Putting Ug99 on the map: An update on current and future monitoring*

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Abstract

Detection of stem rust race TTKSK (Ug99) from Uganda in 1998/99 highlighted not only the extremely high vulnerability of the global wheat crop to stem rust but also a lack of adequate global systems to monitor such a threat. Progress in the development and expansion of the Global Cereal Rust Monitoring System (GCRMS) is described. The current situation regarding the Ug99 lineage of races is outlined and the potential for expansion into important wheat areas is considered. The GCRMS has successfully tracked the spread and changes that are occurring within the Ug99 lineage and is now well positioned to detect and monitor future changes. The distribution of Ug99 variants possessing combined virulence to *Sr31* and *Sr24* is expanding rapidly and future spread outside of Africa is highly likely. Efficient and effective data management is now being achieved via the Wheat Rust Toolbox platform, with an expanding range of dynamic information products being delivered to end-users. Application of new technologies may increase the efficiency of the GCRMS, with mobile devices, molecular diagnostics and remote sensing all seen to have potential application in the medium to long-term. Expansion of the global capacity for race analysis is seen to be critical and integration of the Global Rust Reference Centre into the stem rust monitoring network is seen as a positive development. The current acute situation with severe epidemics of stripe rust in many countries indicates a clear need for more effective global monitoring systems and early warning for this pathogen. The existing GCRMS for stem rust is seen as a good foundation for this to occur.

Keywords

GIS, Information systems, monitoring, pathotypes, *Puccinia graminis tritici, stem rust,* Ug99

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Introduction

Detection of stem rust race TTKSK (Ug99) from Uganda in 1998/99 (Pretorius et al. 2000) highlighted not only the extremely high vulnerability of the global wheat crop to stem rust but also a lack of adequate global systems to monitor such a threat. The expert panel convened by Dr Borlaug in 2005 in response to Ug99 (CIMMYT 2005) recognized this deficiency and recommended that monitoring should be addressed as a priority. The global wheat community responded to this recommendation with a Global Cereal Rust Monitoring System (GCRMS) being developed by an international consortium within the frame work of the Borlaug Global Rust Initiative (BGRI) (Hodson et al. 2009).

Concern over races within the Ug99 lineage is justified by the well documented historical capacity for stem rust to cause severe devastation in all continents in which wheat is grown (see Dubin and Brennan 2009; Hodson 2011). The virulence profile exhibited by races in the Ug99 lineage is unique, both in terms of the range of resistance genes defeated and in the area sown globally to cultivars protected previously by these defeated genes. Combined, these factors make the Ug99 lineage unique and a clear threat to a large proportion of existing commercial wheat cultivars (Singh et al. 2008).

Rust pathogens exhibit two major characteristics that make continual monitoring an absolute requirement. Firstly, they are highly mobile trans-boundary diseases capable of rapid, long distance movements, either by wind-assisted or accidental human-mediated transmission. This mobility makes quarantine a near impossibility and implies the clear need for effective, regular monitoring at national, regional and global scales. Globalization and associated growth in air transportation has increased both the probability of human-borne transmission and the need to monitor areas geographically distant from known infected areas. Secondly, rust pathogens have an inordinate ability to change and evolve through mutation or sexual recombination (Knott 1989; Park 2007; Watson 1981). Ug99 is no exception in this regard, and is mutating and migrating rapidly. Seven variants are now recognized within the Ug99 lineage and confirmed occurrence is known in 10 countries (Singh et al. 2011; Mukoyi et al. forthcoming). Within east and southern Africa, data indicates that members of the Ug99 lineage are now the predominant stem rust pathotypes throughout the entire region.

Monitoring systems alone are obviously not the solution to prevent damaging losses from virulent rust pathotypes like Ug99. However, they are seen as an essential component in a broader, integrated mitigation and control strategy. Effective monitoring plays a vital role in the early detection of new pathotypes and in providing reliable information on disease spread. Regular surveillance in areas of continuous wheat production e.g., the highlands of East Africa and Yemen is seen to be critically important given the opportunities for pathogen persistence and change in such areas. Strong, functional linkages to breeding programs, seed systems and control mechanisms are essential if improved decisions on both preventative and reactive control are to be taken.

This paper describes the considerable progress in the development and expansion of the GCRMS. The current, actual situation regarding the Ug99 lineage is outlined with possible indicators of change highlighted. The potential for future range expansion into important wheat areas is considered. New opportunities to advance the effectiveness of global rust monitoring, resulting from advances in information technology and molecular diagnostics, are described. Current challenges to effective global monitoring of cereal rusts are discussed along with potential solutions.

Current status – An overview

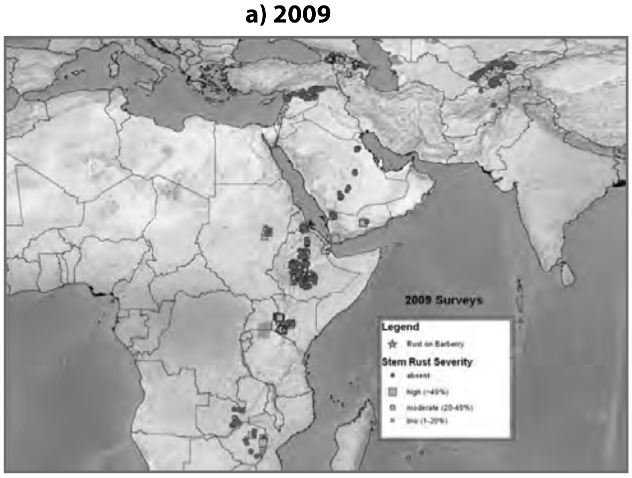
The initial concepts and early development of the GCRMS were described by Hodson et al. (2009). Regular reviews by Singh and co-authors (2006; 2008; 2011) have also provided summarized updates on the global status of the Ug99 lineage. However, since its inception, the GCRMS has undergone a series of major changes and improvements. Spatial aspects of monitoring the Ug99 lineage have been an important component, with GIS technology applied extensively. Mapping the status of Ug99, its distribution and movements – both actual and potential, has been an important communication tool of the GCRMS and this paper will describe some of the background on how Ug99 was put on the map.

