USDA-ARS | U.S. Wheat and Barley Scab Initiative

FY21 FINAL Performance Progress Report

Due date: July 26, 2023

Cover Page

USDA-ARS Agreement ID:	59-0206-0-155
USDA-ARS Agreement Title:	Predictive Models for Fusarium Head Blight
Principle Investigator (PI):	Erick DeWolf
Institution:	Kansas State University
Institution UEI:	CFMMM5JM7HJ9
Fiscal Year:	2021
FY21 USDA-ARS Award Amount:	$73,263
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Period of Performance:	6/7/21 - 6/6/23
Reporting Period End Date:	6/6/2023

USWBSI Individual Project(s)

USWBSI Research Category*	Project Title	ARS Award Amount
MGMT	Continued Deployment of Prediction Models for Fusarium Head Blight	$20,704
MGMT	Application of Model Ensembles and Machine Learning to the Prediction of Fusarium Head Blight	$35,438
MGMT	Integrated Management of Fusarium Head Blight in Kansas	$17,121
	FY21 Total ARS Award Amount	$73,263

I am submitting this report as a: ☒ FINAL Report

I certify to the best of my knowledge and belief that this report is correct and complete for performance of activities for the purposes set forth in the award documents.

Erick DeWolf
Principal Investigator Signature

7/26/2023
Date Report Submitted

‡ BAR-CP – Barley Coordinated Project
DUR-CP – Durum Coordinated Project
EC-HQ – Executive Committee-Headquarters
FST-R – Food Safety & Toxicology (Research)
FST-S – Food Safety & Toxicology (Service)
GDER – Gene Discovery & Engineering Resistance
HWW-CP – Hard Winter Wheat Coordinated Project
MGMT – FHB Management
MGMT-IM – FHB Management – Integrated Management Coordinated Project
PBG – Pathogen Biology & Genetics
TSCI – Transformational Science
VDHR – Variety Development & Uniform Nurseries
NWW –Northern Soft Winter Wheat Region
SPR – Spring Wheat Region
SWW – Southern Soft Red Winter Wheat Region

Project 1: Continued Deployment of Prediction Models for Fusarium Head Blight

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1. **What are the major goals and objectives of the research project?**
   1. Continued deployment of the disease prediction models in the United States including the support of the state commentary tools, FHB Alerts and the web-page information explaining the models.
   2. Refine and maintain web based tools to ensure they are compatible with the latest web browsers and mobile technologies (cellular-based mobile/"smart" phones and tablets).
   3. Estimating historical risk of FHB epidemics throughout the US.
   4. Modifying the expert tools used to test experimental models before public deployment.
   5. Implement a user survey to document value of the prediction system and its impact for stakeholders.

2. **What was accomplished under these goals or objectives?** *(For each major goal/objective, address these three items below.)*

   a) What were the major activities?

   Deployment of disease forecasting models for Fusarium head blight of wheat and barley in the US. This includes development, refinement and quality control of the web-based tools that deliver the daily estimates of disease risk in the United States. During this project the number of states covered by the forecasting system expanded from 30, to 33 in 2021, and 39 in 2022. We coordinated of the state and regional level commentary by wheat and barley disease specialists in the US. This included working with the USWBSI Network and Facilitation Office to deliver this commentary via the FHB Alerts.

   The forecasting system is run by a multi-disciplinary team of plant pathologists, meteorologists, geographers and information technology specialists. This team meets monthly to coordinate projects and review progress. Our activities include daily support and quality control procedures to ensure weather data used by the system is of the highest quality possible and timely risk maps are available to growers each day; Rapid response to problems with data flow or processing errors; Applying disease risk models and publishing daily disease risk maps; Coordination of national efforts to develop and distribute state-level expert commentary via the web-tools and FHB Alert system.

