The growing threat of stripe rust worldwide

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Abstract

Stripe rust of wheat (yellow rust) is a recurring production constraint in the majority of wheat growing areas of the world. The transboundary nature of the pathogen coupled with its current virulence capabilities, favorable environmental conditions, sometimes overlapping and/or continuous cultivation of susceptible varieties in stripe rust-prone zones, and genetic uniformity of certain recent 'mega-cultivars' were major driving forces in stripe rust epidemics worldwide. Breeding for resistance must continue be the central pillar of stripe rust control, and for this to be effective there must be adequate pathogen monitoring combined with commitment to identify and incorporate diverse sources of resistance, preferably of the durable type. Deployment of resistance will only be successful if it is combined with high yield and appropriate end-use quality to meet the needs of farmers and consumers. Suitable seed systems need to be in place for timely distribution of varieties. This paper deals with the historical impacts and current status of stripe rust epidemics and highlights the need for regional and global collaboration in mitigating the global impact of this disease.

Introduction

Wheat was among the first of the domesticated food crops and for more than 10,000 years has been the basic staple food for most of the world. It is the most widely grown cereal crop in the world and one of the central pillars of global food security. About 650 million tonnes of wheat was produced worldwide on 217 million hectares in 2010 with a productivity level of about 3 t/ha^{-1} (FAO 2012). After the quantum leap of the Green Revolution, wheat yields have been rising by only 1.1% per year, a level that falls far short of the demand of a population that is growing 1.5% or more annually. According to some estimates, global wheat production must increase by at least 1.6% annually to meet a projected wheat demand of 760 million tonnes by 2020 (Dixon et al. 2007). This is however, very challenging with the current scenario of climate change, increasing drought/water shortage, soil degradation, declining supply and increasing cost of fertilizers, increasing demand for bio-fuel, and new virulent pathogen and pest strains.

Stripe rust epidemics have frequently occurred in the USA (particularly the Pacific Northwest region of North America), South America (central and southern wheat production areas), North Africa (Morocco, Algeria and Tunisia), East Africa (Ethiopia and Kenya), East Asia (northwest and southwest China), South Asia (India, Pakistan, and Nepal), Australasia (Australia and New Zealand), the Nile Valley and Red Sea (Egypt and Yemen), West Asia (Lebanon, Syria, Turkey, Iran, Iraq, and Afghanistan,), Central Asia (Kyrgyzstan, Uzbekistan, Tajikistan, and Turkmenistan), Caucasus (Georgia, Armenia and Azerbaijan), and Europe (UK, northern and southern France, the Netherlands, northern Germany, Denmark, Spain, and Sweden). Regular regional crop losses in the range 0.1–5% and sometimes up to 25% have been recorded due to stripe rust. However, individual crop losses of up to 80% were reported in the widespread epidemic in the Middle East and North Africa in 2010, when initial infection occurred on susceptible wheat varieties at early growth stages. Considering the epidemiological factors and the history of recurrent epidemics, the wheat areas in Africa (eastern and northern countries), the Middle East, the Caucasus region, and West and South Asia now appear to comprise a single epidemiological zone – hence any new pathotype that evolves in one country in the region is likely to disperse to the entire region.

Although stripe rust is historically considered a disease of lower temperature regions, its relatively recent introduction and establishment in Australia and South Africa suggest a wider level of adaptation. The more recent spread of two new pathotypes/pathotype groups that largely replaced and expanded the range of stripe rust in Australia, central USA, and across CWANA and Europe have exacerbated the situation. These pathotypes appear not only to have the ability to adapt to higher temperatures (and therefore the potential to adapt to climate change), but have undergone rapid mutational changes in Australia, North America and northern Europe to overcome a number of specific resistance genes deployed in wheat and triticale. With current climate change predictions, winters are likely to become warmer and the likely consequence is earlier stripe rust infection and spread and hence more damaging epidemics throughout all wheat growing areas.

