Supplementary Information

We provide additional detail about the wheat rust Early Warning System (EWS) to that outlined in the main paper.

1. The EWS project partners

Here we give further information about the project partners involved in the development and implementation of the EWS.

Ethiopian Institute of Agricultural Research (EIAR)

EIAR oversees the coordination of agricultural research for Ethiopia and advising the government on agricultural research policy formation. EIAR's mission is to conduct research that will provide market competitive agricultural technologies to contribute to increased agricultural productivity and nutrition quality, sustainable food security, economic development, and conservation of the integrity of natural resources and the environment. EIAR, plays a leading role in influencing agricultural policy development. EIAR's vision is to see improved livelihoods for all Ethiopians engaged in agriculture, agro-pastoralism and pastoralism through market competitive agricultural technologies. EIAR has long established working partnerships with a range of international institutions including: CIMMYT, JICA, KOPIA, BMGF, ICARDA, McKnight Foundation, Africa Rice, and others. Extensive research and development work on wheat and wheat rusts has been a component of these partnerships and also represents a core part of the EIAR research agenda.

Ethiopian Agricultural Transformation Agency (ATA)

The Ethiopian Agricultural Transformation Agency (ATA) is an initiative of the Government of Ethiopia (GoE) which was established by federal regulation in January 2011. The primary aim of the Agency is to promote agricultural sector transformation by enhancing and supporting existing structures of government, private-sector and other non-governmental partners, to address systemic bottlenecks in the agricultural sector and deliver on a priority national agenda to achieve growth and food security.

ATA focuses on a set of high-priority programmatic deliverables forming the Agricultural Transformation Agenda, sub-divided into four verticals: Production and Productivity, Agri business and Markets, Sustainable and Inclusive Growth, and Enhanced Implementation Capacity. Across these program areas, the ATA engages public, private and non-governmental stakeholders to support strategic planning, manage and strengthen implementation capacity and test innovative models. The organization does this by leveraging best practice approaches, whether from the public or private sectors. ATA is financed by the GoE and a range of development partners.

Information, data, and research are essential components necessary to inform and fuel transformational change. Information and data, in all of their forms, are the pivotal commodities that inform the identification and prioritization of interventions and deliverables. The availability of objective data is integral for policy and decision makers to make informed decisions and course correct based on information they have at hand. At the smallholder farmer level, local and context specific information is vital to ensure that the investments made on each plot of land are those that will yield the greatest returns.

On both ends of the spectrum, access to relevant and pertinent information is critical in promoting growth and productivity. Without access to this type of information, progress is susceptible to stagnation. The ICT for Agriculture Services Program team has been identifying and implementing innovative approaches to collect and share information across a wide range of actors. The government of Ethiopia is fully aware of the role ICTs play in developing the sector and how adapting these ICTs can bring about dynamic change in the agriculture sector. Based on international best practices, there has been a major shift to integrate ICTs in agriculture development as facilitating tools to enhance the lives of smallholders. As such, ICT is playing a greater role to stimulate agriculture, enhance food security and support rural livelihoods.

The International Maize and Wheat Improvement Center (CIMMYT)

CIMMYT works throughout the developing world to improve livelihoods and foster more productive, sustainable maize and wheat farming systems. CIMMYT's portfolio squarely targets critical challenges, including food insecurity and malnutrition, climate change and environmental degradation.

Through collaborative research, partnerships, and training, the center helps to build and strengthen a new generation of national agricultural research and extension services in maize- and wheat-growing nations.

CIMMYT is the global leader in publicly-funded maize and wheat research and works with hundreds of partners to improve livelihoods and foster more productive, sustainable maize and wheat farming. This work provides at least US $3.5-4 billion in annual benefits to farmers with more than 50% percent of maize and wheat grown in developing countries originating from CIMMYT. CIMMYT has a long-standing partnership with Ethiopia. CIMMYT coordinates the Global Wheat Rust Monitoring System (covering 40 countries, focused on Africa and South Asia), leads efforts to control wheat blast in South Asia, coordinates a Maize Lethal Necrosis (MLN) surveillance network across Eastern and Southern Africa and is engaged with Fall Armyworm in sub-Saharan Africa.

The Atmospheric Dispersion and Air Quality group at the UK Met Office

The Met Office is the UK's national meteorological agency; it delivers weather and climate services to a wide range of customers including UK Government, commercial sector and overseas agencies. The Atmospheric Dispersion and Air Quality (ADAQ) group, within the Met Office, conducts research, develops NAME and applications of NAME to support emergency response activities and studies of atmospheric pollutants.

The Epidemiology and Modelling Group at the University of Cambridge

The Epidemiology and Modelling Group at Cambridge has developed and tested a suite of models and protocols for emerging epidemics of plant disease. The models address a range of scales extending from individual fields through farms across a landscape up to state-wide, country, regional and continental spread of invading vectors and pathogens. The outputs comprise an 'epidemiological toolbox' encompassing mathematical, statistical, computational and economic methods that are used to predict disease spread under uncertainty and to optimise the deployment of genetic, chemical, cultural and biological methods for epidemic management. The research is focused on understanding the mechanisms that govern invasion, persistence, scaling and variability of epidemics within changing agricultural and natural landscapes. Our approach involves a synthesis of epidemiological theory, landscape ecology and economic modelling, drawing upon methods from statistical physics and Bayesian statistical inference and, more recently, meteorological dispersion models. The models are used to predict disease spread, impacts of disease including crop loss and the effectiveness of surveillance and control strategies, while also taking account of uncertainties. The models are tested against extensive field data. Recent and current applications range from large-scale pandemics (ash dieback and ramorum threats to UK, sudden oak death, citrus canker and citrus greening to US, cassava brown streak virus, whitefly, stem and stripe rusts of wheat in East Africa, stripe rust Australia, aflatoxins in India) to the design of intervention strategies for exotic pathogen threats.

2. The wheat rust diseases

In this work, we only look at the economically important wheat rusts in Ethiopia: stem and stripe rust. Stem rust, also known as Black rust and caused by: *Puccinia graminis* f. sp. *tritici.* Stripe rust, also known as Yellow rust and is caused by: *Puccinia striiformis* f. sp. *tritici* (see figure 1).

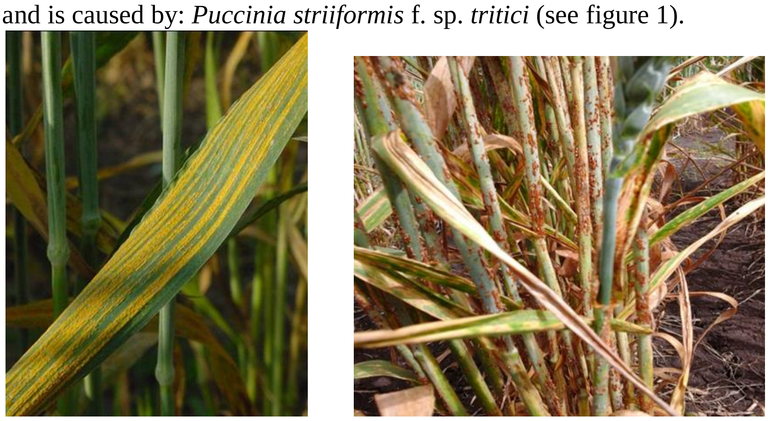


Figure 1: Photos of wheat stripe rust (on the left) and wheat stem rust (on the right)

The wheat rust diseases are obligate biotrophs with complex lifecycles. They are macrocyclic – exhibiting 5 spore types and heteroecious (requiring two different host species to complete their full lifecycle) fungal pathogens. Barberry (Berberis sp) serves as the alternate host for both stem and stripe rust permitting completion of the full sexual cycle and genetic recombination important for the emergence of new races of wheat rusts. However, it is the production of the asexual clonal urediniospores and repeated infections of wheat plants that are responsible for the wheat rust epidemics that can cause devasting losses to wheat yield (Roelfs et al 1992). Stem rust is the most devastating of wheat, with complete crop loss possible under favourable conditions. Stripe rust is capable of losses exceeding 70% and over the last two decades has become the major biotic threat to wheat at the global scale. It is estimated that current global losses to stripe rust amount to over 5 million tonnes with an estimated market value loss of US$ one billion annually (Wellings 2011; Beddow et al 2015).

