# 6 Use of GIS Applications to Combat the Threat of Emerging Virulent Wheat Stem Rust Races

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## 6.1 EXECUTIVE SUMMARY

Historically, wheat stem rust (*Puccinia graminis* f.sp. *tritici*) was the most feared pathogen affecting wheat cultivation. For over 30 years, effective genetic resistance has kept the disease under control. The identification of new virulent races, typified by the Ug99 lineage, in East Africa during the late 1990s has made wheat stem rust once again a cause for global concern. The nature of the threat posed by new virulent races of wheat stem rust is outlined in this chapter. Using the Ug99 lineage of stem rust races as an example, the ways in which GIS/geospatial technologies are being applied to support the global efforts to combat this reemerging threat are described. GIS is playing a vital role because most of the critical factors involved with occurrence, movements, and establishment of the disease are inherently spatial in nature. International collaborative efforts are now underway to develop a global cereal rust monitoring and surveillance system, which is underpinned by GIS. Progress and challenges surrounding these international efforts are also described.

## 6.2 INTRODUCTION

Wheat is one of the world's principal food crops, ranking second only to rice in terms of global consumption. Globally, wheat is grown on over 200 million hectares from the equator to latitudes of 60°N–44°S and elevations ranging from sea level to over 3000 m.[1] Total global production amounts to approximately 600 million tons, with developing countries accounting for nearly half of this total. Wheat accounts for a significant proportion of total calorie intake in several countries, notably in North Africa/Mediterranean, Middle East, and parts of Central Asia where annual per capita consumption rates can reach over 200 kg.[2] Given the importance of wheat, control of economically damaging wheat diseases, such as rusts, has long been the focus of intense study.

Stem (or black) rust (*P. graminis* f.sp. *tritici*) is one of three fungal rust diseases that can inflict serious economic damage on wheat production. In recent years, the other rust pathogens of wheat, namely, leaf (or brown) rust (*P. triticina*) and stripe (or yellow) rust (*P. striiformis*), have caused more damage and, as a result, most of the research and breeding efforts worldwide have focused on these diseases. However, historically, stem rust has been the most feared disease of wheat, capable of causing periodic severe devastation across all continents and in most areas where wheat is grown. There is a solid foundation behind this fear as an apparently healthy crop only 3 weeks away from harvest could be reduced to nothing more than a tangle of black stems and shriveled grain by harvest. Under suitable conditions, yield losses of 70% or more are possible. Starting in the early 1900s, Midwestern States in the United States participated in the Barberry (*Berberis vulgaris*) Eradication Program to control common barberry, an important alternate host of *P. graminis*,[3] which helped mitigate rust spread. However, in the mid-1950s, over 40% of the North American spring wheat crop was lost to devastating stem rust epidemics.[4] These devastating losses were the result of the emergence of a new stem rust race named 15b, which overcame the genetic resistance in widely grown wheat cultivars at the time. The lack of epidemics in recent years, largely due to effective and durable genetic resistance and continued control of alternate hosts, has seen a shift away from stem rust research in terms of priority setting and resource allocation. This shift has been to such an extent that stem rust resistance does not feature in many breeding programs, and many wheat scientists have not even seen stem rust in the field.

As a consequence of the devastating stem rust epidemics in North America during the 1940s and 1950s, Nobel laureate Dr. N.E. Borlaug initiated his wheat improvement program in Mexico, with the development of stem rust resistant varieties being a primary goal. The resulting semidwarf wheat varieties that he developed, which underpinned the "Green Revolution" in the 1960s/1970s and subsequently became adopted on millions of hectares worldwide also had very effective resistance to stem rust. The widespread use of these resistant varieties was one of the principal factors that contributed to reduced stem rust inoculum levels worldwide.

Since the epidemics of the 1950s, the widespread use of resistant wheat cultivars worldwide has reduced the threat of stem rust to the extent that it is not a significant factor in wheat production losses. By the mid-1990s, stem rust was largely considered to be a disease under control.[5] However, with the emergence of a new virulent stem rust race lineage, popularly named Ug99, in the wheat fields of Uganda during 1998,[6] that perspective has now changed. As a result, stem rust is now very firmly back on the agenda of wheat scientists worldwide.

## 6.3 SIGNIFICANCE OF THE Ug99 LINEAGE (WHAT IS SPECIAL ABOUT Ug99?)

In order to understand the significance and threat posed by the new stem rust lineage, commonly termed Ug99, it is useful to consider some of the basic biology, epidemiology, and resistance mechanisms associated with wheat stem rust.

### 6.3.1 Basic Biology of Ug99

Stem rust, like all the wheat rusts, is a biotroph and needs a live primary host—principally wheat, barley, triticale, and related species—in the absence of alternative hosts for survival. The life cycle of the pathogen is complex as it is heteroecious, incorporating an asexual cycle entirely on primary hosts plus a sexual cycle that requires an alternate host (see http://www.ars.usda.gov/SP2UserFiles/ad_hoc/36400500Cerealrusts/PgLifecycle.jpg for a detailed life cycle). The main alternate host for stem rust is common barberry (Berberis vulgaris). The importance of the alternate host relates to its potential to act as an early-season inoculum source and/or a source for new combinations of genes and virulence. As a result, major eradication programs of barberry have been undertaken, for example, in North America.[3,7] These eradications have largely eliminated or reduced the importance of the alternate host as a source of inoculum although it should be noted that barberry remains common in parts of the Middle East and Central Asia. In most parts of the world, the life cycle of stem rust consists entirely of the continual asexual production of uredinal generations and reinfection solely on primary hosts.

Stem rust favors humid conditions and thrives in warmer temperatures (optimal range 15°C–35°C) compared to other wheat rusts.[5] Stem rust is an airborne pathogen, so disease spread occurs when spores are carried on the wind to new wheat plants in close proximity or in distant fields. An enormous number of urediniospores are produced by the pathogen as documented by one of the pioneers of rust research, E.C. Stakman, in 1957—“on an acre of moderately rusted wheat there are about 50 thousand billion urediniospores, each one capable of surviving a long air journey and starting an infection many miles from the place where it was produced.”[8]

An enabling factor in this dispersion is the robust nature of rust spores ensuring protection against environmental damage and permitting them to remain viable for journeys of hundreds or even thousands of kilometers. Singh et al.[9] outlined in some detail the main dispersal mechanisms by which stem rust can spread, so only a brief summary is given in the following section.

### 6.3.2 DISPERSAL

Under normal conditions, the vast majority of rust spores will be deposited close to the source[10]; however, medium- to long-distance dispersal is well documented, and this generally occurs in one of three ways:

1. *Single event, extremely long-distance (up to several 1000 km) movements.* Movements of this type are rare, but several documented examples exist (see review by Brown and Hovmøller[11]) including at least one, and possibly up to three, wheat stem rust windborne introductions into Australia from southern/eastern Africa in the last 50 years. It is also important to note that rust spores can also travel long distances by assisted means—either on travelers clothing or on infected plant material. Despite strict phytosanitary regulations, increasing globalization and international air travel both increase the risk of pathogen spread. As an example, a race of wheat stripe rust was accidently transferred from Europe to Australia in 1979, almost certainly on travelers’ clothing.[12]
2. *Stepwise range expansion.* This is more common than the previous dispersal mechanism and typically occurs over shorter distances, within country or region. Apart from very local movements, this probably represents the normal mode of dispersal for rust pathogens. A good example of this type of dispersal mechanism might include the stepwise spread of a *Yr9*-virulent race of stripe rust *P. striiformis* from Eastern Africa to South Asia over about 10 years in the 1990s and caused severe epidemics in its path.[13]
3. *Extinction and recolonization.* This occurs in areas that have unsuitable conditions for year-round survival of rusts, for example, in temperate areas with inhospitable winter conditions or seasonal absence of host plants. In North America, rust pathogens overwinter in the southern United States or Mexico and recolonize wheat areas further north following the prevailing south–north winds as the wheat crop matures. This seasonal flux has been termed the “*Puccinia* pathways”—a concept that arose from the pioneering work of Stakman and Harrar,[14] and a similar mechanism is now

being observed following the arrival of Asian soybean rust into the United States.[15] In China, a similar pattern has been observed for stripe rust. In the northern winter-wheat-growing areas of Shaanxi, Shanxi, Henan, Hebei, and Shangdong provinces, severe climate and absence of host plants preclude any pathogen survival during the winter months. However, further south in southern Gansu and northern Sichuan provinces, suitable conditions exist for year-round pathogen survival. These southern provinces then act as sources for recolonization movements into the main winter-wheat growing areas as the wheat crop develops in the summer/autumn.[11]

### 6.3.3 RESISTANCE MECHANISMS AND VIRULENCE OF Ug99

Although fungicides may provide effective short-term control of stem rust, genetic resistance offers by far the most effective, affordable, and sustainable long-term control of the disease. Due to the devastating potential for crop damage, resistance to stem rust has been the subject of intense study for nearly a century. Currently, almost 50 stem rust resistance (*Sr*) genes have been cataloged[16] with several of these genes originating from close relatives of wheat. Alien introgressions from close relatives have made significant contributions to the control of stem rust worldwide over the last 50 years.

