2 The wheat rust crisis

2.1 Introduction

A crop-killing fungus is spreading out of Africa towards the world's great wheat-growing areas

IT IS sometimes called the "polio of agriculture": a terrifying but almost forgotten disease. Wheat rust is not just back after a 50-year absence, but spreading in new and scary forms. In some ways it is worse than child-crippling polio, still lingering in parts of Nigeria. Wheat rust has spread silently and speedily by 5,000 miles in a decade. It is now camped at the gates of one of the world's breadbaskets, Punjab. In June scientists announced the discovery of two new strains in South Africa, the most important food producer yet infected.

The World's wheat basket is threatened. The UN Food and Agriculture Organization (FAO) estimates that 31 countries in East and North Africa, the Near East, Central and South Asia, accounting for more than 37 percent of global wheat production area and 30% of production, are at risk of wheat rust diseases including the *Ug99* race of stem rust and *Yr27* strain of yellow rust.

Wheat rust is a fungal infection. Its most devastating form (*Puccinia graminis*) attacks the plant's stem, forming lethal, scaly red pustules. It has plagued crops for centuries. The Romans deified it, and believed that sacrificing dogs warded it off. It was the worst wheat disease of the first half of the 20th century, killing about a fifth of America's harvest in periodic epidemics.

Wheat rust once spurred the Green Revolution, the huge increase in crop yields that started in the 1940s. Now it could threaten those great gains. Norman Borlaug, the great American agronomist who died last year, conducted his original research into wheat rust. After ten years of painstaking crossbreeding, he isolated a gene, *Sr31* (Sr for stem rust) that resisted *P.*

graminis. By wonderful good fortune, *Sr31* also boosted yields (and not only because plants were impervious to rust). Farmers everywhere adopted his seeds enthusiastically, saving millions of lives. So fast did his new varieties spread that by the 1970s, stem rust seemed to have been wiped out.

But in 1998 William Wagoire, a pupil of Borlaug's, was in south-western Uganda researching stripe rust, a less-deadly form of the disease that remains endemic there. While testing a new variety's resistance, he was alarmed to find stems scarred not by the yellow streaks of stripe rust but the angry pustules of stem rust.

At first neither he nor Borlaug's International Maize and Wheat Improvement Centre (CIMMYT) in Mexico could believe their eyes: stem rust could not have survived all those years. The awful truth dawned only after a second opinion, by Zak Pretorius of the University of the Free State in South Africa: stem rust had not only lived on in a remote corner of Africa's Great Lakes. It had evolved to overcome the previously unconquered *Sr31*. After decades without infection, most of the world's wheat crop was defenceless.

Wheat rusts spread as billions of spores in the wind. They usually move incrementally, from field to adjoining field, needing wet weather to thrive. But they can make larger leaps. They also mutate as they go. Rust, Borlaug once said, “never sleeps.”

The new variant is called *Ug99*: Ug for its country of origin; 99 for the year it was confirmed. It soon spread to Kenya and Ethiopia. In 2006 it made a leap over the Red Sea into Yemen, where it appeared in a more deadly form. In 2007 it showed up in Iran, apparently blown from Yemen. In June scientists announced they had found four new mutations of rust (making seven in all) and Mr Pretorius confirmed its presence in a harmful form in South Africa.

