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Wheat stem rust, *Puccinia graminis* f. sp. *tritici*: An evidence note on impacts and management strategies for East Africa

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Credit: Petr Kosina/CIMMYT

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Front page photo: Wheat showing symptoms of stem rust (*Puccinia graminis*), in this case the virulent Ug99 race. Credit: Petr Kosina/CIMMYT - CC BY-NC-SA 2.0. Flickr.

Table of contents

Abstract

Wheat is the second most cultivated cereal globally, and the second most important crop for human consumption after maize. Wheat has become an important crop in Sub-Saharan Africa (SSA) where urbanization, nutrition transition and increasing population are the main driving factors. However, there is a growing gap between production (supply) and demand, particularly in East Africa (EA). Precisely, the imported wheat in Ethiopia, Kenya and Uganda stood at 28%, 75% and 95%, respectively over the period 1990–2021. These wheat production deficits mean that most countries in the region must spend their meagre resources on feeding their people. This evidence note explores wheat production issues within EA, with a focus on Ethiopia, Kenya and Uganda. Among the biotic limitations, wheat stem rust (WSR), caused by *Puccinia graminis* f. sp. *tritici* is discussed in detail because currently it is the most devastating wheat disease. Wheat stem rust re-emerged in 1998 with the race *Ug99* known to attack over 90% of the then released varieties of wheat worldwide. The epidemiology and its impact within EA and beyond is traced. To ensure food security, our review has found that substantial work championed by both international and national research organizations has been done on *Ug99* management. Recommendations for reducing the impact of *Ug99* are made. Specifically, the use of cultural methods, biocontrol approaches, chemical use, breeding and promoting utilization of high yielding *Ug99* resistant varieties and their complementary agronomic technologies can alleviate WSR demage. However, we also note that management of *Ug99* is multifaceted and it requires multidisciplinary and multipronged approaches.

Acronyms and abbreviations

BGRI	Borlaug Global Rust Initiative
CIMMYT	International Maize and Wheat Improvement Centre
DGGW	Durable Grain Gain in Wheat
DRRW	Durable Rust Resistance of Wheat
EA	East Africa
EIAR	Ethiopian Institute of Agricultural Research
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
ha	Hectare
IAEA	International Atomic Energy Agency
ICARDA	International Centre for Agricultural Research in The Dry Areas
KALRO	Kenya Agricultural and Livestock Research Organization
KRS	Kalengyere Research Station
Mt	Metric tonnes
NARO	National Agricultural Research Organization
SSA	Sub-Saharan Africa
USA	United States of America
WSR	Wheat stem rust

Executive summary

Background

Globally, wheat is the second most important food crop after maize and serves as a crucial food and nutrition security crop with per capita consumption of 64.7 kg/year. Moreover, it is the most traded crop worldwide. Currently, China is the largest producer of wheat, followed by the European Union, India and Russia, and it is from these countries that Sub-Saharan Africa (SSA) mainly imports wheat. SSA produces only 7.5 million (M) tonnes of wheat mainly from Ethiopia, South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe and Zambia in descending order. In East Africa (EA), Ethiopia produced 5.2 M tonnes in 2021 which is much more than for example Uganda's 0.025 M tonnes. In the same year, Ethiopia and Uganda imported 1.8 M tonnes and 0.4 M tonnes of wheat, respectively. This implies that these countries have to spend their meagre foreign currency resources on wheat imports to satistfy their domestic needs for wheat products.

Wheat production and production challenges in East Africa

Wheat is produced in most areas of the Eastern African countries among which are Ethiopia, Kenya and Uganda. These countries are making efforts to increase wheat production through either increasing area or production per unit area. For instance, wheat yield in Kenya has increased to 1.8 t ha^{-1}. However, the current average yield is far below the global average yield of 3.5 t ha^{-1}. Even though both abiotic and biotic stresses are crucial limiting factors to wheat production in EA, biotic stresses are the leading cause of low wheat production levels. Among the biotic stresses are those caused by diseases, especially the wheat rusts; fungal pathogens in the genus *Puccinia* including leaf rust (*P. triticina* (*Pt*)), yellow/stripe rust (*P. striiformis* f. sp. *tritici* (*Pst*)) and stem rust (*P. graminis* f. sp. *tritici* (*Pgt*)) (for example, race TTKSK). Of the wheat rusts, stem rust is the most devastating one worldwide. Currently, much effort is directed towards managing stem rust owing to the emergence of the virulent race of stem rust named *Ug99* in 1998.

Wheat stem rust (*Ug99*) life cycle and crop damage

The life cycle of wheat stem rust involves two distinct stages: an asexual and a sexual phase. During the asexual phase there is a rapid multiplication of urediniospores produced in uredinia seen as blisters on the stems of the wheat. These spores are produced in large numbers and are responsible for infection and reinfection of wheat during the growing season. Towards the end of the season, telia form on the stems which habour teliospores as the overwintering spore stage. For stem rust to complete the sexual phase of its life cycle, barberry (*Berberis* spp.), an alternative host needs to be present. Barberry species are infected by basidospores arising from germinating teliospores and basidiospore infection leads to the development of pycnia and subsequently aecia. The latter produce aeciospores which are wind-dispersed and infect receptive wheat plants leading to the development of uredinia producing urediniospores. During the life of the wheat host, *Pgt* can go through numerous asexual cycles and thus it is the urediniospore stage that is destructive to the wheat crop. In regions like EA with no winter season, adequate summer moisture and where there is a continuous green wheat crop in the field also known as a green bridge, *Pgt* persists in the uredinial (asexual) stage on the green wheat crops and/or on volunteer cereal plants or susceptible wild grasses. This scenario makes *Pgt* very destructive to the wheat crop.

Distribution and spread of wheat stem rust (*Ug99*)

Ug99 was first detected in Uganda in 1998 and first described in 1999. It has since spread to 14 countries including Kenya, Ethiopia, Sudan, Yemen, Iran, Tanzania, Eritrea, Rwanda, Egypt, South Africa, Zimababwe, Mozambique and Iraq.

Potential impacts of wheat stem rust (*Ug99*) in East Africa

Ug99 is distinct from other races of *Pgt* as it is the first to overcome the stem rust resistance gene *Sr31* found in wheat, thus rendering over 90% of wheat varieties grown globally susceptible to this disease. There are several variants of *Ug99* that have emerged which can overcome other important resistance genes and to date 15 known variants have been identified within the *Ug99* lineage of wheat stem rust (Olivera *et al.*, 2015). With varieties of wheat being vulnerable to attack by *Ug99*, the reliance on the use of resistant varieties for management of wheat stem rust has been rendered ineffective. Thus, recurrent rust epidemics have been observed to cause large scale wheat production losses in recent years. For instance, the stem rust epidemic outbreak (i.e., race TKTTF) in 2013, caused yield losses ranging from 50% to 100% in EA including Ethiopia.

Management of wheat stem rust (*Ug99*)

Response to the emergence of *Ug99* has been championed by international organizations which arose out of Borlaug's initiative following a Nairobi meeting in 2005. The Borlaug Global Rust Initiative (BGRI), the International Maize and Wheat Improvement Centre (CIMMYT), and the International Centre for Agricultural Research in The Dry Areas (ICARDA) among others then championed the charting out and formulating programmes for combatting *Ug99* to ensure wheat security through the world. In addition, national research organizations such as the Kenya Agricultural and Livestock Research Organization (KALRO) in Kenya and the Ethiopian Institute of Agricultural Research (EIAR) in Ethiopia have been instrumental in wheat stem rust management. Other important players in the region include the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA) whose activities have yielded positive results. Detailed information on stem rust management is available on the websites of these organizations.

The known measures to combat the effects of *Ug99* are either as preventative or emergency control measures including cultural, biological and chemical control, and host resistance. However, no single approach is effective. Therefore, adopting an integrated approach with host resistance as the key component remains critical in *Ug99* management. Given that stem rust spores are wind-blown and thus transported very quickly, the first line of defence hinges on limiting contact with the rust spores. This is enhanced by other cultural methods such as creating environmental conditions unfavourable for infection and disease proliferation. Other measures include biological control – the use of living organisms to suppress a pest and its effects on the host; chemical control – using fungicides to prevent and limit levels of infection; or the use of host resistance which requires breeding to produce and disseminate *Ug99* resistant varieties.

Advice and information on wheat stem rust (*Ug99*)

In this evidence note, recommendations to bridge the gap between production and demand have been made. The actors in this endeavour include policy makers, researchers, advisory service providers and farmers. The actions for managing the disease to ensure acceptable provision of quality wheat are multidisciplinary and diversified. They include the development and promotion of high yielding stem rust (mainly *Ug99*) resistant varieties that are accessible to the farmers in adequate quantities and in a timely manner. Thus, the policy makers must ensure a conducive environment for the actors. Not least is the need for the farmers to be receptive and use the availed improved technologies that are woven around the improved stem rust resistant varieties.

Recommendations

The issues affecting wheat production especially wheat stem rust management are multifaceted and addressing them requires multidisciplinary and multipronged approaches. The main actors here include government, particularly the policy makers, the agricultural service providers such as researchers, extension workers and other advisory service providers, the wheat processors as well as other traders, and farmers. They include:

Research institutions:

- Establishing robust breeding programmes to produce high yielding *Ug99* resistant wheat varieties.
- Explore avenues for and set up innovation and incubation centres for promoting appropriate technologies for the wheat industry.
- Enhance regional and international collaborations for synergies especially on surveillance, identification and utilization of information on *Ug99* spread.

Policy makers:

- Provide adequate funding for infrastructure and research on *Ug99* among others.
- Provide a conducive environment for example through establishment and promotion of cooperatives for the wheat industry.
- Provide for or enhance access to cheap credit, farm inputs, disease resistant and high yielding wheat varieties and accompanying appropriate agronomic technologies.
- Put in place supporting regulations for production of wheat seed of high yielding disease resistant varieties (seed system).
- Government should put in place supporting laws governing wheat trade within the country as well as regional and global markets.

Agricultural extension and advisory support services:

- Provide feasible linkages between researchers and farmers for efficient dissemination of wheat production technologies developed by researchers.
- Strengthen wheat based multi-stakeholder innovation platforms.

