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Abstract

Wheat rust diseases pose one of the greatest threats to global food security, including subsistence farmers in Ethiopia. The fungal spores transmitting wheat rust are dispersed by wind and can remain infectious after dispersal over long distances. The emergence of new strains of wheat rust has exacerbated the risks of severe crop loss. We describe the construction and deployment of a near real-time early warning system (EWS) for two major wind-dispersed diseases of wheat crops in Ethiopia that combines existing environmental research infrastructures, newly developed tools and scientific expertise across multiple organisations in Ethiopia and the UK. The EWS encompasses a sophisticated framework that integrates field and mobile phone surveillance data, spore dispersal and disease environmental suitability forecasting, as well as communication to policy-makers, advisors and smallholder farmers. The system involves daily automated data flow between two continents during the wheat season in Ethiopia. The framework utilises expertise and environmental research infrastructures from within the cross-disciplinary spectrum of biology, agronomy, meteorology, computer science and telecommunications. The EWS successfully provided timely information to assist policy makers formulate decisions about allocation of limited stock of fungicide during the 2017 and 2018 wheat seasons. Wheat rust alerts and advisories were sent by short message service and reports to 10 000 development agents and approximately 275 000 smallholder farmers in Ethiopia who rely on wheat for subsistence and livelihood security. The framework represents one of the first advanced crop disease EWSs implemented in a developing country. It provides policy-makers, extension agents and farmers with timely, actionable information on priority diseases affecting a staple food crop. The framework together with the underpinning technologies are transferable to forecast wheat rusts in other regions and can be readily adapted for other wind-dispersed pests and disease of major agricultural crops.

1. Introduction

Wheat is the most widely grown crop in the world and is globally responsible for 20% of humanity's daily

calories and protein (Shiferaw *et al* 2013). One key risk to global wheat production are losses caused by crop diseases. Among all wheat diseases, the fungal rusts (stem, stripe and leaf rust) are the most important

(Saari and Prescott 1985). Wheat rust fungi produce vast number of spores that can be dispersed by wind over long distances (Meyer *et al* 2017a, 2017b, Visser *et al* 2019). Devastating epidemics can occur over vast areas within a matter of weeks (Leonard 2001).

Ethiopia is the largest wheat producer in sub-Saharan Africa with 1.7 million ha and more than 4.2 million households relying on rain-fed wheat (CSA Central Statistics Agency 2018). Wheat rusts pose one of the key biotic constraints to production in Ethiopia (Bekele 1986). Over the last decades recurrent wheat stem and stripe rust epidemics have reduced wheat yield in Ethiopia. In 2010, a major stripe rust epidemic occurred, affecting approximately 600 000 ha (Singh *et al* 2015). More recently, in 2013/2014, approximately 40 000 ha were infected with wheat stem rust (Olivera *et al* 2015).

The Ethiopian Highlands have long been known as hot spots for wheat rusts (Saari and Prescott 1985). Conducive climatic conditions plus near-continual wheat production are key factors. In the core wheat growing areas of Bale and Arsi, bimodal rainfall patterns permit two wheat seasons per year. This results in a green-bridge allowing the disease to bulk-up locally transferring inoculum from one wheat season to the next and therefore increasing the occurrence of rust epidemics (Zadoks and Bouwman 1985, Bekele 2003). At least two damaging stem rust epidemics have occurred in Arsi/Bale in recent decades - in 1993/1994 on the variety Enkoy (Shank 1994) and in 2013/2014 on the variety Digalu (Olivera *et al* 2015).

The most effective, long-term method of controlling wheat rust diseases is by breeding rust resistant wheat cultivars (Dubin and Brennan 2009, Tadesse 2011). However, in the absence of effective resistance, fungicides are used to control the spread of rust disease.

Fungicide use in Ethiopia is low compared with intensive agriculture systems like western Europe (Singh *et al* 2016). However, increases in on-farm wheat yields, the availability of more affordable fungicides and increasing farmer awareness of wheat rusts are contributing to increasing use of fungicides in Ethiopia. Disease early warning systems (EWSs) that could help to optimise the efficient use of limited fungicides and prioritise the growing of resistant cultivars are seen to be important in the context of smallholder wheat farmers in Ethiopia.

Here we present the development and operationalisation of an EWS to predict and mitigate wheat rust diseases in Ethiopia through the coupling of existing research infrastructures, the development of new tools and the utilisation of expertise across many organisations. The EWS incorporates field and mobile phone survey data, spore dispersion and disease environmental suitability forecasting, as well as communication to policy-makers, advisors and smallholder

farmers through wheat rust advisories and short message service (SMS) wheat rust alerts.

2. Methods

2.1. The EWS project partners

This project could not have been achieved by any one individual organisation. Expertise and environmental research infrastructures from within the cross-disciplinary spectrum of biology, agronomy, telecommunications, meteorology and computer science, were required. This was achieved through collaboration of six organisations, namely the Ethiopian Institute of Agricultural Research (EIAR), the Ethiopian Ministry of Agriculture and Livestock Resources (MoALR), Ethiopian Agricultural Transformation Agency (ATA), the International Maize and Wheat Improvement Center (CIMMYT), the UK Met Office and the University of Cambridge.