Regional impacts of stripe rust

Several worldwide stripe rust epidemics have occurred in recent decades with potential to inflict regular regional crop losses in the range of 0.1–5%, with rare events giving losses of 5–25% (Wellings 2011). Stripe rust can cause 100% yield loss in susceptible cultivars if infection occurs in early growth stages (Chen 2005), and this is likely to be exacerbated in regions with mild winter periods and significant levels of pathogen survival between cropping seasons.

North America

Stripe rust has been historically considered a common disease of wheat in North America since its first detection in 1915 but was not considered a destructive disease in the US from the 1930s until the late 1950s (Line 2002). However, it became increasingly important from the late 1950s and early 1960s (Chen et al. 2002). Since then, stripe rust has been considered the most significant disease of wheat in western North America, and from the 1980s became increasingly important in the south-central USA and the central Great Plains in certain seasons. Comprehensive reviews have dealt with the distribution of stripe rust, yield losses, status of resistance of commercial wheat varieties, and fungicide application in the USA (Line 2002; Chen 2005). During 2000–2007, stripe rust occurred in at least 15 US states each year with yield losses estimated at more than 6.5 million tonnes (Chen et al. 2010). However, yield loss was estimated at 2.2 million Mt (87 million bushels) in the severe 2010 epidemic, and the additional cost of fungicide application was estimated at $30 million in Washington State alone (X.M. Chen pers comm). In 2011, stripe rust was not a large problem in the Great Plains due to widespread drought, although the Pacific Northwest was even more affected by the disease than in 2010. Based on the stripe rust level in experimental fields and on crop growth stage, the potential yield loss on susceptible varieties was estimated to exceed 70%. For the 2012 crop, yield losses were predicted to reach 50% in highly susceptible wheat varieties.

Europe

Stripe rust has been considered one of the most damaging diseases of wheat in Europe for more than a century (Hovmøller and Justesen 2007). It is the most common wheat rust in a region spanning northern France, the Netherlands, northern Germany, Denmark, and the UK (Bayles et al. 2000). Northwestern Europe is considered a source of new pathotype variability due to intensive breeding for resistance that led to the use of major genes (Stubbs 1988). Epidemics have also occurred in southern Europe, but less frequently. Virulence for almost all seedling resistance genes, either present singly or in various combinations, has generally been found following their deployment in commercial cultivars (Stubbs 1985; Johnson 1988). A comprehensive survey conducted during the 1960s and 1970s estimated average annual grain yield losses of 10% in Europe (Zadoks and Rijsdijk 1984). Despite favorable environmental conditions in Europe, stripe rust has been broadly under control since the epidemics of the late 1980s and early 1990s, possibly due to successful deployment of resistance in modern European cultivars, as well as the widespread use of fungicides (Schmits 2003, cited in Hovmøller and Justesen 2007). Nevertheless, failure of resistance genes continues to be observed as consequence of mutation. Virulence for *Yr17* (widely introduced into European cultivars in the early 1990s) was first detected as a single pathotype in the UK in 1994 and this pathotype was subsequently detected in Denmark in 1997 (Justesen et al. 2002), then in France and Denmark in 1997 and 1998, respectively (Hovmøller et al. 2002). This observation indicated that northern Europe remained a single stripe rust epidemiological zone (Hovmøller and Justesen 2007). In France, stripe rust occurs most frequently in the north, with the most devastating epidemics occurring in the 1980s (Mboup et al. 2012; de Vallavieille-Pope et al. 2011).

In 2009, stripe rust spread rapidly and overcame resistance in triticale cultivars in Denmark. This resulted from a new pathotype, different from previously characterized *Pst* pathotypes in Denmark, and caused a 7.5 t/ha grain loss. A recent epidemic of wheat stripe rust in Spain is being investigated as a likely introduction (M. S. Hovmøller pers comm).