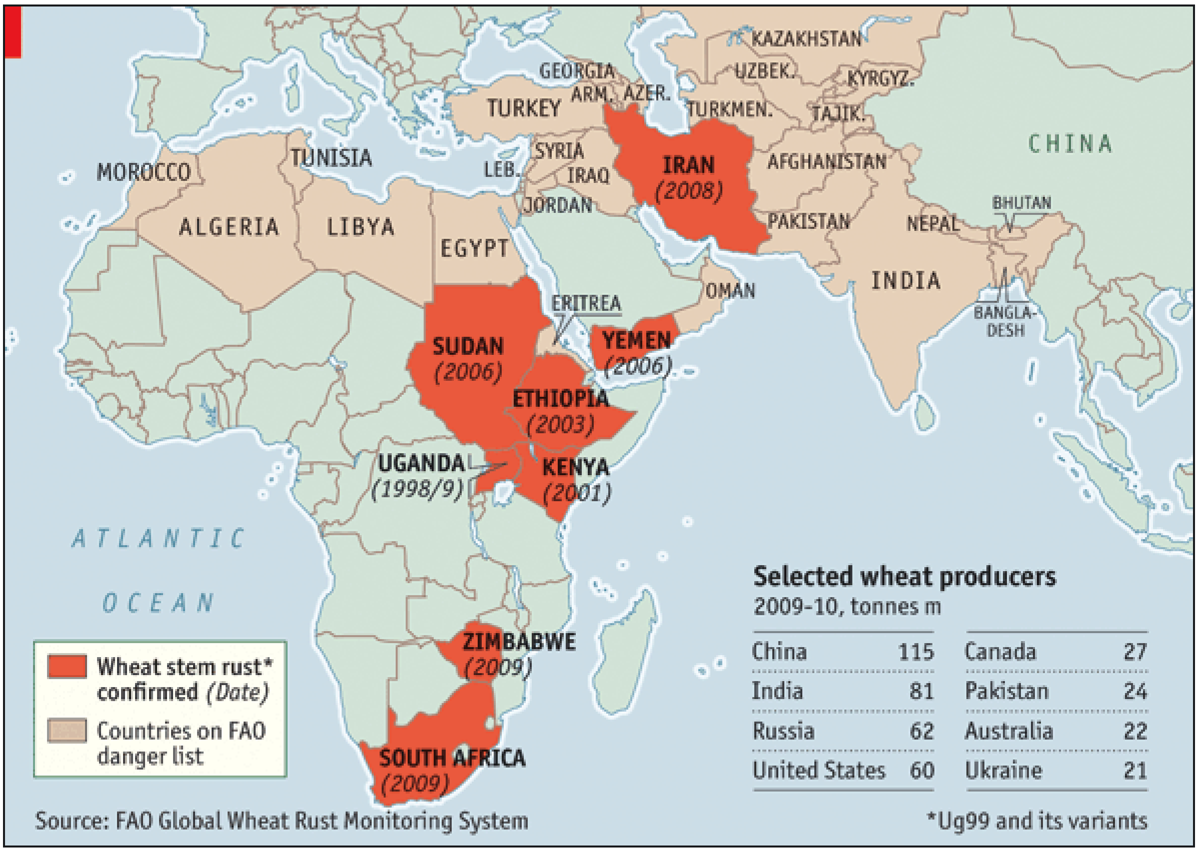
This could mark a final stage before disaster strikes. Rust's appearance in South Africa means the disease has pushed deep into the southern hemisphere for the first time. Mr Pretorius worries that westerly winds might blow spores as far as Australia, which is one of the world's top five wheat exporters. Iran borders Pakistan, which is among the top ten wheat producers and where roughly 100m people depend on the cereal to survive. David Hodson of the UN Food and Agriculture Organisation's Wheat Rust Disease Global Programme thinks it is only a matter of time before *Ug99* appears in Pakistan.

To make matters worse, the threat from stripe rust (*Puccinia striiformis*) has also been worsening. Scientists at the International Centre for Agricultural Research in the Dry Areas (ICARDA) reckon it could affect 50m hectares and that some farmers could lose a third of their crops. Both figures are far worse than previously thought.

So far, wheat rust has not caused the disaster that scientists fear. But that, says Ronnie Coffman of Cornell University, has been mainly a matter of luck. So far, no giant producer (China, India, America, Russia) has been infected. The humid conditions that spread rust most readily have recently been lacking in most places. But where the weather was to its liking – Kenya in 2007, for instance – rust destroyed a quarter of the crop and affected four-fifths of all farms. Fungicides afford some protection but huge quantities of chemicals are an expensive and limited answer. Most small farmers in poor regions, including Punjab, cannot afford them anyway.

When the good luck runs out, stem rust can destroy the entire harvest in an infected area. A full-blown epidemic in a big wheat-growing area could therefore be catastrophic. Only a handful of wheat varieties have any resistance to *Ug99*, implying that harvests could fail even more completely than during earlier epidemics.