3. The Early Warning System Components

Here we provide further details about the EWS components outlined in the main paper.

3.1 The Unified Model (UM)

Meteorological data to drive spore dispersion and environmental suitability models uses analysis and forecast fields from the UK Met Office operational numerical weather prediction (NWP) model, the Unified Model (UM), (Walters et al 2019). In the work presented here, we use the global configuration of the UM, which runs four times a day, at 00:00, 06:00, 12:00 and 18:00 UTC. The global UM provides three-dimensional data of all standard meteorological variables at 3-hourly time intervals, up to seven days from the time of forecast initialisation for the 00:00 and 12:00 UTC runs, on a grid with a horizontal spacing of approximately 10 km. Here we give further details of the different parameters derived from the UM data for the environmental suitability models:

3.1.1 Wheat canopy temperature

We use the predicted 2m temperature above the ground as the wheat canopy temperature.

3.1.2 Leaf wetness/free moisture

Leaf wetness is not directly available from the UM. We can use rain as a source of moisture on the wheat. However, dew is also a source of free moisture, and is not available from the UM forecast data. Sentelhas et al 2008 proposes that relative humidity equal to or greater than 90% can be used as a proxy of leaf wetness duration. We use this approximation for our model, but firstly we needed to calculate relative humidity from the NAME meteorological input of the data.

Relative humidity is the ratio of water vapour pressure to saturation vapour pressure. We use the given specific humidity (the mass mixing ratio of water vapour in air), the pressure and the temperature to calculate the relative humidity (Rogers and Yau 1989):

$$RH = 100\ \frac{\omega}{\omega_s} \approx 0.263pq\left[\exp\left(\frac{17.67(T - T_0)}{T - 29.65}\right)\right]$$

Where: p = pressure, q = specific humidity, ω = water vapour pressure, ω_s = saturation vapour pressure, T = temperature, T_0= temperature at the bottom vertical level.

To summarise, rain greater than 0mm and relative humidity equal to or greater than 90% is used as a proxy for leaf wetness. We assume that this source of moisture is freely available for three hours which is the temporal resolution of the UM forecast data.

3.1.3 Solar radiation

Solar radiation is not available in the NAME input UM forecast data. We calculated solar radiation from Paltridge and Proctor (1976).

$$I(\theta) = 950\{1 - \exp[-0.075(\tfrac{\pi}{2}\ -\ \theta)]\}$$

Where I(θ) is the solar radiation received from clear skies. This is then further modified to allow for the reduction of solar radiation by clouds by incorporating the cloud fraction:

$$I(\theta) = (I - CF\sum_{T_{SR}}^{T_{SS}} I(\cos(\theta)\cos(\theta))$$

where: θ = Solar zenith angle (calculate as a function of model time), CF = fractional cloud cover, TSR= time of sunrise, TSS = time of sunset, I = Solar Intensity at the surface.

We use this as a method for calculating the instantaneous solar radiation intensity received at the wheat canopy. The value of 950Wm^{-2} is the maximum possible solar radiation intensity at the surface as a result of clear skies and overhead solar zenith angle. This value was based on the values in Australia, but a preliminary comparison of UM forecast data shows that this value is reasonable.

The solar zenith angle was calculated using latitude:

1. Calculate solar hour angle
    a. Measured from the solar noon
    b. hh=360*(time from midday/24hours)
    c. eg: BEFORE midday is negative AFTER midday is positive
2. Calculate solar declination
    a. angle between the rays of the Sun and the plane of the Earth's equator
    b. $\delta = -23.44^{o} * \cos((360/365)*N)$ N= number of days after 21st December (winter solstice)
3. Calculate solar zenith angle, θ
    a. $\mu = \sin(latitude)*\sin(\delta) + \cos(latitude)*\cos(\delta)*\cos(hh); \theta = acos(\mu);$

The cloud fraction was also derived from the NAME input UM data.

Calculate Saturation Vapour Pressure (Murray 1967).

$$es \text{ (in mb)} = 6.1078 \cdot \exp[\, a \cdot (T-273.16)/(T-b)\,]$$

1. where: es = saturation vapour pressure, T = temperature, over ice: a = 21.8745584 and b = 7.66, or over water: a = 17.2693882 and b = 35.86.
2. Calculate saturation mixing ratio (Murray 1967).Rs= 0.62197.*(es./((p/1000)-es));
   where: Rs = saturation mixing ratio, p = pressure
3. Calculate cloud fraction for every grid (both vertically and horizontally)
   cloudfraction_level_z= (liquid water mixing ratio+ice mixing ratio)/ (Rs)])
4. Convert the 3D cloud fraction into a 2D cloud fraction

```
for z=1:n_vertical_levels
   cloud_layer=cloud_layer + (1-cloud_layer).*cloudfraction_level_z
end
```

Tropical clouds are mixed phase, the hydrometeors present include liquid water droplets, rain, graupel, snow and ice particles. Therefore, we chose to calculate the saturation vapour pressure with respect to water and not to ice.

Problems occurred with respect to supersaturation which resulted in a cloud fraction value greater than 1. In these situations, the grid point would be considered to be 100% cloudy and therefore the cloud fraction values were reset to equal 1.

3.2 The Numerical Atmospheric-dispersion Modelling Environment (NAME) model

The NAME (Numerical Atmospheric-dispersion Modelling Environment) model brings spore dispersion and deposition forecasts to the EWS. Simulations of wheat rust spore release into the atmosphere, turbulent transport through the atmosphere and removal from the atmosphere are performed using the Lagrangian atmospheric dispersion model (Jones et al 2007). NAME simulates the turbulent transport of material through the atmosphere by time-varying, three-dimensional winds, provided by the UM Numerical Weather Prediction (NWP) output. In addition to the transport by winds, NAME also represents the removal of material from the atmosphere by sedimentation, dry deposition, and in the case of rainfall, wet deposition. NAME is used in an emergency response and research capacity by many different organisations to predict the dispersion of a range of atmospheric material from volcanic, nuclear, chemical, and more recently biological particles. It includes processes that affect the viability of biological particles such as spores during dispersion (Meyer et al 2017b). Here, we provide further detail about aspects outlined in the main paper.

3.2.1 NAME configuration

The NAME spore dispersion runs were initialised with UM analysis data for the three days prior to the date that the simulation was performed, to account for the three-day maximum lifetime of wheat rust spores. It is possible that spores released in the three days prior to the current day may stay aloft in the atmosphere and before becoming deposited later during the forecast period. The full seven days of UM forecast data is then used to perform a NAME forecast of spore dispersion and deposition for the week ahead for both rusts at 3-hourly time intervals.