2.2. The EWS components

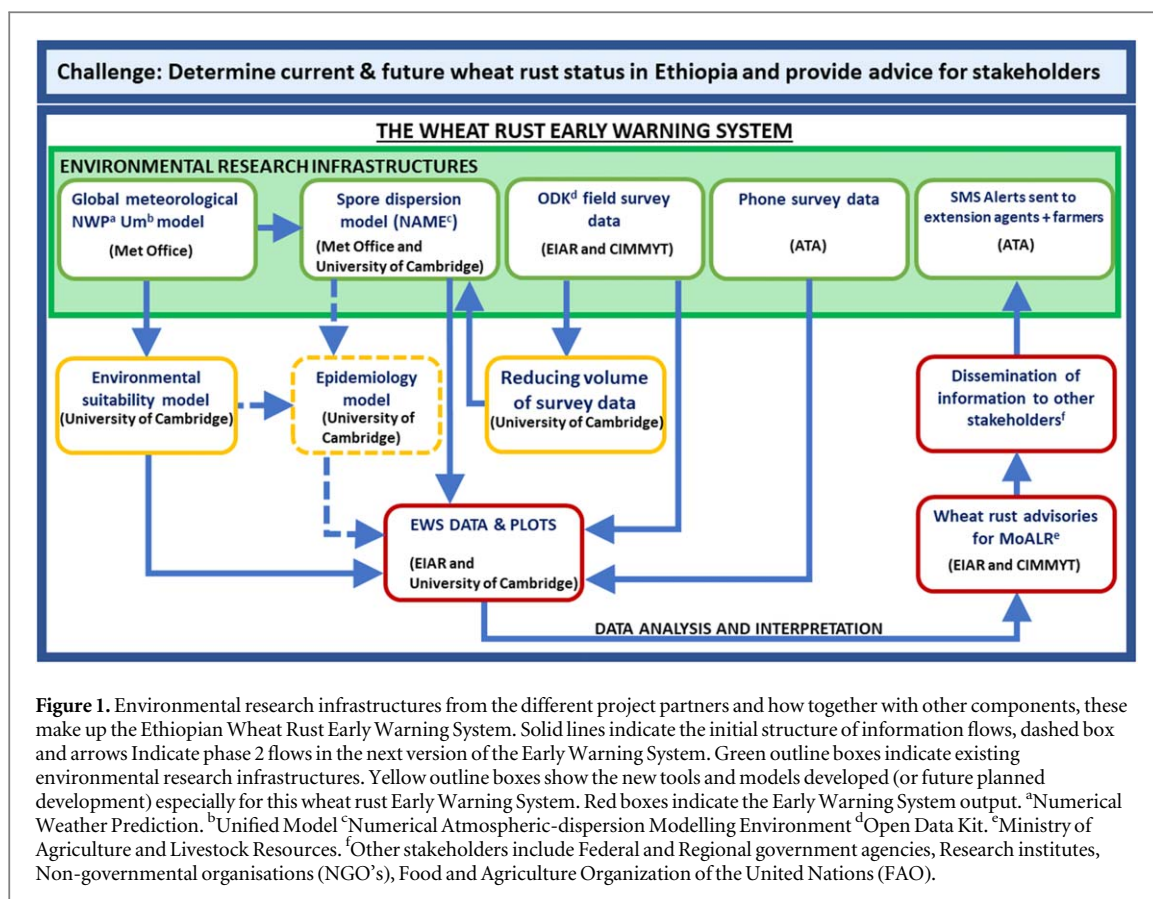
The EWS builds upon comprehensive rust surveillance activities undertaken in Ethiopia over the last ten years and a pilot study that developed 7 day wheat stem rust spore dispersion forecasts for Ethiopia during 2015 and 2016. The spore dispersion model used in the pilot study was improved over two succeeding years of full-scale trials when the model was also extended to include wheat stripe rust.

The EWS framework described in this paper has seen several important innovations developed and incorporated for the 2018 Ethiopian wheat season. These included extending existing smartphone technology for surveying rust diseases in Ethiopian wheat fields through new training programmes, together with the development of a novel algorithm to reduce the volume of near-real time survey data to provide timely representative spore source locations and strengths for the dispersion model forecasts. We developed a meteorologically-based suitability criterion for stem rust infection. The short messaging service (SMS) capabilities of the Ethiopian Farmers' Hotline were also extended to disseminate wheat rust alerts to thousands of farmers and extension agents.

The EWS framework is summarised in figure 1 and the EWS components are outlined below. Additional details are included in the supplementary information (SI) and is available online at stacks.iop.org/ERL/14/115004/mmedia.