Of particular significance in combating stem rust has been the contribution of the *Sr2* gene and this gene in combination with other unknown minor genes, collectively termed the "*Sr2* Complex." The *Sr2* gene alone confers slow rusting resistance that is inadequate under heavy disease pressure, but effective when combined with the other minor genes in the complex. This *Sr2* complex was the primary basis behind resistance seen in the semidwarf Green Revolution wheat varieties developed by Dr. Borlaug that were subsequently adopted on millions of hectares in the 1960s/1970s.[17] This widespread adoption of semidwarf stem rust resistant varieties was one key factor in reducing the incidence of the disease worldwide. The early maturity of these varieties, hence avoiding the buildup of stem rust inoculum levels, was another important contributing factor.

As previously mentioned, another highly significant factor in the reduction of stem rust was the successful transfer of a series of alien genes into wheat from related species. Notably, these genes included *Sr24*, *Sr36* (from *Thinopyrum ponticum*), *Sr31* (from rye, *Serole cereale*), *Sr36* (from *T. timopheevi*), and *Sr38* (from *T. ventricosum*). Incorporation of these resistance genes by many breeding programs into many popular wheat cultivars worldwide during the 1970s and 1980s further reduced stem rust survival and populations. So successful were these global wheat improvement efforts that by the 1990s, stem rust had ceased to be a disease having any real significant negative impact on wheat production.[18] Despite the large-scale global deployment of the *Sr31* gene, used in most wheat improvement efforts with the exception of Australian wheat breeding, resistance remained unbroken until Ug99 was detected in Uganda in 1998.

Ug99 is the only known race of stem rust that has virulence for *Sr31*, a unique characteristic that facilitated its original identification. However, in addition, it also shows virulence to most of the stem rust resistance genes originating from wheat, plus virulence to gene *Sr38*, also of alien origin. This unique combination of virulence to both known and unknown resistance genes in wheat is what makes Ug99 special and why it is considered a potential major threat to global wheat production. Results from Kenya, now, show that the pathogen is continuing to change, resulting in variants that exhibit differing virulence, and render further *Sr* genes ineffective. Two additional new variants of Ug99 are now recognized from Kenya, all very closely related and thought to have arisen through single-step mutations.[19] These new variants have rendered additional important stem rust resistance genes ineffective, namely *Sr24* and *Sr36*. These new variants of Ug99 are not adequately differentiated by the existing standard North American nomenclature system for stem rust and hence have prompted a revision in scientific nomenclature. This has been achieved through the introduction of an additional set of wheat differentials specifically screening for the *Sr* genes of interest. The original "race Ug99," found in Uganda, was initially designated as TTKS using the standard North American system[20]; however, under the new expanded nomenclature system, the three recognized individual races within the Ug99 lineage are now termed: TTKSK (original "Ug99" formerly known as TTKS, i.e., virulent to *Sr31*), TTKST ("*Sr24* variant," i.e., virulent to *Sr31* and *Sr24*), and TTTSK ("*Sr36* variant," i.e., virulent to *Sr31* and *Sr36*).[19]

These new variants in the Ug99 lineage represent an increased level of threat to global wheat varieties. The *Sr24* gene was a valuable source of resistance worldwide, effective against most races of stem rust. This gene is present in many cultivars in South America, Australia, the United States, and CIMMYT germplasm. The *Sr24* variant of Ug99 (TTKST) was only detected in Kenya in 2006 and at low frequency,[21] but, by 2007, it had increased to such levels that major stem rust epidemics were observed on the popular Kenyan variety "Mwamba" covering approximately 30% of the Kenyan wheat area. At the time of writing, both the *Sr24* and *Sr36* variants of Ug99 have not been recorded outside of Kenya, but migration to other areas, as has been observed for the original TTKSK race, is considered to be virtually inevitable. The appearance of the *Sr24* variant of Ug99 is considered particularly significant as the additional breakdown of this *Sr* gene now halves the estimated number of current varieties previously considered resistant to Ug99.

The information above provides a clear indication of the dangers and consequences of reliance on single race-specific genes to control stem rust, especially in areas where the disease is endemic. Consequently, major breeding efforts (e.g., at CIMMYT and ICARDA) are focusing on durable resistance resulting from the combination of diverse sources of resistance and the accumulation of complex resistance from the combination of four to five minor resistance genes. Such approaches are already bearing fruit, and several high-yielding wheat lines having potential durable resistance to Ug99 have now been identified.[18] However, there is an inevitable time lag before any such promising new elite material emerging from breeding programs gets released and then adopted by farmers on significant scales. That leaves a major immediate unanswered question—just how much of the current global wheat acreage in farmer's fields is susceptible to Ug99?

Extensive screening of tens of thousands of wheat varieties from all over the world has been undertaken at key sites in Kenya and Ethiopia since 2005.

Singh et al.[9] and Jin and Singh[22] have provided summaries of this information, all of which highlight a very low frequency of resistant materials in wheat varieties originating from 22 countries. Initial estimates from Reynolds and Borlaug[23] considered that approximately 50 million ha (about 25% of the world wheat area) was susceptible and at risk from Ug99. Changes in the pathogen virulence, notably the breakdown of the *Sr24* gene, and increased information from screening trials have caused an upward revision of these estimates. It is now considered likely that approximately 80% or more of the current global wheat varieties are susceptible to stem rust.

Concerns surrounding the emergence of the Ug99 lineage of stem rust should now be apparent. This is a highly mobile pathogen, capable of devastating losses if conditions are suitable, and one that has overcome the genetic resistance possessed by a large proportion of the world's wheat cultivars.

## 6.4 GIS APPLICATIONS AND Ug99

The emergence of the Ug99 lineage of stem rust in East Africa has prompted a global and concerted effort by wheat scientists to try and mitigate the threat posed. Nobel laureate Dr. N.E. Borlaug was at the forefront of efforts to raise the alarm surrounding the potential threat of Ug99, convening an expert panel that published an assessment report in 2005.[24] Following on from the 2005 expert panel assessment, an international global consortium termed the Borlaug Global Rust Initiative (BGRI) (http://www.globalrust.org/) has been formed bringing together institutions interested in the mitigation of wheat rust diseases.

In the 2005 expert assessment, one of the key recommendations of the panel was that GIS could play an important role in global efforts to combat the reemerging threat of wheat stem rust. A direct quotation from the 2005 expert panel report states:

> **Recommendation #1**. Because the stem rust pathogen is airborne and genetically variable, the Panel **recommends** (1) population monitoring by means of trap nurseries and limited sampling for race analysis for the Kenya—Ethiopia region, adjacent areas, and beyond; (2) the establishment of a warning system based on the above data and modeling, using GIS and other appropriate tools.

This recommendation recognized the fact that many of the factors surrounding the threat posed by Ug99 were inherently spatial—distributions of various stem rust races, movements, risk zones, etc.—hence, GIS could be a valuable tool. The clear risk posed by the Ug99 lineage makes it a priority focus, but the overall goal is to develop a global cereal rust monitoring and surveillance system that has GIS technology as a fundamental component. This section now describes some of the advances that have been made in the use of GIS relating to Ug99.

### 6.4.1 GIS-Based Surveillance and Monitoring Systems

In order to provide effective information to decision makers on the current status and potential future threat of Ug99, several key components need to be integrated in order to form the basis of any effective information or monitoring system. Important elements are considered to include the following:

- Actual locations at which stem rust is present or absent
- Information on which race of stem rust is present at any location
- Location of important wheat areas and other key crops
- Stage of development of the wheat crop
- Susceptibility of wheat varieties being grown
- Likely or potential movement—direction and distance—of rust spores from known sources
- Climatic conditions to favor spore deposition and development or survival of the pathogen

In addition, an effective means to integrate and analyze the information in a timely manner and then communicate the results in an effective way are an absolute requirement.

GIS technology is now forming the backbone of an emerging rust monitoring and surveillance information system being developed collaboratively by two international agricultural research centers (CIMMYT and ICARDA), the UN Food and Agriculture Organization (FAO), several advanced research institutes, and a network of national partners. Although several challenges remain before a fully operational system is created, considerable advances have already been made that address many of the important components needed. The current status of these advances and remaining challenges are now described.

