PhytoFrontiers™
An Open Access Journal from The American Phytopathological Society

Technical Advance

PATHMAP (Pathogen And Tree fruit Health MAP): A Smartphone App and Interactive Dashboard to Record and Map Tree Fruit Diseases, Disorders, and Insect Pests

Wayne M. Jurick II[1,†] | Lindsey Messinger[2] | Anna Wallis[3] | Kari A. Peter[4] | Sara Villani[5] | Michael J. Bradshaw[1] | Holly P. Bartholomew[1] | Michael Buser[6] | Srđan G. Aćimović[7] | Jorge M. Fonseca[1] | Kerik D. Cox[8] |

[1] USDA-ARS, Food Quality Laboratory, Beltsville, MD

[2] Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO

[3] Michigan State University Extension, Grand Rapids, MI

[4] Penn State University, Fruit Research and Extension Center, Biglerville, PA

[5] North Carolina State University, Department of Entomology and Plant Pathology, Mills River, NC

[6] USDA-ARS, Office of National Programs, National Program for Engineering, Beltsville, MD

[7] Virginia Tech, School of Plant and Environmental Sciences, Alson H. Smith Jr. Agricultural Research and Extension Center, Winchester, VA

[8] Cornell University, Plant Pathology and Plant-Microbe Biology Section, School of Integrative Plant Science, Cornell AgriTech, Geneva, NY

† Corresponding author: W. M. Jurick; wayne.jurick@usda.gov

Accepted for publication 5 July 2022.

Mention of trade names or commercial products in this publication is solely for providing specific information and does not imply recommendation or endorsement by the USDA.

Funding

This study was funded entirely by the USDA-ARS National Program 303 Plant Diseases to WMJII USDA-ARS project plan # 8042-42430-002-000-D. This research includes collaborative contributions from the USDA Agricultural Research Service (ARS) Partnerships for Data Innovations (PDI). PDI is supported by the USDA. This project was supported in part by two appointments to the Science Education Programs at National Institutes of Health (NIH), administered by ORAU through the U.S. Department of Energy Oak Ridge Institute for Science and Education.

e-Xtra: Supplementary material is available online.

The author(s) declare no conflict of interest.

Abstract

PATHMAP (Pathogen And Tree fruit Health MAP) is a smartphone application (app) and interactive dashboard developed specifically for support specialists, extension personnel, and university scientists supporting the tree fruit industry. The PATHMAP app collects detailed information about observed diseases, insect pests, and disorders and provides the option to attach photos. The data are then visualized using a graphical interface dashboard displaying an interactive color-coded map. Prior to the development of PATHMAP, abundant tree fruit disorder data were collected each year, but a central interactive repository for archiving data and facilitating communication of field observations did not exist. PATHMAP has been beta tested by university extension personnel, private consultants, and university scientists to ensure usability and functionality. PATHMAP will be used within the tree fruit industry for monitoring known pest patterns, occurrences, and outbreaks of emerging pathogens. It will augment existing extension diagnosis listservs that have value in visual diagnosis but are cumbersome and have no archiving capabilities. Data obtained through the tool can be used in epidemiological meta-analyses and to develop new predictive models, and can serve as a platform to track emerging pathogens, insects, and disorders for a variety of cropping systems.

Keywords: electronic data collection, emerging pathogens, epidemiology, insect pests, interactive data dashboard, physiological disorders, pre- and postharvest diseases

One of the most fundamental aspects of commercial fruit production and applied research is accurate diagnosis of diseases, insect pests, and horticultural/physiological disorders (EPA 2021). Accurate diagnosis, including the spatiotemporal distribution of

disease, facilitates the deployment of appropriate, effective management solutions and enables research examining critical factors (e.g., host, pathogen, environment, and time) that contribute to their occurrence and spread. Current resources available to help with disease diagnosis include user guides developed by scientists for growers (Agnello et al. 2022; Wise 2022), field scouts, and an interconnected network of extension specialists (e.g., Michigan State University Extension, Cornell Cooperative Extension, Virginia Cooperative Extension, Plant Disease Clinic, Virginia Tech, National Plant Diagnostic Network). However, accurate, rapid, and efficient diagnosis and outbreak identification remain a challenge.