   Update web-based tools used to deliver disease forecasts. During this multi-year project we continued the on-going efforts to add new features to the predictive web-based tools and to keep these resources compatible with the latest computer software on desktop and mobile devices. During this funding term we have transitioned to an entirely new user interface, updated the risk maps to reflect cutting edge GIS theory, improved help documents and navigation within the system, and developed tools that will allow users to access site-specific estimates of weather and estimates of disease risk.

   Survey of users of FHB Alerts and forecasting tools. This funding also supported our efforts to verify model performance throughout the US. This includes gathering input

from University cooperators on the model performance in their state. We also work with the NFO to coordinate a user survey via the FHB Alert system. This survey gathers demographic information about the users, provides information about how the system is working for users, and gathers valuable impact information for the USWBSI.

Estimating historical risk of FHB epidemics throughout the US. We also have gathered the needed weather resources to conduct an assessment of the historical risk of FHB epidemics throughout the US. This project requires 30 years of hourly weather data from the continental US. After evaluating several possible sources of this information, we concluded that the ERA5 system which coordinates global weather resources is best suited for this analysis. We established a database for weather observations that will allow us to estimate crop growth stage and disease risk at a 20km grid throughout the spatial domain across the 30 year time frame. Plans are in place to begin the formal modeling of climate-based disease risk this fall.

b) What were the significant results?

Delivery of disease forecasting models for wheat and barley growers in more than 30 states where FHB and DON are known to be a problem. This includes both areas in the Eastern US that have a long history of problems with FHB, and recent expansions of the forecasting system to address western states where the disease emerged as a problem in the last 5-10 years

- The delivery of disease forecasting models that support grower management decisions across United States.
- Transition to a new user interface that keeps these tools compatible with current browser and mobile device technologies
- Completion of user surveys that help us evaluate model performance and gather important impact information.
- Users continue to document the value of the disease forecast model to their farms and agriculture businesses. The current survey indicates that value of the forecasting system exceeds $57 million each year.

c) List key outcomes or other achievements.

Continued the redesign and improvements of the web-based tools. Improvements this year include an enhanced user interface that is easier to navigate, improved help documentation, and increased stability of the weather database used to estimate the risk of disease.

We developed a number of improvements in 2021 - 2022 growing seasons. These improvements include additional graphing features that will allow users to obtain site-specific information about trends in disease risk, and the underlying weather conditions for any location (grid cell) of the disease risk map. We also redesigned the commentary display modules to help growers navigate to commentary for their state and region more efficiently.

3. **What opportunities for training and professional development has the project provided?**
   Although this project does not support formal student training, we regularly use the disease forecasting tools as a platform for demonstrating key concepts of integrated disease management in the graduate courses, and international workshops. Some noted examples include: International Fusarium Workshop, Graduate Courses on Plant Disease Epidemiology, and Multi-State Committees on Small Grain Diseases East of the Rocky Mountains (NCERA-184).

4. **How have the results been disseminated to communities of interest?**
   The Fusarium Head Blight Prediction Center is the primary mechanism of communicating disease risk to farmers and the agriculture industries in the US. These web-based tools and FHB Alerts reach thousands of wheat and barley producers each year. The information distributed by the disease forecasting system is also used to enhance extension newsletters, blog posts and social media feeds in key wheat producing states.

Project 2: Application of Model Ensembles and Machine Learning to the Prediction of Fusarium Head Blight

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1. **What are the major goals and objectives of the research project?**
This project aims to develop the next generation of forecasting models deployed via the national level forecasting effort supported by the USWBSI. During this project these efforts explored the potential of groups of simple forecasting models (ensembles) to improve the overall accuracy and stability of model predictions.

   The primary goals for this project were:
   - *Incorporate additional observations of FHB epidemics into the data sets used to model FHB.*
   - *Explore the potential for ensembles of predictive models and machine learning to improve predictive models for FHB.*

2. **What was accomplished under these goals or objectives?** *(For each major goal/objective, address these three items below.)*

   a) What were the major activities?

   Explore the potential for ensembles of predictive models and machine learning to improve predictive models for FHB.