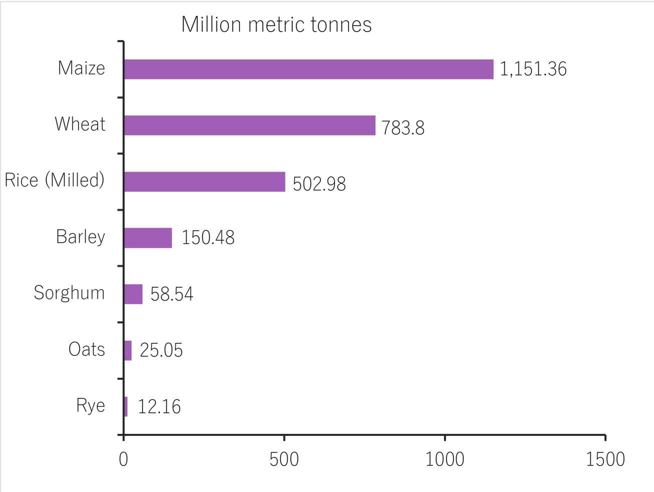
Farmers:

- Embrace and test new technologies on wheat production.
- Adopt high yielding wheat stem rust resistant varieties and complementary agronomic technologies.

1. Introduction

1.1 Global wheat commodity

Wheat (*Triticum* spp.) domestication occurred over 10,000 years ago and has since become an important dietary staple as a source of calories and proteins to millions of people around the world, thereby serving as a crucial food and nutrition security crop (Dixon, 2007). After rice and corn (maize), wheat is the second most cultivated cereal globally, and the second most important crop for human consumption (Fig. 1a) (Statista, 2023).



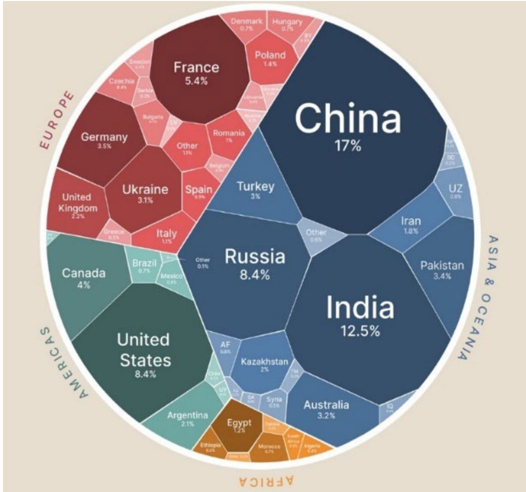


Fig. 1a (left). Top worldwide production of grain food crops 2022/2023. **Fig. 1b (right).** Global wheat production indicating major producers (adapted from World Economic Forum).

As of 2021, globally, wheat was cultivated on 221 million (M) ha of land, occupying more land than any other food crop (Erenstein *et al.*, 2022). Currently, about 784 M metric tonnes of wheat are produced globally for human consumption, with an average per capita consumption of 64.7 kg/year (Statista, 2023). China is currently the largest wheat producer, followed by the EU, India and Russia (Fig. 1b). China, India and Russia are the three largest individual wheat producers in the world, accounting for about 41% of the world's total wheat production (FAO, 2022).

Wheat production is an essential part of world agriculture, helping to ensure food security and combating poverty. With the increasing demand for wheat products, it has become one of the most traded commodities (Shiferaw *et al.*, 2013). Considering the importance of wheat in the global food system, any production constraints such as disease outbreaks, droughts, conflicts and wars, and other events for major producers could trigger global food insecurity.

For instance, Russia and Ukraine together account for nearly 30% of the global wheat trade. Thus, the Russia–Ukraine conflict affected the price of staple crops and spurred interest in tropical wheat production. Global wheat supply was negatively affected by the war. Consequently, many nations have restricted or ended trade links with Russia, which is driving up world wheat prices. Moreover, farming is hampered by high fertilizer prices as Russia has been a significant supplier of fertilizers historically, which are essential in optimizing crop yields.

Today, the global demand for wheat is increasing largely due to the global population boom and urbanization, and is anticipated to continue to do so in forthcoming years. The market is expected to be driven by rising global wheat demand as well as an increased demand from the food and beverage processing sectors to produce goods such as flour, pasta and drinks. To avert this looming crisis, regional wheat consuming countries need to seek effective and sustainable strategies on wheat production and consumption (Laborde and Piñeiro, 2023).

1.2 Wheat in Eastern Africa

Traditionally, wheat is not considered as an important staple food crop in Africa. However, with rising population growth, nutrition transition and rapid urbanization, the demand for wheat in SSA has surged (Tadesse *et al.*, 2019). Yet, Africa produces only 26 M tonnes of wheat mainly from Ethiopia, South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe and Zambia in descending order, which is far below the average wheat imports of 51 M tonnes (Fig. 2a). Similar patterns are observed for wheat production, imports and exports for SSA including Eastern Africa (Fig. 2b). Ethiopia accounts for the largest production area (1.7 million ha) followed by South Africa (0.5 million ha) (Tadesse *et al.*, 2019).

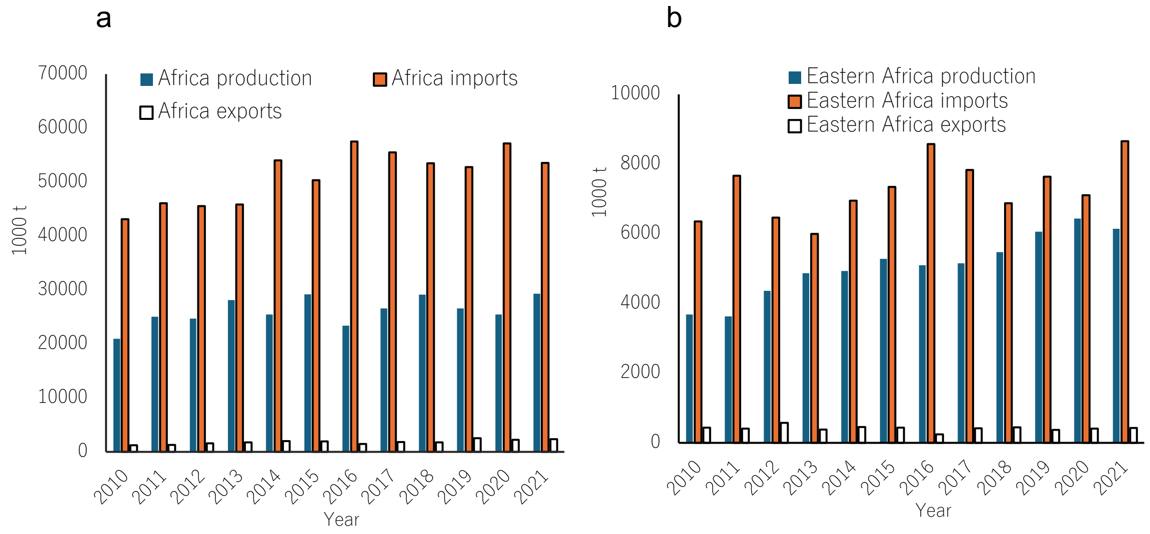


Fig. 2. Wheat food balances (production, imports and exports) in Africa (2a) and Eastern Africa (2b), 2010–2021. Data from FAOStat (2023); http://www.fao.org/faostat/en/#data/QC.

One major insight from Fig. 2 is that most African countries are net importers of wheat. To circumvent global wheat food insecurity associated with disease outbreaks, climate change and conflicts, regional net importers of wheat need to seek effective and sustainable strategies on wheat production and consumption (Laborde and Piñeiro, 2023). Thus, the objective of this evidence note (study) is to understand the current impact of wheat stem rust (*Ug99*) on wheat production, current management options, and recommendations for how it could be managed in the future in EA, with Ethiopia, Kenya and Uganda as special focus countries.

As seen in Table 1, area harvested, yield, production and imports of wheat vary from country to country. However, a few common insights are observed. First, Ethiopia has more land under wheat cultivation than Kenya and Uganda. Second, overall, wheat yields are lower than the global average of 3.5 t ha^{-1} (Mwangi *et al.*, 2021). Third, all the three countries are net importers of wheat and the gap between wheat production and imports is increasing (Table 1, Figs 2 and 3). For instance, the imported wheat in Ethiopia, Kenya and Uganda stood at 28%(1.01/(1.01+2.7)*100), 75% and 95%, respectively over the period 1990–2021 (Table 1).

Table 1. Area harvested, production and imports for wheat in Ethiopia, Kenya and Uganda (Average for 1993–2021).

Country	Area harvested (ha)	Yield (t/ha)	Production (tonnes)	Imports (tonnes)
Ethiopia	1,346,867	2.03	2,728,548	1,056,359
Kenya	141,383	2.16	305,075	927,265
Uganda	10,396	1.64	17,053	306,064

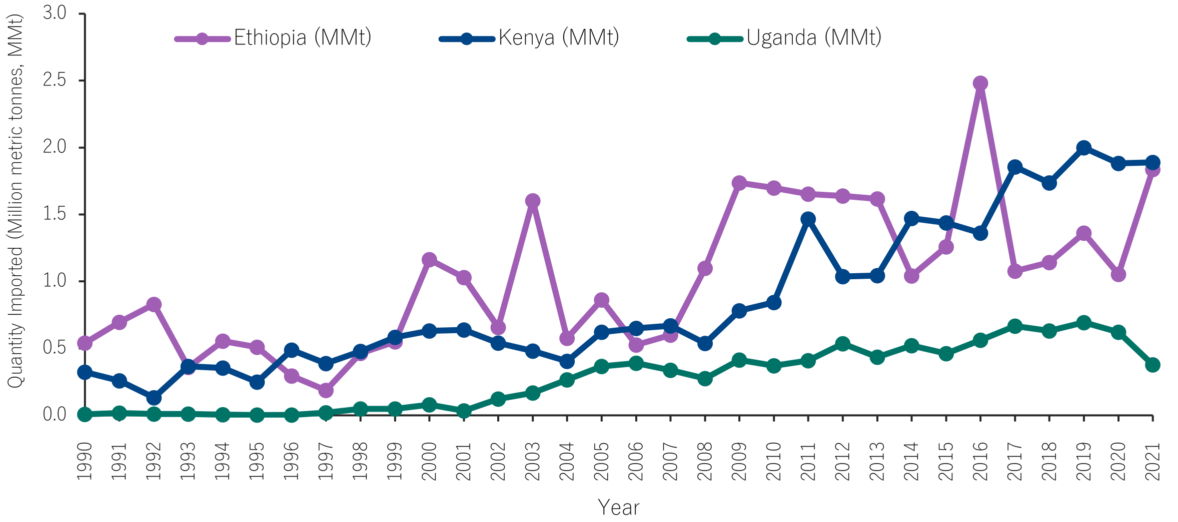


Fig. 3. Quantity of wheat imports in Ethiopia, Kenya and Uganda, 1990–2021. Data from FAOStat (2023); http://www.fao.org/faostat/en/#data/QC.