Each year, fruit industry members (extension specialists, industry support members, and university scientists) collect abundant information on pests and conduct visual and laboratory diagnosis. Individuals frequently engage with each other through unofficial connections to solicit informal diagnosis assistance and share information (Isard et al. 2015). Most often, this happens locally within a state or smaller region and is based on personal and professional relationships between individuals (i.e., an extension educator/agent reaches out to a faculty scientist they have worked with in the past). Moreover, many plant, insect, and pathogen experts accumulated vast database repositories of photographs from farm visits spanning decades and recording disease and disorder symptoms associated with economic losses. A formalized platform for facilitating, hosting, and storing the conversations about causal agents or factors and diagnosis information would enable diagnosis assistance from the most qualified individuals and pooled information from the participating community and save data, observations, and discussions for future use (Delgado et al. 2018; Isard et al. 2015). However, although large networks and data sets such as this are invaluable to addressing industry challenges, there have been many barriers to their adoption, such as cultural and technical challenges, including lack of infrastructure, individual specialization leading to information silos, and desire to hold on to "hard-won data" or restraint from conclusion until a solid lab-based diagnosis result is generated (Delgado et al. 2018; Whitlock et al. 2010). Emerging perceptions of data sharing and technology offer a remedy to this by connecting field and laboratory personnel for rapid, accurate diagnosis and providing a space to archive all collected data in a common, publicly accessible location (Delgado et al. 2018; Isard et al. 2015; Whitlock et al. 2010). This allows the knowledge base to increase and extends diagnostic capabilities beyond regional specialists to include a pool of diverse experts from around the country. This offers many benefits, such as helping bridge the following issues: lost pathogen isolate collections, easier transition of young professionals into their positions with lack of mentor–mentee continuity, and plant sample perishability, which leads to deteriorated ability for diagnosis and makes photo banks the most valuable "return to" resource.

Studies evaluating the distribution and/or spread of phytopathogens, insects, and disorders routinely collect large data sets describing local and regional distribution (Vagefi et al. 2018; Wallis et al. 2021). The results are typically published in the peer-reviewed literature, but the data might not be publicly available or are not presented in a standardized or centralized database that is easily accessed, viewed, and used by the public or specialists (Delgado et al. 2018; Isard et al. 2015; Whitlock et al. 2010). Hence, one of our goals with this application and dashboard was to build a product that connects a broader data set that reaches across individual projects, years, researchers, geographic regions, and specific crops to create a standardized, centralized data repository for visually recorded symptoms of diseases, pests, and disorders. Large spatiotemporal data sets related to disease that are available to the public will be an asset to the fruit industry, who can use these data for downstream applications. For example, distribution of a specific disease, insect pest, or disorder could be used to create alerts for commercial producers in geographic areas deemed at risk.

A few model platforms exist for aggregating environmental and agricultural data sets in public databases and for tracking and diagnosing specific agricultural diseases. These networks enable data sharing between subject area specialists in real time, enabling rapid identification of problems and appropriate actions, as well as development of long-term solutions to grand problems. One of the largest collaborations within the agricultural sector is the Agricultural Collaborative Research Outcomes System (AgCROS). It is a "network of networks" that connects multiple agricultural data networks, facilitates the flow of information, and increases cooperation among participating researchers (Delgado et al. 2018). A similar network in the environmental sector is Sustaining the Earth's Watersheds–Agricultural Research Data System (STEWARDS). This is an online database connecting Agricultural Research Service watershed research programs (Sadler et al. 2020). Some networks exist targeting diagnosis and management of a single disease-crop complex. One example is USABlight, a web-based decision support system (DSS) developed in 2015 for potato and tomato late blight management. USABlight directly informs disease management decisions made by growers during the growing season (Small et al. 2015). A broader example of a network for identifying and tracking agriculturally significant organisms is the Integrated Pest Information Platform for Extension and Education (iPiPE) programs. These are a series of projects for monitoring and forecasting organisms deemed important to U.S. agriculture, with the mission to create a national infrastructure and culture of sharing data between industry professionals who routinely monitoring crop health and pest incidence to share information (Isard et al. 2015). Since the initial development in 2005, these systems have grown and been migrated to EDDMapS, a system managed by the University of Georgia's Center for Invasive Species and Ecosystem Health, under the larger initiative Ag IO: The National Monitoring and Forecasting Service for Agriculturally Important Organisms. Collectively, these networks and collaborations represent an emerging culture and infrastructures for pooling knowledge and data sets of industry members, enabling rapid and long-term solutions to complex problems facing the environmental and agricultural sectors.

In the fruit industry, the Great Lakes Fruit Workers (GLFW) is an existing network of scientists across the Northeast and Great Lakes region. An email list managed by Michigan State University (GLFW@list.msu.edu) is available for individuals to self-subscribe and solicit advice from the community, thus pooling knowledge and experience from other experts who are members of the list. However, the emails exchanged are not archived in a publicly accessible space or in an explicit, searchable data structure that would aid in future use of the information for downstream analysis and applications including training. Therefore, the data contained within the email text, once deleted from the email by an individual user, is not retained for future reference and is not searchable. Through the use of Pathogen And Tree fruit Health MAP (PATHMAP), this existing framework would instead be augmented to serve as an updated data interface with an archive of photos and forum for interchange of expertise and commentary.