2.2.1. Open data kit (ODK) field surveying

Wheat rust disease surveys (~1000 fields) are undertaken by expert pathologists using standardized survey methods (Ali and Hodson 2017). Surveys encompass the short rain season (Belg), early- and late-main (Meher) seasons. Survey data were originally recorded using GPS, pen and paper and later digitised with consequent delays and transcription errors in the



availability of recorded data. A smartphone-based ODK app was introduced during 2017 to provide near-real-time transfer of survey data from the field to a dedicated server housed at EIAR headquarters. Use of the ODK app was expanded in 2018 through training provided by experts from EIAR and CIMMYT. The survey data show current rust status and provide source locations for the spore dispersion model.

2.2.2. ATA mobile phone platform

To address the many challenges smallholder farmers experience in obtaining pertinent and relevant information/recommendations, ATA designed, developed, and launched the 8028 Farmers' Hotline in 2014. This interactive voice response (IVR) and SMS system enables the dissemination of agronomic advice to farmers and development agents (DAs) year-round. Following launch in 2014, over 4.1 million farmers and extension agents have registered with the system and more than 35 million calls have been logged. The 8028 Hotline supports the EWS initiative by providing a means to 'push' warnings to extension agents and directly to large numbers of smallholder farmers. The system now contains a survey tool used by extension agents to collect information on the occurrence of diseases to provide near-real-time information that the MoALR, regional and zonal bureaus and woreda (district) offices can use to inform policy and other decision makers. The wheat rust phone surveys gave

additional information about the presence of wheat rust beyond field survey locations.

For further details of the mobile phone platform, see section 3.5 in the SI.

2.2.3. Meteorological data from the UK Met Office's Unified Model (UM)

The spore dispersion and environmental suitability models require meteorological input from the UK Met Office operational numerical weather prediction (NWP) model, the Unified Model (UM), (Walters *et al* 2019). We use the forecast from the global configuration of the UM, which provides three-dimensional data at 3-hourly time intervals, up to seven days from the time of forecast initialisation on a grid with a horizontal spacing of approximately 10 km. Further details can be found in section 3.1 of the SI.

2.2.4. The Numerical Atmospheric-dispersion Modelling Environment (NAME) model

NAME is a Lagrangian model that predicts the dispersion and deposition of particles through the atmosphere (Jones *et al* 2007). NAME is used in an emergency response and research capacity by many different organisations to predict the dispersion of a range of atmospheric material, for example, volcanic, nuclear, chemical, and more recently biological particles. In previous work, NAME was adapted to simulate long-distance dispersal of wheat stem rust spores, accounting for processes that affect the viability of

stem rust spores during dispersion (Meyer *et al* 2017a, 2017b, Visser *et al* 2019). The model configuration was extended to also include stripe rust for the EWS. Furthermore, we have improved the source strength parameterisation to include dynamic order of magnitude estimates of spore release rates. Details of the NAME model setup for wheat rust spores are given section 3.2 in the SI.

2.2.5. Algorithm to identify source locations for NAME from survey data

As the wheat season progresses, the number of field survey locations increases. Including all survey locations as spore source locations in the NAME model would be computationally infeasible. Prior to 2018, representative locations were manually selected from the survey data. For the 2018 wheat season, a new algorithm was developed and tested to determine representative source strengths and locations by utilising the ODK survey observations. This is the first application of any type in which NAME has used near real-time survey data to estimate source locations and strengths for atmospheric dispersion forecasts.

A maximum of 100 source locations was set by computational limits while still being deemed appropriate for the provision of effective wheat rust spore dispersion forecasts. To ensure this cap of 100 source locations was not exceeded, 100 polygon areas were chosen in key wheat growing areas (see figure 2 in the SI). One source location was calculated for each polygon area. For each polygon area, the survey point location likely to produce the largest number of spores, as determined by disease severity, disease incidence and field size, was chosen as the source location for the NAME model. The maximum possible number of spores released over 24 h (occurring during optimal meteorological conditions—see in the SI section 3.2.2 for further details) was based on an average of all survey points (positive and negative) within the polygon area and scaled up based on the wheat area from MapSPAM (You *et al* 2005). This was repeated for each polygon and each disease. Positive survey points stopped contributing to the NAME source strength from harvest onwards, as estimated from the wheat growth stage recorded during the survey.

This process was repeated every day to incorporate the latest survey data to ensure the NAME dispersion model forecast ran with the most representative spore source locations. For further details, please refer to section 3.2 in the SI.

2.2.6. Environmental suitability models

During the 2018 season, environmental suitability models were introduced to assess the probability of infection at deposition sites.

For assessing environmental suitability for infection with wheat stripe rust, a previously developed model based on experimental results (de Vallavieille-Pope *et al* 1995, 2002) was adapted for use in Ethiopia.

The model takes account of pre-deposition (duration of sunlight prior to spore deposition) and post-deposition conditions (temperature and duration of dew period, i.e. period when free-moisture is available for spore germination to take place). For further details, please refer to section 3.4.1 in the SI.