### 6.4.2 WHERE IS Ug99?—KNOWN DISTRIBUTION AND RANGE EXPANSION OF STEM RUST (Ug99 LINEAGE)

Since the initial discovery and identification of Ug99 (race TTKSK) in Uganda during 1998/1999, the known distribution has expanded considerably. By 2002, reports had been received covering all of the main wheat-growing areas in Kenya. Following the spread across Kenya, reports were received from Ethiopia, and by 2003 the presence of Ug99 (race TTKSK) had been confirmed from several locations dispersed across the main Ethiopian wheat belt. All of the initial reports originated from experimental research stations, where wheat scientists detected the presence of the new race due to infections on varieties known to carry the *Sr31* resistance gene. Despite the fact that no GPS data were recorded with these early reports, presence at established research sites with known coordinates permitted the subsequent retrospective incorporation into a spatial database and corresponding mapping. All of the available data compiled indicated that Ug99 (race TTKSK) had exhibited a gradual stepwise expansion across the highlands of East Africa following the predominant west–east airflows. At the end of 2005, the first preliminary assessment of the Ug99 situation was undertaken using GIS.[25] In this assessment, generalized regional monthly wind vectors[26] were used along with documented movements of another wheat rust pathogen that originated in East Africa in the late 1980s[13] and general climatic information. Results from this initial rapid assessment indicated the potential for rust spores to cross to the Arabian Peninsula and move across the Middle East and onward toward South Asia.

In 2006, reports of stem rust were received from a site close to New Halfa in eastern Sudan and subsequently from at least two sites in Western Yemen. Analysis of rust samples collected from these locations subsequently confirmed the presence of Ug99 (race TTKSK). The observed continued expansion of Ug99 was in line with the prior predictions arising from the initial GIS study and once again indicated stepwise movements following regional winds. Crossing of the Red Sea into Yemen was considered particularly significant as several lines of evidence indicated that this might prove to be a gateway for onward movement into important wheat areas of the Middle East and Asia. In 2008, confirmatory race analysis data were obtained from stem rust samples that had been collected at two sites in Iran—Borujerd and Hamadan—at the end (i.e., July) of the 2007 wheat season.[27] Stepwise expansion of the Ug99 (race TTKSK) range had continued and the pathogen had now reached major wheat-producing areas. In the monitoring of Ug99 to date, a fundamental and basic element of the GIS work has been the creation of a centralized spatial database containing confirmed locations of Ug99 and survey data, plus the subsequent production of regularly updated maps showing current distribution. Figure 6.1 shows current known locations.

Growing awareness of the potential threat posed by the Ug99 lineage of stem rust has attracted the attention of several major donors, resulting in successful projects being developed under the BGRI umbrella to counter the threat of Ug99. These projects are now permitting a more coordinated approach to tracking and monitoring the spread of Ug99. An important part of this emerging approach is the development of standardized field survey protocols, provision of GPS units, and capacity building for survey teams in priority countries. These ongoing activities are already resulting in a very significant increase in the amount of geo-referenced field survey data being collected for stem rust, with subsequent incorporation of the data into the existing centralized spatial database.

### 6.4.3 MOVEMENTS OF Ug99

Recorded known locations of Ug99 over time illustrate the mobility of the pathogen and highlight the possibilities for long-distance airborne transmission. Obviously, understanding and, if possible, predicting likely movements is a critical component of any monitoring system for stem rust. For Ug99, this is vitally important as there is a dual role. Firstly, there is an immediate need to understand potential onward movements of the original TTKSK race, for example, where next after Iran? Secondly, can we learn and apply useful knowledge gained from known TTKSK movements in respect to the new variants that might follow? Both the *Sr24* and *Sr36* variants are at present only known from Kenya, but will they stay there? Obviously, nothing about predicting stem rust, or other airborne pathogen movements, is easy, and any assumptions of "fixed repeatable pathways" must be approached with utmost caution as significant deviations may well occur. Airborne particle movement is a challenging area due to the inherent complexity and variability of the underlying system, so it

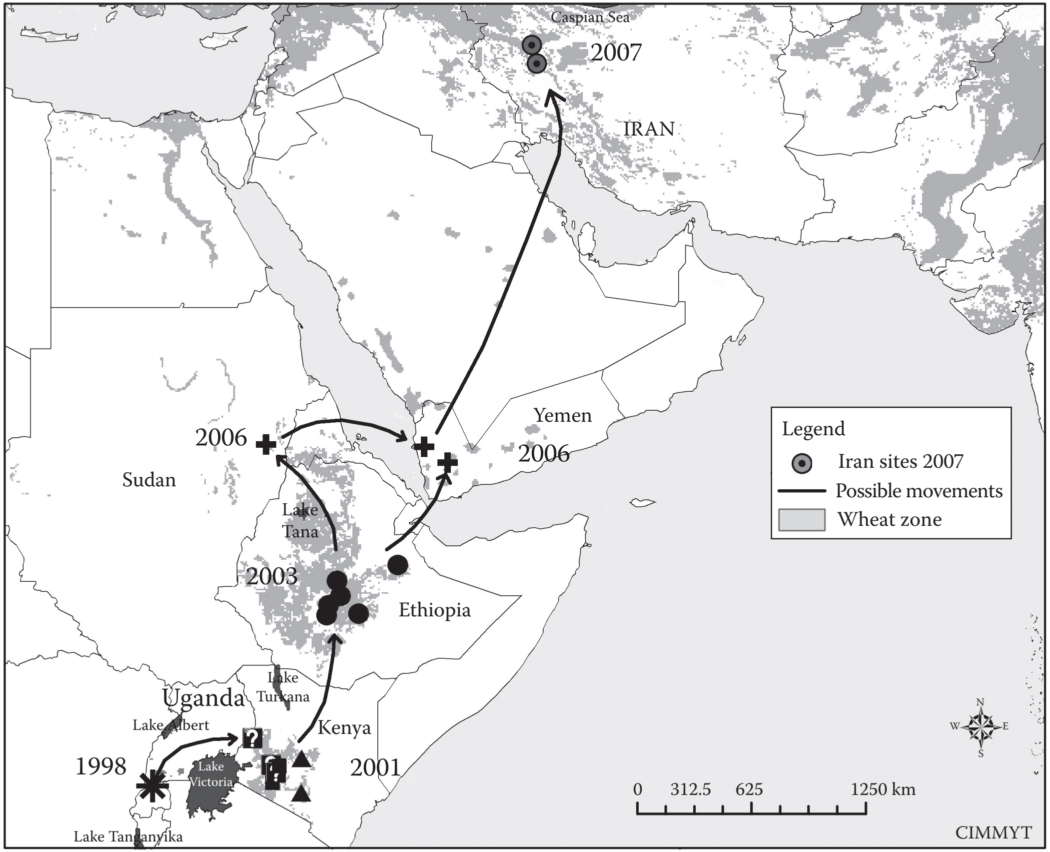


**FIGURE 6.1** Current known distribution map of stem rust lineage Ug99.

must always be borne in mind that there are considerable uncertainties associated with any such pathogen prediction studies.

Initial attempts to understand the potential migration routes of Ug99 relied solely on generalized monthly "normal" wind trajectories.[26] Despite obvious limitations, these data, once integrated into a GIS and coupled with other data, did however provide some useful initial insights.[9] When Ug99 first appeared in East Africa, there was very little information available on where or how quickly it might spread but huge demand and interest for such information. Analysis of the general wind vectors indicated the possibility for movement from the Horn of Africa across to the Arabian Peninsula during May–September (the main wheat-growing season). If the crossing of the Red Sea did occur, then the combination of year-round wheat production and apparently suitable climatic conditions could favor pathogen survival in the coastal areas of the Arabian Peninsula, so that spores could be transported up the Peninsula on the prevailing north/north–west winds during November–February (main wheat season in this region). If any spores did move in this direction, then they would likely encounter the predominant west–east winds around the Mediterranean basin, which would facilitate movement into the Middle East and onward toward South Asia. There was also a remote possibility that the same wind systems that could move spores from the Horn of Africa across to the Arabian Peninsula might be capable of transporting spores all the way to southern Pakistan and western India. Based on available evidence at the end of 2005, two potential generalized migration routes for Ug99 were postulated. These are illustrated in Figure 6.2.

Actual recorded observations of Ug99, outlined in the previous section, obtained only after the first postulated migration routes were produced have been supportive, not contradictory, of the initial GIS-based predictions.