   This funding from the USWBSI supports efforts to improve the FHB forecasting models used in the US. These activities include and gathering weather observations associated with each new location added to the modeling data sets, quality control procedures to identify potential errors, experimentation and tunning of the machine learning and ensemble modeling approaches, assessment of model performance, evaluation of model errors, and verification of model performance with new observations.

   Explore the potential for ensembles of predictive models and machine learning to improve predictive models for FHB.

   We completed an initial analysis of the ensemble modeling approaches during this project. Overall, the ensemble approach did improve the performance for the forecasting models (see details below). These results were published in the journal *PLOS Computational Biology* during 2021. We also began to investigate how machine learning algorithms (Random Forests) might build on the ensemble modeling concepts and better identify weather patterns (key weather variables) that consistently stimulate or suppress outbreaks of FHB and DON. These approaches helped us identify weather patterns that modify these relationships (variable interactions).

   b) What were the significant results?

   The ensemble approach explored in first years this project considered three ways of combing model predictions: soft voting, weighted averaging, and a model

stacking approach based on penalized regression. Soft voting and weighted average approaches generally improved prediction accuracy and other aspects of model fit relative to any individual model alone, but not universally so. Model stacking based on a penalized regression algorithm; however, was superior to the other methods of ensemble modeling considered in this analysis. For example, the ROC-AUC values (a statistic summarizing overall model accuracy) of the stacked ensemble modeling provided 24% , 14% and 12% gains over the individual models, soft vote and model averaging approaches, respectively.

We have also made progress on objectives focused on employing machine learning to identify weather patterns stimulating FHB epidemics. To date, we focused on the random forests (RF) algorithm within machine learning and are currently exploring ways to make the variable selection within the set of >300 candidate predictor variables more efficient. We have identified 13 strategies for improving efficiency of the variable selection process and tested them on example datasets.

Constructing models that predict Fusarium head blight (FHB) epidemics and which are also amenable to large-scale deployment is a challenging task. In the US, the emphasis has been on simple logistic regression models which are easy to implement but may suffer from lower accuracies when compared to more complicated, harder-to-deploy (over large geographies) model frameworks such as functional or boosted regressions. In this project we examined the plausibility of random forests (RF) for the binary classification of FHB epidemics, as a possible middle ground between model simplicity and complexity without sacrificing accuracy.

In this analysis the input variable set of 999 observations from 27 states over 30 years was filtered with the aid of three RF variable selection algorithms (Boruta, varSelRF and VSURF), using nested resampling to quantify the variability and stability of selected variable sets of over 300 different possible representations of weather information. These selection procedures, led to 58 competitive RF models with no more than 14 predictors each, and which had overall superior predictive performance to previously reported simple logistic regression models. Further stacking (ensembling) of the RF models using penalized regressions as the meta-learner did not improve classification of epidemics and nonepidemics, presumably because of high correlations in the predicted probabilities of the individual RF models. Penalization imposed by the meta-learners was viewed as another round of filtering, this time on the RF models, leading to a smaller set which may be amenable for incorporation into regional prediction systems for FHB.

c) List key outcomes or other achievements.

- Publication of ensemble modeling manuscript in *PLOS Computational Biology*
- Developing strategies for testing the deployment of model ensembles in operational disease forecasting system

- The modeling work supported by the USWBSI has assembled one of the best datasets for modeling FHB in the world. The quality of this data has enabled the modeling team to explore novel modelling approaches and make potentially valuable advancements in model accuracy.

- The ensemble modeling approaches used in this research represent a departure from the common paradigm of modeling plant diseases. For decades, plant pathologists have developed groups of models then systematically search through the candidate models to identify a single model to apply as part of an operational disease forecasting system. The ensemble modeling approaches demonstrate an approach for combining multiple models that can improve performance (accuracy and stability) of disease forecasting systems.