The configuration of the daily NAME simulations is based upon that of Meyer et al (2017), with two modifications, (i) an improved calculation of the timing and rate of release of wheat rust spores into the atmosphere and (ii) an extension to include the dispersion of stripe rust and well as stem rust.

3.2.2 Determining NAME source strength

There are few references or observations that give the maximum number of stripe and stem rust spores that can be produced in optimal conditions. Nagarajan and Singh (1990) state that a moderate infection of *Puccinia graminis* would produce 4 x 10^{12} urediniospores/day/ha, whereas *Puccinia striiformis* would produce between 0.6 to 2.0x10^{13} urediniospores/day/ha. If we assume that a moderate infection is equivalent to disease exhibiting moderate severity and moderate incidence, then we approximate this to 10^{12} urediniospores/day/ha for stem rust and 10^{13} urediniospores/day/ha for stripe rust. However, we also must consider the unique properties of stripe rust where the urediniospores aggregate together; which does not occur for stem or leaf rust. The amount of aggregation depends on the relative humidity (RH). The stripe rust urediniospores have a mucilaginous layer, which as RH increases becomes thicker and consequently the spores stick together and are dispersed as clusters of between 2 and 10 spores. Currently NAME does not parameterise the aggregation of particles. We assume in our NAME modelling that the stripe rust spores are dispersed as individual spores and not clumps of spores in a similar manner to stem rust spores. We therefore the reduce number of stripe rust spores to 10^{12} urediniospores/day/ha for moderate incidence and moderate severity. Young (1977) reported a daily production of 3-35x10^3 urediniospores per cm^2 for stripe rust, which also varies by an order of magnitude. Hau and De Vallavieille-Pope 2006 quote values for daily sporulation (spores/lesion). For stripe rust this is 15x10^3 and for stem rust this is 20x10^3. There are many uncertainties: for example, we have no information on the density of the wheat plants, the leaf area index, or the number of spores washed off the plants by rain. For simplicity, we reduce the maximum possible spores released by an order of magnitude, giving 10^{11} urediniospores/day/ha for low severity and low incidence observations. We increase the maximum number of spores released to 10^{13} urediniospores/day/ha for high severity and high incidence observations.

The source strength needs to be defined for the NAME model. In this context it will be the maximum possible number of spores per hectare that can be released during a 24-hour period. Here, the maximum possible number of spores will depend on the incidence and severity observed in the ODK survey data. The incidence of rusts was calculated by using the number of infected plants and expressed as a percentage of the total number of plants assessed. The disease severity was examined visually on the whole plants within the quadrants as the percentage of plant tissue affected and recorded. Spore numbers for different combinations of severity and incidence are shown in table 1.

		Severity		
		Low (<20%)	**Moderate (20-40%)**	**High (>40%)**
Incidence	**Low (<20%)**	10^{11} spores	$\sqrt{10^{11}}\,\sqrt{10^{12}}$ spores	$\sqrt{10^{11}}\,\sqrt{10^{13}}$ spores
	Moderate (20-40%)	$\sqrt{10^{12}}\,\sqrt{10^{11}}$ spores	10^{12} spores	$\sqrt{10^{12}}\,\sqrt{10^{13}}$ spores
	High (>40%)	$\sqrt{10^{13}}\,\sqrt{10^{11}}$ spores	$\sqrt{10^{13}}\,\sqrt{10^{12}}$ spores	10^{13} spores

Table 1: The total possible spore number that could be released per hectare in a 24-hour period is calculated as a function of recorded survey incidence and severity.

The spore release rate is discussed next.

3.2.3 Spore release rate

In Meyer et al 2017, a constant fraction of daily available wheat rust spores at source locations was released into the atmosphere at a constant rate, over a fixed 6-hour time window between 09:00 and 15:00 local time. In the NAME simulations performed as part of the EWS, the fraction of daily available wheat rust spores released into the atmosphere was varied with time, as a function of the instantaneous wind speed and precipitation rate during the whole of the 24-hour period. Spores are only released if the precipitation rate is less than 2.54 mm h^{-1}, and the rate of release is then dependent on the wind speed at the source. The fraction of spores escaping the canopy is modelled as a two-regime function of wind-speed: linear increase at low wind speeds, and monomolecular-like increase at high wind-speeds (Aylor & Taylor 1983, Geagea et al 1987, Sache 2000 and Smith 1966). The fraction of spores released is given by:

$$
\begin{cases} (0.1/u_{crit}) * u & \text{if } u < u_{crit} \\ 1 - 0.9 \exp(-(u - u_{crit})) & \text{if } u > u_{crit} \end{cases}
$$

where u is the wind speed and u_{crit} is the crticial wind speed at which the transition between the two regimes occurs.

3.2.4 Stem rust and stripe rust

The difference between stem rust and stripe rust species in the NAME simulations for the EWS are that stem rust spores are larger than stripe rust spore, have a lower u_{crit} (hence have a higher release rate for a given speed), and less sensitive to UV radiation. These differences are manifest in the following parameters:

	Stem rust	Stripe rust
Spore diameter (μm)	26	23
Critical wind speed (m s^{-1})	1.5	1.8
UV viability-reduction exponent	-1.1	-2.9

Table 2: Showing parameters used for stem rust spores and stripe rust spores.

3.3 Algorithm to reduce survey volume

During the 2018 main wheat season, individual survey points could not be used for the NAME model as source locations while still producing a timely forecast. It was advised that a maximum of 100 sources could be incorporated into the NAME model. To ensure that 100 source locations would not be exceeded, an algorithm was developed to reduce the number of survey points yet give sources representing all survey points. The key wheat areas were split into 100 polygon areas as shown in figure 2. Only one NAME spore source location per polygon area was allowed. It was checked that the past survey points fell into one of the polygon areas.

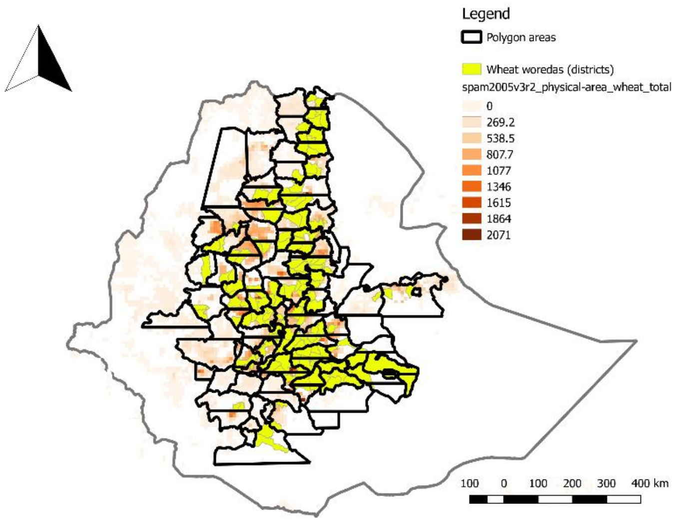


Figure 2: The black outline shows the 100 polygon areas over the main wheat regions in Ethiopia. The circles show the past survey data. The yellow areas show the Wheat districts. The green shading shows the wheat areas estimated in data obtained from MapSPAM (You et al. 2005).

A high number of small polygon areas were placed over the key wheat producing regions to ensure a higher number of NAME spore sources in these important regions.