Based on these encouraging results, and given the obvious importance of airflows for the movement of stem rust, it was seen as high priority to improve the spatial and, more critically, the temporal resolution of the airflow predictions. This resulted in a search for suitable, accessible models and final implementation of the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model developed by the Air Resources Laboratory at NOAA and the Australian Meteorology Bureau.[28] This impressive public-domain model permits the generation of air parcel trajectories from user-defined source locations for specified start times, release heights, and durations. The HYSPLIT model also permits the generation of "back trajectories," which allows the exploration of potential source locations for, and routes to, known final destination sites. Critically important is that the model uses near-real-time data inputs and also permits access to a historical data archive. Another big advantage of the HYSPLIT model is that outputs are produced in GIS format; hence, integration with other spatial data is easily achieved.

Implementation of the HYSPLIT model using Ug99 data has resulted in an improved understanding of observed movements recorded to date and offers the potential to gain insights into potential future spread. Following the confirmed spread of Ug99 (race TTKSK) into both Sudan and Yemen during 2006, an analysis of trajectories from these sites during the main wheat-growing season was undertaken using data from December 2005 to April 2006 and December 2006 to April 2007. The aim was to determine if any consistent seasonal trends in trajectory patterns

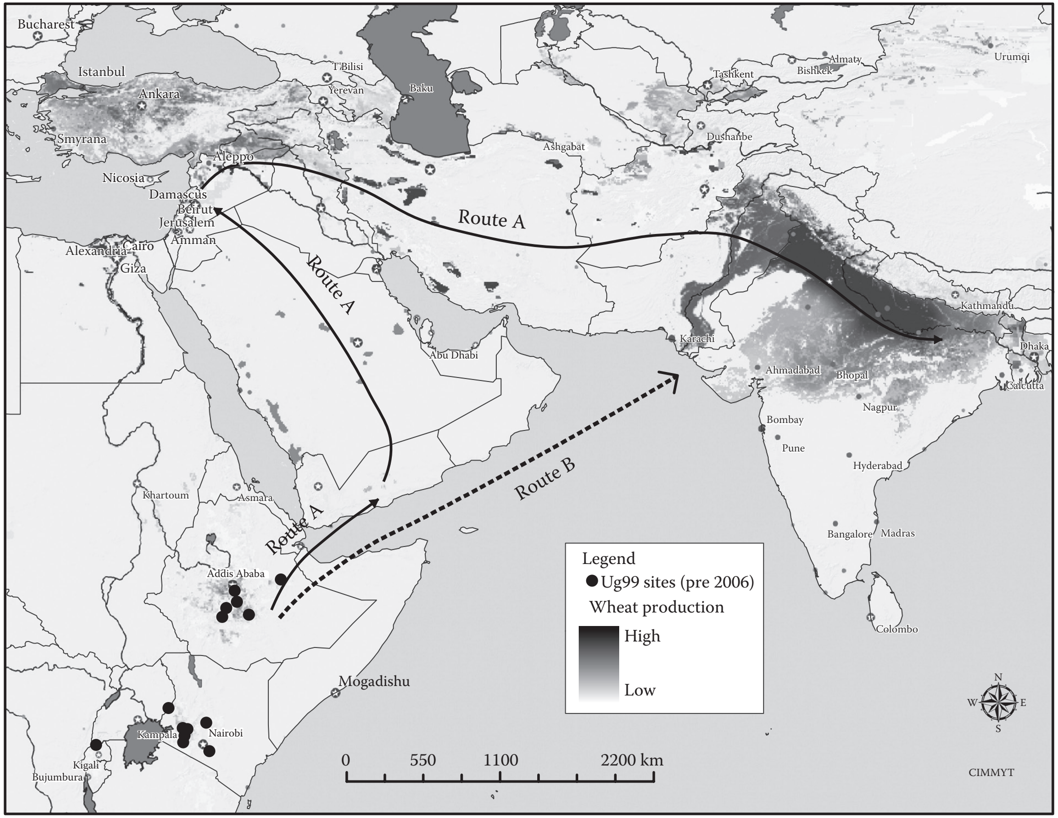


**FIGURE 6.2** Initial migration routes prediction map. (After Singh, R.P. et al., *CAB Rev. Persp. Agric. Vet. Sci. Nutr. Nat. Resourc.*, 1, 1, 2006.)

were apparent that might be indicative of onward movements. Both seasons provided near-identical outcomes. The results obtained supported the previous hypothesis that crossing of the Red Sea was a significant event and that Yemen could act as a gateway to the important wheat areas of the Middle East and Asia. Trajectories from Yemen indicated the potential for spore movements in a predominantly northeasterly direction, across the Arabian Peninsula and toward Iran and Iraq. Trajectory model results implied the possibility for movements into both of those countries in 72 h or less. Conversely, trajectory data from the New Halfa site in eastern Sudan indicated a predominantly southwesterly direction for potential spore movements. Hence, two locations (New Halfa, Sudan and Al Kedan, Yemen) on equivalent latitudes and less than 850 km apart produced almost diametrically opposing airflow patterns during the main wheat-growing season. Summary trajectory patterns are illustrated in Figure 6.3.

The observed south-westerly trajectory pattern originating from New Halfa in Sudan was not totally unexpected, as generalized regional wind vector data had already indicated that the prevailing winds during this period were likely to be in a southerly direction moving up the Nile valley from the Mediterranean. This was one factor in the decision to exclude Egypt from the initial postulated potential migration routes (in Figure 6.2). The trajectory model results obtained from New Halfa added support to this original hypothesis. However, this does not in any way imply that the important wheat areas of Egypt are free of risk from infection by Ug99. Wind patterns around the Red Sea are complex; dust storms moving from Saudi Arabia across into Egypt have been captured by MODIS satellite imagery on a regular basis (e.g., http://www.redorbit.com/images/gallery/modis_moderate_resolution_imaging_spectroradiometer/dust_storm_across_the_red_sea/156/307/index.html). If dust can move in this direction, then rust spores could do the same. In addition, entry of Ug99 spores at the Nile delta following movement up the Arabian Red Sea coast and subsequent movement up the Nile valley at some point in the future cannot be ruled out.

Interestingly, the trajectory model data also indicated a direct connection between New Halfa in Sudan and Al Kedan in Yemen (results not shown). These trajectory paths occurred outside of the "main" wheat-growing season, but given the presence of wheat virtually year-round in Yemen, the possibility of a route across the Red Sea, originating in eastern Sudan, cannot be excluded.

The implications of the trajectory model using the Yemeni sites as sources are interesting. They clearly indicated the potential for rust movements across the Arabian Peninsula in the direction of Iran, rather than directly up the Peninsula in the direction of Jordan and Syria as had been implied by the original generalized NOAA wind vector data. After the trajectory model results had been obtained, reports from Iran indicated that stem rust—potentially Ug99—had been observed on the 2007 wheat crop. Final published race analysis in 2008[27] confirmed that Ug99 (race TTKSK) was indeed present at two sites, Borujerd and Hamadan, in western Iran in 2007. The two confirmed Iranian sites were not exactly in the trajectory paths, previously produced by the model, but in reasonable proximity—being no more than 500–600 km distant from the closest trajectory paths. Further analysis is currently ongoing to determine a more precise reconstruction of the possible route that Ug99 (race TTKSK) may have taken to arrive in Iran. However, initial indications are that