The mobility of the stem rust pathogen requires monitoring to be undertaken over a vast geographical area. The trans-boundary nature of the disease requires communication and information sharing at the regional or global scale. The only means of undertaking this in effective manner is through a coordinated network of national surveillance teams collecting standardized data and contributing to a consolidated, centralized global information system. Under the auspices of the Borlaug Global Rust Initiative (BGRI), this network is now a functional reality, with a rapidly expanding number of countries now undertaking regular rust surveys and contributing with standardized data. The current geographical coverage of about 20 wheat growing countries in Africa and Asia is a substantial achievement, but further expansion is required. Ultimately, a network of 30–35 priority countries is the target for the next 2-3 years. Regular surveillance and pathogen monitoring over such an extensive geographical area will provide a solid information base to mitigate and control rust for a considerable proportion of the developing world wheat areas.

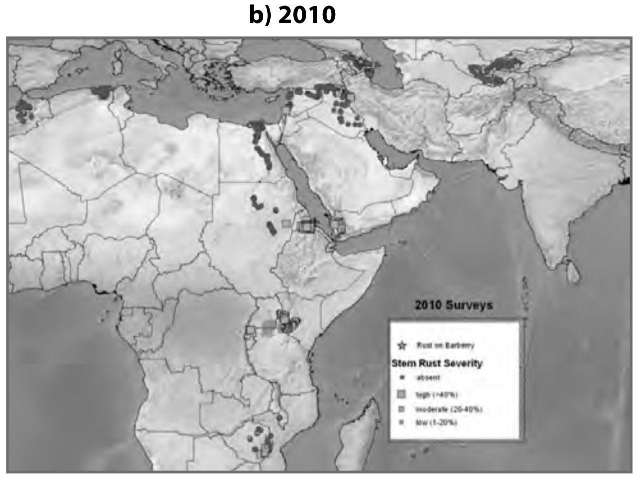
Standardized field surveys now cover most of the main wheat growing regions in the reporting countries. All data are geo-referenced using GPS, permitting survey data to be mapped accurately as soon as they have entered the centralized database and quality control has been undertaken. Consolidated datasets are starting to provide an indication of the distribution of stem rust incidence and severity in any given year on a scale that was unattainable in the past. Data showing recorded stem rust severity from 2009 and 2010 field surveys are given in Fig. 1. Obviously, field survey data provides no indication of specific races, hence these general distribution maps include all races and not only those belonging to the Ug99 lineage. The most comprehensive

Fig. 1. ***Stem rust severity from BGRI field survey data in 2009 and 2010***

a) 2009



b) 2010



monitoring of stem rust is occurring in eastern and southern Africa. Isolated occurrences of stem rust are regularly recorded in other regions e.g., Middle East, Caucasus and Central Asia. Increased surveillance efforts are obviously a contributing factor to the increased detection of stem rust, although other factors may play a role. An increasing number of countries are now recording potentially comparable multi-year survey data and with time these data will become more valuable as a monitoring tool. Current data are too limited to detect any long-term trends, but some possible indicators of change are apparent. Short-term changes may solely be artifacts of the survey approach or may reflect either changing pathogen populations and/or changing environmental conditions. More detailed examples of possible indicators of change are given in the following section.

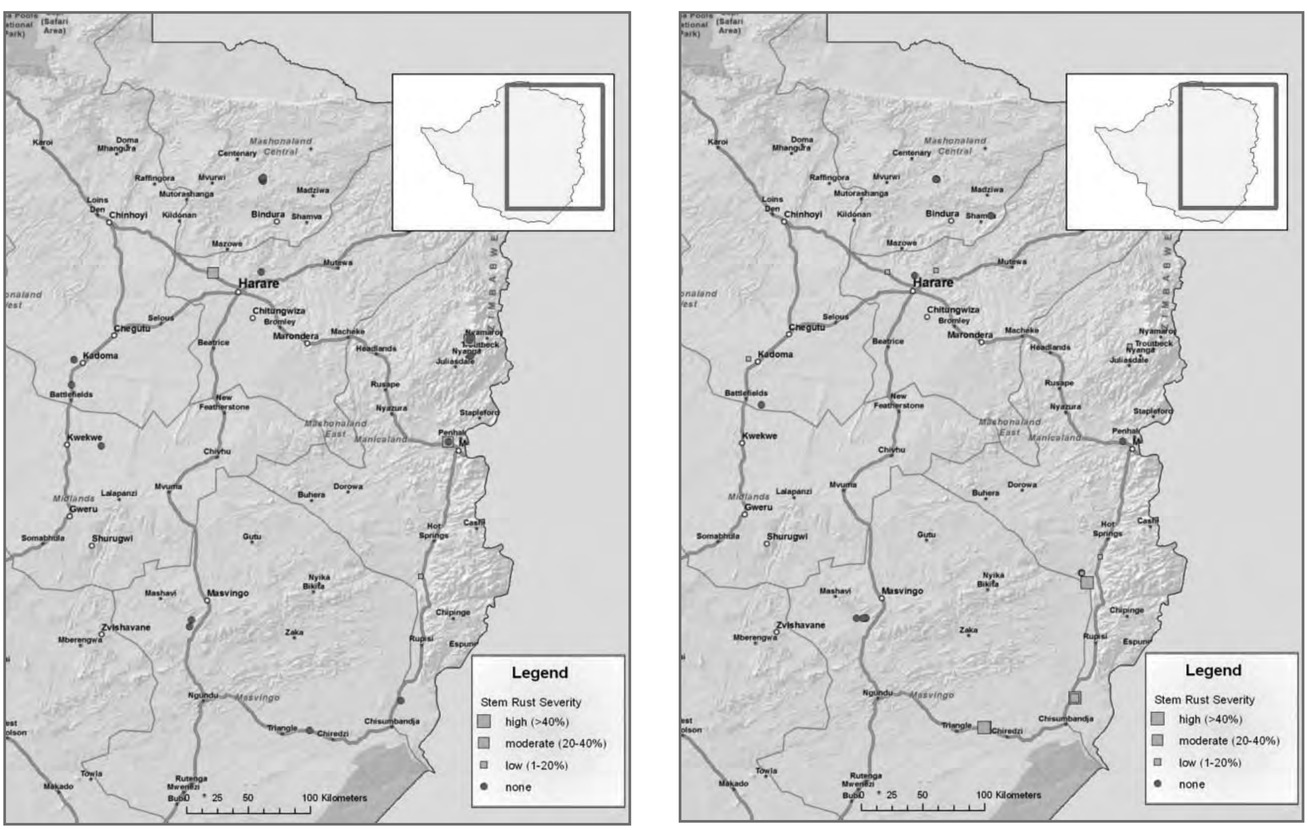
Indicators of change and emerging concerns