In this work, we developed PATHMAP, a new, user-friendly tool that can help efficiently collect data on observations of diseases, insects, and other disorders and facilitate visual diagnosis. PATHMAP incorporates an online dashboard for archiving and visualizing data and augments existing frameworks by serving as

not only an updated data interface but an archive of photos and interchange of expertise and commentary. This system will be instrumental in connecting industry members, specialists, and researchers involved in fruit pests and problems that impact quality and lead to waste. The PATHMAP system will archive information for future reference and enable further research investigating the distribution, spread, and management of fruit disorders to help with model development. The application and dashboard could also serve as a practical framework on which to build tools for other cropping systems (e.g., row crops, vegetables, citrus, etc.) and the associated diseases, pests, and disorders.

METHODS

PATHMAP data collection and application development

A collaborative working group, consisting of university (Colorado State University, Cornell, Michigan State, North Carolina State, Penn State, and Virginia Tech) and federal researchers (USDA-ARS Food Quality Laboratory, USDA-ARS National Programs for Engineering) developed an electronic data collection application to facilitate the development of a standardized and centralized data source for tree fruit crop disorders. First, the working group identified and described important data collection variables that were used to build a CSV input file (Supplementary File S1). These data variables can be broken into six different subgroups:

1) Temporal and spatial (calendar date and time, latitude, longitude, country, state/province, and county).
2) Observation type (environment/setting where observation was made, including field, storage, or retail).
3) Observer information (observer name and expertise).
4) Diagnosis information (including a measure of certainty about the diagnosis and a flag for soliciting assistance from the PATHMAP community on the diagnosis, method of diagnosis, and photo attachments).
5) Crop information (crop common name with auto-populating scientific name based on selection and age of crop/time since planting).
6) Disorder information (disorder type and name).

After identifying data variables, the data collection tool was constructed using ESRI's Survey123 Connect program and published on ArcGIS Online (https://survey123.arcgis.com/). Specific information on the tool for creating cell phone apps and a dashboard is succinctly summarized at https://www.esri.com/en-us/arcgis/products/arcgis-survey123/overview. The survey tool was designated as publicly available, allowing users to access and use the tool without providing a username or password. Users can collect data using a smartphone, tablet, or desktop device by downloading the Survey123 Mobile application and searching for "PATHMAP" or using a QR code to quickly access the survey tool within the application (Fig. 1).

PATHMAP dashboard development

In addition to developing a standardized and centralized database for tree fruit disorder observations and an electronic data collection tool, a goal of the working group was to allow users to visualize, archive, and interact with the data (Fig. 2). Thus, an online, interactive dashboard was created to help users filter and visualize stored data. The dashboard (https://arcg.is/ziaOW) was developed using ESRI's Operations Dashboard. Code and