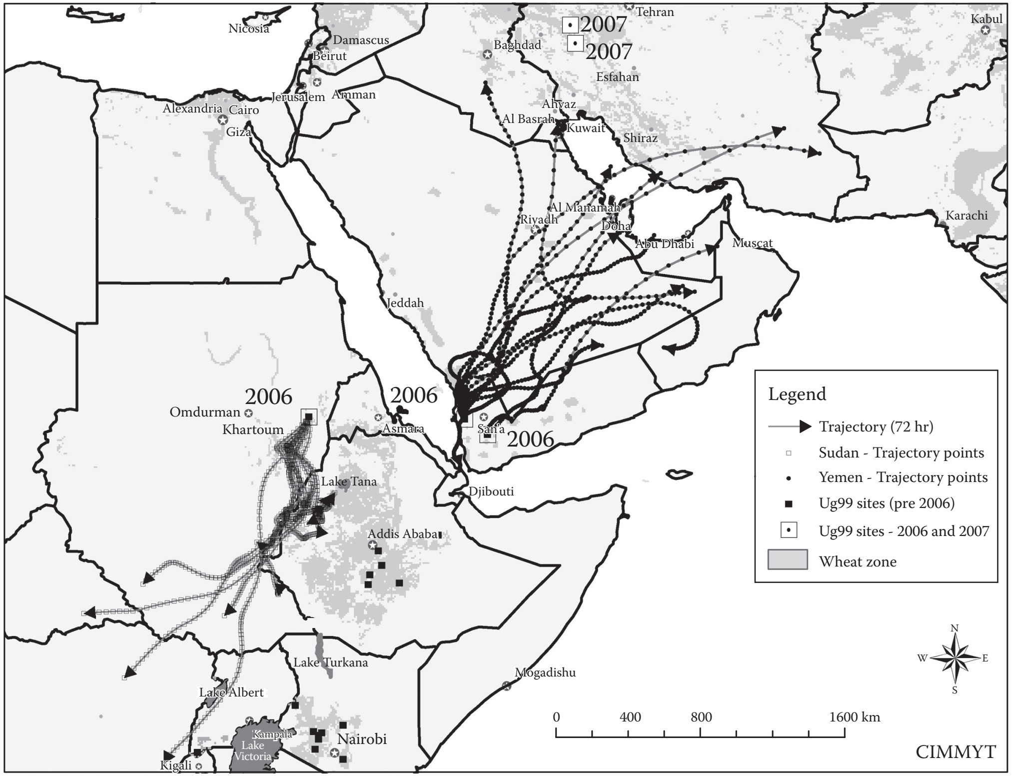


**FIGURE 6.3** Selected wind trajectories (72 h) from the HYSPLIT model from December 2006 to March 2007 originating at confirmed Ug99 sites in Yemen and Sudan.

the Al Kedan area in Yemen was a possible source and that staging at a previously undetected and unreported intermediate location in southern Iran or Iraq occurred earlier in the 2007 crop season, prior to onward movement to the confirmed sites at Borujerd and Hamadan at the end of the crop season. In this reconstruction, the forward and back trajectory models of HYSPLIT are being combined with daily rainfall and climatic data within a GIS. Rainfall data are especially important, since rainfall events are one of the principal means by which rust spores contained within an air parcel are deposited into new areas, a process termed "rain scrubbing"[29] (see Section 6.5.4 for more details).

Experience to date with the HYSPLIT model and Ug99 data indicates that the model can produce valuable insights, and these increasingly appear to coincide with observations in the field. This implies that some advances might be possible in terms of forward predictions for Ug99. However, given the number of coincident factors needed in order for a rust infection to occur, many uncertainties will almost certainly remain. It also must be borne in mind that accidental, assisted movement, for example, on contaminated clothing or via infected plant material is always possible. At present, based on known information, this does not appear to have occurred with Ug99; however, detection or prediction of any such occurrence is beyond the scope of any model.

Another area of potential concern is that currently nothing/very little is known about the potential status of Ug99 in areas to the south of Kenya or Uganda in Africa. Although wheat is a minor crop in much of this region, with the notable exception of South Africa, the basis of concern is the region's potential as a source for onward movement (albeit at low probability) to either Australia or the Americas. Documented historical evidence indicates the potential threat is real. Nagarajan and Singh,[30] Brown and Hovmøller,[11] Isard et al.,[31] and Prospero et al.[32] all cite convincing examples supported by high-altitude balloon data, wind trajectory model data, and sample analysis of cross-continental rust or bacteria movements originating from southern or western Africa. The possibility of a similar rare event type movement involving Ug99 cannot be totally excluded; hence, vigilance and surveillance activities in southern Africa appear warranted.

Movement of rust, despite the obvious complexity, is only one factor important for effective monitoring, and many other elements also need consideration. In order for colonization of new areas to occur, several other factors apart from the potential for movement have to occur simultaneously in time and space.

## 6.5 DEPOSITION/COLONIZATION FACTORS

A number of factors influence the ability of stem rust to colonize new areas. These are in line with the classical "disease triangle" concept, with the three elements being susceptible plants, a suitable environment, and the presence of the pathogen—all of which have to occur simultaneously for the disease to occur. Without exception, all of them have a spatial dimension and are hence amenable for inclusion into a GIS-based analysis. Major factors currently being considered in the assessment of Ug99 include the following:

### 6.5.1 WHEAT AREAS

Stem rust is a biotroph, so it needs living green material in order to survive. Hence, a primary factor for the establishment of stem rust is the presence of suitable hosts. Crop species of primary importance include bread wheat, durum wheat, barley, and triticale, although it must be noted that many additional wild grass species can also serve as hosts.[5] In the existing spatial database that has been created for Ug99, efforts so far have focused on the development and incorporation of a data layer for major wheat production zones.

Despite the global importance of wheat as a primary cereal crop, surprisingly, few datasets exist in the public domain that provides a detailed representation of global or regional wheat distribution in a format suitable for GIS. Many OECD countries make available regular census data on production, area planted, and yield at a disaggregated level, for example, county level in the United States.[33] However, in many parts of the world, including those that are priority regions for Ug99, no equivalent data are readily available. This lack of knowledge relating to accurate distributions of major crops is seen as a major shortcoming, although a few initiatives are now trying to address this. The study undertaken by the SAGE group at the University of Wisconsin-Madison, reported by Leff et al.,[34] was one of the first efforts to describe global distributions of major crops at subnational scales. This work has continued, and a new updated version has just been released.[35] In both cases, it is commendable that actual GIS raster data have been made publicly available on the Internet (see http://www.sage.wisc.edu/pages/datamodels.html). The basic approach used by the SAGE group has been to use satellite imagery to determine crop zones and then combine that with available subnational agricultural census information to produce global crop distribution maps at a 5 arcmin resolution (approximately 9 km grid at the Equator). A very similar approach has been pursued by the spatial analysis group at the International Food Policy Research Institute (IFPRI) using a cross-entropy approach that triangulates and optimizes crop allocations across multiple sources of relevant information, including satellite imagery (to identify croplands), subnational agricultural census data, biophysical crop suitability assessments, and population density.[36,37] This methodology simultaneously allocates distributions of 20 major crops, including wheat, again producing global distributions at a 5 arcmin grid resolution. These raster-based crop distribution mapping efforts have been a huge advance, but problems remain, and the quality of the final outputs can be variable, that is, in some areas, the crop distributions appear accurate, but this is not the case in all areas. Major problems are seen in areas where satellite imagery is unable to accurately detect croplands, for example, in complex small-holder farming systems in Africa and other parts of the developing world. The recent release of the new high-resolution (300 m grid based on MODIS imagery) global landcover map "GlobCover"[38] might help resolve some of the problematic results observed in the current distributions, and at least the IFPRI group plan to evaluate this information in order to guide their future crop allocations.

At present, the wheat distribution information being used in the Ug99 analysis work is a composite—based primarily on the IFPRI dataset, but incorporating some of the SAGE data and also some expert assessments by CIMMYT wheat scientists.

Work is ongoing to try and improve the quality of this data layer, but despite noted limitations, the available data are considered to provide a reasonable initial indication of the major wheat-growing areas.

### 6.5.2 SUSCEPTIBILITY OF WHEAT CULTIVARS

Another key set of information, beyond knowing where wheat is being grown, relates to the susceptibility of wheat cultivars present in farmers' fields. Given the constantly changing nature of varieties, obtaining this information in a timely fashion and at a spatially disaggregated level is extremely challenging. At present, for Ug99, only country-level data, relating to varietal area estimates reported in 2002, have been obtained to date. Improving the timeliness and resolution of this information is a high priority.

Information obtained to date results from two sources: First, the extensive Ug99/stem rust screening nurseries that are being undertaken at key sites in Kenya (Njoro in the rift valley) and in Ethiopia (Kulumsa and Debre Zeit, again in the rift valley) by national agricultural programs, that is, KARI in Kenya and EIAR in Ethiopia. Intensive screening efforts started in 2005, and by 2007 tens of thousands of different wheat varieties, originating from 22 different countries, had been evaluated. Second, these extensive screening data have been linked via known pedigrees to estimates of areas planted to known varieties held in a CIMMYT database—these latter estimates being obtained from surveys of in-country wheat experts, based on their own personal experience and knowledge of the wheat varietal releases in country. All of the available information indicates that resistance to the Ug99 lineage of races occurs at a very low frequency, with up to 80% of the wheat varieties currently grown in farmers' fields being susceptible. In 2006, only an estimated 5% of a total estimated area of 75 m ha was thought to be planted with resistant varieties.[9] In some countries, for example, South Asia, extremely large areas of wheat are planted to popular, but highly susceptible cultivars, and there is a clear and urgent need to replace these with durable resistant varieties. Repeat surveys of wheat experts are planned as a priority, and it is hoped to obtain updated estimates on areas planted to specific varieties at the subnational level. This information will be vitally important in order to improve impact assessments for Ug99 and for entry into early warning or monitoring systems.