The ODK survey data were downloaded near to real-time and then the survey points were classified by location into one of the polygon areas. The survey incidence, severity and field area were used to calculate the level of disease for every survey point. The survey point with the highest level of disease was chosen as NAME spore source location. The number of spores released at the NAME source locations; the source strength was calculated by taking the average disease level and this was then multiplied by the wheat area (source: MapSPAM You et al. 2005) found within the polygon area to represent all wheat areas, not only those surveyed. The disease level was then allocated an appropriate number of spores to give the required NAME source strength. This was repeated for all the polygon areas with survey points recording wheat rust.

This algorithm runs every day to incorporate new survey points. If a new survey point with a higher level of disease is observed, the NAME source location would change to the new survey location. If there are two or more locations with equal levels of disease, then the NAME spore source location would be chosen randomly from these survey locations. This could be modified to include further criteria for location choice.

The "switching off" of survey points was also considered. Not all the survey points would continuously contribute to the NAME source, primarily due to the harvest of the wheat. This was taken into account by estimating the number of days until harvest from the ODK survey wheat growth stage data (table 3). Upon the harvest date and thereafter, the level of disease from the "switched off" survey point no longer contributed to the NAME spore source.

Wheat Growth Stage Name	Approximate number of days until harvest
Tillering	110
Boot	60
Heading	50
Flowering	40
Milk	30
Dough	20
Maturity	7

Table 3: Showing the wheat growth stage as recorded in the ODK surveying and the number of days remaining before harvest. When the wheat stage was not given, a value of 40 days was assumed.

3.4 Environmental suitability models

Once a rust spore has been deposited on a susceptible wheat plant, the environmental conditions must be suitable for infection to occur. Wheat will not exhibit symptoms until between 7 and 14 days of infection giving time for the application of fungicides (Tollenaar 1984).

During the 2018 wheat season, environmental suitability models were used for the first time contributing to the EWS. Further details are given in the following subsections.

3.4.1 Stripe rust environmental suitability model

A stripe rust environmental suitability model based on experimental results (de Vallavieille-Pope et al. 2002) was adapted for use in Ethiopia. This predicts the probability of stripe rust infection occurring by spores deposited on a susceptible wheat host. See figure 3 for an example of the weekly averaged environmental suitability for wheat stripe rust. There are two main stages that are represented by the stripe rust environmental suitability model: pre-deposition of the spore and post-deposition of the spore. The first stage relied on sunlight duration in the 24-hours prior to spore deposition. Wheat that received more sunlight were more susceptible to infection than those receiving less, say during a dull, overcast day. The post-deposition of spores relates to the duration of the dew period – how long free moisture was available for spore germination to take place. Infection efficacy was also dependent on temperature during the dew period (de Vallavieille-Pope et al. 2002). This stripe rust environmental suitability model was piloted in 2018 and is undergoing testing and validation.

The overall stripe rust infection efficiency can be calculated from:

$$\mathrm{IE}(L,T,DP) = \mathrm{IE}_{\mathrm{max}} \times \mathrm{RIE}(L) \times \mathrm{RIE}(T) \times \mathrm{RIE}(DP)$$

Where: IE = Infection Efficiency [0,1], $\mathrm{IE}_{\mathrm{MAX}}$ = Maximum Infection Efficiency (for stripe rust this is 42.1%), T = Temperature (^{o}C), L = Light (mol quanta m^{-2}), DP = Dew period (hours), RIE = Relative Infection Efficiency [0,1].

RIE(L) was determined experimentally to give:

$$\mathrm{RIE}(L) = \{1 - \exp[-c(L+d)]\}$$

Where: c = 0.045 and d = -0.065. L is the solar radiation in the 24 hours prior to inoculation. Therefore, analysis UM data for the day before the first day of forecast was required to calculate RIE(L) and this was used to determine the IE for the first forecast day.

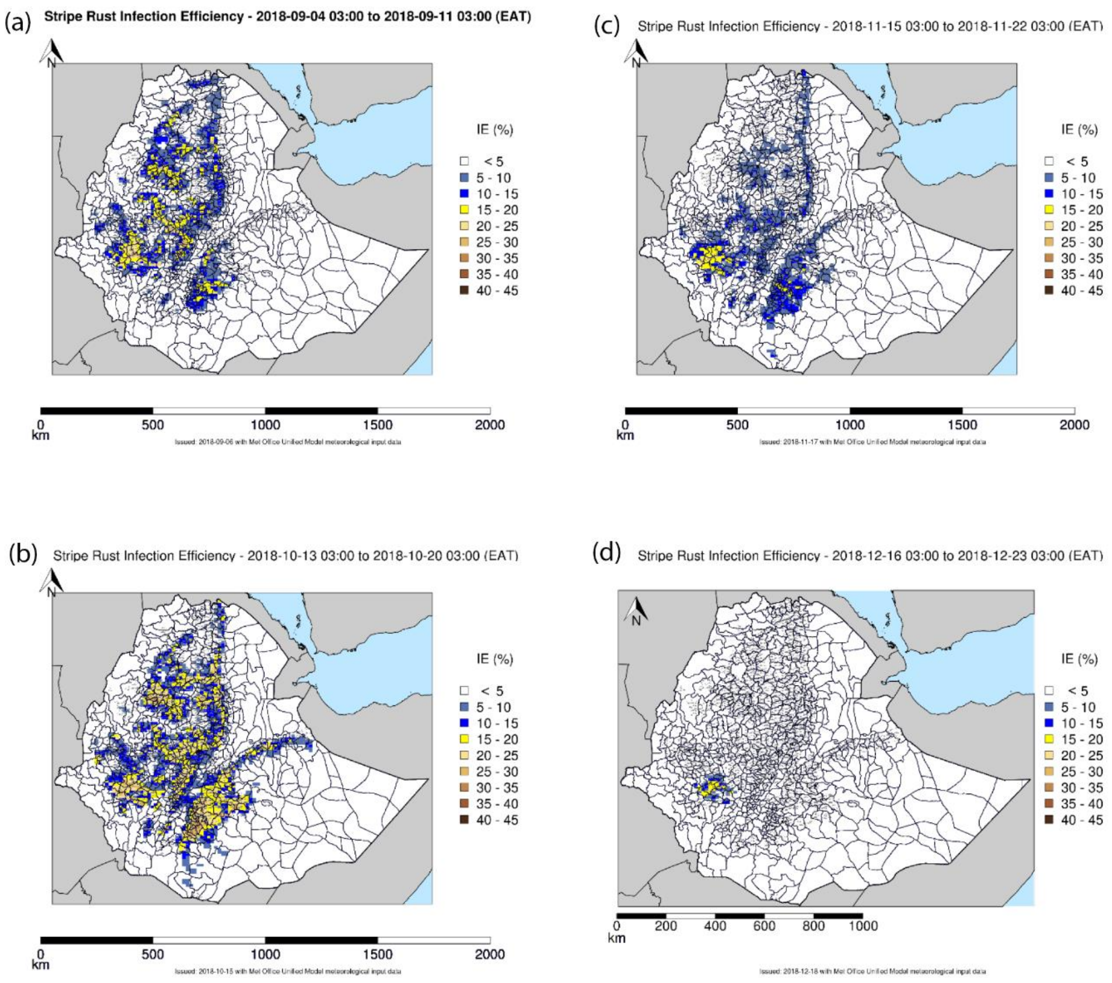


Figure 3: Weekly averaged wheat stripe rust infection efficiency from stripe rust environmental suitability forecast model. These forecasts give the probability of stripe rust infection occurring based on meteorological factors. The maximum infection efficiency that can occur is 45%. This means that 45% of the spores deposited on susceptible wheat plants could complete the infection process. Therefore, a forecast Infection Efficiency of 45% indicates a very high risk of stripe rust infection occurring in susceptible wheat varieties.