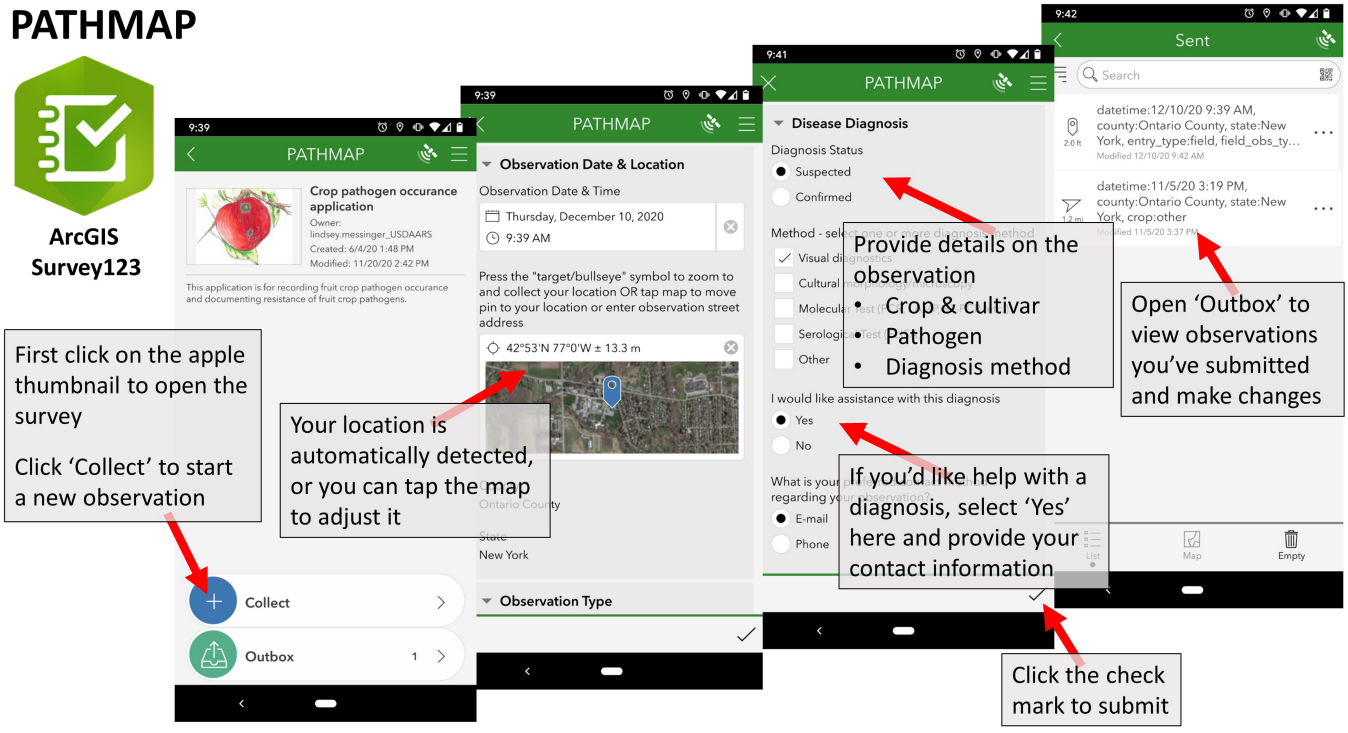

FIGURE 1
Screenshots of the PATHMAP data collection application (app). The app was constructed using ESRI's Survey123 Connect and published on ArcGIS Online. Panels illustrate screenshots of the app that users see when collecting observation data using a smartphone, tablet, or desktop device. The app can be installed by downloading the Survey123 Mobile application at https://www.esri.com/en-us/arcgis/products/arcgis-survey123/overview and searching for "PATHMAP" or using a QR code to quickly access the survey tool within the application.

other data files used to build the app and dashboard can be found online at https://waynemjurick.wixsite.com/my-site-1. There are two primary panes within the dashboard, "Observations" and "Diagnosis Assistance & Commentary."

Observations pane

On the left side of the dashboard, the "Observations" pane provides users with information about PATHMAP, as well as a color-coded map displaying observations by crop type and two numeric indicators displaying the total number of observations in the database and the total number of observations currently displayed. Data filters on the far-left portion of the dashboard allow users to subset observation data for what they are most interested in (e.g., specific observation dates, locations, host crops, disorder type, observations flagged for diagnosis assistance, etc.). Combinations of one or more filters help users narrow down data displayed on the dashboard.

Diagnosis Assistance & Commentary pane

On the right half of the dashboard, the "Diagnosis Assistance & Commentary" pane consists of two subpanes. The subpane on the left contains a "how-to tutorial" with instructions on how to use the dashboard. This subpane also contains a tab with the "Diagnosis Assistance Survey." This survey provides an interface for PATHMAP community members to comment on existing observations and provide diagnosis assistance if it has been requested by the original observer. The subpane on the right contains three tabs. The "Observations" tab displays a subset of important attributes of the observations. The observations displayed on this list are responsive to any data filters applied. Once a user selects an observation from the "Observations" tab, they can click the "Observation Images" tab to see any photo attachments that were submitted with the observation and the "Observation Comments & Attachments" tab to see any comments PATHMAP community members have made on that specific observation. Selecting from the "Observations" tab also allows users to submit a diagnosis assistance survey and comment on an observation. Code and other data files used to build the diagnosis assistance and commentary section can found online at https://waynemjurick.wixsite.com/my-site-1.

Diagnosis Assistance Survey

The Diagnosis Assistance Survey is a secondary survey that relates data back to the observations database and is embedded into the dashboard (Fig. 3). This survey can be accessed and used within the online dashboard and provides a mechanism for users to comment and provide feedback on existing observations. The survey is a truncated version of the original observation survey and collects information about the commenter, including name and contact email (for notification when additional comments are made on an observation), and information regarding the commenter's opinion on an appropriate diagnosis, including the disorder type, common name (with scientific name auto-populating), and method of diagnosis. Finally, the survey also provides space to add a text comment and attachments including image,