### 6.5.3 CROP CALENDARS/CROP GROWTH STAGE

The growth stage of the crop is a critical factor in the establishment of the pathogen and subsequent infection. Living green tissue is a primary requirement for the pathogen, but local temperature and moisture conditions must be conducive for pathogen survival and infection. Obviously, if no susceptible crop is in the ground, no infection is possible, although "green bridges," that is, a year-round wheat crop (as occurs in east Africa and Yemen), off-season volunteer plants, and presence of alternative hosts all play a vital role in the provision of inoculum sources for infection once the main wheat crop reaches a susceptible stage. Stem rust is more important late in the growing period, primarily as a functional requirement for warmer temperatures compared to other rusts, that is, in many areas, optimal temperatures only occur late in the growing season. A classic example of this is the "Puccinia pathway" of North America in which stem rust finds suitable year-round survival conditions only in the extreme south of the United States or Mexico. Then, a northward expansion is observed following prevailing winds as the wheat crop matures and temperatures become optimal as the season progresses. Hence, in northern U.S. states like North Dakota, optimal stem rust temperatures occur only during later maturity stages late in the season, and in Manitoba, Canada, stem rust would only start to appear late June to mid-July.[39] As a result, any factors that prolong the growing season, for example, late-sown crops or slow-maturing varieties, increase the risk of infection by stem rust. The optimal timing of field surveys for stem rust is to coincide with approximate heading of the wheat crop.

General crop calendars based on recorded/known or estimated planting, heading, and harvesting dates provide important information for planning national field surveys and also serve as indicators when major production areas are likely to be at risk. At present, expert local knowledge combined with information held in international wheat trial databases are being compiled to provide broad indications of when specific wheat-producing areas are likely to be at increased risk of infection by stem rust. This information will be incorporated as spatial layers in the geo-database.

In the future, it may be possible to refine the growth stage estimates using a model-based approach. The Foreign Agricultural Service (FAS) division of USDA has already implemented a winter wheat growth model based on growing degree days.[40] A similar approach, but using crop simulation models, has been implemented as part of the Pest Information Platform for Extension and Education (PIPE) developed for Asian Soybean Rust monitoring in the United States by USDA APHIS, Penn State University and ZedX Inc. (see http://sbr.ipmpipe.org/cgi-bin/sbr/public.cgi).

### 6.5.4 CLIMATE/ENVIRONMENT

Climate plays a major role in the deposition and subsequent increase of pathogen populations. The role of winds in the movement of the pathogen has already been outlined in some detail in previous sections, but several additional factors are also important.

In order for spore deposition to occur, there are two principal mechanisms: dry deposition and wet deposition. Dry deposition, where the spores simply land following sedimentation and gravitational pull after being blown by the wind, is an important mechanism for local short-distance movements, but potentially less important for long-distance movements. Wet deposition, or rain scrubbing, is the principal mechanism for deposition over longer distances. Rainfall is a key factor in bringing rust spores down to earth and can provide the required moisture needed for infection to occur. However, intense rainfall events may wash spores off the plant material.[41] As little as 2 mm of rain can be effective in removing spores from the air.[42]

Moisture and temperature both play a vital role in spore germination, infection, and disease development. Spores that land on a suitable host germinate 1–3 h after contact with free moisture and require 6–8 h of dew or free moisture (e.g., from rain or irrigation) to complete infection.[5] Optimal infection conditions occur when nighttime dew lasts for 8–12 h, nighttime temperatures are around 18°C, the plant and pathogen are exposed to daylight, dew dries slowly, and daytime temperatures rise to 30°C.[43] In general, stem rust is favored by hot days (25°C–30°C) and mild nights (15°C–20°C) with adequate moisture for nighttime dews. Despite the fact that stem rust favors warmer conditions compared to other rusts, it should be noted that a wide range of temperatures are tolerated. Roelfs et al.[5] report minimum, optimum, and maximum temperatures for urediniospore germination as 2°C, 15°C–24°C, and 30°C; and for sporulation 5°C, 30°C, and 40°C. Within 10–15 days, a typical asexual cycle is completed, and fungal pustules burst to release millions more urediniospores into the atmosphere. Spore release is favored by warm dry days with low humidity.

At present, only generalized long-term normal climatic data have been incorporated into assessments for Ug99. Hodson et al.[25] used monthly long-term normal temperature and relative humidity data to outline areas with potential for year-round survival of stem rust. Incorporation of daily weather data, such as the precipitation estimates originating from the Climate Prediction Center Morphing Technique (CMORPH)[44] and delivered through the IRI/LDEO climate data library at Columbia University as a component of the Desert Locust monitoring program at FAO (see http://ingrid.ldeo.columbia.edu/maproom/.Food_Security/.Locusts/.Regional/.Rainfall/), is already being initiated for Ug99 work.

Despite documented environmental conditions that favor stem rust development and increasing access to relevant datasets, it is extremely difficult to predict exactly when or where an epidemic may occur. No reliable climatic predictor of stem rust epidemics has been documented to date. Presence of the pathogen and seemingly favorable conditions on the ground may still not result in a disease epidemic. Singh et al.[18] succinctly outlined some of difficulties and the complex interactions between time, pathogen, host, and environment. Observed outbreaks of stem rust associated with the Ug99 lineage in East Africa are illustrative of the complexity. Ug99, race TTKSK, has been present in both Kenya and Ethiopia for over 5 years, yet no major losses to the wheat crop have been reported from this race despite the presence of susceptible hosts. In contrast, in 2007, Kenya experienced major stem rust epidemics resulting from the new *Sr24* variant of Ug99, race TTKST—only 1 year after the race was first detected. Although the exact triggers of the 2007 Kenyan epidemics remain unknown, the specific combination in time and space of several factors is likely to have been important. Changing virulence patterns of the pathogen and large areas planted to a susceptible cultivar (Mwamba) were important; in addition, higher-than-normal rainfall proceeding and during the main wheat season was probably favorable for stem rust. Additional unrecorded microclimatic factors will almost certainly have also played a role. The overall favorable environmental conditions are assumed to have resulted in an inoculum buildup in the off-season and subsequent early infection of the main wheat crop. Despite similar general climatic conditions in Ethiopia at the same time, no epidemics were observed.

Although major climatic factors, for example, above-average rainfall at critical times, have no absolute predictive power for epidemics, the generally favorable conditions they may create are undoubtedly a potential influence. It is not unrealistic to speculate, therefore, that the extensive and detrimental regional drought in the Middle East during 2008[45] may have some influence on reducing inoculum levels of stem rust in drought-affected rainfed wheat areas.

## 6.6 INFORMATION TOOLS

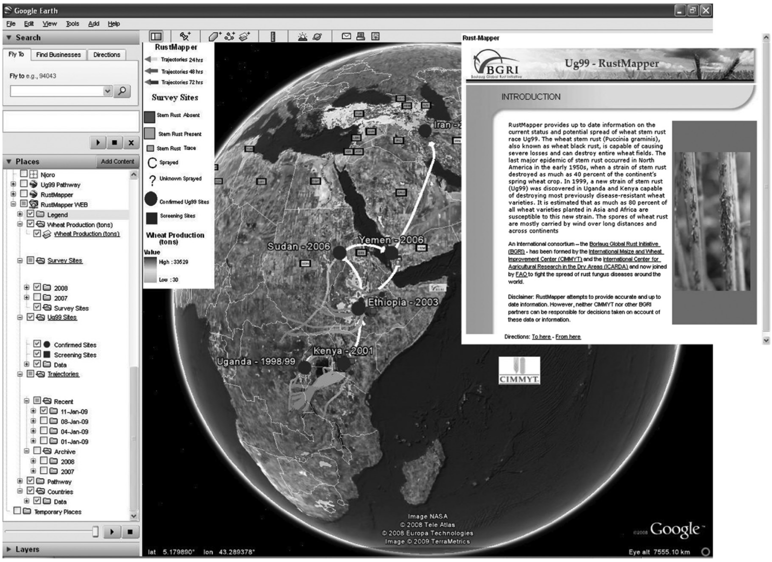
All of the preceding sections have outlined some of the key spatial datasets and models that are being used in the work on the Ug99 lineage of stem rust. However, to be useful, all this information needs to be integrated and made available in a timely and targeted manner. GIS/geographic-based tools are proving to be extremely valuable for this task. Several tools have already been developed that attempt to present synthesized information, with other products planned in the near future. Publicly available tools are briefly described in the following sections.