- Our recent efforts to model FHB with machine learning have produced multiple candidate models (ensembles) with overall superior predictive performance to previously deployed logistic regression models.

3. What opportunities for training and professional development has the project provided?

In 2021, we initiated a post-doctoral training project that focuses on developing the next generation of plant disease epidemiologists. This project includes colleagues at Penn State University, Ohio State University, and North Carolina State University. The FHB modeling dataset is one of several key data sets used in this training initiative. This project involves four post-doctoral researchers.

Presentation and discussion of the modeling results at the International Fusarium Workshop, 2022. This workshop brings Fusarium researchers from around the world together to learn about Fusarium identification and management. Discussion of the FHB modeling effort at the workshop provides training for an international group of Fusarium researchers.

4. How have the results been disseminated to communities of interest?

The disease forecasting models developed by the FHB modeling team are deployed through the FHB Prediction Center that is supported by the USWBSI. This forecasting system brings daily estimates of disease risk to wheat and barley growers in 39 states.

Project 3: Integrated Management of Fusarium Head Blight in Kansas

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1. **What are the major goals and objectives of the research project?**
   1. Evaluate the effectiveness of integrated management strategies that combine varieties with best available genetic resistance with fungicide products for suppressing FHB in Kansas.
   2. Collaboration with the multi-state effort to combine the integrated management of FHB and DON. A powerful tool for evaluating the efficacy of management strategies and specific fungicide products new to the wheat and barley community.
   3. Communication of these results to wheat producers in Kansas

2. **What was accomplished under these goals or objectives?** *(For each major goal/objective, address these three items below.)*

   a) **What were the major activities?**

   Replicated research plots were established near Manhattan KS and Belleville KS, which have a history of FHB epidemics. These plots included three wheat varieties with differing levels of genetic resistance to FHB (S, MS, and MR). Plots were inoculated with spores (macroconidia and ascospores) of Fusarium graminearum and treated with fungicides according to the protocols established for the IM-CP. Disease incidence and severity (FHB index) was rated at least two times at each location. The plots were harvested at maturity, and grain evaluated for symptoms of Fusarium damaged kernels (FDK). The replicated grain samples were ground and sent for DON analysis. Disease data were entered and preliminary analysis conducted. We are currently waiting for DON results

   b) **What were the significant results?**

   Severe FHB developed at both Manhattan and Belleville locations in 2021. Susceptible inoculated control plots had >15% FHB Index at Belleville and >30% Index at Manhattan. Results indicate that wheat varieties with moderate levels of genetic resistance had lower levels of disease, than susceptible varieties. Fungicides also suppressed disease development when applied at anthesis. Fungicides applied at heading provided less disease suppression. Plots with the lowest FHB Index and FDK were planted with varieties that were MR to FHB and received fungicide applications.

   All treatments and procedures were conducted during the 2022 growing season as planned. This includes inoculations, fungicide applications disease assessments and harvest. The weather conditions were not conductive to the development in 2022 across Kansas. As a result, only low levels of disease developed at both the Manhattan and Belleville locations.

   Data from both years were shared with projection coordinators at Ohio State University in support of group objectives on fungicide efficacy and forecasting model development.

c) List key outcomes or other achievements.
We made several adjustments to our inoculation protocol in 2021. Enhancements included integration of several recent Fusarium isolates into the inoculum production, addition of ascospores within the inoculum, and a 10X increase in the number of spores used to inoculate the plots.

3. What opportunities for training and professional development has the project provided?
The USWBSI does not formally support the graduate student training. None the less, we use the FHB IM projects in Kansas to train graduate students on how to inoculate, rate disease

4. How have the results been disseminated to communities of interest?
The results of the replicated trails here in Kansas are incorporated in newsletter articles and extension presentations in Kansas. These resources help keep wheat growers in Kansas up-to-date on the best available varieties and fungicides. The Kansas data also provides specific examples of how these management tools can be combined to provide improved suppression of the FHB and DON.