Such a failure would be felt on a vast scale. Wheat is the world's most widely planted crop and accounts for a fifth of humanity's calorie intake (rice has a similar share; all other foods combined account for the rest). Since its discovery, *Ug99* and its descendants have shown up in eight countries ranging from South Africa to the Middle East; 26 others are on the FAO's danger list, accounting for about a third of wheat production. Kathy Kahn of the Gates Foundation says the disease is potentially "devastating".



Scientists such as Mr Coffman say they know how to attack stem rust. The question is how fast and how completely they can do it, and at what cost. Borlaug used a mighty rust-resisting gene that lasted 40 years. The new approach uses four or five weaker defences, for example reducing the area of the wheat plant that *Ug99* destroys, or slowing down the spread of the fungus. Each would be inadequate on its own. But put together, they achieve something close to full resistance. Multiple barriers also make it harder for *Ug99* to overcome them all. A single gene will eventually be defeated—as *Sr31* was. Knocking down a series of obstacles is much harder.

So far, researchers have developed about 60 experimental wheat varieties with multiple low-resistance genes. CIMMYT sent out a first batch of 15 for development and nine have made it into production and distribution on a wide scale. ICARDA has sent out two more seed lines and India and Pakistan have released rust-resistant seeds of their own. Scientists are also investigating how rust secretes the substances that enable it to break into the plant's cells. If the wheat can learn to recognise this as it is happening, it might also be engineered to generate its own *Ug99*-resistant proteins.

Separately, researchers have cracked the mystery of how stripe rust is able to overcome resistance in wheat so quickly. Until recently it was thought that stripe rust reproduces asexually. But new research found that, like stem rust, stripe rust increases its genetic variability by reproducing sexually on the leaves of another host plant (the barberry), making itself more adaptable—and more deadly.

Advances like these suggest the march of wheat rust can be halted, though at a cost. That is not just money, but a trade-off of lower yields for more resistance (i.e., the opposite of what Borlaug achieved).

But if the signs in the laboratory look propitious, out in the fields the distribution problems are formidable. Over 47,000 hectares have been planted with the new seeds. But that is only 0.1% of the total area planted to wheat in the countries on the FAO's danger list. The astonishing spread of wheat rust makes quick containment impossible. In some places stem rust may become endemic before the outside world even spots it.

The high-yield seeds of the Green Revolution were not only developed but often marketed by state-financed agricultural institutions. In many poor African countries such institutions barely exist, whereas in wealthier ones spending on them has fallen over the years. Worst of all, farmers in earlier generations had a big incentive to get their hands on high-yielding seeds. Now, the vast majority have no experience of wheat rust. They may therefore see no reason for sowing rust-resistant seeds when they first appear – until the disease destroys their harvest. By then it will be too late.

Figure 1.
Yellow rust of wheat *Stem rust of wheat*

Rust diseases are also among the major concerns in more developed wheat producing countries but thanks to improved technology, capacity and awareness, implementation of management strategies is easier. However in many countries at risk of rust epidemics in North Africa, Near East and Central and South Asia wheat production is done by small holder farmers with limited capacities. Thus, technical and policy assistance for planning and implementation of effective rust management strategies is required.

Therefore continuous vigilance and preparedness are essential to combat wheat rust diseases at a time when in these regions food security and price stability concerns are high in the international agenda.

Wheat stem rust, also known as black rust, is caused by the fungus *Puccinia graminis*. Although wheat stem rust is not the most common rust disease of wheat rust, with wheat leaf rust being the most common, it certainly currently is the most dangerous (Signh, et al 2008).

Wheat resistance to stem rust was largely believed to be held in the gene *Sr31* (Pretorious et al., 2000). But on February 1999, large amounts of stem rust were observed in Uganda's wheat plantations (2000). After running studies for the resistance in wheat for stem rust, it was found that a new strain of stem rust had mutated, making the resistance to stem rust that was found in *Sr31* obsolete. This new strain of stem rust was name *Ug99* due to its country of origin and the year it was discovered.