Australasia

Australia produces 20-25 million tonnes of wheat annually. Wellings and McIntosh (1990) stated that a single *Pst* pathotype was introduced into eastern Australia in 1979 and moved to New Zealand) in 1980. More than 20 new closely related pathotype derivatives were subsequently detected over two decades. A new exotic pathotype was reported in Western Australia for in 2002 (Wellings et al. 2003). This pathotype was virulent for *Yr6*, *Yr7*, *Yr8*, *Yr9*, and *YrA*, and avirulent for *Yr1*, *Yr2* (Heines VII), *Yr3*, *Yr4*, *Yr5*, *Yr10*, *Yr15*, *Yr17*, and several uncharacterized resistances in the differential set. It was clearly exotic because it was pathogenically and molecularly distinctive from the pathogen population in eastern Australia at that time. During 2003-2006, an estimated $40-90 million was spent annually on fungicides by Australian farmers (Wellings 2007). Pathotypes virulent for *Yr17* and *Yr27* are currently considered a serious threat to wheat growing areas in Australia. Despite periodic epiphytotics and occasional exotic pathotype introductions, the national breeding program for rust resistance in Australia is considered a success in containing the worst effects of rust epidemics. Murray and Brennan (2009) estimated the value of the national breeding effort for resistance at $AUS million 438, 431 and 152, respectively, for stem rust, stripe and leaf rust.

Central and West Asia and Northern Africa (CWANA)

Reports indicate that at least three widespread stripe rust epidemics have occurred in this region since the 1970s. In each case the epidemics were considered a consequence of favorable environmental conditions, emergence and subsequent wide distribution of new virulent pathotype/s, and most notably, deployment of a narrow genetic base of resistance in recently released popular cultivars. Importantly, local susceptible cultivars in all three epidemics made very significant contributions to disease development and crop loss.

A major factor in the epidemics of the 1970s was the widespread cultivation of susceptible local cultivars together with improved varieties based on *Yr2* resistance. Siete Cerros, Kalyansona, PV 18A, Indus 66, Mexipak, Ouds and Mivhor 77 were planted across wide areas including North Africa, the Indian sub-continent, the Middle East, the East African highlands, Iran and China (Saari and Prescott 1985).

The second classical example of stepwise regional dispersal of the stripe rust pathogen was the widespread distribution of *Yr9*-virulent pathotypes during 1985–1997, following initial detection in the Horn of Africa. These pathotypes subsequently migrated northwards into CWANA, and progressively in a west-east direction that eventually included the Indian sub-continent. This caused severe crop losses in widely grown cultivars covering more than 20 million hectares. In 1993 and 1995, stripe rust epidemics occurred in most wheat-growing areas in Iran and caused in excess of 30% crop loss. Estimated grain losses were in the order of 1.5 million Mt in 1993 and one million tons in 1995 (Torabi et al. 1995). In Turkey, the wheat cv Gerek 79 grown on more than one million hectares endured losses of 26.5% due to the stripe rust epidemic of 1991 (Braun and Saari 1992).

In the southern region of West Asia, severe epidemics of stripe rust were also recorded. In Yemen losses in grain yield were in the range 10-50% during 1991-1996 (Bahamish et al. 1997). These epiphytotics occurred in crops seeded in both the main and off seasons. In Central Asia a stripe rust epidemic in Azerbaijan in 1996 caused significant yield losses. In 1997, the wheat crop in Tajikistan incurred greater than 60% loss (Yahyaoui et al. 2002). The facultative winter wheat regions of Uzbekistan and southern Kazakhstan frequently report stripe rust incidence, with recent severe epidemics occurring in 2009 and 2010.

In Ethiopia, epiphytotics occurred in 1977, 1980-1983, 1986, 1988, and 1990. Yield losses in 1988 were severe in bread wheat, and as high as 58% on cv Dashen (Badebo and Bayu 1992). Ethiopia and Yemen form an ecological unit in regard to rust epidemiology and may have an important role in inoculum spread and virulence changes across the CWANA region.