This finding entails that reducing the wheat deficits and attaining wheat self sufficiency in the three countries requires substantial attention to wheat production challenges.

1.2.1 Wheat situation in Ethiopia

Ethiopia is the largest wheat producing country in SSA, and in 2021 it had an annual production of 5.2 million tonnes from 1.6 million ha in 2001 (Fig. 4). Bread wheat is one of the most important food security crops in Ethiopia, and it is estimated that 4–5 million households depend on wheat production for both food and cash (Taffesse *et al.*, 2018). Wheat is produced under both rainfed and irrigation, accounting for 1.7 million ha and 0.4 million ha, respectively (Tadesse *et al.*, 2022). The average annual wheat grain production is about 6.7 million tonnes. Wheat yields are slightly higher (4 t ha^{-1} *vs* 3 t ha^{-1}) under irrigation than the rainfed production system.

In Ethiopia, wheat ranks third after maize (*Zea mays* L.) and teff (*Eragrostis tef* Zucc.) in terms of total production, and fourth after maize, teff and sorghum (*Sorghum bicolor* L.) in area of cultivation (FAO, 2021a). The major wheat producing areas are mainly found in the mid-altitude (1900 to 2300 m above sea level) and high-altitude (2300 to 2700 m above sea level) regions of the country that are regarded as high-potential environments due to their high and reliable rainfall.

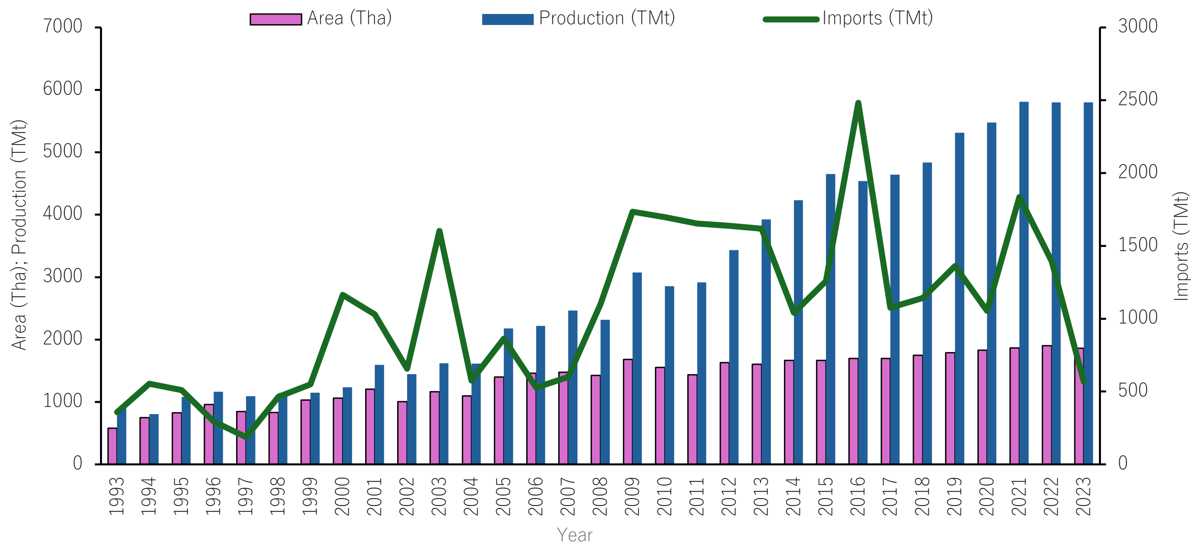


Fig. 4. Wheat production area, production, and imports in Ethiopia, 1993–2023. Data from FAOStat (2023); http://www.fao.org/faostat/en/#data/QC

Wheat is used for making traditional bread, bakeries, pastries, couscous, and mixed with other cereals to make *injera*. For smallholder farmers, the grain straw is used for animal feed, fuel, as a source of income and for roof thatching (Hodson *et al.*, 2020). The increasing demand for wheat is attributed to, among other factors, population growth, the emergence of agro-processors, urbanization, nutrition transition, and increased household income (Semahegn *et al.*, 2021). For instance, the country imported an additional 1.84 MMt of wheat worth US$ 936.6 million to meet the domestic consumption needs in 2021 (Fig. 4; FAO, 2023). The need for imported wheat has consistently been there as can be seen in Fig. 4 and arguably, it is taking a large amount of the country's foreign currency reserves.

Wheat is mainly grown by smallholder subsistence farmers and its productivity is affected by both biophysical and socio-economic challenges (Hodson *et al.*, 2020; Semahegn *et al.*, 2021). Among the limiting factors cited are: use of low yielding varieties, sub-optimal cultivation methods, and abiotic and biotic stresses. These are notably drought and wheat rusts and limited use of necessary inputs such as inorganic fertilizers and fungicides. Other factors include lack of a well-developed seed system and limited access to credit.

1.2.2 Wheat situation in Kenya

In Kenya, wheat is the most important cereal after maize, substantially contributing to food security, poverty reduction and employment creation. The major wheat growing areas are Narok, Nakuru, Uasin Gishu, Meru, Laikipia, Nyeri and Nyandarua counties in descending order of importance. Unlike in Ethiopia, the bulk of wheat production in Kenya is done by large scale farmers who account for 80% of the national production. Farmers growing wheat on less than 8 ha are classified as small scale while those with over 8 ha are considered large scale. Area under wheat production fluctuates over time and so does the production quantity (Fig. 5) but is generally within a range of 300,000 tonnes produced on 140,000 ha, representing an average yield of 1.8 t ha^{-1}, compared to global wheat average yield of 3.5 t ha^{-1} (Mwangi *et al.*, 2021).

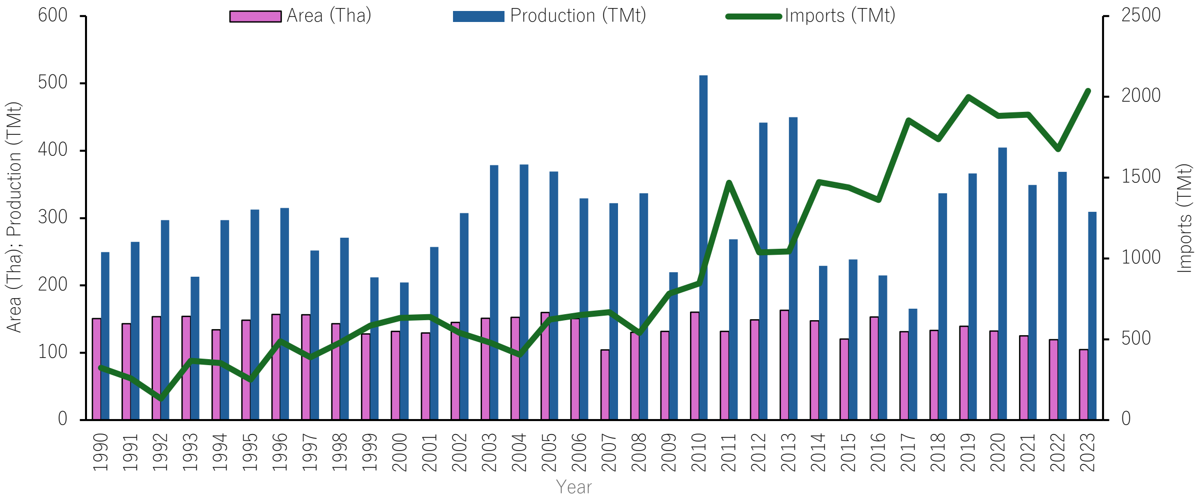


Fig. 5. Wheat production area, production and imports in Kenya, 1990–2021. Data from FAOStat (2023); http://www.fao.org/faostat/en/#data/QC).

In Kenya, the per capita consumption of wheat stands at about 41 kg. The estimated annual wheat consumption in Kenya is 2.1 MMt, thus national production accounts for only 11% of the demand, leaving a deficit of more than five times, a gap always bridged through wheat importation (FAO, 2021a). The over-reliance on imports not only drains the foreign currency reserves but also presents a risk of food insecurity and high commodity prices in case of disruption to trade due to conflict like the Ukraine-Russia war (Mottaleb *et al.*, 2022) or the COVID pandemic that affected free flow of commodities.

The sub-optimal yields realized in wheat is attributable to erratic rainfall, drought and heat due to climate change, high cost of inputs, collapse of extension services hence low uptake of new technologies, biotic stresses (diseases like rusts and insect pests) and land subdivision that interferes with the economies of scale (Mwangi *et al.*, 2021; Tadesse *et al.*, 2019).

1.2.3 Wheat situation in Uganda

In Uganda, wheat was introduced in 1912 on the slopes of the Rwenzori mountains and later promoted on the slopes of Mt Elgon on a farm with tractors, drills and combine harvesters (Masefield, 1962). Since its introduction, wheat has traditionally been grown above 1500 m above sea level mainly on the slopes of Mt Elgon, Mt Rwenzori and Mt Muhavura covering an area fluctuating around 16,000 ha (Kagorora *et al.*, 2021). These wheat production areas lie between 1500 and 2500 m a.s.l. and are characterized by cool climates, with mean annual maximum temperatures not exceeding 26°C. The rainfall is bimodal and generally adequate, exceeding 800 mm per annum (Gumisiriza *et al.*, 1993).

Land holdings for wheat production in Uganda range from 0.3 to 3.4 ha of land, with averages of 2.41 ha in Eastern Uganda and 1.65 ha in the southwest per household. Average wheat yields in Uganda vary from 1.2 to 2.5 t ha^{-1} with the highest yields registered in Southwestern Uganda due to the relatively fertile soils. However, wheat production levels have been fluctuating and in 2021, they stood at 25,000 tonnes (Fig. 6). On average, Uganda's wheat production constitutes only about 5% of its national requirements leading to importation of about 95%.