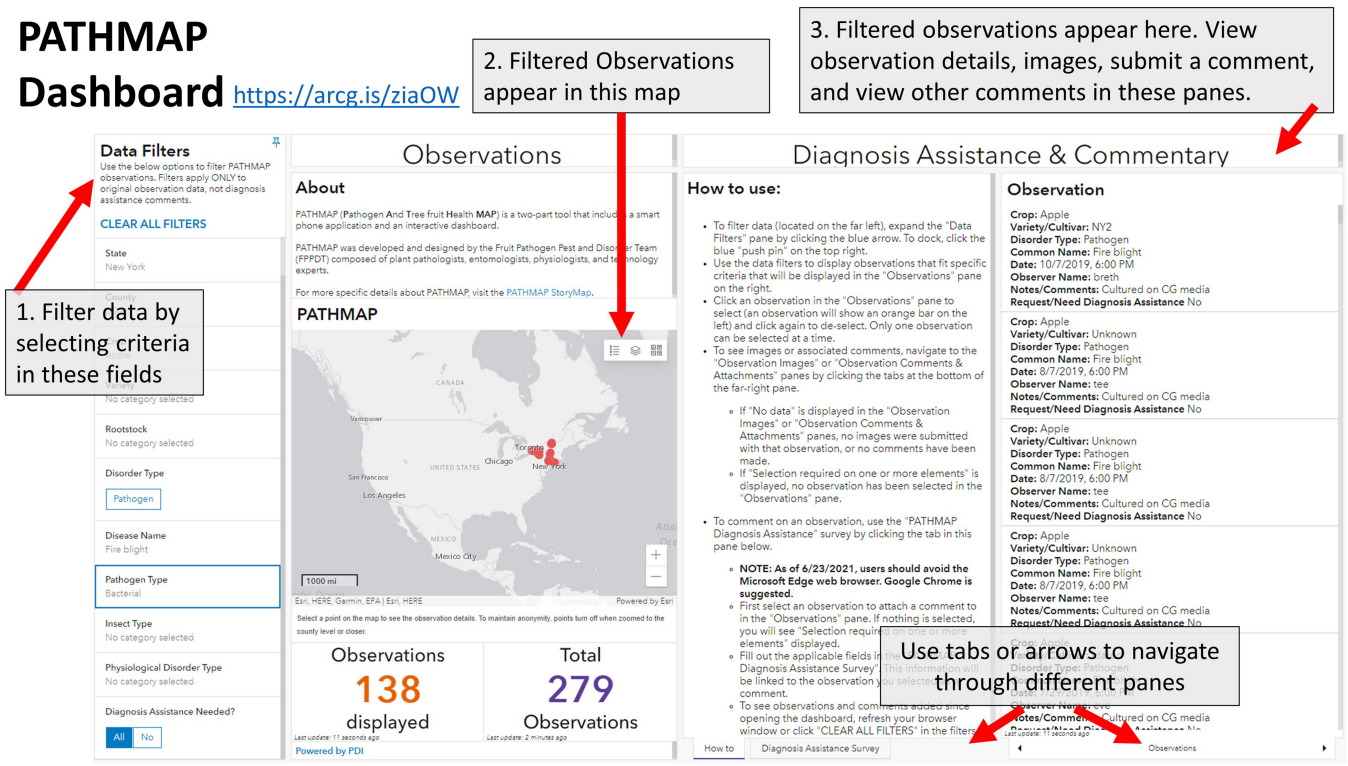

FIGURE 2
Screenshot of the PATHMAP dashboard. The dashboard is a user-friendly interface to the standardized and centralized database for tree fruit disorder observations that allows users to visualize, archive, and interact with the data collected using the PATHMAP electronic data collection tool. The PATHMAP dashboard is online and interactive and can be used to filter and visualize stored data. The dashboard was created using ESRI's Operations Dashboard. There are two primary panes within the dashboard: 1) Observations pane, in which users can visualize observations submitted to PATHMAP, and 2) Diagnosis Assistance & Commentary pane, in which users can dialogue to diagnose field observations.

document, audio, data, video, and archive file types. PATHMAP is integrated with the GLFW email list, a platform described above, currently used by individuals in the fruit industry for diagnosis assistance. This email list is subscribed to the PATHMAP Diagnosis Assistance Survey, such that when one user solicits assistance, the GLFW email list will receive a notification, and all self-subscribed members will be alerted. Users can then navigate to the PATHMAP dashboard to reply to the request, as described above. Each subsequent reply is also reflected to the GLFW email list, maintaining the functionality and logistics of the diagnosis conversation for GLFW users. The emails also provide a link that automatically filters the dashboard to that specific record when it is clicked, aiding the recipient in navigating to the observation of interest and facilitating commenting on that specific observation.