### 6.6.1 RUSTMAPPER

Google Earth is one of the most widely known and used virtual globes, with over 350 million downloads claimed by Google (http://google-latlong.blogspot.com/2008/02/truly-global.html). Google Earth provides excellent neo-geographic visualization capacity and offers many opportunities for customization using the KML scripting language. For these reasons, Google Earth was chosen as the platform for an initial information tool named RustMapper developed by the GIS unit at CIMMYT. RustMapper is publicly available at http://www.cimmyt.org/gis/RustMapper/index.htm as a KMZ download file for Google Earth; it is a networked link, so automatically updates after download. The idea behind RustMapper is to provide synthesized information regarding the current status of Ug99 with clear visualization. Key information incorporated into RustMapper includes all known sites for Ug99 or variants and recent survey sites—indicating the presence or absence of stem rust, near-real-time wind trajectories from the HYSPLIT model originating from known Ug99 sites or sites recording stem rust (these trajectories are run for 24, 48, 72 h durations and updated every 5 days), and major wheat-growing areas in Africa and Asia (see Figure 6.4). In addition, country-level summary information is provided on susceptibility estimates to Ug99 and basic wheat production statistics. A complete archive of wind trajectories back to April 2007 is also included. Any new information that is obtained and cleared for public release, for example, sites, wind trajectories, etc., is automatically incorporated into RustMapper.

### 6.6.2 RUSTMAPPER WEB

Following the release in 2008 by Google of the free “Google Earth Plug In,” options to embed Google Earth within a web browser were created. Based on positive reactions to RustMapper, it was decided to implement the Google Earth Plug In to broaden the range of access options. Key components of RustMapper were migrated into a browser-based tool. As a result, RustMapper Web is a derived “lite” version of the original RustMapper running within a browser environment. Like RustMapper, it is publicly available and updated every 5 days (see http://www.cimmyt.org/gis/



INTRODUCTION

RustMapper provides up to date information on the current status and potential spread of wheat stem rust race Ug99. The wheat stem rust (Puccinia graminis), also known as wheat black rust, is capable of causing severe losses and can destroy entire wheat fields. The last major epidemic of stem rust occurred in North America in the early 1950s, when a strain of stem rust destroyed as much as 40 percent of the continent's spring wheat crop. In 1999, a new strain of stem rust (Ug99) was discovered in Uganda and Kenya capable of destroying most previously disease-resistant wheat varieties. It is estimated that as much as 80 percent of all wheat varieties planted in Asia and Africa are susceptible to this new strain. The spores of wheat rust are mostly carried by wind over long distances and across continents

An International consortium – the Borlaug Global Rust Initiative (BGRI) - has been formed by the International Maize and Wheat Improvement Center (CIMMYT) and the International Center for Agricultural Research in the Dry Areas (ICARDA) and now joined by FAO to fight the spread of rust fungus diseases around the world.

Disclaimer: RustMapper attempts to provide accurate and up to date information. However, neither CIMMYT nor other BGRI partners can be responsible for decisions taken on account of these data or information.

Directions: To here - From here

**FIGURE 6.4** RustMapper—a Google Earth–based information tool.

rustmapper/RustMapper_Web.html). All of the primary components of RustMapper are included in the web version, although only the most recent wind trajectories are presented. RustMapper Web now functions on all major browsers on both Windows and Mac.

The above examples illustrate how geography-based visualization platforms are being used to present integrated information relating to the Ug99 lineage of stem rust in a timely manner. Despite the progress that has been made, further improvements and advances are still needed if the goal of a fully operational monitoring and surveillance system is to be achieved.

## 6.7 CHALLENGES/FUTURE ACTIVITIES

One major challenge is the determination of host crop zones, and this is a priority area for future work. As explained earlier, GIS-based surveillance and monitoring systems for stem rust need to address not only the challenge of tracking the pathogens but also the uncertainty about the presence of suitable host crops in the target region. Whereas the broad wheat regions are well known, the diversity in ecological conditions and farming systems makes it difficult to assess at a fine resolution where the wheat is actually grown and at what growth stage it is. Such uncertainty about the areas at risk makes it difficult to target rust surveys or cost-effective spraying campaigns.

Without expensive crop distribution surveys, involving farming systems research, agricultural surveys, remote sensing, and field validation, it is indeed difficult to identify crop zones in more than a sketchy pattern. Yet there is an affordable approach that allows compiling a base of "circumstantial evidence" that may point to the likelihood that a given crop occurs within a certain area. In GIS, it is possible to adopt such a method, similar to a criminal investigation, which could lead to the most likely crop to be designated as "prime suspect."

The application of Bayesian statistics in GIS, using "evidence layers" combined with local expert knowledge, has much potential for mapping probabilities of wheat occurrence. The way it works is that each GIS layer brings a bit of evidence about the likelihood of wheat occurrence. Each layer in isolation may not be conclusive in its own right, but the integration through expert knowledge and statistics may present a compelling case for either accepting or rejecting the hypothesis of wheat occurrence.

Obvious choices for evidence layers would be, for example, climate surfaces, digital elevation models, and satellite imagery. These are prime candidates, first and foremost, because the information they contain is of direct relevance to decide on the likelihood of wheat occurrence. Gridded data on the distribution of precipitation, temperature, and humidity indicate whether an area is not too wet, too dry, too cold, too warm, or too humid to grow wheat. A digital elevation model indicates whether an area is too steep, and satellite imagery whether an area is cultivated or not, and, if the images are taken at the right time of the year, whether the crops are grown under either rainfed or irrigated conditions. However, direct differentiation of specific crops by remote sensing is a very costly and time-consuming exercise and can realistically not be undertaken for the huge target region.

Another good reason for taking this approach seriously is that, owing to a huge recent advance in accessibility of geospatial technology, this information is now available free of charge for most parts of the globe to anyone with an Internet connection. For example, the WorldClim dataset[46] (http://www.worldclim.org/) is a set of global climate layers (climate grids) with a spatial resolution of about a square kilometer. The high-resolution global digital elevation model SRTM (Shuttle Radar Topographic Mission; http://srtm.csi.cgiar.org/), which was released in 2000, has a resolution of 3 arcsec (90 m). The GeoCover dataset, a global coverage of Orthorectified Landsat Enhanced Thematic Mapper Compressed Mosaics, is available (https://zulu.ssc.nasa.gov/mrsid/), showing the earth around the year 2000 at 14 m resolution. Electronic access to the entire USGS Landsat 5 and 7 archives enables users since late 2008 to download at no charge for selected areas' more recent scenes. Google Earth's growing database of very high-resolution images even constitutes a mechanism for ground truthing in sample areas, as individual objects such as trees can be distinguished, offering additional clues on what kind of crops are grown.

Whereas these datasets are useful to identify major biophysical constraints that may exist in an area and thus allow some assessment of how *unlikely* it is that wheat is grown in an area, they do not confirm its presence. For that goal, *local* knowledge is needed, and the most useful sources of knowledge about crop distribution exist in the form of crop statistics and farming system studies. Every country in the target region issues annual reports with statistics on crop area, production, and yield at subnational level, mostly at the provincial but sometimes at the district level as well. The quality of this information varies considerably between countries, but as a rule of thumb, the reliability decreases with the areal unit of data aggregation (the provincial data are more reliable than the district-level data, etc.). Although crop statistics are the only objective information source about the presence of wheat or any other crop, the main disadvantage is that these data are usually aggregated at a high administrative level, usually the province, often including areas with different ecological conditions, some of which may be physically unsuitable for wheat. As an exception to this general rule, in Syria, the province (Muhafaza)-level crop statistics are further disaggregated according to precipitation zones, a.k.a. Agricultural Stability Zones.[47]

Studies of farming systems or agricultural systems, if reasonably up-to-date, are potentially a goldmine of information about the crops being grown in an area, the people who grow them, and the economics of growing them. The characteristics of the described systems may encompass a wide range of attributes, related to population, integration within markets, resource access, culture, agricultural practices, input–output relationships, public investment, poverty, and tenure systems. However, for the purpose of mapping crop zones, common problems to be expected are that, like gold, farming system studies are relatively rare and, usually, cover small areas that are not necessarily representative. Moreover, these studies are, in general, not spatially explicit and therefore difficult to integrate in a GIS.

Remote sensing may help overcome these difficulties in spatializing farming system studies. Wattenbach[48] describes the development of a farming systems map for Syria in which a tentative initial sketch map is integrated with a spatially explicit map of agricultural regions in Syria, obtained by the interpretation of Landsat imagery, resulting in a geographically correct map of the farming systems.