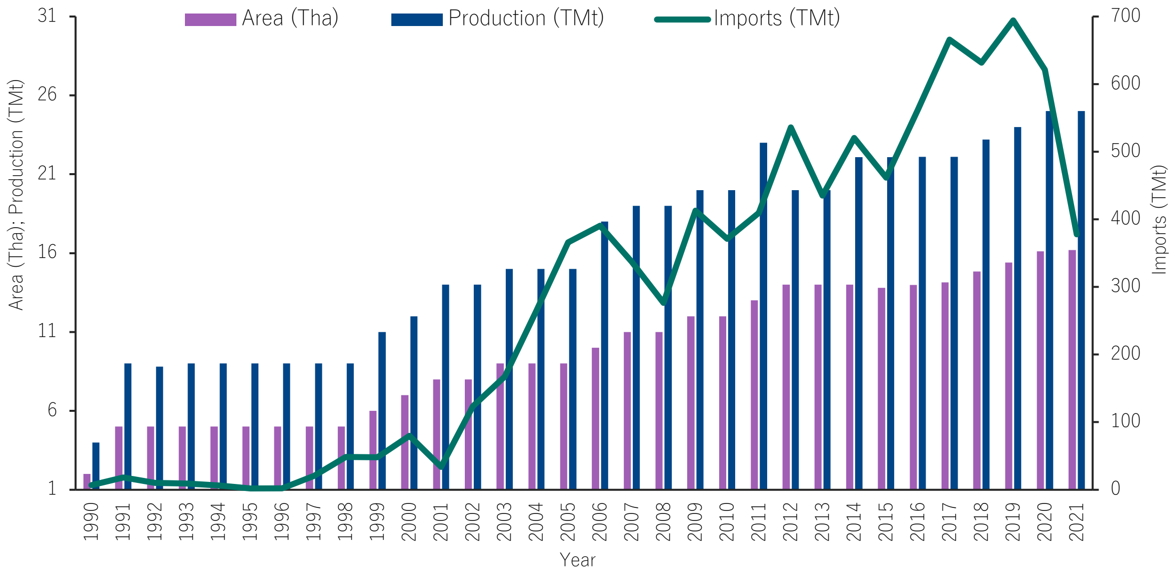


Fig. 6. Wheat production area, production, and imports in Uganda, 1990–2021. Data from FAOstat (2023); http://www.fao.org/faostat/en/#data/QC).

Land preparation is mechanized across the eastern belt while it is largely manual in the South-western highlands. Very limited fertilizer is used in wheat production across the country, where mainly a basal application of diammonium phosphate (DAP) and nitrogen, phosphorus and potassium (NPK) are applied at planting without any top dressing or manure use. Optimum fertilizer combination for high yields and good grain quality is 60 kg ha^{-1} N and 15 kg ha^{-1} P (Nakanwagi *et al.*, 2018). The improved methods applied by the farmers in Eastern Uganda is due to influence and proximity to the large commercial wheat farms in Western Kenya and relatively better access to markets.

Wheat is generally grown as a monocrop across the country however some farmers intercrop it with young tree lots. However, in Eastern Uganda, the cropping system is also characterized by a crop rotation between potato, beans and maize. The elite farmers in Eastern Uganda access seed of new varieties through Kenyan contacts across the border although 90% of the farmers continue to use farm saved seed. It has also been observed more recently that growing barley seems to be replacing wheat in Eastern Uganda. Thus, if no remedy for alleviating the pull to barley is found, the wheat production area will continue to shrink.

2. Wheat stem rust and its epidemiology

2.1 Introduction

Globally, cereal rusts are among the most damaging plant diseases that result in massive yield losses putting at risk livelihoods, food and nutrition security of millions of people (Singh *et al.*, 2016). Rust pathogens persist in every wheat-growing environment, posing a consistent threat to global wheat production. This menace has persisted since the early days of wheat cultivation and remains an ongoing concern, jeopardizing global wheat supplies.

There are three predominant wheat rusts: (i) leaf rust, (ii) yellow/stripe rust, and (iii) stem rust. They are all caused by fungal pathogens in the genus *Puccinia* of different species: leaf rust (*P. triticina* (*Pt*)), yellow/stripe rust (*P. striiformis* f. sp. *tritici* (*Pst*)) and stem rust (*P. graminis* f. sp. *tritici* (*Pgt*)). These rusts occur in all places where wheat is grown; however, their prevalence and economic importance varies from region to region. Nevertheless, among the three, wheat stem rust is the most devastating worldwide (Roelfs *et al.*, 1992) and is the main focus of this evidence note.

2.2 Life cycle of wheat stem rust

Unlike most plant diseases, stem rust requires two different plants to complete the entire life cycle, the host - usually wheat plants and common barberry. Common barberry (*Berberis vulgaris*) is the alternate host for the stem rust fungus and is crucial for the pathogen to complete its life cycle, specifically its sexual phase. Because of this reason, elimination of barberry was used as an important tool to control stem rust during epidemics in countries like the USA (Leonard, 2001; Leonard and Szabo, 2005). In countries with cool winter conditions, the stem rust cannot survive in its uredinial stage and persist in the field without barberry, the host of its sexual stage. This is unlike countries without winter, where the stem rust can cycle repeatedly through its uredenial stage, multiplying and surviving on "green bridges", which are volunteer crops and residual wheat plants. The different spore stages of *Pgt* have different optimum temperatures for infection, but all require free water for germination and infection of their host (Schumann and Leonard, 2000). Thus, *Pgt* thrives best in conditions of hot days (25–30˚C), mild nights (15–20˚C), and wet leaves from rain or dew (Schumann and Leonard, 2000).

Wheat stem rust life cycle involves two distinct stages: the asexual and sexual cycles (Fig. 7). The asexual phase of stem rust is characterized by rapid multiplication and dispersal of urediniospores leading to repeated infection cycles of wheat. This part of the life cycle is thus the most detrimental and observable cause of crop damage. In regions like East Africa, with no winters but adequate summer moisture, and where there is a continuous green wheat crop in the field (green bridge), *Pgt* persists in the uredinial (asexual) stage on the green wheat crops in the field, and/or on volunteer cereal plants or susceptible wild grasses. The asexual uredinial stage is repeated on the grass host (wheat) with a new generation of dikaryotic urediniospores developing every 14–20 days under favourable conditions (Brennan, 2010; Leonard and Szabo, 2005).

The sexual phase of the life cycle begins with the teliospore stage replacing urediniospore production typically as the grass host matures and dies back towards the end of the growing season. Teliospores are thick walled and remain viable and apparently dormant through winter. Like urediniospores, teliospores are dikaryotic as they have two haploid nuclei per cell. During the apparent dormant period, the two nuclei in the teliospores fuse to form diploid nuclei, which rapidly begin meiosis to produce four recombinant nuclei. The teliospores germinate at the start of the growing season producing basidia. Individual basidia bear four basidiospores, each of which contains one of the recombinant haploid nuclei (Fig. 7).

Basidiospores are forcibly ejected from the basidium and carried by air currents. Where they land on barberry leaves, basidiospores will infect this host, if abiotic conditions are suitable, to produce pycnia on the upper side of the leaf. The pycnia produce receptive hyphae (which act as the female organ), spores called pycniospores (which act as the male organ) and a sugary nectar.

The pycnia are self-incompatible and the nectar is required to attract insects, which transport the pycniospores to pycnia of the opposite mating type to effect fertilization. The fertilized receptors produce dikaryotic hyphae which give rise to aecia, forming on the underside of the barberry leaf (Fig. 7). The aeciospores produced from these aecia are dispersed by wind and can infect susceptible wheat plants to produce uredinia bearing urediniospores, which can go through many cycles of asexual reproduction during the life of the host (Brennan, 2010; Leonard and Szabo, 2005).

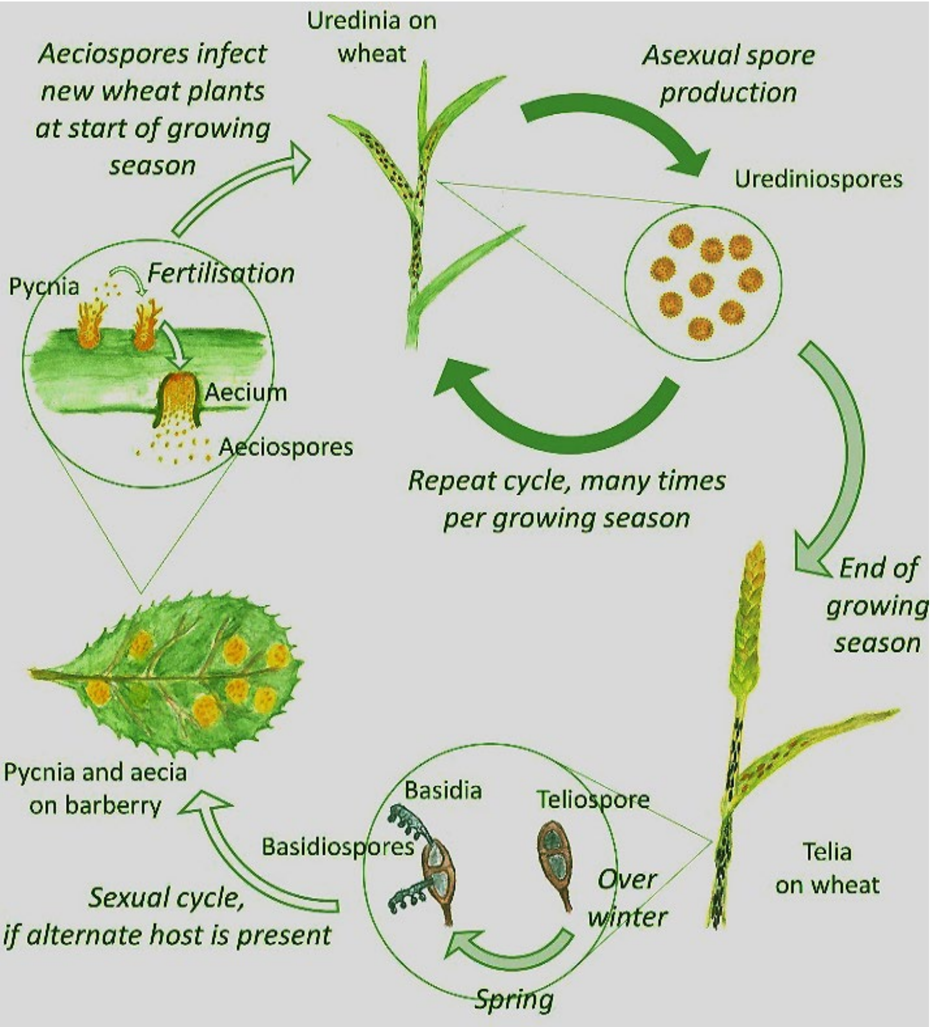


Fig. 7. Life cycle of *Puccinia graminis* f. sp. *tritici* (Hawkins, 2020).