Use of standardized survey techniques and survey routes in consecutive years are now permitting the detection of at least indicators of potential change in terms of stem rust distribution and occurrence. Two examples of possible change are highlighted from African countries using 2009 and 2010 surveillance data. These examples also illustrate some of the difficulties in interpretation of the changes observed at the field level.

In Zimbabwe, surveys were undertaken throughout the wheat growing areas in early September 2009 (Mutari et al. 2009). A total of 21 sites were surveyed using standard BGRI methodology. Stem rust was recorded at only four sites; Gwebi Variety Testing Centre, Birchenough, Sisal Farm Mutare, and Nyanga (Fig. 2a). Very low incidence of stem rust was recorded at all sites apart from Nyanga, but high severity of infection was recorded at all sites apart from Birchenough. The latter was the only lowveld (elevation <800m) site in Zimbabwe at which stem rust was recorded in 2009. In early September 2010, repeat surveys were undertaken in Zimbabwe using an essentially identical survey route and methodology. Stem rust was recorded at 12 of the 27 sites surveyed. In contrast to 2009, stem rust was widespread in the lowveld areas with eight out of nine lowveld sites recording the disease. Very high severity of infection was observed at five of the lowveld sites in 2010 and disease incidence was also very high at three of the sites (Fig. 2b).

Fig. 2. Stem rust severity in Zimbabwe from BGRI field survey data in 2009 and 2010

a) 2009 **b) 2010**



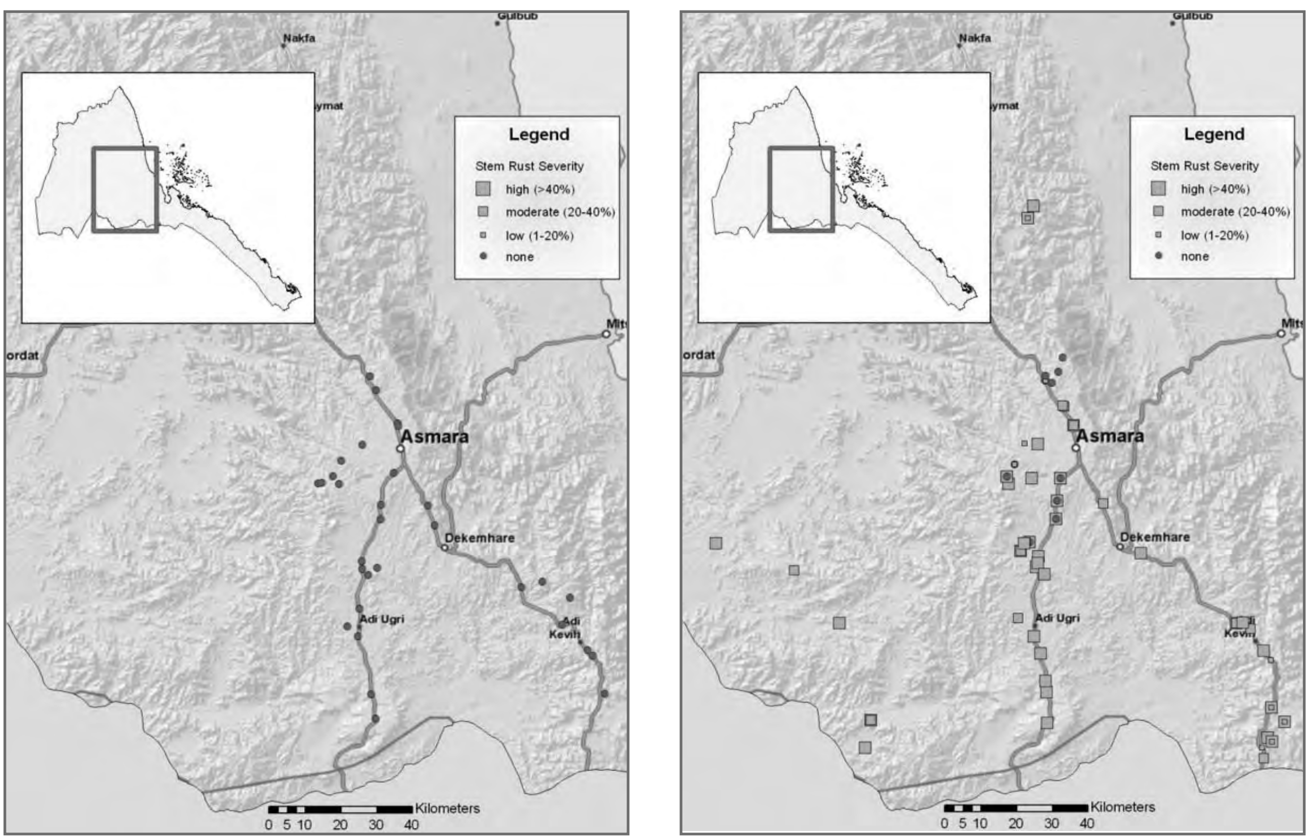
These data implied a quite dramatic change in the stem rust situation in Zimbabwe in 2010 compared to 2009. It was unlikely that this could be attributed to cultivar change, but pathogen change and/or a more conducive environment may be responsible. There is little evidence of a more conducive environment prevailing in 2010, although influences of micro-climatic factors or irrigation schedules/methods cannot be excluded. Rainfall during the preceding wet season (i.e., Nov. 2009 to March 2010) was lower than average for 1998 to 2009 (WFP 2010). It is therefore more likely that pathogen population changes have played a role in the difference in stem rust occurrence between the two years. Race analysis conducted on the 2010 samples detected the presence of the Ug99 lineage races PTKST and TTKSF (Mukoyi et al forthcoming). The presence of race PTKST, with virulence on both *Sr31* and *Sr24*, was only confirmed in 2010.