Not only does *Ug99* carry virulence to gene *Sr31*, but overtime it has also mutated to be resistant against most variations of stem wheat rust resistance that originated in wheat itself (Singh et al., 2008). Due to this fact, genetic engineering has started to be employed in order to try and find resistance genes in species closely related to wheat. These genes could then be transferred to wheat and give it resistance against the different variations of *Ug99* as well as other different races of wheat rust.

It is extremely important to find a way to stop the expansion of *Ug99*. Although the exact route of expansion of the *Ug99* strain is unknown, models have given it the trajectory to reach India, whose wheat production is one of the highest in the world (Figure 1). It has been estimated that 85% of the global population require wheat as one of their only calorie sources (Singh et al., 2008). If a way to stop the *Ug99* strain is not found, one of the world's largest sources of wheat could be destroyed, and it would bring a major food scarcity problem down with it.

Figure 2. A barberry bush which is a common host for *Puccina graminis*.

http://www.apsnet.org/edcenter/intropp/lessons/fungi/Basidiomycetes/Pages/StemRust.aspx

The fungus *Puccinia graminis* requires living in another organism, benefiting from it while the host organism is usually being stressed or eventually killed in the process. *P. graminis* also requires living in two distantly related species throughout its life cycle. These two distantly related species that stem wheat rust requires are wheat and barberry plants

(Schumman and Leonard, 2000). Barberries are a type of shrub that is either deciduous or evergreen, and it can be found in temperate and subtropical regions (Figure 2). While the best mode of reproduction for *P. graminis* is by completing its life cycle in both wheat and barberry, it can still grow without having to infect the barberry by acquiring spores from other regions (Schumann and Leonard, 2000).

The life cycle of the stem wheat rust starts by the introduction of a spore to a wheat plant. The spores can either come from a distant region carried by the wind, from barberry, the alternate host, or from the wheat plant itself if it is already infected. The pathway cycle that the disease will take depends on the region where the wheat is being grown. Temperate regions mostly only grow wheat during the spring since winter is too cold for wheat to grow. So the plants in temperate regions may either be exposed to spores from barberry or from spores being carried by the wind from the south, where wheat is grown year-round or just at an earlier time than the wheat in the north (Schumann and Leonard, 2000). The complete life cycle of *Puccinia graminis* can be seen on the figure below.

In the disease cycle with barberry, the teliosperes of *Puccinia graminis* are not able to germinate unless they are exposed to cold temperatures for a substantial amount of time. Due to this fact, the stem wheat disease that includes barberry mostly happens in the temperate regions where the cold temperatures of winter allow the teliospores to germinate (Schumann and Leonard, 2000). Once the growing season is over in the temperate regions, the barberry acts as a host for *P. graminis*. After the winter is over, the barberry can pass on the disease to wheat.

Towards the end of the growing season, teliospores are produced. Teliospores appear as thick black stripes on the stems of the wheat. Once the winter is over, teliospores then germinate in the spring to spores, which appear to have no colour and have really thin walls unlike the teliospores. These spores are the one that infect the barberry (Schumann and Leonard, 2000).

In order to infect the barberry, the spores have to germinate and produce haploid mycelium. These haploid myceliums then infect the surface of the leaves of the barberry. Once on the leaves, the haploid mycellims are able to produce Pycnia. Once on this form, the fungus is able to infiltrate the leaf. Inside the leaf, the pycnia produces receptive hyphae and pycniospores. The pycniospores of an individual plant can only be fertilized by the pycniospores of a different host plant (Schumann and Leonard, 2000)

The production of pycniospores is important since it allows cross-fertilization to happen. The pycniospores are spread thanks to the insects that are attracted to the honeydew that is produced alongside the pycniospores. Cross-fertilisation between plants produces dykaryotic mycelium. This is one of the most important steps in the life cycle of P. graminis since it allows its transfer from one of its host, the barberry, to the other, wheat (Schumman and Leonard, 2000).

Once the barberry is infected, only a few days have to pass in order for aecium to grow from the dikaryotic mycelium through its leaves. The dikaryotic myselium is able to produce spores, which can infect wheat or other grass hosts. Once the wheat is infected, *P. graminis* is able to produce another set of dycariotic mycelium, which ultimately is able to produce its own dikaryotic spores (Schumman and Leonard, 2000). The production of these spores can start the "repeating cycle" in crops with favourable conditions since spores can only infect the host plant that produced them (2000).