PATHMAP StoryMap development

To aid potential users in understanding the goals and objectives of PATHMAP, as well as how to access and use the data collection and dashboard tools, the working group developed an online resource for users. Using ESRI's StoryMap application, we created a website (https://arcg.is/1OyjGj) consolidating information about PATHMAP including informational and instructional videos, images, and text instructions.

RESULTS

Beta testing with regional specialists

Both the data collection tool and dashboard were shared with 22 fruit specialists and industry members in the Great Lakes region and northeastern United States for evaluation in 2021. Beta testers used the app to log "dummy" observations and then interacted with them via the dashboard. Beta testers provided feedback to the working group for further improvement and refinement of the platforms. Overall feedback was positive and helpful, but there was concern regarding the highly sensitive nature of farm-level data. Making disease, insect pest, or antimicrobial resistance observations publicly available has the potential for negative consequences for the farm or region implicated.

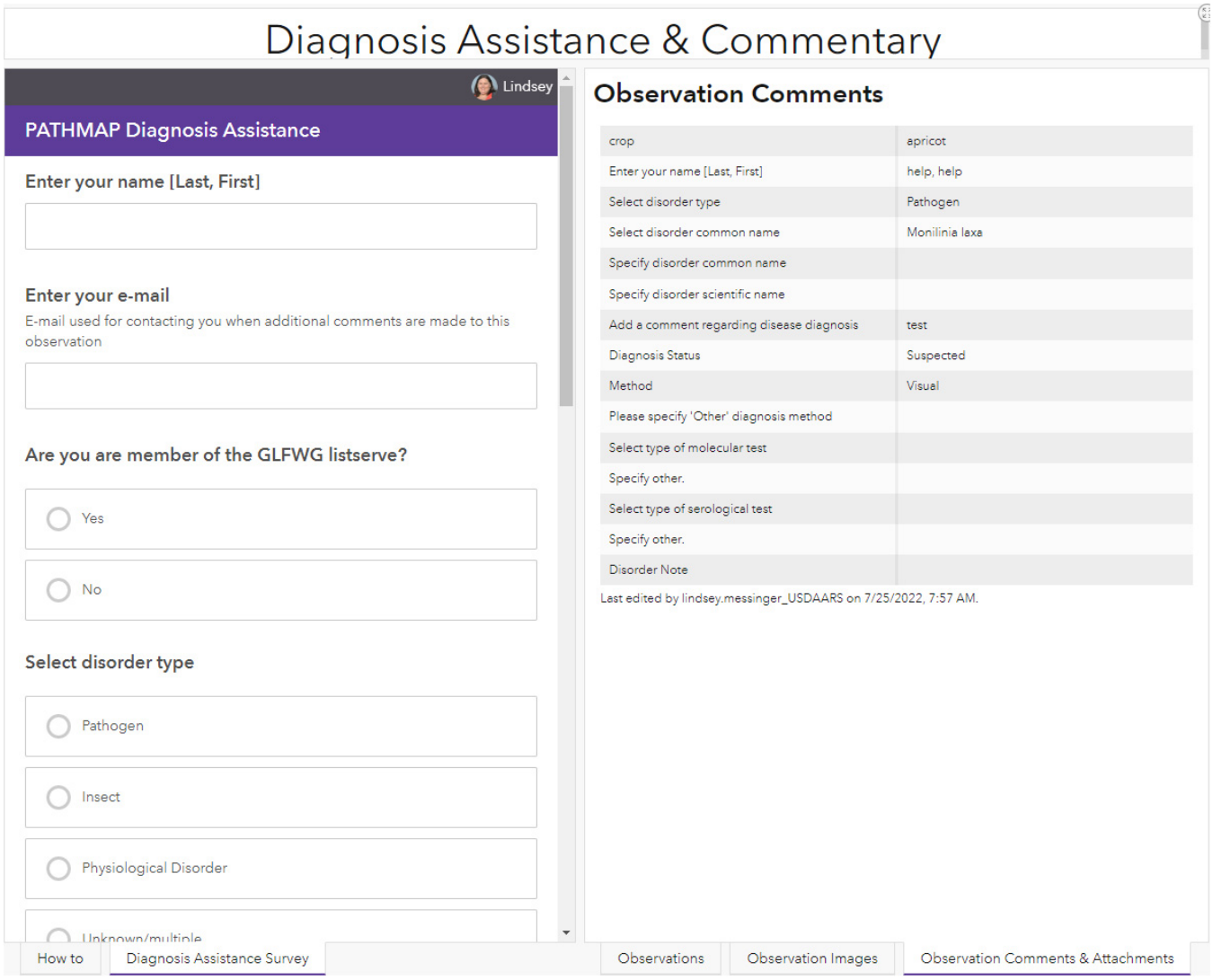

FIGURE 3
Screenshot of the PATHMAP dashboard showing the Diagnosis Assistance and Commentary pane. On the left side is the embedded survey form for diagnosis assistance commenting, where an expert can provide guidance, and on the right side are tabs (bottom) for "Observation," including a list of observations submitted through the app and filtered by the user; "Observation Images," displaying any images attached to the original observation submission; and "Observation Comments & Attachments," showing all comments associated with a specific observation and any files attached with these comments.