In Eritrea, an apparently analogous situation of substantial change was observed in surveys undertaken in late September 2009 and late October 2010. In 2009, no stem rust was observed in any of the 32 fields surveyed. In 2010, stem rust was recorded in 76 of the 92 fields surveyed (Fig. 3). For Eritrea, several factors may contribute to this situation. Firstly, the timing of surveys was quite different, with the 2009 surveys possibly being undertaken too early to detect stem rust reliably. Secondly, the environmental conditions were very different between years: in 2009, rainfall was below average, whereas in 2010, rainfall was above average and prolonged, resulting in excellent growing season conditions. Climatic conditions in 2010 undoubtedly favoured rust development and similar conditions in neighbouring Ethiopia were one factor behind the serious stripe rust epidemics. It is unknown at the current time if races within the Ug99 lineage were present in Eritrea in 2010, although given the close proximity of confirmed occurrence in neighbouring countries this is considered likely. Samples collected from Eritrea in 2010 are now undergoing race analysis.

The evidence available indicates that stem rust is widespread in eastern and southern Africa, and from sampling data, races within the Ug99 lineage are becoming increasingly predominant throughout the region. Obviously, several factors other than pathogen population changes are behind many of the perceived

Fig. 3. ***Stem rust severity in Eritrea from BGRI field survey data in 2009 and 2010***