In summary, in the absence of barberry or other alternate hosts, urediniospores are the only functional spores in the disease cycle of *Pgt*. In tropical and subtropical climates, the production of urediniospores on volunteer wheat and noncrop grass hosts can sustain the disease in the field and give rise to new epidemics.

2.3 Symptoms of wheat stem rust

Wheat stem rust also known as black rust affects all plant parts including foliage, leaf sheath, stem and spikes. Stem rust development favours warm moderate temperatures of about 15-35ºC, and free moisture - rain or dew (Roelfs *et al.*, 1992). In such conditions, it can develop quickly, causing severe yield losses.

The stem rust fungus produces several different structures during its life cycle. The most obvious of these on wheat are manifested as masses of brick-red urediniospores that form on leaves, stems (Fig. 8a), glumes, heads and awns of susceptible plants during the growing season (Kolmer, 2005). These spores are spread by wind and infect wheat or barley plants. The black-colored teliospores where the disease derives its name "black stem rust" (Fig. 8b)

Fig. 8. Wheat stem rust symptoms.

are produced toward the end of the growing season and are structures specialized for survival. The teliospores enable the fungus to survive on straw over winter and only spread with the straw. On barberry, orange- to salmon-colored aecia are produced on the lower leaf surfaces early in the spring. Aeciospores are produced in the aecia and are spread to wheat by wind.

Historically, wheat stem rust has been a major problem in all of Africa, the Middle East, Asia, Australia, New Zealand, Europe and America (Saari and Prescott, 1985; Singh *et al.*, 2011). Stem rust epidemics caused severe yield losses in Asia (Joshi and Palmer, 1973; Nagarajan and Joshi, 1985), Australia (Park, 2007; Rees, 1972; Watson, 1981), the USA (Leonard, 2001; Leonard and Szabo, 2005) and Europe (Zadoks, 1963). The last major stem rust epidemic occurred in Ethiopia in 1993 and 1994 (Shank, 1994).

2.4 The emergence of *Ug99*

The story of *Ug99,* hence the re-emergence of stem rust, started in 1998 at Kalengyere Research Station (KRS) in the southwest of Uganda. KRS is located at an altitude of 2,450 m.a.s.l., and is characterized by two rainy seasons per year. According to Kankwatsa *et al.* (2002), the mean minimum and maximum temperatures at KRS from August to December 1998 were 11°C and 22°C, respectively. The average monthly rainfall and relative humidity during these months were 82.9 mm and 89.1%, respectively (Kankwatsa *et al.*, 2002). Hitherto, KRS was known for being a hotspot for testing for yellow rust (Wagoire, 1997).

From nurseries that were screened for yellow rust, Wagoire had observed higher than expected stem rust scores. Consequently, field samples from this nursey were sent to South

Africa for virulence characterization. The results from this analysis showed that several wheat lines in the nursery suspected to contain the *Sr31* resistance gene, succumbed to a new *Pgt* race now commonly called *Ug99* (Pretorius *et al*., 2000). Among the lines from which the samples were selected were: 'Kavkaz', Federation4*/Kavkaz, Bobwhite S and Alondra S; these are all known to contain *Sr31* (McIntosh *et al.*,1995), confirming rust virulence for *Sr31*.

The nomenclature of '*Ug99*' depicts country of origin (Ug for Uganda), and actual year of field sample collection (1999). Virulence for *Sr31* was suspected based on field scores taken in 1998, but the race was not officially characterized until 1999. The name *Ug99* is likely to remain entrenched in the scientific nomenclature (Fetch *et al.*, 2021). Because Uganda is the source of wheat stem rust (*Ug99*), the country is extremely important in wheat rust research, studies and its management. Further tests of available differential and tester lines indicated avirulence for *Sr21, Sr22, Sr24-27, Sr29, Sr32-36, Sr39, Sr40, Sr42-43, Agi* and *Em*, and virulence for *Sr5-6, Sr7b, Sr8a, Sr8b, Sr9b, Sr9e, Sr9g, Sr11, Sr15, Sr17, Sr30-31* and *Sr38* (Pretorius *et al.*, 2000). The classification of avirulence for *Sr21* should also be put into perspective. In the first description of *Ug99* in South Africa, the *Triticum monococcum* accession 'Einkorn' was the only source of *Sr21* available. In follow-up tests using the differential line CS_T.mono-deriv. line containing *Sr21* in the hexaploid 'Chinese Spring' background, the gene was ineffective (Jin *et al.*, 2007).

2.5 Dispersal/migration of wheat stem rust

Wheat stem rust produces vast numbers of urediniospores by clonal repeating cycles. These spores can be carried over long distances in the wind. Examples have been given for such movements between the southern USA to the north and Canada; from southern Europe and North Africa to northern Europe; from the South Indian hills to the Central Indian plains; and from southeast to northern China (Roelfs *et al.*, 1992). These regular "rust tracks" carry early-season inoculum from winter wheat in warmer climates infecting spring crops where the climate is too cold for the rust to over-winter on wheat locally, re-introducing the pathogen after any break in wheat cropping, and crucially, causing extensive long-distance gene flow. This means that any new rust variants, including new virulence types, can rapidly spread throughout a region along the prevailing wind direction.

Nevertheless, rarer dispersal events can also take place over far longer distances. For example, there is evidence of rust spores in high-level air currents having carried new *Pgt* genotypes for thousands of kilometres from South Africa to Australia (Visser *et al.*, 2019), and humans can also inadvertently spread rust spores on plant material or clothing. The aeciospores are also dispersed over shorter distances, resulting in noticeably higher infection levels in fields next to barberry bushes than other fields nearby. However, once an aeciospore infects a nearby wheat plant, urediniospores will be produced, dispersing any new variants more widely.

In the East African region, Nagarajan *et al.* (2012) has described the wheat growing area and occurrence of *Puccinia graminis* and charted out what they call the Rift Valley conduit. The Rift Valley conduit interconnects the wheat-growing areas of Tanzania through to Yemen (Fig. 9) thus making a single epidemiological zone. This path had been observed by Stubbs (1985) for *Puccinia striformiis*. Based on the available agro-ecological information on wheat/barley cultivation in Uganda-Kenya-Ethiopia to Yemen, it can be inferred that *Pgt* survives in the uredinial stage throughout the year either on the main host or on a green bridge. This epidemiological advantage lends *Pgt-Ug99* spatial and temporal leverage to spread in the Rift

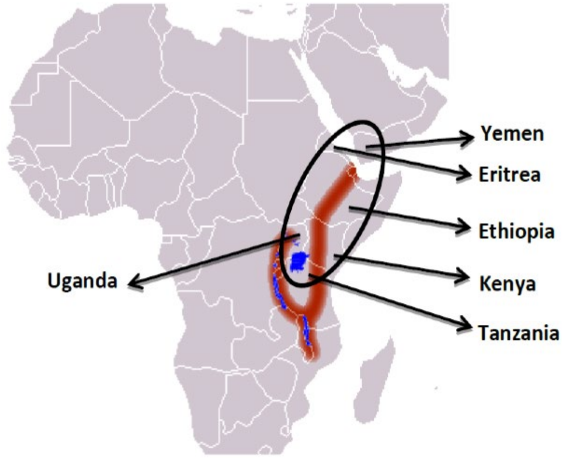


Fig. 9. The Rift Valley conduit supports the EA *Puccinia* pathway and forms one large epidemiological zone (Nagajaran *et al.*, 2012).

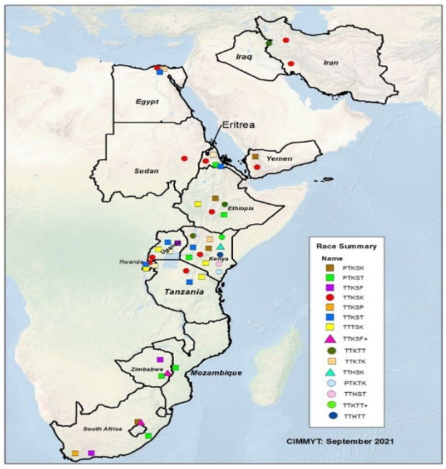


Fig. 10. Status summary: *Ug99* lineage, September 2021 (https://rusttracker.cimmyt.org/wpcontent/uploads/2021/09/race_summary_2021Sep28.jpg).

Valley, as illustrated in Fig. 9, within the area marked in red. The Rift Valley conduit phenomenon explains the observed movement and hence the timing of the occurrences of the *Ug99* races (Table 2) and their spread (Fig. 10). However, like all cereal rusts, the spores of *Pgt* also spread by plant-to-plant contact and by air dispersal (Hodson *et al.*, 2005) and most spores move only small distances and contribute to local epidemics within the crop. A very small proportion of spores get into the atmosphere and move long distances to cause new infections in new areas (Prank *et al.*, 2019).

Table 2. Summary lineage of *Ug99* in 2021 (adapted from FAO, 2021b).