For assessing environmental suitability for infection with wheat stem rust, a new model was developed based on an extensive literature review of previous laboratory and field experiments. The model includes different stages of infection (pre-germination, germination, appressorium formation, penetration) and each stage requires specific environmental conditions which include moisture availability, differing temperature thresholds and lighting conditions (Sharp *et al* 1958, Hogg *et al* 1969, Burrage 1970). For further details please refer to section 3.4.2 in the SI. The environmental suitability models were piloted in 2018 and are undergoing testing and validation.

2.2.7. EWS dissemination of information

Daily forecasts for dispersion and environmental suitability for infection of wheat stem and stripe rust are calculated on high-performance computing resources available at the UK Met Office and the University of Cambridge. Experts in Ethiopia from CIMMYT and EIAR continuously analyse and interpret the 7 day model forecasts as well as the surveillance data throughout the wheat season for assessing the current and future risks of disease. Wheat rust advisories summarise and synthesise the information to give recommendations of action and an overall wheat rust alert level. The advisories are distributed to key stakeholders on a fortnightly basis, including policy makers in the MoALR, as well as Federal and Regional government agencies, Research institutes, Non-governmental organisations (NGO's), and the Food and Agriculture Organization of the United Nations (FAO).

The information and warnings from the wheat rust advisories are used to catalyse actors at the various administrative boundaries to address the issues in their respective regions, zones, and woredas. There are instances where regions disseminate this information to their zones and woredas to address the issues directly, and there are also instances where regions will instruct ATA to broadcast alerts and warnings to affected areas on how to identify, treat, and prevent further spread of disease.

Federal ministries and regional bureaus send SMS messages using the ATA's IVR/SMS system to warn smallholders of the occurrence of diseases and pests. Using this 'push' functionality, the IVR/SMS system has helped to alert over 2 million farmers on the prevalence of crop protection issues such as wheat rust, maize lethal necrosis, and fall armyworm in areas affected by these threats.

An example of a wheat rust advisory taken from 22 November 2018 is available in section 4 of the SI.

2.3. The EWS logistics

A successful logistics strategy is critical for a complex EWS involving several organisations with interlinking environmental research infrastructures (figure 1). Many of the EWS components ran automatically every day through the wheat season. The latest ODK survey data were downloaded and representative NAME source locations were calculated. Then, once the UM had completed the global forecast run, the NAME spore dispersion and the environmental suitability forecasts were run. All forecast images were plotted using R (R Core Team 2019) and simple parallelisation on servers was achieved using GNU parallel (Tange 2011). Data sourced from each institution were placed on individual web servers hosted by the data provider. All other organisations had access to acquire the data by file transfer protocol. Automated scheduling of data transfer and running the different EWS components was handled by the operating command Cron. Phone survey results were distributed to all organisations on a weekly basis. Experts in Ethiopia continuously evaluated the surveillance and modelling data and wheat rust advisories were distributed to key stakeholders every fortnight.

Further details of the data flow schedule can be found in the SI section 3.6 and table 4.

3. Results

The EWS was achieved through successful collaboration and a well implemented logistics strategy resulting in the daily automation of forecast data and output plots. Fortnightly wheat rust advisory reports were produced that integrated disease intelligence from field surveys and forecast models to produce risk assessments for all wheat growing areas in Ethiopia. The wheat rust advisories provided actionable and timely recommendations which were distributed to a wide range of stakeholders, and examples of recommendations can be seen in table 1. Where there were serious risks of outbreaks, wheat rust alerts were widely disseminated amongst many stakeholders. Dissemination was coordinated by policy makers in the Ministry of Agriculture and Livestock Resources (MoALR) as well as other federal and regional government agencies, research institutes, and non-governmental organisations. These stakeholders subsequently disseminated the EWS information to an estimated 150 000 smallholder farmers and extension agents in core wheat areas: Arsi, West Arsi and Bale in 2018. The phone technology also pushed SMS wheat alerts out to 10 000 extension agents and 125 000 smallholder farmers during the 2018 wheat season.

The EWS framework relied on the success of each component. There was progressive updating and improved integration of the components during 2017 and 2018. Field surveys started during the Belg-wheat season, from 20th June 2018 and finished towards the

main wheat season harvest on 24th November 2018. This was the second year that the ODK app was used by EIAR and CIMMYT for recording wheat rust disease in Ethiopia. This replaced paper-based records which required digitisation, often delayed till near the end of the season. Training in use of the ODK app was given before the wheat season, and consequently, the uptake of the app was very successful with 71% (681/959) of the survey observations recorded by the ODK app in 2018, compared to only 16% (284/1759) of observations in 2017.

Coincident with the increase in availability of near real-time field observations was the automation of representative source strengths for the dispersion forecast model first available in 2018.