Following the *Yr9* virulence-driven epidemics, the *Yr9*-susceptible varieties were extensively replaced with CIMMYT-derived germplasm (e.g. cvs Kauz, Atilla, Opata, Nacozari, Buckbuck, and Crow). The resistances in many of the replacement cultivars, including the mega-cultivars PBW343 (in India), Inquilab 91 and Bakhtwar (in Pakistan), Chamran and Shiroudi (in Iran), Kubsa (in Ethiopia), and Cham 8 (in Syria) were later reported to be based on *Yr27*, an all-stage resistance gene effective against the *Yr9*-predominant pathotypes of that time. The third episode of regional stripe rust epidemics developed when these resistant varieties showed increased rust levels, mainly in Pakistan, India, and southern Iran. Loss of effectiveness of *Yr27* resistance in cvs PBW343, Inquilab 91 and Chamran (in India, Pakistan, and Iran, respectively) were reported during 2002-2004. Although sporadic stripe rust outbreaks appeared in some areas, unfavorable environmental conditions possibly restricted rapid increases of the *Yr27*-virulent pathotypes until 2009 when conducive conditions resulted in severe epidemics in a number of CWANA countries (Pakistan, Morocco, Algeria, Tunisia, Uzbekistan, Turkey, Iran, Yemen, Azerbaijan, Georgia, Uzbekistan and Afghanistan). Environmental conditions favoring rust development continued into 2010, with a mild winter and adequate rainfall in several CWANA countries, resulting in early stripe rust outbreaks. The consequence was the 2010 stripe rust pandemic throughout the major wheat-growing areas in CWANA and Caucasus countries, causing very high yield losses, particularly in Syria where, for example, cultivar Cham 8 (with *Yr27*) occupied over 70% of the wheat area. Despite favorable environmental conditions in many areas in CWANA in 2011 and 2012, severe stripe rust epidemics did not eventuate, illustrating the year-to year variability of plant disease and its consequences. In 2010, the absence of resistant varieties in Ethiopia led to more than US$3.2 million expenditure on fungicides, and over 750,000 ha were sprayed against stripe rust in Iran. All major wheat cultivars grown in Uzbekistan, Morocco, Iraq, Azerbaijan, Afghanistan, and Tajikistan were susceptible. A devastating epidemic occurred across the Central Plateau in Turkey where the susceptible cv Gerek 79 predominated.

India, Pakistan and China

Following the Green Revolution in the mid-1960s, wheat production in India incrementally increased to the present level of 86 Mt in 2010-11 (Sharma and Saharan 2011). Stripe rust is an important disease in India, particularly in northwestern regions and the northern hills. During the 2010-11 season, it was severe in several areas, particularly where the majority of varieties was susceptible. However, timely fungicide intervention largely averted major crop damage. Pathotypes with virulence for *Yr9* and *Yr27* currently predominate in India (Sharma and Saharan 2011).

With 22.8 million ha of wheat and total wheat production exceeding 100 million Mt, China is the world's largest wheat producer (Wan et al. 2004). Stripe rust epidemics are major recurrent problems that can annually affect more than 20 million ha resulting in inter-regional epidemics (Li and Zeng 2000) with reported yield losses totaling 14.38 Mt in the severe epidemics in 1950, 1964, 1990, and 2002. China is considered a unique epidemiological zone and is considered to have the largest independent epidemic region. Extensive surveys in the last 60 years indicated very high pathogenic variability (Wan et al. 2004) and breeding has been the main focus of mitigation. Despite successes, stripe rust remains the most destructive wheat disease in China (W. Q. Chen pers comm).

Stripe rust is a serious threat to wheat production in northern and central-west areas of Pakistan. High production losses were reported in 1995 when cv Pak 81 (synonym Veery#5, carrying *Yr9*) predominated. This epidemic was attributed to *Yr9*-virulent *Pst* pathotypes. As elsewhere in the region, stripe rust epidemics in Pakistan fall into three periods: before 1993 when *Yr9* was effective; 1993-2002 when *Yr9*-virulence was widespread in major wheat-growing areas; and after 2002 with the occurrence of virulence for *Yr27*. The two mega-cultivars Pak 81/ Pirasabak 85, and Inquilab 91, became susceptible due to ineffectiveness of *Yr9* in 1994/95 and of *Yr27* in 2002, respectively, resulting in significant yield losses. Yield losses of 20% were estimated as a consequence of *Yr9* virulence. The high-yielding cultivar Seher 2006, which is resistant to *Yr27*-virulent pathotypes, was to replace Inquilab 91, but became susceptible to leaf rust –illustrating the seriousness of leaf rust in Pakistan and the need for multiple rust resistances.