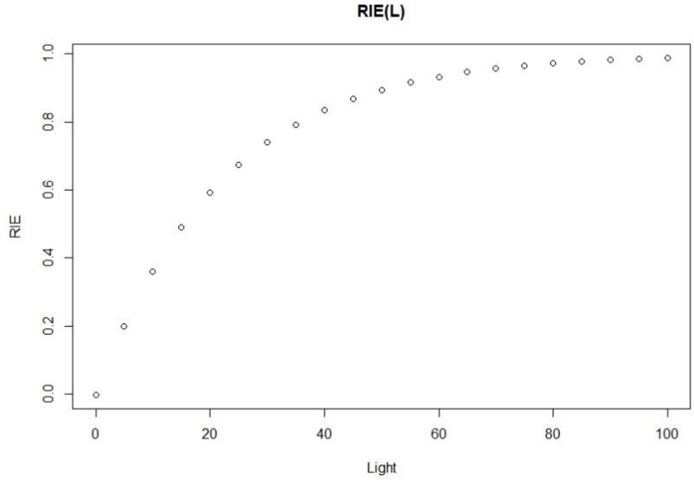


Figure 4: Showing how RIE(L) can vary for different light intensities.

RIE(T) can be calculated by:

$$\mathrm{RIE}(T) = p[(T - T_{\min})/(T_{max} - T_{min})]^n[(T_{max} - T)/(T_{max} - T_{min})]^m$$

Where: n = 0.87, m = 0.41, $p=(n+m)^{(n+m)}/(n^n m^m)$, T_{min} = minimum temperature that infection can occur (for wheat stripe rust this is 2.37 °C), T_{max} = maximum temperature that infection can occur (for stripe rust this is 19.8°C)

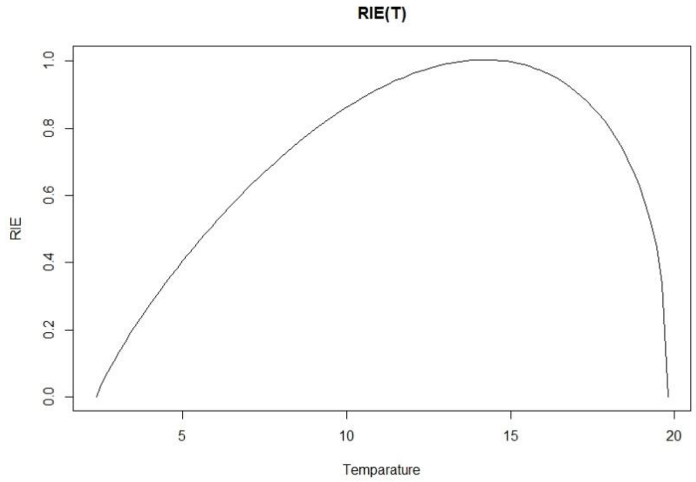


Figure 5: Shows how RIE(T) varies as a function of temperature

RIE(DP) can be calculated by:

$$\mathrm{RIE}(DP) = 1 - \exp\{-b(T)[DP - DP_{\min}(T)\}$$

Where $DP_{min}(T)$ is the minimum dew period necessary for infection at temperature T (which is assumed to be a quadratic function of T) and is shown here:

$$\mathrm{DP}_{\min}(T) = 10.14 - 1.024T + 0.0427T^2$$

While b(T) = initial infection rate (assumed to be a quadratic function of T) and is shown here:

$$b(T) = -0.023 + 0.0246T - 0.00101T^2$$

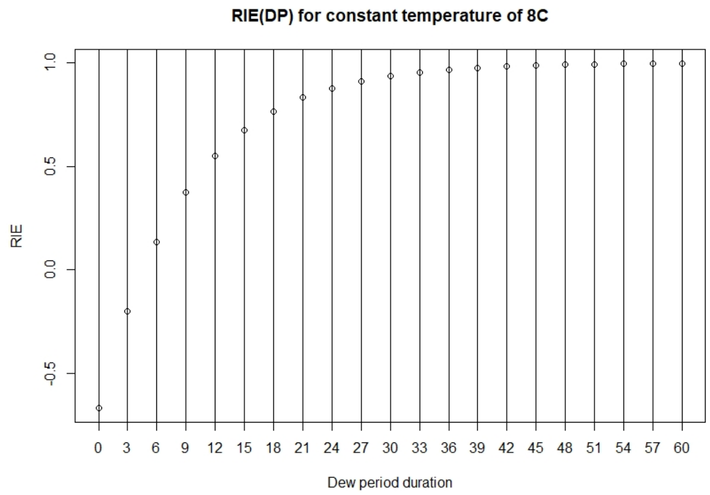


Figure 6: Shows how RIE(DP) varies with different dew period lengths with a temperature of 8°C. This curve changes for different temperatures.

3.4.2 Stem rust environmental suitability model

There was not a published model available that incorporated the many stages of stem rust infection and could be utilised as a forecast model. Therefore, a new environmental suitability model for stem rust was developed at the University of Cambridge. This environmental suitability model predicts the absence or presence of optimal environmental conditions suitable for stem rust infection to occur. It is a mechanistic model and considers 4 stages sequentially taking place for stem rust infection. Once the spore has been deposited on a susceptible wheat variety, the spore enters the pre-germination stage in which the spore requires contact with free moisture for up to 3 hours (Hogg et al 1969, Sharp et al 1958, Burrage 1970). Then the spore can enter the germination stage, where free moisture is essential for the formation of the germ tube, and this optimally occurs in dark or dull conditions (solar radiation ≤ 3200lux), with a temperature range between 15 to 24ºC (Hogg et al 1969, Sharp et al 1958, Burrage 1970). During the third stage, the optimal conditions required are similar to that for germination. This involves the differentiation of a germ tube to produce an appressorium – a specialised fungal organ (Hogg et al 1969, Sharp et al 1958, Burrage 1970). In the final stage, a peg can develop from the appressorium and penetrate through the plant tissue completing infection providing the temperature is higher than that during the appressorium formation and bright sunlight is present (>16000lux) (Hogg et al 1969, Sharp et al 1958, Burrage 1970). The stem rust environmental suitability model was also piloted in 2018 and is undergoing testing and validation.

3.5 ATA communication of agronomic information and phone surveys

To address the many challenges smallholder farmers experience in obtaining pertinent and relevant information/recommendations, the ATA designed, developed, and launched the 8028 Farmers' Hotline. An interactive voice response (IVR) and short message service (SMS) system to disseminate agronomic advice to farmers and DAs year-round. These agronomic best practices are encouraged to be utilized throughout the year and intended to improve the flow of information (1) between stakeholders implementing farmer-targeted interventions, and (2) towards the farmers that these interventions are intended to benefit. This system provides and collects information to farmers and decision-makers in four ways: (1) a call-in automated helpline (2) a push-based alert system using IVR/SMS (3) a helpdesk that allows farmers to ask question and experts to respond to their inquiries (4) an IVR Survey that is pushed to all users of the system and the information is arrogated and shared with experts.