Soil or land capability maps for the target region are another useful addition to the suite of evidence layers that can be integrated into the probabilistic approach for mapping the wheat-growing areas, especially for defining areas suitable for specific crops. Soil maps need, however, to be interpreted with caution. Many maps are either at too general scale to be useful, or are out of date, with most surveys dating from the 1960s to 1980s. Often, they fail to incorporate land improvements, which may raise the land quality for crop production, such as terracing, new irrigation development, saline land reclamation, stone and rock removal, or alternatively land degradation trends, particularly due to salinization of irrigated areas. However, also in this case, remote sensing can help with updating the soil information. A more serious problem is that many soil maps use a taxonomic classification, such as Soil Taxonomy[49] or the FAO classification system,[50] which do not necessarily have a direct linkage to the physical and chemical soil properties that determine the suitability for wheat. For this reason, in most cases, it will be necessary to undertake a land suitability evaluation first by matching the biophysical factors affecting wheat growth (climate, terrain, and soils) to the requirements of the crop. Adapting text book methods for land evaluation[51,52] to the available databases and local conditions may be the best way forward.

How can these information sources be combined and yield country-level maps of the probability of wheat at a fine (e.g., $1\,\text{km}^2$) resolution? A good way to start would be by the elimination of areas where wheat is highly unlikely to be present. The first step would be to remove from the analysis those statistical mapping units in which no wheat has been reported. The second step, to be performed through image analysis of satellite imagery, is to extract the areas with cropland. These areas, which contain the full mix of crops reported for the statistical unit, can then be differentiated into rainfed and irrigated croplands, again through remote sensing. Using local knowledge and farming systems studies, one could then obtain information which crops are only grown under either irrigated or rainfed conditions, or both.

The next step is to determine the comparative advantage of each crop in the statistical reporting unit from two perspectives: biophysical potential and social preference. Biophysical potential can be assessed for each crop through an adapted land evaluation method, leading toward a crop-specific classification of the croplands into one of four classes, "highly suitable," "moderately suitable," "marginally suitable," and "unsuitable,"[53] which in turn can be linked to average yield levels, again obtained from local knowledge and farming systems studies. Social preference for a crop will depend on its ability to maximize farm income itself determined by the average expected yield level and the price for the crop.

The final step for preparing a probability map for wheat (or any other crop) is to use a Bayesian approach of convergence of the available evidence from a prior to a posterior probability. Bayes Theorem states that

$$p(h/\varepsilon) = \frac{p(\varepsilon/h) \times p(h)}{\sum_i p(\varepsilon/h_i) \times p(h_i)}$$

where

$p(h/\varepsilon)$ is the probability of the hypothesis being true given the evidence (posterior probability)
$p(\varepsilon/h)$ is the probability of finding that evidence given the hypothesis being true (conditional probability)
$p(h)$ is the probability of the hypothesis being true regardless of the evidence (prior probability)

is a useful basis for combining different types of evidence, as derived from direct sampling, local knowledge, and secondary sources. Starting with a prior probability determined by the share of wheat in the crop mix of the statistical reporting unit, Bayesian statistics allows adjusting this first guess in the light of the maps used as predictors. Land suitability is a particularly useful layer, as the modeling involved allows integrating the key factors of the environment (climate, soils, and topography) into a single crop-specific score. Spatialization of crop prices, even if tentative, results in another useful evidence layer. Policy-related evidence layers could also be considered where relevant. For example, in Syria, rainfed cropping below 200 mm annual precipitation is prohibited. Relatively simple implementations of Bayesian statistics in a GIS environment are available,[54] which can be adapted for calculating the conditional probabilities arising from the possible combinations of land being in a particular suitability class with a given crop.

Another major challenge is the changing nature of the pathogen. Two major new variants of Ug99 have been detected in less than 5 years. For germplasm deployment strategies, it is essential to know which pathotypes are present in which areas and how these are likely to move. Race analysis of rust pathogens requires bioassays performed on collected rust samples under controlled conditions, using sets of differential testers, that is, specific wheat varieties that have known stem rust resistance genes. At present, not all countries have the capacity to undertake such analysis, and transfer of samples to advanced research laboratories in North America is required.

Strict quarantine regulations introduce a considerable time lag (up to 6 months or more) between sample collection in the field and final race analysis confirmation. This time lag, combined with the multi-institutional and cross-continental elements of race analysis, implies the requirement for a very stringent procedure to track samples and trace race analysis results back to source collection sites. At present, race analysis data have not been integrated into the centralized rust database, but this needs to occur. Strict sample coding, or even bar coding, will be required to effectively connect pathotype data to field collection sites.

## 6.8 CONCLUSION

Historically, wheat stem rust was the most feared plant disease capable of devastating epidemics and crop losses. By the mid-1990s, widespread use of resistant cultivars had reduced disease incidence to nonsignificant levels worldwide. Stem rust research and resistance breeding ceased to be a priority activity. The emergence of a new virulent stem rust race lineage in Uganda in 1998/1999, popularly named Ug99, and subsequent variants have rendered 80% or more of global wheat varieties stem rust susceptible. Emergence and spread of the Ug99 lineage have put stem rust firmly back on the agenda of wheat scientists worldwide.

The response of the global wheat community in relation to the threat raised by Ug99 has been positive and effective. Already, significant progress has been made in the identification and development of new resistant materials, but several challenges still remain before those varieties find their way into farmer's fields on a large scale. Considerable progress has also been made in raising awareness of the threat posed by Ug99 and in providing access to reliable and timely information on current status.

In line with the recommendations of an expert panel convened to assess the threat of Ug99, GIS technology forms the backbone of an emerging monitoring and surveillance system for cereal rusts. This embryonic system is initially focused on the emerging stem rust threat but over time plans to incorporate other cereal rusts and is being developed collaboratively by CIMMYT, ICARDA, and FAO. Few, if any, other technologies apart from GIS possess the capacity to seamlessly integrate the multitude of factors relevant to stem rust movements, establishment, and impact. Online, geographic-based visualization tools are already playing a critical role in the dissemination of complex datasets in a timely fashion.

A series of factors have been identified as being important if an effective surveillance and monitoring system for stem rust is to be created. These include location information regarding presence or absence of the disease and the specific race involved, location of important wheat-growing areas and the susceptibility of cultivars being grown, potential direction and distance of spore movements, and local climatic conditions favoring spore deposition pathogen survival and development. Without exception, all of these key elements have a spatial component and as such are amenable for incorporation into a geo-database and analysis using GIS. Absolutely critical is the requirement for timely, geo-referenced field survey data.

Through a successful international collaboration, several of the required elements of the monitoring and surveillance system are already starting to be addressed. Standardized field protocols have been developed; provision of, and training in the use of, GPS has been initiated via existing and expanded national partner networks—resulting in a substantial increase in the amount of survey data incorporated into a centralized geo-database. As a result, regularly updated known distribution maps for Ug99 are now being produced. Routine incorporation of wind trajectory models is providing improved information on potential movements, with results so far corresponding closely to actual confirmed observations in the field. Results obtained to date indicate movements and range expansion of Ug99 in-line with predicted regional airflows, and generally following previously reported movements of other rust races originating in east Africa.[13] However, there is neither room for complacency regarding future movements nor any substitute for regular, timely field surveys of the key wheat areas. Factors associated with spore deposition and pathogen establishment have started to be addressed, but many challenges remain. Predominant wheat-producing areas have been identified, and initial, albeit somewhat outdated, estimates have been made regarding susceptibility and areas of existing wheat varieties. However, both sets of information are seen as being high priorities for future improvement, and efforts are underway to address these aspects. Similarly, crop growth stages and key climatic factors are starting to be addressed, but, significantly, more progress is required. Obtaining reliable and timely data for all of the key climate variables at the required temporal resolution over large data sparse regions presents some challenges, although the increasing availability of remotely sensed weather data in near real time might provide some useful options.

Good progress has been made in the development and release of initial information tools that draw upon existing centralized data and provide near-real-time information on the current status of Ug99. The ready availability of powerful geographic-based visualization options, such as provided by Google Earth, has been a key factor in the successful presentation of information in a clear and flexible way. In the future, an expansion of the type and range of information products is planned. These will be targeted very closely to wheat scientists and decision and policy-makers in at-risk countries. Using the successful FAO desert locust monitoring system as a model (see http://www.fao.org/ag/locusts/en/info/info/index.html), an improved and expanded web presence will be created issuing status reports and alerts, along with lightweight rapid mapping capacity, plus regular summary bulletins.

GIS has already proved to be a useful and critical tool in providing support to the ongoing global efforts addressing the threat posed by emerging new races of wheat stem rust. As these efforts continue and expand, GIS technology will undoubtedly underpin a large proportion of the monitoring and surveillance activities required for these economically important fungal diseases of wheat.

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