a) 2009 **b) 2010**

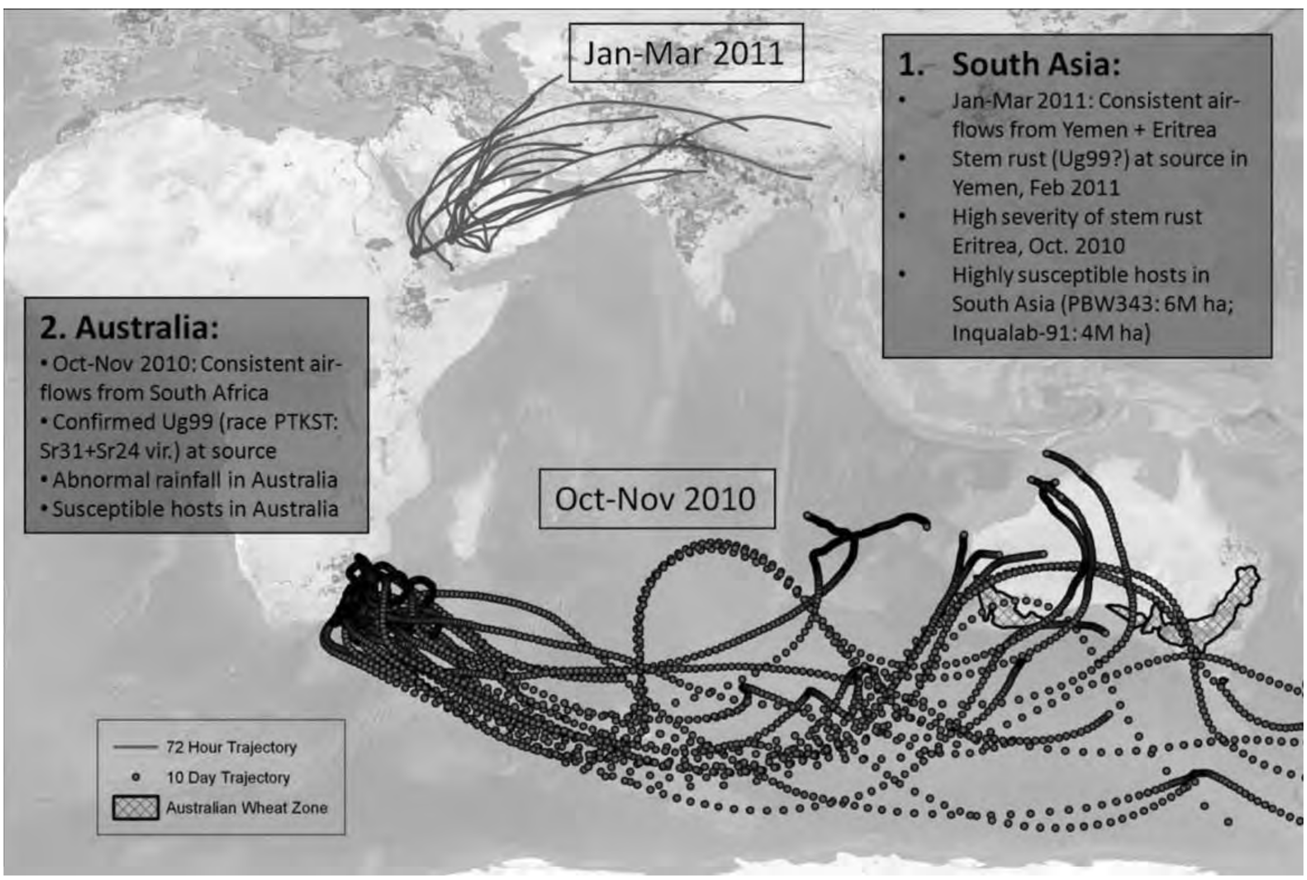


changes, with environmental factors playing a key role in all of the countries. From the very limited time-series data available, it is impossible to determine if stem rust is occurring at increased incidence compared to previous years.

Assessment of potential for movements of the Ug99 lineage beyond the known current range has also been undertaken. Prior use of the HYSPLIT wind model (Draxler and Rolph 2003) yielded valuable information regarding the likely migration of Ug99 out of Africa (Singh et al. 2006; 2008) in terms of general movement routes rather than specific time-bound events. Continued use of the HYSPLIT model is providing some insights into potential future movements. With the current known distribution of the Ug99 lineage, two potential onward movements are of concern. Potential for occurrence of these scenarios has been raised before (Singh et al. 2008; Watson and de Sousa 1982), but recent HYSPLIT model outputs and other factors give additional credence to possible occurrence at some point in the future.

Firstly, onward movement of the UG99 lineage into South Asia has been a concern since 2005 (Hodson et al. 2005). The importance of the wheat crop in this region and the known very high susceptibility of mega-cultivars like PBW343 and Inqualab-91, covering millions of hectares, are key factors. Prevailing wind patterns and historical evidence implying movements of rust pathogens from the Middle East into South Asia e.g., *Yr9*, *Yr2* (Nagarajan and Singh 1990; Singh et al. 2002; 2004) indicate the distinct possibility that rust pathogens like Ug99 may move into South Asia at some point in the future. Wind trajectories observed during the period January to March 2011 added further weight to this hypothesis. On several occasions during this period air movements were observed from known stem rust sites in both Yemen and Eritrea and reached South Asia within 72 hours (Fig. 4). Stem rust infections were confirmed in the southern highlands of Yemen during this time and although pathotypes still require confirmation there is a high probability that races within the Ug99 lineage were present. As described previously, a high incidence and severity of stem rust was observed in Eritrea in October 2010, however given the absence of any cereal crop during January–March it is unlikely that any significant amount of inoculum would have been present in Eritrea at this time. Timing of these observed wind movements coincides with the main wheat season

Fig. 4. ***Emerging concerns in 2010/11 related to the Ug99 lineage and modeled air-flow patterns***



in South Asia; hence large areas of extremely susceptible cultivars were present at this time. To date no unusual stem rust occurrence has been reported from South Asia and long distance dispersal events are always a very low probability. Several interacting factors beyond simple air movements are required for successful long-distance transport of rust spores to occur, but the existence of such wind movements coupled to known sources of inoculum at source illustrate the very real possibility for movement into this key wheat growing region.

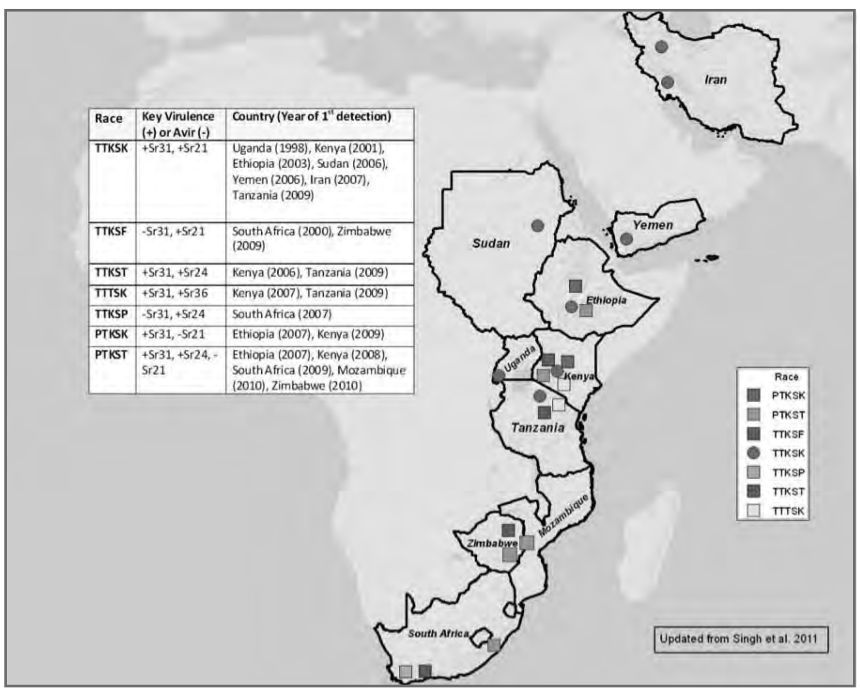
A second cause for concern is the apparent build up of Ug99 lineage races, especially those with combined virulence for *Sr31* and *Sr24* in Southern Africa. There is good historical evidence of rare foreign incursions into Australia of rust pathogens originating in this region (Luig 1977; Watson and de Sousa 1982). There is also considerable evidence of airflows moving out of southern Africa and into Australia (Sturman et al. 1997). During October to November 2010, Ug99 race PTKST (virulent to both *Sr31* and *Sr24*) was present at two sites in KwaZulu-Natal, and one site in the eastern Free State South Africa (Z. Pretorius pers. comm.). Modeled airflows from the KwaZulu-Natal source locations indicated several air movements that crossed the Australian wheat growing areas within 6–8 days of leaving South Africa (Fig. 4). Numerous rain bearing fronts were crossing southern Australia at this time and stem rust susceptible wheat cultivars were being grown in this region of Australia. While stem rust incidence increased in south eastern Australia during 2010, no unusual instances of the disease were reported and only one race was identified in that region (34-1,2,7 +Sr38, R.F. Park unpublished). However, the series of air movement events observed during Oct–Nov 2010 illustrate the potential for foreign incursions into Australia from South Africa. Such an event would be of very low probability due to the low chances of spore release at the right time, low spore survival, and limited or no successful deposition, but the historical evidence gives warning that such low probability events are possible. It is hypothesized that a similar series of events to those observed in Oct–Nov 2010 may have been responsible for the documented foreign rust incursions into Australia from southern and central Africa.