Minimizing the impacts of stripe rust epidemics

A. Coordinated pathogen monitoring

The rapid spread of highly virulent and aggressive *Pst* strains, and the genetic uniformity of mega-cultivars across large areas, emphasizes the relevance of pathogen surveys covering larger areas (Hovmøller et al. 2011). In response to the need for a global rust survey, an important step towards a unified and intensive *Pst* survey was taken in 2008 when ICARDA, CIMMYT, and Aarhus University launched the Global Rust Reference Center (GRRC) at Aarhus University, Flakkebjerg, Denmark (Hovmøller et al. 2010). The Center is accessible year-round for rust samples from all countries. One purpose of the establishment of the GRRC, which has become part of BGRI, is to complement existing stripe rust and stem rust surveillance efforts by ICARDA, CIMMYT, and the NARs, particularly in developing countries. The principal objectives of the GRRC are:

1. Facilitating an early global warning system for transboundary spread of pathotypes through:

    a. Pathogen fingerprinting for rapid detection of incursions on a global scale and on understanding dispersal pathways

    b. Assessment of pathogenic variability and aggressiveness to determine wheat varieties at immediate risk

    c. Risk analysis of rust pathogen adaptation to changing climates

2. Securing unique pathogen resources to assist breeding for rust resistance

3. Providing and facilitating specialized training in epidemiology, population genetics, and pathogen evolution

4. A global source of publically available information on the cereal rusts and rust pathogen virulence surveys

The success of the GRRC will depend on global communication networks that allow rapid and free exchange of information to inform local advisory personnel in a timely and effective manner. National pathotyping capability will nevertheless be crucial in managing the large sample volumes necessary for effective regional surveillance of *Pst* populations. The GRRC will be a valuable reference for local pathology teams in gaining confidence in pathotype identity and confirming the potential of newly identified variants.

B. Resistance gene monitoring in commercial cultivars

Unless a comprehensive understanding of resistance genes in major cultivars within and between regions is established and updated, the outputs of the very best efforts to monitor *Pst* populations will remain largely irrelevant. Characterized pathotype collections of *Pst* are frequently used for postulation of resistance genes in multi-pathotype seedling tests (Perwaiz and Johnson 1986; Dubin et al. 1989; de Vallavieille-Pope et al. 1990; Nazari et al. 2008).

The development of diagnostic molecular markers has allowed some genes to be routinely screened in laboratories supporting breeding programs. The most important gene in this respect is the durable adult plant resistance gene *Yr18* which can now be conveniently monitored without the need for field disease nurseries. An international effort is needed for collaboration in marker development and utilization of linked markers, and especially in breeding for multiple gene resistance.

C. Effective resistance breeding

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Development and use of resistant cultivars is widely considered the most economically feasible and environmentally appropriate way to combat wheat rusts. The international wheat breeding programs at CIMMYT and ICARDA have been developing high yielding, widely adapted wheat germplasm with resistance/tolerance to major biotic and abiotic stresses following the classical breeding approaches and strategies whereby crossing blocks are assembled using hallmark cultivars and elite genotypes; the segregating generations are evaluated in shuttle breeding and inoculated rust nurseries, followed by key location testing of fixed lines to identify stable genotypes with appropriate combinations of desired traits. Distribution of elite material globally through the international nursery and yield trial system has resulted in the release of many high yielding, rust resistant and widely adapted wheat varieties in many countries. However, use of single resistance genes has repeatedly led 'boom and bust cycles' as the pathogens adapt and increase as evidenced above. The assembly of adult plant minor gene resistances (APR) has been the dominant breeding approach for reducing the impacts of 'boom and bust' by CIMMYT and ICARDA over the past decade. The development of molecular markers closely associated with APR genes will enable the assembly of gene pyramids to combat the evolutionary capacity of *Pst*. However, there is only one currently available marker (CsLv34 for selecting *Lr34/Yr18*) and more research and development is required in this area. Future strategies may also involve genomic selection (GS) which allows prediction of genotypic values, and thereby facilitate the selection of multiple minor QTLs associated with presumed non-race specific APR genes. Conventional breeding approaches complimented with GS and doubled haploid production systems would also enable the enhancement of breeding efficiency in developing high yielding, widely adapted genotypes with durable resistance to rusts.