The IVR/SMS system was first piloted in February 2014, in 21 woredas (districts) in the four main regions Oromia, Amhara, SNNPR and Tigray for approximately five months. Following the pilot, the ATA, in collaboration with the MoANR, EIAR and Ethio Telecom, expanded the service nationwide. To date, the system has handled more than 36 million calls from over 4 million registered callers. Users of the system can call into and receive information on a wide range of agricultural activities on all major cereal, pulses and high-value crops. Keypad menu options allow farmers and Development Agents to select their particular areas.

The system's main objective is to ensure that smallholders have real-time and immediate access to pertinent agronomic information, which will help them to make more informed decisions about their farming practices. The hotline is utilised by a range of stakeholders, including policy and decision makers, in the agriculture sector. Smallholder farmers call into the 8028 Farmer Hotline to get information on farming best practices, while federal ministries and regional bureaus send SMS messages to warn smallholders of the occurrence of diseases and pests. Using this "push" functionality, the hotline has helped to alert farmers on the prevalence of crop protection issues such as what rust, maize lethal necrosis disease, and fall army worm in areas affected by these threats.

Additionally, an 8028 Farmers' Hotline helpdesk allows smallholders to get customised information from woreda experts by calling in and leaving voice messages with questions on content that is not covered by the pre-recorded menu options. Nearly 8,000 such questions have received satisfactory responses from woreda experts to date. Lastly, the system contains a survey feature used by Development Agents to collect information that allows for real-time decision making by policy makers.

Lastly, the system contains a survey tool used by DAs to collect information on the occurrence of diseases to provide near-real-time information that the MoALR and the regional, zonal and woreda (district) bureaus can use to inform policy and other decision makers. The information collected from the surveys gives information beyond the field survey locations. The data generated by the EWS and models are then cascaded through MoALR as advisory reports to regional bureaus and research institutes. To date, these reports have been disseminated as alerts via 8028 to more than 500,000 smallholders and 16,000 DAs to ensure that they are sufficiently informed to combat these diseases in a timely manner. As such the 8028 Farmers' Hotline has contributed to mitigating epidemics of wheat rust and stem diseases over the past four years.

Overall, this is the first of its kind in Ethiopia, designed for primary use by smallholder farmers. It represents a shift toward Ethiopian farmers using ICT tools to access agronomic updates and incorporate best practices into their farming. The service is proving to be a timely and cost-effective mechanism to disseminate information and gather critical data for institutions in the agriculture sector.

3.6 Scheduling of the EWS

The implementation of a logistics strategy was essential for the automation of the EWS.
The EWS is spread across the following servers:

- EIARSERVER – where EIAR archives the ODK survey data
- PINE – University of Cambridge worker server
- WILLOW – University of Cambridge public webserver
- MO_SUPER – Met Office supercomputer that runs the UM, NAME and the environmental suitability models.
- MOFTP – Met Office public webserver

See table 4 for further details.

Time (East African Time)	Institution	Action
Continuously	EIAR	Receives data from field surveyors, data available in real-time on EIARSERVER
0200	UNIVERSITY OF CAMBRIDGE	Cambridge pulls survey data from EIARSERVER then on PINE runs Algorithm to identify source locations for NAME from survey data
0215	UNIVERSITY OF CAMBRIDGE	NAME source strengths and locations available WILLOW
0800	MET OFFICE	MO_SUPER completes daily UM run
0815	UNIVERSITY OF CAMBRIDGE - MET OFFICE	MO pulls source data from WILLOW
0820	MET OFFICE	MO uses source strength data and UM forecast met data to run NAME
0820	MET OFFICE	MO uses UM forecast met data to run environmental suitability models
1030	MET OFFICE	MO posts data on MOFTP
1035	MET OFFICE – UNIVERSITY OF CAMBRIDGE	CAM pulls ENV and deposition results from MOFTP
	UNIVERSITY OF CAMBRIDGE	PINE creates plots for environmental suitable and spore deposition forecasts, (In the next EWS version, Cambridge will run the epidemiology model)
1115	UNIVERSITY OF CAMBRIDGE	CAM posts data on WILLOW
1130	UNIVERSITY OF CAMBRIDGE – EIAR – CIMMYT	EIAR and CIMMYT pull results from WILLOW

Table 4: The scheduling of data flow between the EWS organisations

4. Wheat Rust Advisory from 22 November 2018

The following is an example a Wheat Rust Advisory issued 22nd November 2018.

Wheat Rust Advisory No. 8
22 November 2018

Wheat Rust Advisory – risk assessment of wheat rust outbreaks and spread in Ethiopia

Summary Period: 22 October - 21 November 2018

Summary:

- Most wheat growing areas are now at or getting close to harvest, with the exception of late planted areas (Belg growing areas e.g., Bale etc).
- **Recent surveys in Oromia (Holeta, Ambo, Bako, Kulumsa, Sinana) indicate that both stem and stripe rust are prevalent in most of the areas surveyed.** In Holeta surveys stem rust was present in 39% of survey fields and stripe rust in 75%. In Ambo surveys stem rust was present in 94% of survey fields and stripe rust in 30%. In Sinana surveys stem rust was present in 68% of survey fields and stripe rust in 95%. In Bako surveys stem rust was present in 92% of survey fields and stripe rust in 84%. In Kulumsa surveys stem rust was present in 25% of survey fields and stripe rust in 34%.
- Northern areas based on available survey data appear to have relatively lower rust pressure, especially stem rust but stripe rust was present in pocket areas in Amhara
- Environmental/climate suitability forecasts for stripe rust infection (Cambridge Uni/UK Met Office) are now showing much lower risk of infection, due to the cessation of rains.
- Dispersal models indicate a west to south-westerly dispersal direction with Bale/Arsi/West Arsi, SNNPR and east Wellega likely to have the highest spore deposition. into SNNPR highlands from known infected sites in Bale/Arsi. Based on previous years it is likely that these dispersal patterns will continue.

Recommendation:

- **In any late planted areas in Oromia/SNNPR there is a continuing risk, especially stem rust outbreaks. Highest risk areas are in Bale, West Arsi, Arsi (e.g., Arsi Robe, Sude) and SNNPR (late planted areas). Control should be undertaken in areas with emerging rust infections. Other at risk areas should be monitored closely and control undertaken if needed on susceptible varieties.**
- **Awareness should be raised amongst stakeholders at all levels, including farmers, to be vigilant for appearance of rusts (both stripe and increasingly stem rust)**
- **Control should be considered if susceptible varieties are grown and disease is present (>10-20% of leaf / stem area infected). Early control to stop increased spread and further build-up of disease is very important.**
- Sampling of both stem and stripe rust should be undertaken to determine races present.

Overall Risk Level: Caution: local **HIGH**

Wheat Rust Advisory No. 8
22 November 2018

Field Surveys:

Maps 1 & 2 summarize all the Meher season survey data reported to date. These surveys cover the period 10th August to 21st November 2018. These are updates of surveys since the last advisory.

Tigray:

No new updates

Amhara:

No new updates

Oromia:

Holeta: A total of 61 fields were surveyed during the period 23-30 Oct 2018. Stem rust was observed in 24 of the fields (39%), with moderate / high incidence in 16 of these fields. High severity was observed in 6 fields – up to 90S on Kubsa; with Alidoro, Kakaba and Danda'a also susceptible. Stripe rust was observed in 46 fields (75%), with moderate/high incidence in 31 fields. Highest severity was 80S on both Digalu and Danda'a.

