial effect on disease control because it increases the window when wheat grows under less heat stress. After anthesis, the crop becomes more susceptible to spot blotch and the increasing temperature in the spring intensifies the stress and disease severity resulting in lower yield (Sharma and Duveiller 2004; Duveiller et al. 2005). Epidemiological studies have shown that timely sowing avoids the physiological stress that often coincides with the flowering stage when wheat is sown late, which, in turn, reduces spot blotch. However, with surface seeding, a resource conserving practice conducted in wet areas where

tilling is impossible and wheat is broadcasted on moist soil, higher moisture levels tend to increase disease severity (Mahto et al. 2006). If aerobic rice becomes a new cropping system implemented to reduce water consumption and rice farming on irrigated raised beds becomes popular, the risk of green bridges between rice and wheat cannot be discounted, and diseases such as tan spot and spot blotch should be monitored carefully since survival on stubbles may increase too.

Fusarium head blight

Several species of the genus *Fusarium* are known to cause scab or *Fusarium* head blight (FHB), a main production constraint in the warm humid and semi-humid wheat areas where the flowering stage coincides with rainy periods. The most important species is *Gibberella zeae* (anamorph: *F. graminearum*). *G. zeae* is a facultative parasite and is pathogenic on many grasses, including common weeds and cereal crops (maize, rye, rice, barley, and triticale). The point of entry of *F. graminearum* is the spike, especially the floral organs. Perithecia represent the sexual stage (teleomorph) of the fungus, *G. zeae*, and are produced on wheat glumes. Perithecia play an important role in the pathogen's survival from year to year and coexist with mycelia in residues of the previous crop to constitute the initial inoculum source for scab. Adoption of zero tillage in areas where wheat is rotated with maize or other cereals is probably one of the factors that has increased the incidence of FHB in some countries. The rapid global reemergence of FHB of wheat in the last decade, together with contamination of grain with mycotoxins attributable to the disease have spurred basic research on the fungal causal agent (Goswami and Corby Kistler 2004). One of the major challenges for all wheat producers and exporting countries will be to meet strict regulatory standards for low deoxynivalenol (DON) toxin content. European Union (EU) regulation 856/2005 establishes a maximum level of 750 µg/kg (0.75 ppm) for DON in cereal flour (excluding durum wheat, oat and maize flour). However, in many countries regulations are not enforced, and many people,

especially in rural areas, eat the cereals without any control.

In the developing world, FHB has been a major concern in China, where the disease is endemic in the Yangtze River Basin. It is estimated that scab may affect up to 7 million hectares in all China, and that 2.5 million tons of grain may be lost in epidemic years (Dubin et al. 1997). FHB is also present in parts of South America (Argentina, Brazil, Uruguay). In Rio Grande do Sul, Brazil, damage caused by wheat scab, calculated by the difference between the actual yield and the estimated yield potential (based on the total number of spikes, the number of healthy spikes, and the number of scabed spikes) is around 12% of the potential harvest (Casa et al. 2004). *F. graminearum* is also present in South Asia, however, wheat flowering there coincides with low relative humidity conditions and FHB is found only sporadically in the Himalayan foothills and in Bangladesh (Duveiller 2004b). However, new challenges may emerge with changing rainfall patterns, as shown in 2005 in parts of the Punjab (India) where FHB increased dramatically, particularly in durum wheat.

Sources of FHB resistance have been categorized into three groups: China and Japan, Argentina and Brazil, and Eastern Europe (Singh and Rajaram 2002). Genetic analyses indicate that a few additive genes confer resistance in Chinese and Brazilian wheats, but that those genes differ between the Chinese and Brazilian sources (Singh et al. 1995; van Ginkel et al. 1996). The Chinese sources probably represent the best resistance currently available and should be combined with other sources of resistance. The Chinese cultivars that best combined with CIMMYT materials to transmit scab resistance are Sumai #3, Ning 7840, Shanghai #5, Yangmai #6, Suzhoe #6, Wuhan #3, and Chuanmai 18.

Soilborne dryland root rots and nematodes

Soilborne pathogens, including the dryland root rots and cereal nematodes, have a global distribution and cause economic yield losses in areas of the world where cereals dominate the cropping

system and suboptimal growing conditions are common. Although they do not cause significant problems under optimum conditions in irrigated areas, water supply or rainfall may not always be adequate, thus exposing the crops to water stress and potential damage by these pathogens.