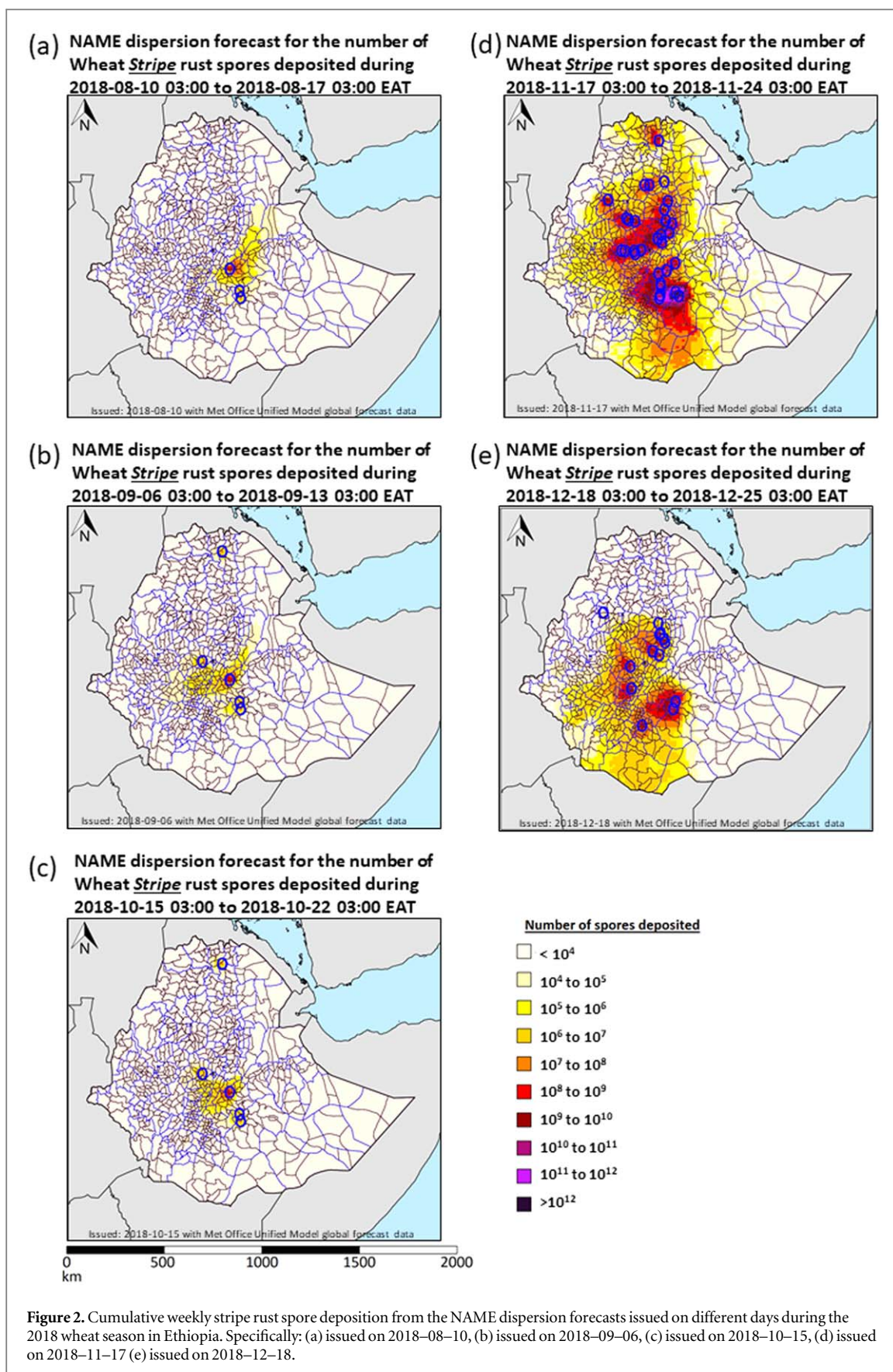
In 2017 as a pilot, the ATA broadcasted more than 340 000 surveys to approximately 20 000 DAs, who were neither trained or explicitly instructed on this initiative. The response rate from the 2017 surveys was approximately 25%. In 2018, the phone surveys were pushed out to trained extension agents from 18th September to 18th December 2018. Over 9000 respondents were targeted in the phone surveys, with approximately 300 experts receiving direct instruction and training, and approximately 3000 receiving very basic training on the use of the phone survey tool. The response rate increased to over 35% for all respondents, whilst the trained experts' response rate was nearly 44%.

Originally developed for stem rust, the dispersion model was adapted for stripe rust during 2017 and 2018, indicating the potential flexibility of the framework to incorporate new pathogens. Important differences included spore characteristics for the dispersal model and different criteria for environment suitability for infection for the two rust species. The combined effect of these changes is to introduce greater realism in the spore forecasting component while retaining tractability and relevance. The spore dispersion forecasts ran successfully from June to December 2018, and the environmental suitability forecasts were operationalised from September to December 2018. By the end of 2018, there was an efficient pipeline for integrating survey data, model predictions using detailed weather forecast data, reporting and dissemination of information.