Race [a]		Alias	Key virulence (+) or avirulence (-) *	Identification year	Confirmed countries (year)
TTKSK		*Ug99*	*+Sr31*	1999	Uganda (1998/9), Kenya (2001), Ethiopia (2003), Sudan (2006), Yemen (2006), Iran (2007), Tanzania (2009), Eritrea (2012), Rwanda (2014), Egypt (2014)
TTKSF			*-Sr31*	2000	South Africa (2000), Zimbabwe (2009), Uganda (2012)
TTKST		*Ug99 + Sr24*	*+Sr31, +Sr24*	2006	Kenya (2006), Tanzania (2009), Eritrea (2010), Uganda (2012), Egypt (2014), Rwanda (2014)
TTTSK		*Ug99 + Sr36*	*+Sr31, +Sr36*	2007	Kenya (2007), Tanzania (2009), Ethiopia (2010), Uganda (2012), Rwanda (2014)
TTKSP			*-Sr31, +Sr24*	2007	South Africa (2007)
PTKSK			*+Sr31, -Sr21*	2007	[Uganda (1998/99)?], Kenya (2009), Ethiopía (2007), Yemen (2009), South Africa (2017)
PTKST			*+Sr31,+Sr24,-Sr21*	2008	Ethiopia (2007), Kenya (2008), South Africa (2009), Eritrea (2010), Mozambique (2010), Zimbabwe (2010)

Race [a]		Alias	Key virulence (+) or avirulence (-) *	Identification year	Confirmed countries (year)
TTKSF+			*-Sr31, +Sr9h*	2012	South Africa (2010), Zimbabwe (2010)
TTKTT			*+Sr31,+Sr24,+SrTmp*	2015	Kenya (2014), Iraq (2019)
TTKTK			*+Sr31, +SrTmp*	2015	Kenya (2014), Egypt (2014), Eritrea (2014), Rwanda (2014), Uganda (2014)
TTHSK			*+Sr31, -Sr30*	2015	Kenya (2014)
PTKTK			*+Sr31,-Sr21, +SrTmp*	2015	Kenya (2014)
TTHST			*+Sr31, -Sr30, +Sr24*	2015	Kenya (2013)
TTKTT+			*+Sr31,+Sr24,+SrTmp, +Sr8155B1*	2019	Kenya (2019)
TTHTT			*+Sr31, -Sr30, +Sr24, +SrTmp*	2020	Kenya (2020)

Notes: [a]Some uncertainty exists over the reaction of the Sr21 gene (this influences the initial code letter being "T" (+Sr21) or "P" (-Sr21). Current table presents most plausible races.* Only key Sr genes are indicated, not the complete virulence/avirulence profile. Detailed information on these races can be found at: https://rusttracker.cimmyt.org/?page_id=22#:~:text=tritici%20with%20virulence%20to%20the,lineage%20of%20wheat%20stem%20rust .

To understand the migration and dispersal of the *Ug99*, CIMMYT and FAO have been facilitating routine surveillance and race typing through country National Agricultural Research Systems (NARES) in the major wheat-producing areas of Africa (Park *et al.*, 2011). The resulting information and knowledge on *Pgt* is essential for successful breeding of resistant cultivars (Chemayek *et al.*, 2021). As shown in Table 2, from 1999 to 2020, *Ug99* has evolved into 15 different races starting with TTKSK in Uganda into TTHTT in Kenya (Newcomb *et al.,* 2016). It has spread to 14 countries (Fig. 10) including both northwards to Yemen (2006), Egypt (2014), Iran (2007), Iraq (2019) (Nazari *et al.,* 2022) and southwards into South Africa (2000) and Zimbabwe (2009) (Pretorius *et al.,* 2012).

3. Potential impacts and management of wheat stem rust

3.1 Losses due to wheat stem rust

Globally, wheat rust is reported to cause significant yield losses especially during epidemics. Infection with stem rust affects quality (shrivelled grain) and quantity of wheat grain through reduction in grain yield, kernel size, number of grains per spikelet and kernel weight. When the pathogen strikes early in the crop season, the effects can be severe: reducing tillering, grain weight and grain quality. Yield losses of 100% have been observed especially when left uncontrolled (Leonard and Szabo, 2005; Singh *et al.*, 2011).

Stem rust also can weaken wheat stems, so plants lodge, or fall over, in heavy winds and rain. Where severe lodging occurs, crops cannot be mechanically harvested (Schumann and Leonard, 2000). The impact of rust depends on cultivar susceptibility, stage of crop during the initial attack, severity of infection, rate of disease development and duration of the disease. The yield losses vary with location, climate conditions, disease pressure and wheat production practices (Chai *et al.*, 2022). Thus, even within a country, reduction in yield data is diverse varying from year to year and location to location.

Estimates of yield and economic losses due to stem rust have been documented worldwide by several authors (Table 3). Current estimates suggest that the annual global losses caused by wheat rust pathogens amount to approximately 15 MMt, valued at a staggering US$ 2.9 billion (Huerta-Espino *et al.*, 2020; Lidwell-Durnin and Lapthorn, 2020). It is however difficult to accurately compute the yield losses especially when infections are not severe. Furthermore, reduction in yield is often confounded with abiotic challenges further complicating the segregation of rust induced losses (Marasas *et al*., 2003).

Table 3. Wheat stem rust epidemics and reported yield and economic losses.

Location	Year(s)	Losses
India	1946–1947	2 million tonnes
Canada	1953–1954	1.7, 5.5 million tonnes
United States	1953–1954	2.5, 2.1 million tonnes
Australia	1973	$ 200 – 300 million
Ethiopia	1993, 1994	65%, 100% yield reduction
Ethiopia	2013–2014	100,000 tonnes
Sicily	2016–2017	10,000+ hectares 2017

Notes: Adapted from Fetch *et al.* (2021).

Recently, using a probabilistic bio-economic assessment model, Chai *et al.* (2022) found that wheat stem rust will cause an annual average yield loss in the range of 8.7M and 11.6M metric tonnes between 2020 and 2050 at the global level. This translates to $1.5 – 2.0 billion losses per year. However, most of the available data on yield loss is derived from experimental conditions because even during an epidemic, data on yield losses or the relationship to wheat prices, output levels, or imports is not recorded (Marasas *et al.*, 2003).

Existing evidence suggests that yield losses ranging from 20–70% are not uncommon when susceptible cultivars are planted during an epidemic (Degete, 2021). In Australia, yield losses from wheat stem rust ranged from 10 to 45% (Loughman *et al.*, 2005). In South Africa, race PTKST led to an average yield loss of 21.3% in fungicide protected and unprotected trials and

47.9% loss in susceptible lines. Lower yield reductions are observed on cultivars with adult plant resistance (19.5%) and all stage resistance (6.4%) (Soko *et al.*, 2018).

In Ethiopia, stem rust led to 40.2 to 44.8% yield losses and up to 70% on susceptible cultivars (Degete, 2021). Recently, an epidemic caused by the race TKTFF in wheat growing areas in southern Ethiopia caused yield losses of 100% on the popular variety Digalu in three consecutive years: 2013, 2014 and 2015 (Beyene, 2018; David, 2016). In Kenya, grain yield reductions of up to 71% due to stem rust have been observed under experimental conditions (CIMMYT, 2005). Macharia and Wanyera (2012) found grain yield losses ranging from 6% to 66%; Madahana *et al.* (2021) observed a reduction of 14% in grain yield, 22% in kernel weight and 13% biomass while Wanyoike *et al.* (2022) recorded a 12.87% and 21.95% reduction in yield and kernel weight, respectively. Overall, these findings suggest that if wheat stem rust is not managed in time, the yield and economic losses are immense. Consequently, this development (i.e., *Ug99* outbreak) could risk wheat food security and lead to increased poverty in the region.

3.2 Management of wheat stem rust

Over the past 60 years, wheat stem rust was successfully controlled through eradication of barberry plants and deployment of host plant resistance at the global level (Singh *et al*., 2008). However, in recent years, stem rust has gained significance as new virulent pathotypes have evolved in *Pgt* populations (Pretorius *et al.*, 2000; Singh *et al.*, 2015). The emergence of *Ug99* race in Uganda in 1998, with virulence on the widely deployed *Sr* gene *Sr31* and its subsequent geographical expansion within Africa, to the Middle East, has demonstrated the vulnerability of broadly used wheat cultivars worldwide (Singh *et al.*, 2008; 2015) and hence serious threat to humanity through destruction of a main food source.

Management of cereal rust diseases is complex because of their rapid dissemination and the frequency of evolution of new genetic variants with increased virulence and aggressiveness. The genetic plasticity, constant evolution and easy dispersion of rust populations are global reasons for concern in wheat genetic improvement programs. Once established, rusts are very difficult to eradicate since they spread very fast and easily adapt to new environments, owing to their high rates of evolution and selection (Singh *et al.*, 2009; Vergara-Diaz *et al.*, 2015).

In areas where susceptible cultivars are grown, stem rust has caused havoc to wheat production leading to 100% yield loss when no control measures are applied (Wanyera *et al.*, 2010). Thus several measures are recommended either as preventative or emergency control measures including cultural, biological and chemical control, and host resistance. However, no single approach is effective. Therefore, adopting an integrated approach with host resistance as the key component is critical in wheat rust management (Abebe, 2021). In the following subsections, we highlight several approaches which could be implemented to manage wheat stem rust.

3.2.1 Cultural control

Cultural control of wheat stem rust aims at preventing crop contact with the pathogen, enhancing crop vigour, reducing the amount of inoculum available and creating environmental conditions unfavourable for infection and disease proliferation. These include removal of alternative hosts and volunteer plants (Abebe, 2021; Roelfs *et al.*, 1992; Wan *et al.*, 2007), crop rotation to break the pathogen cycle (Abebe, 2021), appropriate fertilizer regimes, use of early maturing varieties, early planting and varietal mixes (Knott, 2012), and timing, frequency and amount of irrigation (Roelfs *et al.*, 1992). Spraying wheat with carnation or ginger + cinnamon plant extracts reduce disease severity and increase grain yield and is proposed as an alternative rust management strategy (El-Gamal *et al.*, 2022).

3.2.2 Biological control

Biological control refers to the use of living organisms to suppress a pest and its effects on the host. Biological control agents (BCAs) are alternative products for the control of wheat rust. Bacterial endophytes like *Bacillus subtilis* (Li *et al.*, 2013) and *Pseudomonas putida* (Pang *et al.*, 2016) are reported to suppress urenidiospore germination and growth. El-Sharkawy *et al.* (2018) reported that a combination of arbuscular mycorrhizal fungi and *Trichoderma harzianum* spores significantly reduced the disease severity, promoted growth and yield parameters.