D. Encouraging national action plans

An effective national strategy for combating wheat rusts has four key components: surveillance and rapid reaction plans; information sharing within and between countries; capacity strengthening – for government officials, extension services, and farmers; and participation in ongoing research programs to develop resistant wheat cultivars. A multi-faceted approach is needed by countries to combat wheat rusts. The obvious immediate response to combat rust outbreaks (whether new pathotypes or not) is fungicides wherever possible. Reducing the cropping area of susceptible cultivars across large areas is perhaps the best insurance against widespread rust damage. Countries can consider policies to plant a range of resistant wheat types in their farming systems – greatly reducing the risk of widespread epidemics. A long-term plan includes participation in international research efforts to continually monitor and develop wheat varieties that resist rust and other diseases.

One core issue for planners and policy makers is that stripe rust does not respect national borders. The rusts are 'social diseases' and can best be managed by shared agricultural practices and policies agreed across regions. The fight against rust requires good neighbors, working together. The role of policy makers and global leadership is crucial if we are to take a significant step forward in minimizing the impacts of this disease.

At the regional and international level there is a need to build a cooperative attitude for information sharing, the mutual sharing of risk analyses, and trust. The information that needs to be collected and shared across regions includes data on changing rust disease patterns, wheat variety distribution, changing agronomic practices, and climate change and weather patterns. The use of 'rust trap nurseries' across affected regions is a good example of an effective strategy for early detection and prevention of stripe rust. As rust moves across a region, researchers and planners can see the effect of new pathotypes on wheat varieties, and organize for dissemination of the most resistant varieties for the following season.

E. Accelerated seed delivery system to combat the threat of rusts

Seed is the most efficient mechanism for delivering rust-resistant wheat varieties to farmers. Availability and access to quality seed is expected to accelerate the adoption and dissemination of new durable rust-resistant varieties and associated production technologies. However, weaknesses in national seed systems threaten to impede the diffusion and adoption of replacement varieties.

For an effective seed delivery system, it is important to develop and implement the following approaches:

a. Fast-track variety testing and release (e.g. adaptation trials) systems by pursuing flexible policy/regulatory options with partners.

b. Accelerate pre-release seed multiplication of promising lines and large-scale production of released varieties for distribution through both formal and informal channels.

c. Popularize and promote rust-resistant varieties among farmers (including targeted small-pack seed distribution) to initiate informal farmer-to-farmer seed sharing and diffusion.

d. Build capacity in technical aspects of seed production and in the provision of infrastructure (training and critical equipment).

e. Develop methods to rapidly dis-adopt cultivars that are susceptible or whose resistance is at threat from an emerging new pathotype.

Conclusions

The current challenges facing the global wheat production are complex, and addressing them requires an understanding of the drivers of past trends and prediction of future changes. Designing an effective research strategy with application of new breeding tools, such as genome-wide selection and resistance gene pyramids, needs a matching effort in establishing communication net-works and collaborations. The concept of food security involves the ability to improve and sustain production consistent with an array of economic and social measures. NARS must provide a significant contribution to this goal by improving and securing production in the long term.

Wheat cropping technologies, including varieties, are specifically important factors for controlling pest outbreaks. Developing and disseminating cultivars with progressively improved rust resistances needs to be strengthened with technological packages, such as integrated pest management (IPM). In addition to the availability of resistant varieties that are known to, and accepted by, farmers, country preparedness for stripe rust outbreaks necessitates the availability of sufficient seed in both quantity and quality. In most cases, the bottleneck for getting resistant varieties into the field is lack of local and national capacity to rapidly multiply seeds and deliver them to the market.

Improving national seed production capacity and delivery requires long-term planning and funding, and must involve government, private enterprise and farmers. There are many complex organizational, procedural and legal issues that differ between countries, but for success, coordination and timely information-sharing among all stakeholders - including pathologists, plant protection officers, breeders, seed system and extension agents, marketers and farmers - are paramount.