A total of 8 wheat rust advisories were widely distributed between early August and mid-November 2017. Overall, 18% of surveyed fields were reported to have high to moderate levels (both incidence and severity) of stripe rust with only 3% of fields recording high or moderate levels of stem rust. Outbreaks of both stripe rust and stem rust occurred during the 2018 season with approximately 17% and 11% of surveyed fields reporting moderate to high stripe and stem rust, respectively. The dispersal models showed a high risk of stem and stripe rust dispersal over extensive areas in 2018, eliciting wide-scale dissemination of 11 wheat rust advisories that year.

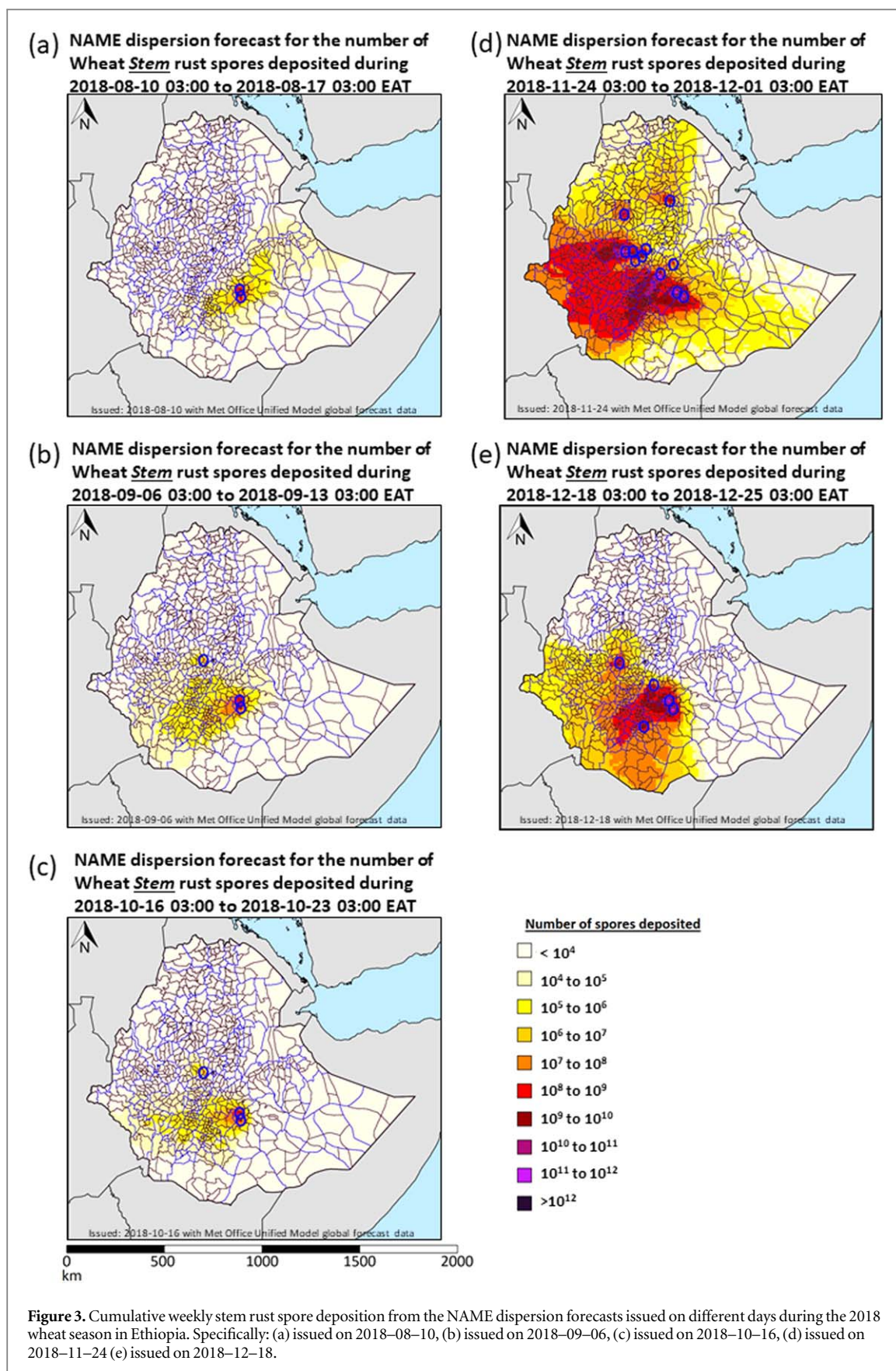
Table 1. Examples of summaries, recommendations and overall risk level from the wheat rust advisories issued during the 2018 wheat season in Ethiopia.