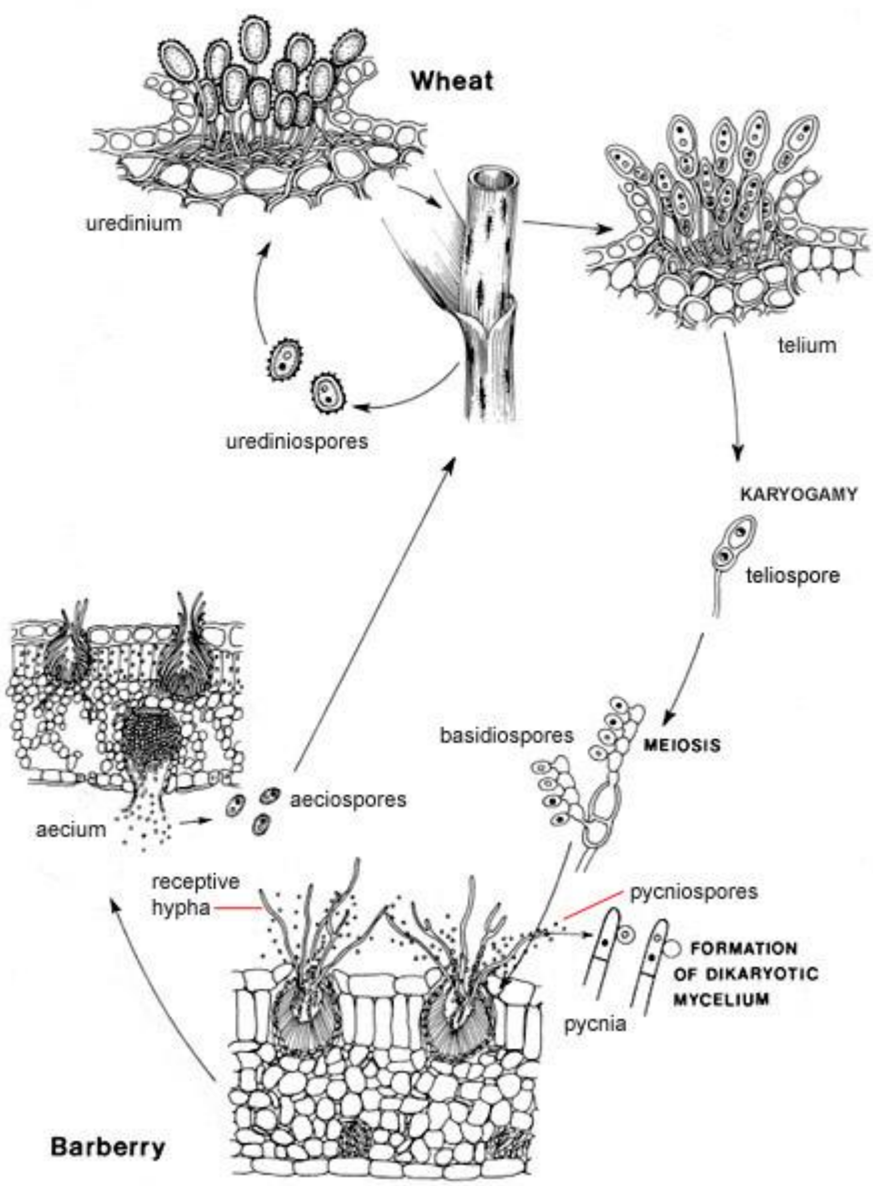


Figure 3. The complete life cycle of *Puccina graminis*.

http://www.apsnet.org/edcenter/intropp/lessons/fungi/Basidiomycetes/Pages/StemRust.aspx

Once the growing season ends, teliospores are formed again on the stem of the wheat in order to start the cycle all over again.