Ambo: A total of 33 fields surveyed during the period 31st Oct – 2nd Nov. Stem rust was observed in 31 of the fields (94%), with moderate/high incidence in 7 of the fields. Highest severity was 40S on Danda'a. Stripe rust was observed in 10 of the fields (30%), with moderate/high incidence in 3 fields. Highest severity was 70S on Digalu. Crops were mainly at dough to maturity stage.

Sinana: A total of 22 fields were surveyed during the period 20th Oct to 8th Nov 2018. Stem rust was observed in 15 fields (68%), with moderate/high incidence in 2 fields. Highest severity was 40S on Hidasie. Stripe rust was observed in 21 fields (95%), with high incidence in 13 fields. Highest severity was 60S on Ogolcho. Crops were mainly at flowering to milk stage.

Bako: A total of 25 fields were surveyed during the period 21-22 Nov 2018. Stem rust was observed in 23 fields (92%), with moderate/high incidence in 13 fields. Highest severity was 60S on unknown variety. Stripe rust was observed in 21 fields (84%), with high/moderate incidence in 18 fields. Highest severity was 80S on Digalu. Crops were mainly at dough stage.

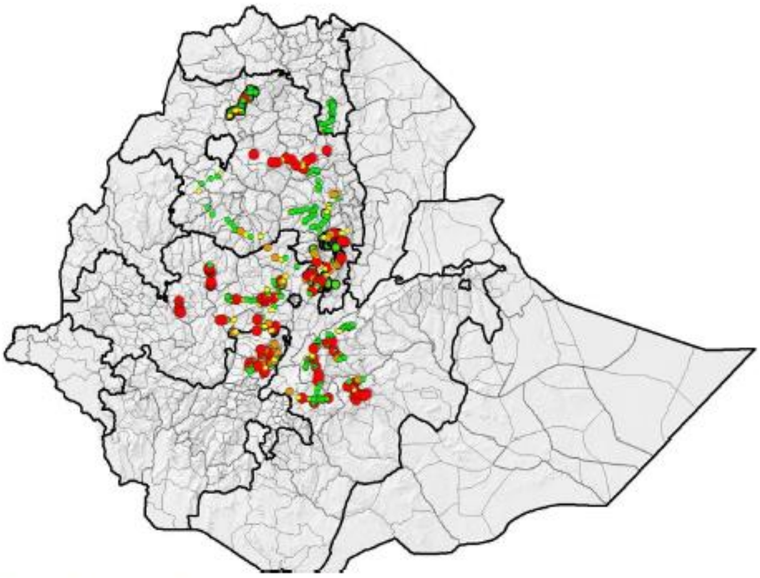
Kulumsa: A total of 107 fields were surveyed during the period 9-29th Oct 2018. Stem rust was observed in 27 fields (25%), with moderate/ high incidence in 4 fields. Highest severity was 40S on Hidasie. Stripe rust was observed in 36 fields (34%), with moderate/high incidence in 19 fields. Highest severity was 50S on Kubsa and an unknown variety. Crops were mainly at flowering to dough stage.

SNNPR:

No updated reports

Wheat Rust Advisory No. 8
22 November 2018

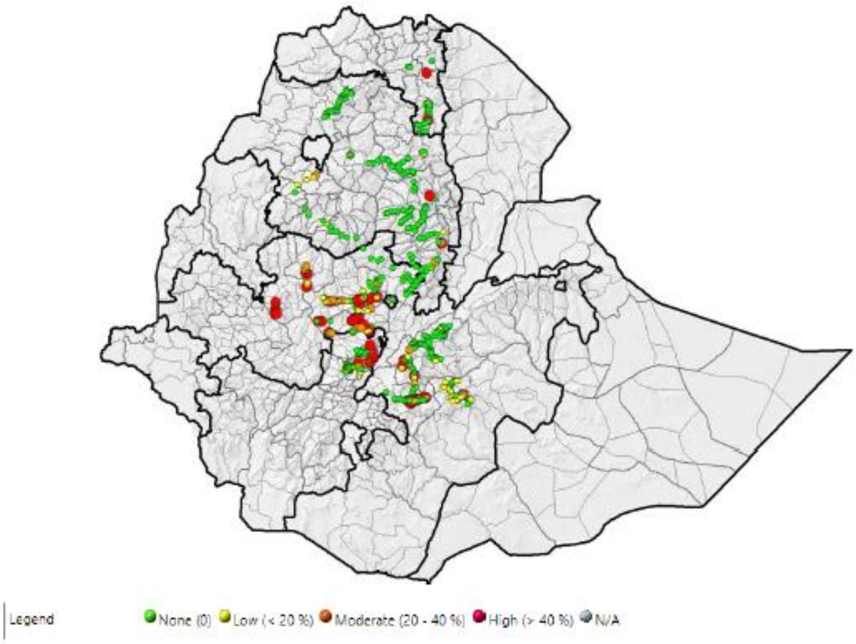
Map 1. Stripe Rust Incidence Meher season surveys (to 21st Nov 2018)



Legend None (0) Low (< 20 %) Moderate (20 - 40 %) High (> 40 %) N/A

Wheat Rust Advisory No. 8
22 November 2018

Map 2. Stem Rust Incidence Meher season surveys (to 21st Nov 2018)



Rust Races Present:

Stem Rust: Initial analysis by the Ambo group on 73 samples have detected 5 races – TKTTF (n=23), TTTTF (22 samples), TKKTF (22 samples), TTRTF (4 samples), and TTKTF (2 samples). Further race analysis is on-going.

Race TKKTF is emerging as a dominant race. This race is being detected on Hidasie.

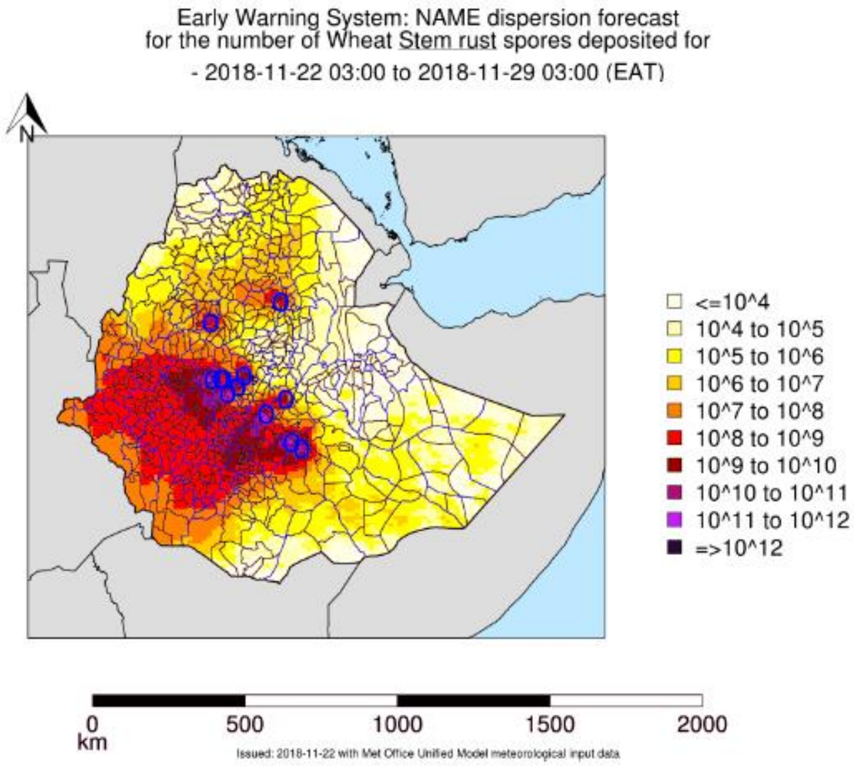
Dispersal Forecast:

Most recent dispersal forecasts (22-29th Nov) run by the UK Met Office and Cambridge University are displayed. The most recent source locations are included for both stem and stripe rust.