An international forum to discuss the way forward in stripe rust R&D was held at ICARDA headquarters in Aleppo, Syria, in April 2011. The following resolutions from that meeting continue to provide a framework for the future:

1. Long-term investment is needed to reduce the threat of stripe rust

While a significant investment has been made over the past five years in surveillance and control of stem rust, stripe rust remains the most significant endemic threat across a majority of the global wheat producing regions. In spite of its preference for cooler environments, stripe rust is rapidly spreading to new areas where it was not previously a problem. Aggressive new stripe rust pathotypes are adapting to warmer climates, causing recent outbreaks at the global level. Comparatively, investments in stripe rust R&D are small and less coordinated across countries. To reduce the current spread of stripe rust, more investment to support countries to improve surveillance and in breeding of durable varieties that resist stripe rust.

2. Strategies to address wheat stripe rust disease

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a. Surveillance and information exchange between countries.

b. Planning, awareness, and preparedness to rapidly deliver appropriate seeds and fungicides where they are needed to arrest the spread of wheat rust diseases.

c. New capacity and skills in ministries, extension services, and at the farm level to develop effective strategies for managing rust diseases.

d. Crop research for a continued, long-term effort in developing new varieties that are resistant to the emerging pathotypes of wheat rust.

3. Approaching stripe rust as a social disease

One core issue for planners and policy makers is that stripe rust does not respect national borders. The rusts are 'social diseases' and can best be managed by shared agricultural practices and policies agreed across regions. The fight against rust requires good neighbors, working together. The role of policy makers and global leadership is crucial if we are to take a significant step forward in minimizing the impacts of *Pst*.

At the regional and international level there is a need to build a cooperative attitude for information sharing, the mutual sharing of risk analyses, and trust. The datasets that need collecting and sharing across regions include information on monitoring of changing rust disease patterns, wheat variety use per region, changing agronomic practices, and observations of climate change and weather patterns. The use of 'rust trap nurseries' across affected regions is a good example of an effective strategy for early detection and prevention of stripe rust. As rust moves across a region, researchers and planners can immediately see the effect of new pathotypes of rust on wheat varieties, and organize for dissemination of the most resistant varieties for the following season.

4. Encouraging the development of national action plans

An effective national strategy for combating wheat rust has four key components: surveillance and rapid reaction plans; information sharing across countries; capacity strengthening – for government officials, extension services, and farmers; and participation in ongoing research programs to develop resistant wheat varieties. A multi-faceted approach is needed by countries to combat wheat rusts. Immediate action to combat new rust pathotypes is often the use of fungicides. Reducing the cropping of susceptible mega-cultivars across vast wheat growing areas is perhaps the best insurance policy against widespread rust damage. Countries can consider policies to plant a range of resistant wheat types in their farming systems – greatly reducing the risk of emerging virulent rust types spreading over the entire area. A long-term plan includes participation in international research efforts to continually develop wheat varieties that resist rust and other diseases.

5. Reducing the impacts of narrow range variety dependence

Diversified cropping of wheat – avoiding the sowing of mega-cultivars across large cropped areas – is another possible defense against wheat rust. In most areas of the Middle East, East Africa, and South Asia, farmers have been planting the same varieties for 20–30 years. This practice is not advisable in a situation where stripe rust pathotypes are mutating and new ones are emerging much more rapidly than in the past and overcoming resistance in current varieties.

6. Developing a clear approach to seed multiplication and farmer engagement with new, diverse varieties

Efficient and effective seed delivery systems are critical for new crop varieties to reach farmers and bring impacts in ensuring food security and improving livelihoods of farmers. However, most national seed systems operate under heterogeneous environments in terms of agro-ecology, farming systems, crops and markets. They face a broad range of constraints including policy and regulatory frameworks; inadequate institutional and organizational arrangements; deficiencies in production, processing, and quality assurance infrastructure; and lack of trained personnel limiting technical and managerial capacities, compounded by farmers' difficult socio-economic circumstances. It is therefore important to assist and strengthen NARS in capacity development, establish fast-track variety release systems, and participatory demonstration and accelerated seed multiplication of newly released wheat varieties to ensure fast replacement of existing vulnerable commercial varieties.

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