Monitoring the Ug99 lineage

Current knowledge on the Ug99 lineage has been obtained primarily from race analysis undertaken at specialist international rust laboratories. Rust laboratories in Canada, South Africa and USA have provided most of the information to date, but the expectation is that in-country laboratories will increasingly undertake routine monitoring activities. Establishment of the Global Rust Reference Centre (GRRC) in Denmark, initially for stripe rust (Hovmøller et al. 2009), and with subsequent expansion in 2011 to include stem rust analysis on foreign isolates, is expected to provide a valuable additional new resource in the international network of benchmark rust analysis laboratories.

Since regular international monitoring of Ug99 started in 2005, over 400 samples have been analyzed and race identity confirmed. Several important variations in the virulence / avirulence profile of the Ug99 lineage have been detected since monitoring started. Currently, seven variants are recognized in the Ug99 lineage (Singh et al. 2011). Notable is the acquisition of virulence to additional important resistant genes i.e., *Sr24* and *Sr36* (Jin et al. 2008; 2009). Park et al. (2011) outline a putative evolutionary pathway for the known races in the Ug99 lineage, with single step mutations considered to be the primary source of variation.

Fig. 5. ***Overview of the current known status for the Ug99 lineage of races (Nomenclature using the North American system based on 5 differential sets (Jin et al. 2008)***



Race	Key Virulence (+) or Avir (-)	Country (Year of 1st detection)
TTKSK	+Sr31, +Sr21	Uganda (1998), Kenya (2001), Ethiopia (2003), Sudan (2006), Yemen (2006), Iran (2007), Tanzania (2009)
TTKSF	-Sr31, +Sr21	South Africa (2000), Zimbabwe (2009)
TTKST	+Sr31, +Sr24	Kenya (2006), Tanzania (2009)
TTTSK	+Sr31, +Sr36	Kenya (2007), Tanzania (2009)
TTKSP	-Sr31, +Sr24	South Africa (2007)
PTKSK	+Sr31, -Sr21	Ethiopia (2007), Kenya (2009)
PTKST	+Sr31, +Sr24, -Sr21	Ethiopia (2007), Kenya (2008), South Africa (2009), Mozambique (2010), Zimbabwe (2010)

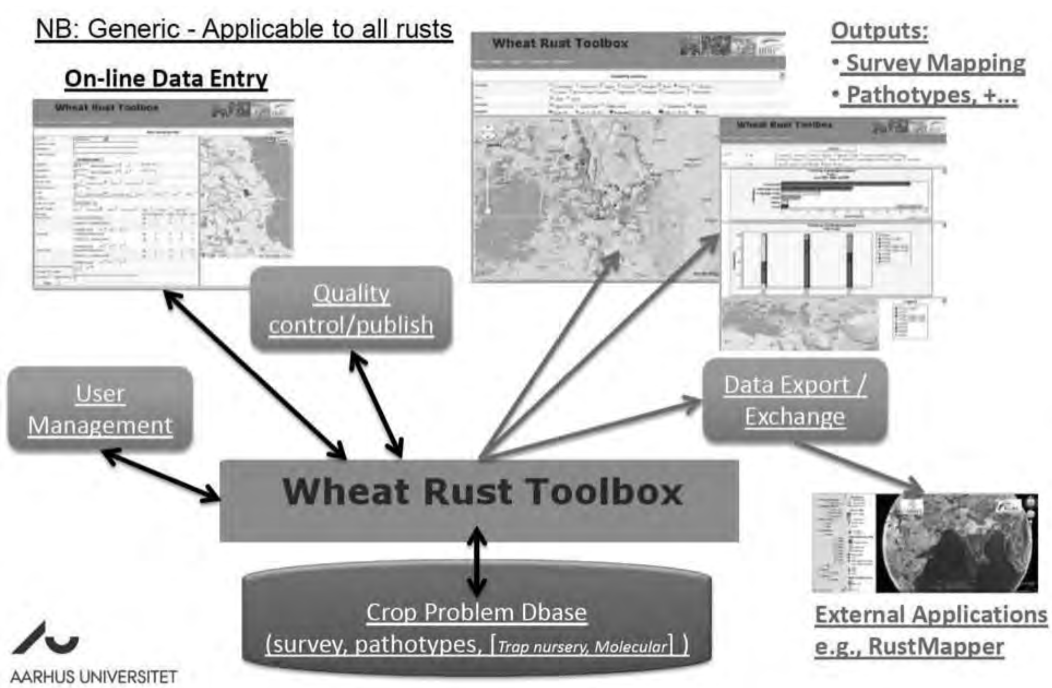
Race variants in the Ug99 lineage have been successfully detected and tracked (Park et al. 2011), and the number of countries in which these races have now been confirmed is increasing. New information from southern Africa (Mukoyi et al. forthcoming) takes the number of confirmed countries with races within the Ug99 lineage to 10 (Uganda, Kenya, Ethiopia, Sudan, Yemen, Iran, South Africa, Tanzania, Zimbabwe, Mozambique). To date, only the original Ug99 variant - race TTKSK – has been confirmed outside of Africa. However, future spread of additional Ug99 variants out of Africa is considered highly likely. An overview of the current status of the Ug99 lineage races is summarized in Fig. 5