Summary period	Summary	Recommendations
20 July–8 August 2018	<p>Belg season survey in Arsi Zone (Arsi Robe, Diksis, Lude Hitosa, Sire, Jeju, Guna, Merti) indicated high prevalence of yellow [stripe] rust. No stem rust was reported in Arsi surveys. In some fields severity of yellow [stripe] rust was as high as 80MSS. This is an additional source of inoculum for the main season crop.</p>	<p>Field scouting for early appearance of rusts in emerging Meher season crops is critical. Emerging wheat crops in West Arsi, Arsi and Bale zones are the highest priority areas, but other regions should be alerted for the early appearance of rusts and undertake surveillance.</p>
<i>Overall risk level: Caution: HIGH</i>	<p>Dispersal model forecasts indicate that susceptible wheat crops in Bale zone, West Arsi, Arsi and are at highest risk from known rust infected sites in Bale and Arsi zones. Some dispersal into and across the Rift Valley into Southern Nations, Nationalities, and Peoples' Region (SNNPR) is also likely.</p> <p>Varieties with some degree of susceptibility to known stem and stripe rust races are likely to be grown.</p> <p>Weather conditions, current and forecast, are extremely favourable for rust development.</p> <p>There is a very high risk of rust outbreaks on susceptible varieties in the Meher season.</p>	<p>Awareness should be raised amongst stakeholders at all levels, including farmers, to be vigilant for early appearance of rusts (both stripe and stem rust).</p> <p>Control should be considered if susceptible varieties are grown and disease is present (>10%–20% of leaf/stem area infected).</p> <p>Sampling of both stem and stripe rust should be undertaken to determine races present.</p>
22 October–21 November 2018	<p>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).</p>	<p>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.</p>
<i>Overall Risk Level: Caution: local HIGH</i>	<p>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%.</p> <p>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.</p> <p>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.</p> <p>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.</p>	<p>Awareness should be raised amongst stakeholders at all levels, including farmers, to be vigilant for appearance of rusts (both stripe and increasingly stem rust).</p> <p>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.</p> <p>Sampling of both stem and stripe rust should be undertaken to determine races present.</p>



For the purposes of wheat rust advisories, spore dispersal forecasts were aggregated to show predicted dispersal risks over the coming week. (See figures 2 and 3 for examples for stripe rust and stem rust over

five contrasting periods). The figures show characteristic early development of wheat stripe and stem rusts in the southern Bale and Arsi zones in August 2018 (figures 2(a) and 3(a)) then forecast dispersal across



the Rift Valley and further north by early September (figures 2(b) and 3(b)). Following a period of drought in October 2018 during which there was little change (figures 2(c) and 3(c)), both stem and stripe rust then

appeared widely with major risks of spore dispersal over large areas of the wheat crop by mid to late November (figures 2(d) and 3(d)) and thereafter a decrease by mid-December as crops are harvested

(figures 2(e) and 3(e)). Examples of maps for suitability criteria for stripe rust are shown in the SI.

The EWS forecast data are outputted every 3 h for the week ahead providing the diurnal variation which is important for future work in which the dispersal and environmental suitability models are integrated with an epidemiological model to assess the local build-up of infection at newly infected sites.

Feedback from Ethiopian partners indicates that farmers are reported to have increased preparedness and control ahead of disease outbreaks in some areas.

4. Discussion

The wheat rust EWS is the first system to combine near real-time field survey observations, advanced numerical weather prediction (NWP) meteorological forecast data, Lagrangian spore dispersion forecasts along with detailed environmental suitability model forecasts, and wide-ranging communication methods to predict near real-time risks of disease occurrence in a developing country context. The EWS is also designed to provide wide-scale management advice to extension agents and smallholder farmers and is one of the first systems of this level of sophistication for plant diseases, bringing Ethiopia to the forefront of EWSs for wheat rusts.

Communication of the current and predicted wheat rust situation with recommendations and alerts, is an integral part of the EWS. Together with meteorologists and epidemiologists, scientific experts in Ethiopia were key to the joint interpretation of the results and the communication process. In addition to daily forecasts, Ethiopian-based scientific experts produced concise wheat advisory reports about risks and management advice about using fungicides.

The advisory reports were shared from the regional bureaus and zonal offices of MoALR to reach over 150 000 smallholders and extension agents in key wheat regions of Arsi, West Arsi and Bale in 2018. Information on critical wheat rust threats were also disseminated as alerts via the ATA's 8028 phone system to an additional 125 000 smallholders and 10 000 extension agents to ensure that they are sufficiently informed to apply control measures in a timely manner. Forecasts of likely dispersal and infection of wheat by stem and stripe rust during the coming week, provide farmers with a possible three-week window of opportunity in which to purchase and apply fungicide before the epidemic becomes established in their fields.

The uptake of the ODK app for recording field survey data increased substantially from 2017 to 2018, reflecting an intensive training programme for surveyors on the advantages and use of the app. For the first time, near real-time data from surveyed locations were available to identify likely sources of spores in the dispersion model. Additional training for the ODK

app, using a combination of hands-on approaches and video tutorials, and expansion of the system is planned.