3.2.3 Chemical control

When susceptible cultivars are grown or when resistance fails, chemical control is the only short-term strategy to protect yields; and chemicals are used worldwide to control wheat stem rust. Many fungicides are effective against *Pgt* at different stages of crop growth (Soko *et al.*, 2018; Wanyera *et al.*, 2009; 2010). Choice of fungicide and timing of application determine the effectiveness, as crops receiving up to three ill-timed sprays have been found to suffer as much disease as untreated crops (Wanyera *et al.*, 2010; Wanyera and Wamalwa, 2022). This is especially true for stem rust where preventive application provides better protection than when disease has already occurred.

Some scholars have recommended application of fungicide at tillering and flowering growth stages (GS), which increased grain yield by 66.3%, grain weight by 41.6%, and test weight by 17.27% (Wanyera *et al.*, 2009). Different classes of fungicides with protectant and curative activity e.g., triazoles, strobilurins, carbendazim, chlorothalonil, quinone outside inhibitors (QoIs), demethylation inhibitors (DMIs) and succinate dehydrogenase inhibitors (SDHIs) exist (Cook *et al.*, 2021; Faske and Emerson, 2021). These fungicides have proved to be effective in wheat stem rust management and as a result they are widely used. SDHIs possess a single action site and are thus prone to resistance development especially with the high genetic plasticity in stem rust.

In Kenya, different active ingredients are used to control wheat stem rust (Wanyera *et al.*, 2010), some of which are listed in Table 4. Among the large-scale wheat farmers in Kenya, there is intensive fungicides usage with a calendar-based application schedule alternating between contact and systemic compounds, with some farmers applying up to 5 sprays per cycle under heavy infection (Wanyera *et al.*, 2010). Prevalence and frequency of chemical use for rust among the small-scale farmers vary from region to region. For example, Tenge *et al.* (2016) reported higher fungicide usage in Mau-Narok with 43.2%, Kabatini 38.9%, and Njoro 17.8% among respondent small-scale farmers. Small-scale farmers are reported to apply up to three fungicide sprays within a season to achieve rust control depending on the severity of disease.

Table 4. Fungicides currently used to control/reduce wheat stem rust damage in Kenya.

No	Chemical name	Common name	Rate L/ha
1	Trifloxystrobin 100 g/L+ Tebuconazole 200 g/L	Nativo 300SC	1.0
2	Prothioconazole 125 g/L + Tebuconazole 125 g/L	Prosaro 250EC	1.0
3	Epoxiconazole 250 g/L	Twiga Epox GF	1.0
4	Tebuconazole 200 g/L	Fezan 250 EW GF	1.0
5	Picoxystrobin 200 g/L + Cyproconazole 80 g/L	Acanto Plus	1.0
6	Epoxiconazole 62.5 g/L + Pyraclostrobin 62.5 g/L	Abacus SE	1.0
7	Epoxiconazole 18 g/L + Thiophanate methyl 310 g/L	Rexduo SE	1.0
8	Metconazole 27.5 g/L+ Epoxiconazole 37.5 g/L + Picoxystrobin 200 g/L+ Cyproconazole 80 g/L	Osiris EC	1.0
9	Propiconazole 62.5 g/L+ Chlorothalonil 375 g/L + Cyproconazole 50 g/L	Cherokee 487.5 SE	1.0
10	Propiconazole 250 g/L + Cyproconazole 60 g/L	Menara 410EC	0.5
11	Tebuconazole 430 g/L	Tebulis 430 SC	0.5
12	Tebuconazole 200 g/L + Azoxystrobin 200 g/L	12 Azimut SC	1.0
13	Bixafen 75 g/L + Prothioconazole 100 g/L + Tebuconazole 100 g/L	Skyway Xpro 275 EC	1.2
14	Propiconazole 150 g/L + Difeconazole 150 g/L	Atlas 300EC	1.0
15	Propiconazole 172.4 g/L + Azoxystrobin 141.1 g/L	Quilt Excel 265 SE	1.25
16	Epoxiconazole 187 g/L + Thiophanate methyl 310 g/L	Swing Xtra 497 SC	1.0
17	Monopotassium phosphate 43% + dipotassiumphosphate 19%	Fosphite Liquid	4.0
18	Azoxystrobin 80 g/L+ Chlorothalonil 400 g/L	Amizoc 480 EC	1.8
19	Bixafen 50 g/L + Tebuconazole 166 g/L	Zantara 216 EC	1.0
20	Fluxapyroxad 41.6 g/L + Epoxiconazole 41.6 g/L + Pyraclostrobin 66.60 g/L	Ceriax 149.8 EC	1.0
21	Azoxystrobin 200 g/L+ Tebuconazole 300 g/L	Stamina 500SC	0.9
22	Difenaconazole 125 g/L + Azoxystrobin 200 g/L	Token 325 SC	0.75
23	Benzovindiflupy 30 g/L + Azoxystrobin 114 g/L + Propiconazole 132 g/L	Elatus Arc 265.14 SE	1.0
24	Tebuconazole/tridimenol	Silvacur 375 EC	1.0
25	Tebuconazole	Folicur 250 EC	1.0
26	Trifloxystrobin 250 g/Kg + Tebuconazole 500 g/Kg	Shadow 750 WG SC	400g

Notes: Adapted from Wanyera and Wamalwa (2022).

3.2.4 Host resistance

Wheat improvement programs worldwide have prioritized rust resistance as a key trait in the development and dissemination of new improved varieties. For example, the Ethiopian national and regional wheat programs, in partnership with international agricultural research centres such as CIMMYT and the International Center for Agriculture Research in the Dry Areas (ICARDA), have successfully released over 100 bread wheat and more than 40 durum wheat varieties since the late 1960s. This impressive track record of variety release, which has been supported by several national and international investments, is considered an important factor behind the rapid wheat productivity gains reported in Ethiopia in recent years. In parallel, there have been extensive efforts to fast-track the release of rust resistant varieties through favourable policy measures from the Ethiopian government, plus seed promotion and dissemination efforts from different research and development partners (Hodson *et al.*, 2020; Singh *et al.*, 2015; Tadesse *et al.*, 2022).

Although host resistance is the most preferable rust management option, breeding for resistance is faced with a myriad of challenges including climate change, pathogen evolution and a narrowing genetic base. Race specific resistance conferred by the R gene is highly effective against a single pathogen race and is effective at all stages of wheat growth. Single R-gene is easily selected and introgressed into breeding materials. It is unfortunately easily overcome by the pathogen, as the case was with the widely used *Sr31, Sr24* and *Srtmp* that succumbed to *Ug99* (Bhavani *et al.*, 2019). Partial resistance also known as adult plant resistance is derived from multiple genes and is characterized by slow rusting from the additive effects of different genes. It is more durable and thus mostly preferred, for example the *Lr34, Lr46, Lr67*, *Lr68 and Sr*56 *genes* used for breeding at CIMMYT offer durable resistance (Bhavani *et al.*, 2019; Singh *et al.*, 2015). The proven approach to enhance durability of genetic resistance is better management of resistance genes and the deployment of combinations of multiple effective resistance genes (Ayliffe *et al.*, 2008).

Breeding for complex adult plant resistance that requires accumulating four to five minor, slow rusting resistance genes to achieve high levels of resistance is a difficult task. This difficulty is compounded by the absence of disease pressure caused by race *Ug99* at most breeding sites and the lack of molecular markers associated with genes contributing to resistance (Singh *et al.*, 2011). However, CIMMYT overcame this problem by introducing what they called "*Shuttle Breeding*" where materials bred in Mexico that have low stem rust pressure were screened at Njoro, Kenya, a high stem rust site. In this way, it was possible to generate and test many derivatives from the various crosses made at CIMMYT (Singh *et al.*, 2008).

When initial worldwide wheat germplasm phenotyping commenced in 2008, 90% of wheat germplasm was susceptible to stem rust which resulted in massive investment in resistance breeding. Globally, 200 resistant wheat varieties have been released in different wheat agro-ecologies (Bhavani *et al.*, 2019; 2022). In East Africa, Kenya and Ethiopia, screenings that have been conducted over the last decade have revealed increased resistance, with 10-20% resistance and 20% moderate resistance among the CIMMYT and national breeding materials (Bhavani *et al.*, 2019). Seventeen varieties with resistance to stem rust have been released in Kenya and Ethiopia (Bhavani *et al.*, 2022), a clear indication of the progress in breeding for stem rust resistance. Some of the varieties with moderate to high resistance to rusts in Kenya released for different agro-ecologies include Njoro 2, Hornbill, Deer, Kasuku, Weaverbird, Peacock, Falcon, Jacana, Impala, Tai, Eagle 10, Songbird, Kwale, Duma, Hyrax Eldo-Mavuno and Eldo- Baraka, and KS Wheat 04. In Uganda, a few *Ug99*-resistant varieties including NARO-Wheat1 (Sipi), NARO-Wheat2 (Elgon), and NARO-Wheat3 (Nyonyi) were released by the NARO through mutation breeding in 2014 (NARO, 2022).

3.2.5 Integrated disease management

A combination of *Ug99* rust management approaches mentioned above, leads to faster and more sustainable control of stem rust. Thus, the use of resistant varieties combined with timely appropriate chemical interventions can mitigate the stem rust epidemics (Badebo *et al.*, 2008; Bhavani *et al.*, 2022). It is also important to monitor and determine when the disease is developing. The latter calls for early warning systems with continuous screening of the released varieties for effectiveness of the available resistance. The use of certified seed to guarantee their freedom from rust pathogens is also important. These applications must be supported with proper information and advice dissemination particularly to the farmers.

4. Resource materials on wheat stem rust

The first announcement of *Ug99* and its likely effects were of concern to the world, and led to the convening of a conference in Nairobi, Kenya to examine the subject (CIMMYT, 2005). The resulting CIMMYT experts panel report triggered many scientific investigations. From this conference, it emerged that very little was known about *Ug99* since it had been reported. The CIMMYT expert panel report mentioned the regular occurrence of stem rust in Kenya in 1996, 1999, 2000 and 2002–2004. In addition, Singh *et al.* (2008) had observed that *Ug99* was present at several locations in Ethiopia in 2003. However, the identity of the race(s) responsible for these outbreaks had not been known as no formal race analysis had been done during that period.

Among the outstanding outcomes of the CIMMYT experts panel of 2005 was the creation and operationalization of the Borlaug Global Rust Initiative (BGRI) which was dedicated to improving genetic gain and optimizing disease resistance in wheat. At that time, the focus disease was stem rust – *Ug99*. BGRI brought together scientists from around the world who were committed to sharing knowledge, training the next generation of scientists, and engaging with farmers for a prosperous and wheat-secure world.