For the disease cycle without barberry, in North America, the Great Plains are a great example to show how *Puccinia graminis* spreads without barberry. Since the winter is too cold for the spores to survive, spores from other regions need to be donated. The spores from the warmer Great Plains of the south can then be introduced to the northern Great Plains by northward blowing wind. Since wheat is usually planted on the south earlier than on the north, there always seems to be a fresh batch of spores just waiting to be picked up by the wind. The disease ends once the wheat season of the north is over (Schumman and Leonard, 2000).

It is worth noting that the cycle starts again on the south by having spores that were produced by the wheat planted for the fall infect the wheat seedlings planted for the winter. In the south, *P. graminis* is able to survive the winter since the temperature is not as cold. The infected winter wheat then infects the summer wheat crops and the spores from those crops eventually find their way north again (Schumman and Leonard, 2000).

Figure 4. The appearance of uredinia on the stem of wheat.

http://www.apsnet.org/edcenter/intropp/lessons/fungi/Basidiomycetes/Pages/StemRust.aspx

The symtoms of stem wheat rust are not apparent until a few days have passed from the day of infection. Most of the time the symtoms start to be noticeable after 7 to 15 days have passed (Schumann and Leonard, 2000). After those few days, uredinia start to appear. Uredinia appear as little red dots on the stem or leaves of the wheat (2000). They sometimes appear to be slightly crystallized (Figure 4). Once the end of the season is nearing, the uredinia start to decrease and the teliospores start to form (Figure 5).

The symptoms of the infected barbery are similar to those of wheat. In the spring, before the wheat is present, pycnia starts to form on the surface of the leaves (Schumman and Leonard, 2000). The infection starts to be noticeable a little earlier than on wheat, since the infection starts to be noticeable after 5 to 10 days. After that time, the spores break open through the bottom of the leaves (Figure 6).

Figure 5. The appearance of teliospores on the stem of wheat.
http://www.apsnet.org/edcenter/intropp/lessons/fungi/Basidiomycetes/Pages/StemRust.aspx

Figure 6. The appearance of pycnia on the surface of barberry leaves.
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For dispersal and environmental conditions, there are three modes of transportation that the spores can take. One of them is long distance dispersal by a single event as well as assisted dispersal, the second one being stepwise range expansion, and the third being extinction and recolonisation (Singh et al., 2008). All of these modes of transportations have been observed before, although some of them are more common than others.

Dispersal by a single event is the most rare of all the modes. This type of mode includes the movement of the spores across whole continents. Although it has been noted that this type of transportation is extremely rare, it has been recorded before. Brown and Hovmoller report that stem rust spores have moved up to 8000 km from the south of Africa all the way to Australia (2002). Although these events are rare, the ability for spores the withstand a high range of environmental pressures make these large distance travels completely possible (Singh et al., 2008) Another type of dispersal by a single even is assisted dispersal. Unlike the previous example, humans mostly cause assisted dispersal. In assisted dispersal, the spores mostly travel on clothing as well as through the trade of infected wheat (2008)

Unlike dispersal by a single event, the second mode of event travels in smaller distances as well as taking more time for the spores to travel. Stepwise range expansion does not expand across continents like single event dispersal. This type of transportation mostly spreads at the slightly smaller scale of countries and regions. Out of all the transportation modes, this is the most common one. The current expansion of the stem rust strain *Ug99* is an example of stepwise range expansion. The strain first originated in Uganda in 1999, hence getting its name, then migrated into the Middle East, and now has made its way into Asia (Singh et al., 2004). Although the effects that *Ug99* has left in its path are devastating, its slow expansion, taking it 10 years to spread to Asia, are giving scientists time to try and come up with a wheat resistant strain against *Ug99* before it reaches India.

The third and last mode of dispersal is extinction and recolonisation. Although it is generally believed to be a different mode of dispersal, it is very similar to the stepwise range mode of expansion. Both of these modes expand through smaller distances, as well as moving much slower than the single event mode. The only difference is that this type of dispersal happens on land that is too stressful for the spores to survive (Singh et al., 2008). The “Puccina pathway” of North America, where spores are transferred by wind from south to north, exemplifies the extinction and recolonisation mode, since the disease eventually ends once the wheat season is over (Schumann and Leonard, 2000).