The EWS provides high resolution information at the landscape scale over all of Ethiopia, for the current rust situation through to the week ahead. The dispersal and environmental suitability models, therefore, provide effective means to predict the extent of infection ('predicting the present') as well as predicting future regions at risk of infection in successive weeks. Building on the experience from exploratory analyses in 2017 and 2018, we propose to supplement and integrate field surveys with data collected from large numbers of smallholders via the ATA 8028 system in the coming seasons. The ATA phone-based technology is the first of its kind in Ethiopia and represents a shift towards Ethiopian farmers using ICT tools to access agronomic updates and to incorporate best practices into their farming. The service is proving to be a timely and cost-effective mechanism to disseminate information, including the wheat rust warnings. Pilot investigations indicate that phone-based surveys are best carried out using trained extension agents to provide regular reports on disease status of farms they visit. Ultimately, with suitable training, reporting can be escalated to large numbers of farmers. Access to rapid, practical, expert-derived control advice in the ATA 8028 hotline system is seen as an incentive to encourage farmer reporting.

A comprehensive analysis of the spread of the disease during the study is difficult. Disease could only be detected from the formal field surveys. The reported patterns for disease spread therefore follow closely the routes undertaken by the surveyors rather than the intrinsic spread of the pathogen during each season. Future plans will address this problem by directing ground survey teams to regions predicted by the models to have low as well as high probabilities of infection. Revolutionary, new near real-time diagnostics for stripe rust have been developed using nanopore sequencing (MARPLE diagnostics: <https://acaciafrica.org/marple-diagnostics/>) and are now beginning to be used in Ethiopia. In the future, with these new diagnostic tools specific rust races can be tracked in near real-time. We believe that this information, coupled with the dispersal modelling of the EWS, will permit increased accuracy in the assessment and prediction of disease spread within Ethiopia.

Formal validation of the forecasting models and assessment of the uptake and response of growers to the wheat rust advisories is challenging. The research has progressed from two years of pilot studies (2015–2016), followed by two years of extensive trial (2017–2018) and has now been approved for a further two years of validation. The reports on the success of the EWS are remarkably positive, if anecdotal, from Ministry officials, researchers, extension agents and smallholder farmers. Officials have indicated that information from the wheat rust advisories has enabled smallholder farmers to apply fungicides in a

timelier manner to reduce the impact of wheat rust diseases during epidemic spread for the first time in Ethiopia. More formal validation is planned for the 2019 and 2020 seasons, using a combination of targeted field surveys and phone-based reporting. Use of a smartphone, automated disease recognition app is also planned to be piloted. Surveys will include regions that are predicted as low risk as well as high risk to evaluate the forecasts for false positives and false negatives. Repeat visits to key regions are also important to assess the time of arrival and rates of spread of disease. The use of ATA 8028 telephone surveys offers opportunities to substantially increase the numbers of fields for which disease status is reported.

The NAME model has been widely validated for a range of particulate dispersals and more recently for wheat rusts. Model predictions have been shown to agree with surveys of wheat rust (Olivera *et al* 2015). Incursions of new rust races were shown to be consistent with NAME predictions based on detailed analyses of historical meteorological data by Meyer *et al* (2017a, 2017b) and Visser *et al* (2019). One of the confounding factors in model validation is the degree to which farmers apply fungicidal control in response to wheat rust advisories of epidemic risk. It is not known what would have happened if fungicide had not been applied, although further simulation modelling could assist here (e.g. Cook *et al* 2008). Detailed reporting of fungicide use is difficult to obtain in Ethiopia, although data are available for the supply of fungicide at the woreda (district) scale. The ATA phone surveys, together with the use of an epidemiological model to analyse likely disease spread and yield, with and without fungicide application, provide a way forward. With a wide reach to large numbers of growers distributed across the major wheat producing regions in Ethiopia, it will be possible to obtain data on fungicide use and disease incidence as well as yield at finely resolved scales for statistical and epidemiological analysis. Using this array of innovative technologies, future work will focus on developing robust techniques to address the important issue of model validation.

Plant disease forecasting platforms are not new: see for example the notable examples of EPIPRE in Western Europe in the 1980s (Zadoks 1981, Rabbinge and Rijsdijk 1983); iPiPE (Integrated pest information platform for extension and education for major crops in the US (Isard *et al* 2005)). The framework described in this paper has unique innovations in the integration of meteorologically-driven epidemiological forecasting, using computationally intensive methods. It also represents one of the first advanced crop disease EWSs implemented in a developing country.

5. Conclusion

Wheat rusts are an increasing threat to global food security. The re-emergence of stem rust in Africa and Europe and the rapid global spread of aggressive stripe

rust races are of major concern. They provide concrete examples of the ever increasing threats to global food systems from invasive and transboundary pests and pathogens. To combat these threats responsive crop disease early warning frameworks are increasingly needed. The framework described in this paper provides policy-makers, extension agents and farmers with timely, actionable information on priority diseases affecting a staple food crop. Effective partnerships and integrated state-of-art research infrastructures are essential components of the operational system. The framework together with the underpinning technologies are transferable to forecast wheat rusts in other regions and can be readily adapted for other wind-dispersed pests and disease of major agricultural crops. From a near-future perspective, we are currently transferring the EWS framework to predict and mitigate wheat rust diseases in Bangladesh and Nepal during the 2019 wheat season, illustrating the wide applicability of the wheat rust EWS framework in contributing to safeguarding food security in other countries.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for legal and/or ethical reasons.

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