The BGRI was based at Cornell University with collaborations throughout the wheat growing areas worldwide. Such centres included CIMMYT and ICARDA whose activities were spread also in the East African region with centres in Ethiopia and Kenya. In Kenya for example, BGRI developed an International Wheat Screening Facility at Njoro - KALRO, which was utilized as a training ground for hot-spot screening for rust disease resistance. The materials developed elsewhere in the world were tested for resistance against *Ug99* at Njoro and information attained was shared among wheat breeders for local use. In Ethiopia, *Ug99* research was managed by EIAR.

The BGRI research activities focused on resistant genes; pathogens such as *Ug99* and workshops to share the outcomes of their work whose deliberations are available online as “Proceedings Workshop Abstracts” almost annually from 2009 to 2022. Information and knowledge arising from the BGRI and their partners as well as collaborators can be found at: www.cimmyt.org/funder_partner/borlaug-global-rust-initiative-bgri; https://rusttracker.cimmyt.org/; https://bgri.cornell.edu/; www.globalrust.org; ICARDA: http://icarda.org; CIMMYT: http://www.cimmyt.org and Aarhus University (Denmark): http://wheatrust.org. Other projects within the BGRI that have generated and disseminated information on wheat include:

1. Delivering Genetic Gain in Wheat (DGGW) for transforming how the world grows wheat for a wheat-secure world. Information on the DGGW can be found at: https://bgri.cornell.edu/delivering-genetic-gain-in-wheat.

2. Durable Rust Resistance in Wheat (DRRW) conducted in the period 2008–2016 used interdisciplinary approaches to mitigate rust threats through coordinated breeding and surveillance activities and replace susceptible varieties with durably resistant ones. Further, it assisted in delivering breeding pipelines to churn out improved varieties as well as their seed. Information on DRRW can be found at: https://bgri.cornell.edu/durable-rust-resistance-in-wheat.

The FAO also supports the management of wheat rust diseases including *Ug99* by promoting integrated disease management approaches. Emphasis is put on preventive approaches as they are the most effective and environmentally friendly means of wheat rust management. The use of resistant cultivars is known to be the most effective tool. Therefore, FAO like the other organizations especially under the BGRI, puts emphasis on breeding resistant varieties and seed multiplication with the aim of making these seeds available to farmers as quickly as possible.

Breeding varieties is however known to be a slow process and thus should be supported by other processes such as better coordination among the stakeholders and contingency planning. For instance, FAO organised a conference (6–8th November 2008) in India with the theme “Stem rust *Ug99* – A threat to food security” that brought together eminent organizations such as Indian Council of Agricultural Research (ICAR), CIMMYT, ICARDA, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australian Centre for International Agricultural Research (ACIAR), Cornell University and the Gates Foundation. The main purpose of this conference was to raise awareness on the status of *Ug99* and wheat threats and promote global knowledge sharing. It was attended by 170 participants from 33 countries among which were Ethiopia, Kenya and Uganda. The participants were expected to disseminate the messages about *Ug99* in their home countries. Detailed information of some of the FAO wheat rust and *Ug99* activities can be found at: wheatrust@fao.org; www.fao.org/agriculture/crops/wheatrust/ and IFAD: http://www.ifad.org.

IAEA is another resource on *Ug99*. The IAEA facilitated a project “Responding to the transboundary threat of wheat black stem rust (*Ug99*) INT/5/150”. The project generated genetic variation for combatting *Ug99* and thereby produced *Ug99* resistant varieties. Kenya and Uganda were participants in the project and have since released varieties based on mutation technology. Details of this project can be found at: https://www.iaea.org/sites/default/files/documents/tc/INT5150.pdf.

5. Recommendations

Given the nature of the main elements in wheat production, all factors along the wheat value chain must be looked at critically to develop and implement strategies for the improvement of the wheat industry. The issues affecting wheat production are multifaceted and addressing them requires multidisciplinary and multipronged approaches. The main actors here include government, particularly the policymakers; the agricultural service providers, mainly research and advisory services; the wheat processors; as well as other traders and farmers.

5.1 Research institutions

Although agriculture remains the backbone of most of the SSA countries, most of the research is funded through development partners. The research institutions need to lobby governments to review their priorities and expand the agricultural funding base to support research activities that facilitate breeding of high yielding *Ug99* resistant wheat varieties. The research institutions should promote incubation centers and support local innovation hubs, for example locally produced fungicide molecules to address the high cost of chemicals and other locally assembled or fabricated farm tools that are affordable to farmers.

Increasing numbers of wheat scientists as well as their skills in new approaches to meet the increasing demand for new production options is necessary. For example, technologies such as introduction and promotion of irrigated wheat would help to mitigate against unpredictable rainfall patterns as has happened in other wheat producing countries like Ethiopia, Zambia, Egypt, India, China and Mexico. Increasing access to sources of resistance and mechanisms for breeding new varieties is also critical, to match the challenges brought about by climate change that promotes for example the rapid change in the rust disease populations.

The research institutions need to be pro-active in establishment and promotion of collaborations for multiskill development and access to new knowledge. Good examples of such collaborations include working with Consultative Groups on International Agricultural Research (CGIARs) like CIMMYT and ICARDA that have led to the current advancement in containing *Ug99*. Furthermore, wheat scientists should therefore strive to maintain the surveillance programs to be able to detect new threats as well as be able to share this knowledge to feed into early warning systems in the region.

In summary, the following are key recommendations:

- Establishing robust breeding programmes to make available high yielding *Ug99* resistant wheat varieties.
- Explore avenues for and set up innovation and incubation centres for promoting appropriate technologies for the wheat industry.
- Enhance regional and international collaborations for synergies especially on surveillance, identification and utilization of information on *Ug99* movements.

5.2 Policy makers

Policy makers should develop policies that create a conducive environment to facilitate the actors along the wheat value chain to have gainful ventures. These include promotion of cooperatives for the wheat industry, provision of affordable access to farm machinery and its maintenance, improvement of access to credit especially for farm inputs, such as improved disease resistant wheat seed, and other productivity-enhancing technologies.

Other policies should touch on improvement of regulations for utilization and consumption of locally produced wheat grain, support to access market information and regional wheat trade. Further, wheat seed systems should be strengthened and streamlined, making them profitable for wheat seed production and distribution to enhance timely and easy accessibility. For example, in most SSA countries, introduction and registration of improved varieties is expensive and time consuming. Arrangements to fast track these varieties to allow farmers to reap benefits before the process of registering is completed could be put in place.

In summary, the following are key recommendations:

- Provide adequate funding for infrastructure and research on *Ug99* among others.
- Provide a conducive environment, for example through establishment and promotion of cooperatives for the wheat industry.
- Provide for or enhance access to cheap credit, farm inputs, disease resistant and high yielding wheat varieties, and accompanying appropriate agronomic technologies.
- Put in place supporting regulations for the production of wheat seed of high yielding disease resistant varieties (seed system).
- Government should put in place supporting laws governing wheat trade within the country as well as regional and global markets.

5.3 Agricultural extension and advisory support services

Extension plays a crucial role in disseminating information to farmers. There is a need to revamp this sector and build their capacity to facilitate expanding their reach to farmers.

This can be achieved by adoption of digital technology in information dissemination. The extension and advisory services should equip themselves with knowledge and information for improvement of appropriate wheat production technologies including utilization of new wheat varieties that are resistant to wheat rust and other diseases, and disease control measures (Allen-Sader *et al*., 2019). They should demonstrate technologies such as promotion of wheat climate smart technologies but above all, be pro-active in improving collaboration and linkages with research and other value chain actors. Their role in strengthening wheat based multi-stakeholder innovation platforms cannot be underestimated.

In summary, the following are key recommendations:

- Provide feasible linkages between researchers and farmers for efficient dissemination of wheat production technologies developed by researchers.
- Strengthen wheat based multi-stakeholder innovation platforms.

5.4 Farmers

Wheat producers or farmers are considered to be the primary stakeholders in the wheat value chain. Therefore, it is important that they maximize its yield through better use of information on management of *Ug99*. Wheat production in SSA and especially Eastern Africa has always been viewed as a cash crop, “rich man’s venture” based on how wheat was introduced in the region.

Recent consumption trends have however changed and this needs to align with production. Farmers need to view wheat as a food security crop and adopt production technologies even for dual purposes i.e., consumption and trading the surplus as is the case with other crops like maize. In addition, use of wheat blends have been proposed as a way of lowering demand for wheat imports. Studies on the potential of blending wheat with up to 10% pearl millet or sorghum, maize and tubers like cassava have been undertaken with promising results.

Wheat producers therefore need to improve their awareness on appropriate wheat productivity-enhancing technologies, among which are use of rust resistant wheat varieties, improved agronomic practices, and application of integrated disease management approaches. With frequent extreme weather events, adoption of climate smart agricultural techniques such as irrigation and mechanization could significantly improve yields. Collective marketing through contract farming could further maximize benefits from wheat farming.

In summary, the following are key recommendations:

- Embrace and test new technologies on wheat production.
- Adopt high yielding wheat stem rust resistant varieties and complementary agronomic technologies.

Conclusion

Prevalence of wheat stem rust poses a serious food security threat not only to the Eastern African region but also at the global level. With rapid urbanization, nutrition transition and high population growth, the regional and global demand for wheat products will continue to rise. Among the biotic factors, wheat stem rust is the most devastating wheat disease. Hence, this disease has the potential to significantly reduce wheat production, perpetuating global food insecurity, and further widen the gap between wheat supply and its demand.

To fill this gap, the objective of our evidence note has been to understand the current impacts of wheat stem rust (*Ug99*) on wheat production, current management options, and recommendations for how it could be managed in the future in East Africa, with Ethiopia, Kenya and Uganda as special focus countries. Our review suggests that management of *Ug99* requires multidisciplinary and multipronged approaches. Based on pioneering work done by both international and national research organizations, we have made several recommendations on how best *Ug99* could be managed. Among notable interventions, promoting use of cultural methods, biocontrol approaches, chemical use, breeding and promoting adoption of high yielding *Ug99* resistant varieties and complementary agronomic technologies are ideal strategies to manage *Ug99*.

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