Publications, Conference Papers, and Presentations

Please include a listing of all your publications/presentations about your FHB work that were a result of funding from your FY21 grant award. Only citations for publications published (submitted or accepted) or presentations presented during the **award period** should be included.

Did you publish/submit or present anything during this award period?

☒ Yes, I've included the citation reference in listing(s) below.
☐ No, I have nothing to report.

Journal publications as a result of FY21 award

List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Include any peer-reviewed publication in the periodically published proceedings of a scientific society, a conference, or the like.

Shah, D., De Wolf, E.D., Paul, P.A. and Madden, L.V. 2023. Into the trees: random forests for predicting Fusarium head blight of wheat in the United States. Phytopathology (in press).
Status: Journal Publication Available On-line as First Look Acknowledgement of Federal Support: YES (publication)

Shah, D.A., De Wolf, E.D., Paul, P.A., and Madden, L.V. 2021. Accuracy in the prediction of disease epidemics when ensembling simple but highly correlated models. PLOS Computational Biology. https://doi.org/10.1371/journal.pcbi.1008831. Status: Journal Publication Published Acknowledgement of Federal Support: YES (publication)

Other publications, conference papers and presentations as a result of FY21 award

Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication.

De Wolf, E. 2023. Modeling diseases and environmental hazards affecting wheat production in Kansas. Department of Energy (DOE) National Virtual Biosecurity for Bioenergy Crops Center (NVBBCC), Virtual Meeting Format, May 17-18, 2023.
Status: Abstract Published and Presentation delivered Acknowledgement of Federal Support: YES (Abstract and presentation)

Moraes, W., Bergstrom, G., Bissonnette, K., Bowen, K., Bradley, C., Byamukama, E., Chilvers, M., Collins, A., Cowger, C., Darby, H., DeWolf, E., Dill Macky, R., Esker, P., Friskop, A., Kleczewski, N., Koehler, A., Langston Jr., D., Madden, L, Marshall, J., Mehl, H., NegelKirk, M., Rawat, N., Smith, D., Telenko, D., Wegulo, S., Young-Kelly, H., and Paul, P. (2022). Fusarium Head Blight Management Coordinated Project: Integrated Management Trials 2022. Proceedings of the 2022 National Fusarium Head Blight Forum. Tampa Bay FL, Dec. 4-6, 2022. Retrieved from: https://scabusa.org/forum/2022/2022NFHBForumProceedings.pdf
Status: Abstract Published and Poster Presented Acknowledgement of Federal Support: YES (Abstract and Poster)

Moraes, W., Bergstrom, G., Bissonnette, K., Bowen, K., Bradley, C., Byamukama, E., Chilvers, M., Collins, A., Cowger, C., Darby, H., DeWolf, E., Dill Macky, R., Esker, P., Friskop, A., Kleczewski, N., Koehler, A., Langston Jr., D., Madden, L, Marshall, J., Mehl, H., NegelKirk, M., Rawat, N., Smith, D., Telenko, D., Wegulo, S., Young-Kelly, H., and Paul, P. (2022). Fusarium Head Blight Management Coordinated Project: Uniform Fungicide Trials 2022. Proceedings of the 2022 National Fusarium Head Blight Forum. Tampa Bay FL, Dec. 4-6, 2022. Retrieved from: https://scabusa.org/forum/2022/2022NFHBForumProceedings.pdf
Status: Abstract Published and Poster Presented Acknowledgement of Federal Support: YES (Abstract and Poster)

Andersen Onofre, K. and De Wolf, E., Moraes, W., and Paul, P. (2022). MGMT Coordinated project overview and Kansas perspective. Proceedings of the 2022 National Fusarium Head Blight Forum. Tampa Bay FL, Dec. 4-6, 2022. Retrieved from: https://scabusa.org/forum/2022/2022NFHBForumProceedings.pdf
Status: Abstract Published and Poster Presented Acknowledgement of Federal Support: YES (Abstract and Poster)