Monitoring data indicates that members of the Ug99 lineage with combined virulence to *Sr31* and *Sr24* (i.e., races TTKST or PTKST) are spreading rapidly. These races now predominate in Kenya and are increasing in frequency in other countries. Throughout east and southern Africa, the results obtained indicate that races within the Ug99 lineage now predominate in the region.

Data management and dissemination

With the ever increasing amounts of data now being received by the GCRMS, effective data management is a critical issue Collaboration with Aarhus University, Denmark has permitted the development of an innovative data management platform – The Wheat Rust Toolbox –based on existing tools and experiences from information systems on potato late blight (Hansen et al. 2007) and IPM in wheat (Jørgensen et al. 2010). The Wheat Rust Toolbox is a web-based data management system that controls both inputs and outputs from a centralized database, which is currently populated with survey and race data. In the near future, expansion of this system is planned to include trap nursery data and molecular diagnostic probe data. On-line data entry permits quality controlled and standardized data to be entered into the database by any authorized national rust surveillance team. Once validated and approved, data is published and automatically disseminated via a series of graphical and mapping tools. An overview of the Wheat Rust Toolbox is provided in Fig. 6. This new data management system greatly improves the efficiency of managing and distributing cereal rust information. The Wheat Rust Toolbox also permits standardized data exchange with other applications; for example, the RustMapper tool managed and developed at CIMMYT. A dedicated web portal - Rust SPORE (http://www.fao.org/agriculture/crops/rust/stem/rust-report/en/) provides the primary dissemination mechanism for all of the information available, with several Wheat Rust Toolbox or external visualization and query tools embedded within the web portal. This distributed mode of operation provides a very rich and diverse set of information in a seamless way to end users.

Fig. 6. ***An overview of the Wheat Rust Toolbox data management system***



Current challenges and future activities

Considerable progress has been made in the implementation of an operational monitoring and surveillance system for stem rust in response to identification of Ug99. Knowledge regarding race distribution and diversity has increased, along with a much clearer picture on the occurrence of stem rust on an annual basis over a wide geographical region. However, several areas exist in which substantial improvements could be made. Emerging technology options and increasing technical capacity offer some interesting opportunities to overcome existing challenges and bottle-necks.

Advances in mobile phone technology present several opportunities to increase the efficiency of field data collection and transmission. Smart phones now permit field data entry via standard forms, plus GPS location data and photos can be collected and transmitted to a central database. Aanensen et al. (2009) describe such a system, Epicollect, based on the open-source android operating system. The Epicollect system is generic and could easily be adapted to the collection of wheat rust data. Current cost of android smart phones makes large-scale deployment of such a system quite costly, but with phone costs decreasing equipping core surveillance teams in several countries could be feasible. Quality controlled data collection at source, coupled to automatic transmission into centralized databases, would offer many advantages with considerable efficiency gains in terms of the timeliness and ease of data transmission. Disadvantages might include; limited robustness in the field, poor screen visibility or battery life, limited ease of use and user acceptance. Extensive field testing would be a critical requirement before any large-scale deployment. However, in the future field data collection through smart phones, or equivalent mobile devices, could provide a useful alternative to the existing systems of field data collection.

Another area in which mobile phone technology may play a role in monitoring and surveillance systems is via crowd sourcing techniques i.e., capturing disease information from a large number of respondents in a rapid way. Mobile phone SMS networks targeted towards farmers, extension workers and the general public could provide one mechanism for wide coverage disease reporting. For any system to be successful it would need carefully planned and widespread publicity targeted at interested user groups and also clear incentives for people to report presence of the disease. Systems that have demonstrated success usually rely on valuable information being returned to any participating users, usually in local languages. In the case of rust diseases, expert information on control measures, sources of resistant seed or rapid targeted control measures by government agencies might be options to be considered as part of any incentive system. Follow up by formal surveillance teams is likely to be necessary to confirm reported disease outbreaks.

Race analysis is another area in which improvements are required. Currently, considerable time delays can exist between a field sample being collected and final race identification. Global capacity to undertake high quality race analysis is also limited. Established rust laboratories in Australia, Canada, South Africa and the USA have done an outstanding job and provided most of the current information relating to races in the Ug99 lineage. All these laboratories face strict restrictions on receiving and working with foreign rust isolates, with good reason as accidental transfer of dangerous isolates must be avoided at all costs. For the North American laboratories, foreign isolates can only be received and analyzed during the northern hemisphere winter months, when cold and absence of hosts provide further containment. This restricted time period for analysis does however limit the possibility to analyze samples collected in countries with wheat crops that mature in the period March–September. In-country analysis of stem rust samples is an obvious and desirable solution to avoid movement of isolates, but capacity (human resources and infrastructure) remains limited. Some progress, resulting from investments in both human capacity and physical infrastructure from international and national donor sources, is now beginning. Advances in race analysis capacity are now being seen in some priority countries within Africa and Asia. Establishment of the GRRC in Denmark started as a collaborative effort between Aarhus University and two CGIAR centers (CIMMYT and ICARDA) is another very positive development. Initially focused on stripe rust, the GRRC has now been expanded with improved bio-safety facilities to incorporate analysis of foreign stem rust isolates. This facility in collaboration with the other advanced rust laboratories will permit year-round analysis of priority stem rust samples. Expansion of the capacity of the international network of rust laboratories in this manner is seen as a very beneficial development.