Therefore, measures were taken to protect the privacy of industry members by controlling the zoom level on the dashboard map so that points indicating observations turn off once zoomed at the city level. In addition, coordinate information, although collected and stored when an observation is made by a user, is not included in the observation information pane. A username and password are needed to access these hidden location data from ArcGIS Online and can be obtained by sending an email request for access to Lindsey Messinger (lindsey.messinger@usda.gov). Thus, data can be used for various applications with no or little chance of compromising the privacy of the commercial operations.

Case studies

During the development of the user survey and online dashboard, several case study data sets were utilized. These data sets were either created for the PATHMAP platform specifically to enable development and or were produced as part of other research projects on fire blight and bitter rot and added to the PATHMAP platform to demonstrate possible applications (Martin et al. 2021; Wallis et al. 2021). Three specific examples are outlined below.

Beta-testing data set

To evaluate the functionality and usability of the platform, a new data set was produced during development of PATHMAP within the platform. Over 20 individuals in the fruit industry from across the Great Lakes and Northeast added observations using the Data Collection Observation Application. Some of these data points were genuine observations from field work during the 2021 season. Other data points and corresponding observations were created (made-up, AKA dummy, data by Messinger and Jurick II) purely for their ability to test the system and visualize its mapping capabilities. Each type of observation data served to evaluate the usability of the data collection app and to develop the online, interactive dashboard portion of PATHMAP. Through this work, the user interface, data collected for each observation, and display of data were optimized in the app and dashboard.

Fire blight and antibiotic resistance

As part of previous research studies (Tancos and Cox 2016; Wallis et al. 2021), data were collected from commercial farms in New York State on the incidence of fire blight. Fire blight, a bacterial disease caused by *Erwinia amylovora*, is one of the most devastating diseases of the apple industry worldwide, including New York, the second largest producer of apples in the United States. Over the course of 19 years (2002 to 2020), samples of infected plant material were sent to the Cox lab at Cornell AgriTech in Geneva, New York, for diagnosis. Over 200 samples of fire blight were confirmed by identifying pure culture isolates through molecular testing. Data were collected on various aspects of each observation, including location and farm, plant material infected, and resistance to streptomycin, the antibiotic used for management of the disease. Data were uploaded to the PATHMAP database and visualized on the dashboard (Fig. 4). Data can be filtered by characteristics such as strain, year collected, and AMR phenotype (Supplementary File S2). This case study demonstrated the capability of PATHMAP for capturing and visualizing the occurrence and spread of a disease and AMR on a year-by-year basis. It enables tracking of individual strains, observation of spread over time, and further investigation of the source of a particular infection. Visualizing these data on a statewide level provided the opportunity for scientists to identify and communicate to stakeholders the level of streptomycin resistance across the industry (Fig. 5).

Apple bitter rot

Data were collected from commercial farms in Pennsylvania, New York, and surrounding states on the incidence of apple bitter rot (Khodadadi et al. 2020; Martin et al. 2021). Bitter rot is caused