In dryland areas, root rot diseases often occur as a complex of soilborne fungi and nematodes. Characteristic symptoms of common root rot caused by *C. sativus* (anamorph *B. sorokiniana*, the same fungus that causes spot blotch in humid and warm environments) would be brown to black lesions on the sub-crown internode; typically lesion severity increases throughout the growing season. Crown root rot is caused by *Fusarium culmorum*, *F. pseudograminearum*, *F. graminearum* and other species (Wiese 1987), with initial symptoms resulting in browning of the stem base or crown tissue. Later in the season, the premature death of tillers with little or no grain occurs, which appear as scattered whiteheads varying from a few tillers to large irregular patchy areas involving many plants. In most climates, the development of whiteheads is correlated with drought stress. In areas prone to root rot, as the level of drought stress increases, whitehead symptoms increase proportionately. Regions that practice residue retention or emphasize durum wheat in their cereal systems are associated with greater indices and severity of crown rot.

The cereal nematodes include the sedentary cereal cyst nematode (CCN) (*Heterodera* spp.), which is complex, with several species and pathotypes, and two species of migratory endoparasitic root lesion nematodes (RLN) (*Pratylenchus thornei*, *P. neglectus*), with no known pathotype variation. Both CCN and RLN have global distribution and can cause significant yield losses in cereals worldwide (Nicol et al. 2003), and notable economic losses under stress conditions, i.e., with poor soil nutrition or structure, temperature, or water stress (Barker and Noe 1987; Cook 1981; Nicol and Ortiz-Monasterio 2004; Paulitz et al. 2002).

One of the most effective control methods for soilborne pathogens is the use of host resistance, which has wide application because it requires no additional equipment or cost. Rotation is also part of an integrated control option, however, in

many cereal-dominated cropping systems in dryland areas, it is not available or economic. As mentioned, although these nematodes and fungi have been considered important for several decades in certain countries, the identification of resistance has been relatively slow in comparison to the foliar diseases. This is partly due to lower levels of investment in research and the difficulties encountered in working with soilborne pathogens to screen, identify and incorporate resistance. Nevertheless, several sources of resistance have been reported for both cereal nematodes and root rots (Nicol et al. 2003; Burgess et al. 2001), especially from *T. tauschii*. With the exception of CCN, the genetic control of identified resistance sources are polygenic and partial, highlighting the importance of gene pyramiding in this work. Molecular localization and characterization of the resistance genes with markers (major and QTL) offer tremendous potential to advance breeding efforts for both cereal nematodes and more recently crown rot (Nicol et al. 2003; Chakraborty et al. 2006).

Viruses

Wheat plants attacked by viruses can exhibit many symptoms that are described in detail in

plant disease compendia (Wiese 1987; Lapierre and Signoret 2004). Barley yellow dwarf virus (BYDV), soilborne wheat mosaic virus (SWMV) and wheat yellow mosaic virus (WYMV) are the most important ones found in developing countries. BYDV, transmitted by aphids including *Rhopalosiphum padi*, is perhaps the most widespread and well known viral disease (Henry and Plumb 2002). If infection occurs early, the number of tillers can be reduced and plants are stunted, but in cases of late infection, the effect on yield is less. Wheat spindle strike mosaic (WSSM) is mainly found in North America and Europe. Viral diseases reported on bread wheat in developing countries have been compiled in Table 1 according to Lapierre and Signoret (2004); more details about viruses affecting wheat in other areas may be found in Henry and Plumb (2002). Some of these diseases have a local distribution and are dependent on the presence of the vector and the cropping system.

It is interesting to note the number of viral diseases transmitted by *Polymixa graminis*, a worldwide obligate parasitic fungus of plant roots. The fungus transmits Indian peanut clump, Chinese wheat mosaic virus, SWMV, and soilborne cereal mosaic. The viruses are protected from the environment in dormant spores of the fungus, which can remain alive in a field for years until a

Table 1 Main virus diseases naturally occurring on bread wheat and found in developing countries^a