Stem rust: for the period 22-29 November (Map 3A) the dispersal pattern is towards south-west with the majority of spore deposition occurring in Bale / Arsi / West Arsi, SNNPR, West Shewa/SW Shewa/Eats Wellega. Based on previous years, it is highly likely that this south-westerly dispersal from Bale will continue.

Wheat Rust Advisory No. 8
22 November 2018

Map 3A: Stem rust weekly dispersal pattern 22-29th Novenber 2018

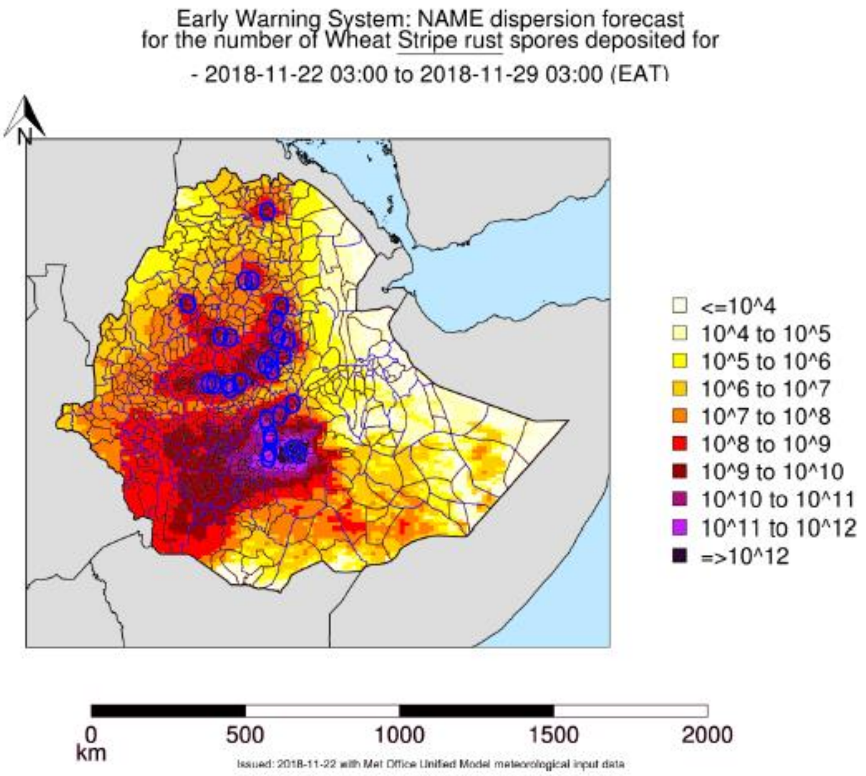


NB. Map shows estimated total of number of spores deposited. Darker colours represent higher deposition.

Wheat Rust Advisory No. 7
23 October 2018

Stripe Rust: for the period 22-29th November (Map 3B) most source locations showed a westerly / south-westerly trend in dispersal. Highest spore deposition was in Bale/Arsi/West Arsi and SNNPR.

Map 3B: Stripe rust weekly dispersal pattern 21-28th October 2018



NB. Map shows estimated total of number of spores deposited. Darker colours represent higher deposition

NB: It cannot be discounted that additional rust sources are present in other parts of Ethiopia, but have not been reported

5. References

Aylor D and Taylor G 1983 Escape of Peronospora tabacina spores from a field of diseased tobacco plants. *Phytopathology* **73** 525–529

Beddow J M, Pardey P G, Chai Y, Hurley T M, Kriticos D J, Braun H-J, Park R F, Cuddy W S, Yonow T 2015 Research investment implications of shifts in the global geography of wheat stripe rust *Nature Plants* **1** 15132 de Vallavieille-Pope C, Huber L, Leconte M, Bethenod 2002 Preinoculation Effects of Light Quantity on Infection Efficiency of *Puccinia striformis* and *P. tritica* on Wheat Seedlings *Phytopathology* **92** 1308

Geagea et al 1997 Removal of urediniospores of brown (*Puccinia recondite* f. sp. *tritici*) and yellow (*P. striiformis*) rusts of wheat from infected leaves submitted to a mechanical stress. *European Journal of Plant Pathology* **103** 9 785–793

Hau B, de Vallavieille-Pope C 2006 *The Epidemiology of Plant Diseases.* Wind-dispersed diseases. ed B Cooke, D Jones, B Kaye (Springer, Dordrecht)

Hogg W H, Hounam C E, Mallik A K and Zadoks J C 1969 Meteorological factors affecting the epidemiology of wheat rusts. WMO, Tech. Note 99, 1–143

Jones A, Thomson D, Hort M and Devenish B 2007 The UK Met Office's next generation atmospheric dispersion model, NAMEIII *Air Pollution Modelling and its Application* ed C Borrego and A-L Norman (Springer) 580-589

Meyer M, Burgin L, Hort M C, Hodson D P and Gilligan C A 2017 Large scale atmospheric dispersal Simulations identify likely airborne incursion routes of wheat stem rust into Ethiopia. *Phytopathology* **107** 1175–1186.

Murray F W 1967 On the Computation of Saturation Vapor Pressure *Journal of Applied Meteorology* **6** 203-204

Nagarajan S and Singh D V 1990 Long-distance dispersion of rust pathogens *Annu. Rev. Phyopathol.* **28** 139-153

Paltridge G W and Proctor D 1976 Monthly mean solar radiation statistics for Australia *Solar Energy* **18** 235-243

Roelfs A P, Singh, R P and Saari, E E 1992 ‘‘Rust Diseases of Wheat: Concepts and Methods of Disease Management.’’ CIMMYT, Mexico, D.F.

Rogers R R and Yau M K 1989 A Short Course in Cloud Physics (International Series in Natural Philosophy)

Sache I 2000 Short-distance dispersal of wheat rust spores by wind and rain. *Agronomie-Sciences des Productions Vegetales et de l'Environnement* **20**, 7 757–768.

Sentelhas P C, Dalla Marta A, Orlandi S, Santos E A, Gillespie T J, Gleason M L 2008 Suitability of relative humidity as an estimator of leaf wetness duration *Agricultural and Forest Meteorology* **148** 392-400

Smith, R S 1966 The liberation of cereal stem rust uredospores under various environmental conditions in a wind tunnel. *Transactions of the British Mycological Society* **49** 33–41

Tollenaar H 1984 Uredospore Germination and Development of Some Cereal Rusts from South-central Chile at Constant Temperatures *Phtopath. Z.* **114** 118-125

Wellings C R 2011 Global status of stripe rust: a review of historical and current threats *Euphytica* **179** 129-141

You L, Wood-Sichra U, Fritz S, and See L 2005 Spatial production allocation model (SPAM) 2005. v2.0 Available on-line at: www.mapspam.info.

Young S A 1977 Quantitative epidemiology of stripe rust (*Puccinia striiformis* West.) in wheat cultivars (Triticum aestivum Vill.) with general resistance. PhD thesis, Oregon State University