Rust trap nurseries are a valuable tool for the early detection of changes in rust populations and in the status of key resistance genes. The concept of trap nurseries is extremely simple, but appropriate application is often lacking. In the worst case, poorly managed trap nurseries can be extremely misleading and a source of inaccurate data. Purity of seed stocks is vital, but has long been problematic. However, extensive seed purification undertaken by the Cereals Research Centre, AAFC, Canada and subsequent field multiplication measures undertaken by ICARDA have overcome concerns in this area. Timely reporting of trap nursery data is another critical issue, with current data reporting rates extremely low (K. Nazari pers. comm.). Planned expansion of the Wheat Rust Toolbox data management system to include trap nursery data may facilitate easier data entry and faster, more effective dissemination of trap nursery information.

Advances in molecular biology, notably molecular diagnostics, look set to have a major impact on stem rust analysis and monitoring. Considerable progress has been made in the development of diagnostic DNA probes based on single nucleotide polymorphism (SNP) markers (Crouch et al. 2010). Identification of specific stem rust races is not possible with current methods, however a panel set of probes shows considerable promise in ability to identify the general Ug99 lineage race group using a simple and rapid real-time PCR assay. Further testing of this rapid (48 hour) molecular diagnostic assay is on-going, but if proved to be reliable, it offers the possibility for fast, in-season diagnosis of Ug99 lineage group members. The other major advantage of this approach is that it may reduce the need to transport live stem rust isolates around the world. However, it must be noted that molecular diagnostic assays cannot replace traditional bioassays on live isolates, the latter being the only option to identify specific races and virulence profiles. Another unforeseen minor problem with the DNA sampling approach is the restrictions on sending flammable solvents e.g., ethanol via international couriers. However, there is little doubt that molecular diagnostics look set to play an increasingly important role in the future for the rapid detection of important pathotype groups like Ug99. Work is being initiated in order to expand the capacity of the Wheat Rust Tool box to manage molecular diagnostic probe data.

The integration of diverse datasets into the centralized Wheat Rust Toolbox platform will permit a more comprehensive assessment of emerging disease situations using harmonized and quality-controlled data. Increasing use of web-based platforms will improve timeliness of data upload, data consolidation and information dissemination. Ultimately, improved decisions regarding disease control and mitigation should be possible based on accurate and timely, integrated information.

Remote sensing technologies may have a future role in the assessment of disease spread or damage evaluation under a major epidemic. As far back as 1980's, Najaragan et al. (1984) reported the use of Landsat imagery to detect wheat crops damaged by leaf rust epidemics in Pakistan. With the serious stripe rust epidemic in Syria and neighbouring countries in 2010, disease damage was clearly visible in high resolution Quickbird imagery and a putative damage signal from premature senescence was reported (USDA, 2010). However, at present there seems to be no good example of an operational remote sensing rust monitoring or damage assessment system operating routinely over large geographical scales. Limitations might include reliable differentiation of a stress signal attributable to a specific disease, spatial resolution of detection and feasibility of routine operation over large geographical areas. However, with the rapid advances occurring in remote sensing technology future routine operational assessments may be realistic.

The acute and widespread epidemics of stripe rust that are occurring throughout the CWANA region highlight the need to have more coordinated global monitoring systems for stripe rust as well as stem rust. Existing monitoring systems now in place for stem rust provide an excellent foundation for expansion to include stripe rust. The surveillance networks, data collection, data management and information systems used for stem rust are readily applicable to stripe rust. However, several challenges will need to be addressed for an effective global stripe rust monitoring system to be implemented. Early infections mean that adjustments will be needed in survey planning, with multiple survey visits optimal. The widespread nature of the disease and multiple races causing losses add complexity to monitoring efforts. High inoculum levels increase the likelihood of accidental human-borne movements, which are beyond the scope of any model-based prediction system. Climatic and environmental factors appear to play a very major role in driving current outbreaks, so increased attention may be required on climate-based early warning systems. Systems that permit much more rapid detection linked to mechanisms that allow subsequent targeted control are likely to be required. Despite the challenges, implementation of a global monitoring system for stripe rust is seen as a high priority.

Conclusions

Through an extensive global surveillance network, routine monitoring of stem rust across a vast geographical area is now becoming a reality. The identification of Ug99 provided the impetus to put such a system in place and remains the clear focus. However, the true value of robust monitoring systems is their ability to detect any new significant change as it occurs. The current global cereal rust monitoring system has successfully tracked the spread and variation that are occurring within the Ug99 lineage and is well positioned to detect and monitor any future significant pathotype changes that might arise. Future geographical expansion of the Ug99 lineage races is a near certainty. Variants possessing combined virulence to *Sr31* and *Sr24* are exhibiting rapid range expansion and future spread outside of Africa is highly likely. Efficient and effective data management is now being achieved via the innovative Wheat Rust Toolbox platform, with an expanding range of dynamic information products being delivered to end-users. Application of new technologies may increase the efficiency of the GCRMS, with mobile devices, molecular diagnostics and remote sensing all seen to have potential application in the medium to long-term. Expansion of the global capacity for high quality race analysis is seen to be critical and expansion of the international stem rust pathogen monitoring network via the GRRC is seen as a very positive development. The current acute situation with stripe rust in many countries indicates the clear need to more effective global monitoring systems for this pathogen. The existing systems in place for stem rust can provide a good foundation for this to occur.

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