Disease	Group	Vector	Distribution	
Brazilian Wheat Spike	BWSpV	Tenuivirus	–	Brazil
Barley Yellow Dwarf Virus	BYDV-Pav	Luteoviridae	<i>Rhopalosiphum padi</i> , ...	China, Mexico, etc.
Chinese Wheat Mosaic Virus	CWMV	Furovirus	<i>Polymixa graminis</i> ?	China
Cereal Yellow Dwarf	CYDV-Gpv	Polerovirus	<i>Schizaphis graminum</i>	China
	CYDV-Rps	Luteoviridae	<i>Rhopalosiphum padi</i>	Mexico
	CYDV-Rpv	Polerovirus	<i>Rhopalosiphum padi</i>	Mexico
Indian Peanut Clump	IPCV	Pecluvirus	<i>Polymixa graminis</i>	India
Iranian Wheat Stripe	IWSV	Tenuivirus	<i>Unkanodes tanasijevici</i>	Iran
Mal de Rio Cuatro	MRCV	Fijivirus	<i>Delophacodes kuscheli</i>	Argentina
Northern Cereal Mosaic Virus	NCMV	Cytorhabdovirus	<i>Delophacodes kuscheli</i>	China, Japan ^b
Soilborne Cereal Mosaic	SBCMV	Furovirus	<i>Polymixa graminis</i>	Europe ^b , ...
Soilborne Wheat Mosaic Virus	SBWMV	Furovirus	<i>Polymixa graminis</i>	China, ...
Wheat Rosette Stunt Virus	WRSV	Cytorhabdovirus	<i>Laodelphax striatellus</i>	China
Wheat Spindle Streak Mosaic	WSSM	Bymovirus	<i>Polymixa graminis</i>	Europe, USA ^b , ...
Wheat Yellow Leaf Virus	WYLV	Luteoviridae	Aphids	China, Japan ^b
Wheat Yellow Mosaic Virus	WYMV	Bymovirus	<i>Polymixa graminis</i>	China

^a List compiled from Lapierre and Signoret (2004)

^b Principal region of distribution but considered of importance and likely found elsewhere in developing countries

susceptible plant is found. The persistent soil-borne nature of these parasites makes virus resistant varieties the only practical option for control. Progress in understanding and controlling virus diseases transmitted by *P. graminis* have been hampered by the difficulties involved with working on an obligate, root-infecting, vector (Kanyuka et al. 2003). Indian peanut clump pecluvirus is highly infectious on graminaceous plants and it has been reported on wheat in India. It presently does not incur significant losses because of the limited wheat area grown after peanut (Rajasthan). To date, its virulence has been tested on wheat only in marginal area environments (monsoon, high temperatures) that are out of wheat production. The risk of its spread, however, should not be ignored given the general distribution of the vector and the survival period of dormant spores should new fields and these vectors become contaminated (Delfosse et al. 1999).

Insects

Many insects have been described on wheat worldwide. Although damage caused by most of these insects is either insignificant or limited to isolated areas, other pests inflict serious yield and forage losses. Some of these pest problems are directly linked to the unique farming system employed in a particular area, while other pests are opportunistic or generalist herbivores that do not specifically target wheat as a host (Miller and Pike 2002). Chewing and feeding insects usually do not cause major direct damages in wheat, unless populations reach very high levels; infestation by several aphids feeding on wheat, such as *Sitobion avenae* or *Rhopalosiphum padi*, result in higher BYDV incidence. In some areas, greenbug (*Shizaphis graminum*) and Russian wheat aphids (*Diuraphis noxia*) cause damage by injecting a toxin when they feed on leaves. In North Africa, the Mediterranean region, and parts of West Asia, Hessian fly (*Mayetiola destructor*) may cause significant damages; it causes tillers to stop growing, kernels to stop filling, or stems to lodge. Sources of host plant resistance have been identified in cultivated and wild wheats; they are

widely used in breeding programs (Miller and Pike 2002). One of the most important wheat insect pests found in some developing countries, principally in dryland areas in North Africa and West Asia, is the suni bug (*Eurigaster integriceps*), which injects a toxin into the grain, resulting in both shriveled grain and inferior dough making properties for bread. In Tajikistan and Afghanistan, the cereal leaf beetle *Ulema melanopus* causes severe crop damage by reducing the plant's photosynthetic area.

Emerging challenges: new epidemics, climate change, and other long-term environmental effects

Changes in cropping systems, resulting from changes in rotations or tillage practices, influence the survival and prevalence of residue borne pathogens. They can lead to a shift in the disease spectrum if new agronomic methods are not accompanied by adoption of cultivars with adequate resistance. With the exception of an accidental introduction of a new race or parasite, the occurrence of a “new” disease in a determined geographic area or cropping system is rare. Nonetheless, if a minor pathogen is present and remains marginal due to an unsuitable environment, but suddenly climatic conditions become favorable for its development, a green bridge between two crops may emerge and a disease previously considered as an oddity may become a significant constraint.

After initial reports of its occurrence in the mid-1980s (Igarashi et al. 1986), wheat blast caused by *Magnaporthe grisea* is now a disease in need of urgent attention by wheat breeding programs in Brazil. Due to the lack of resistance, the disease poses a potential threat to wheat in other geographical areas with similar climate. Yet due to the host range—maize and triticale are susceptible—it also is a potential threat to these crops (Urashima et al. 2005). Recent studies have shown that wheat blast did not originate from the rice blast fungus and that rice and wheat strains were genetically different (Urashima et al. 2004, 2005). The fungus attacking wheat is probably an adaptation to wheat as

its new host of blast isolates from a weed (*Digitaria insularis*) (Urashima et al. 2005). It attacks at the rachis level and may completely hamper the grain fill, causing total losses in susceptible genotypes, depending on the timing of infection.

In some regions with intensive wheat cropping systems, such as parts of China, sharp eye spot caused by *Rhizoctonia cerealis* may be an emerging problem, although current economic losses due to this disease are generally low. Sharp eye spot was recently diagnosed in Egypt, where the incidence was around 20–30% of sampled areas (Hammouda 2003).

Climate change may also have a major long-term effect on wheat growing areas, possibly inducing a shift in the geographical area grown to wheat and associated biotic constraints to higher latitudes. Likewise, the present pathogen and pest spectrum may evolve in a given wheat area. For example, by 2050, as a result of possible climate shifts in the Indo-Gangetic Plains—currently part of the favorable, high potential, irrigated, low rainfall mega-environment, which accounts for 15% of global wheat production—up to 51% of its area might be reclassified as a heat stressed, irrigated, short-season production mega-environment (Ortiz pers. commun.). If this scenario proves to be correct, an increase in spot blotch severity and incidence can be anticipated in optimum wheat growing areas where the disease does not figure prominently today. Furthermore, irrigation water is expected to become more limited in many parts of the world due to increased competition for it spurred by urbanization and industrialization. Many wheat growing regions will become suboptimal for production, and some diseases, notably soilborne pathogens, may increase in importance. Lastly, the long-term anthropic effects may be surprising. In Europe, the occurrence of *P. nodorum* has become relatively less important in the last 30 years compared to the increased prevalence of *M. graminicola* (Zhang 2005). Although changes in varieties may partly explain the higher prevalence of *M. graminicola* over *P. nodorum* in recent years, a new study suggests that long-term changes in sulfur dioxide

levels may be associated with this phenomenon (Beauchell et al. 2005).

Conclusions

Knowing the enemy is the first step toward better control of diseases and minimizing the gap between actual and attainable yields. This entails understanding the ecological conditions that favor a disease and pathogen and pest variability across geographical areas, including their evolution over time. Resistance breeding remains essential and it is the cornerstone of economical and ecologically friendly approaches to limit disease outbreaks. Identification and characterization of sources of resistance are critical as is ensuring that broad and diverse sources of resistance are effectively employed. Genetic resistance is the main method for controlling obligate parasites. However, effective disease control requires that durable, race nonspecific resistance is incorporated into high yielding genotypes. In some areas, a shift in breeding strategies toward this durable type of resistance, based on minor additive genes, is required to avoid the ‘boom and bust’ cycles that are frequently observed. This is particularly true for areas where a single genotype is sown and the risk of mutation to new virulent races increases under selection pressure. Integrated efforts to identify and incorporate resistance with international organizations, national programs, and advanced research institutions will enable all parties to harness resistant germplasm more rapidly and have it adopted more widely.

In addition to identifying and incorporating genetic resistance, improved crop management will be necessary to control non-obligate parasites. This again assumes an understanding of the epidemiology—environmental conditions change both annually and on a long-term basis—and incorporating cropping practices that will reduce the effects of stress, which influences susceptibility to some diseases. We underscore the importance of crop rotation to minimize pathogen populations.

Finally, one should never underestimate the importance of genotype and gene flow in terms of

the spread of diseases. As international travel continues to increase, so does the possibility of the accidental introduction and evolution of a new pest or disease to a region.

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