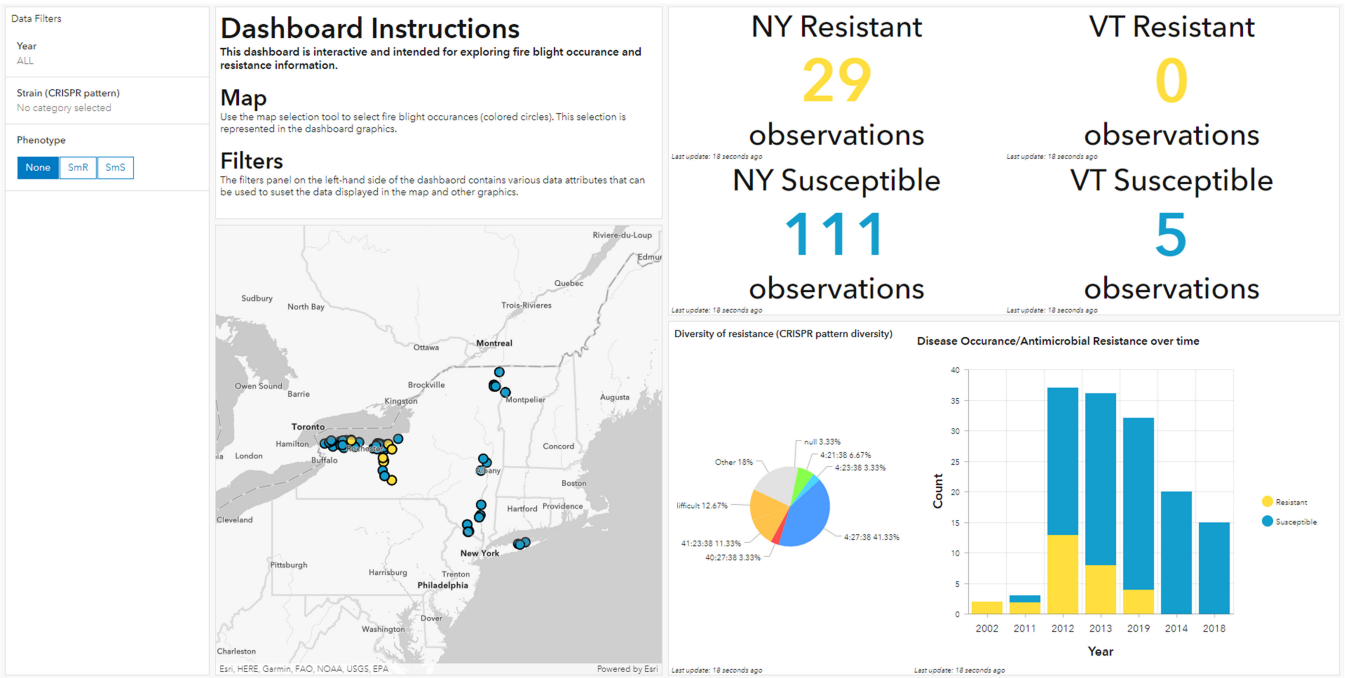

FIGURE 4
Screenshot of a beta dashboard showing the observations submitted for the fire blight research project. This dashboard was filtered to display the strain, year collected, and AMR phenotype in addition to the mapped location and observation totals. Observations from the fire blight case study can also be viewed in the fully functional PATHMAP dashboard.

by fungi in the *Colletotrichum* genus and has become the most problematic fruit rot occurring in Eastern U.S. orchards, resulting in significant losses. To better understand the causal species infecting apples, disease epidemiology, and ultimately optimized management strategies, over 1,000 apple fruits exhibiting bitter rot symptoms were collected throughout the Mid-Atlantic (New York, Pennsylvania, Maryland, Delaware, Virginia, and Ohio) from 2016 to 2018. From these fruit, 800 *Colletotrichum* spp. isolates were collected and molecularly identified to the species level. In addition to species, other data recorded were apple cultivar, county (state) of origin, and collection date. These data were uploaded to the PATHMAP database and visualized on the dashboard. Data can be filtered by strain, year collected, and other variables. This case study illustrated the power of PATHMAP to visualize the spread of an important pre- and post-harvest fungal pathogen on a year-by-year basis over a wide geographic area. Furthermore, PATHMAP enables tracking of individual strains, observation of spread over time, and further investigation of the source of a particular infection (Fig. 5). Visualizing these data on a statewide level will allow scientists to quickly identify and illustrate to stakeholders the incidence of bitter rot across the Mid-Atlantic and Midwest apple producing areas, and it is envisioned that quick access can aid the appropriate cultural and fungicide resistance management strategies.

DISCUSSION

The PATHMAP data collection tool, dashboard, and StoryMap are intended to facilitate accurate and efficient diagnosis of fruit diseases, insect pests, and disorders. PATHMAP offers a conduit for field personnel to submit observational data and solicit assistance in diagnosis. By enabling collaboration with laboratory facilities, diagnoses can be determined using case-appropriate tests and conversations with appropriate specialists. One barrier to adoption of new platforms such as PATHMAP is user buy-in. To facilitate maximum adoption, we built upon the existing infrastructure and connections that currently exist within the fruit industry for diagnosis, integrating PATHMAP with the GLFW email list (GLFW@list.msu.edu). This email list is subscribed to the PATHMAP Diagnosis Assistance Survey so that when one user solicits assistance, the GLFW email list will receive a notification, and all self-subscribed members will be alerted. Using this format, we maintain the structure with which fruit specialists have interacted for ∼7 years for requesting assistance. Therefore, the system will be immediately visible to and usable by the industry. In addition, it will act as an archival space for diagnosis data and conversations already taking place in the community, which is currently lacking and results in loss of critical information.

FIGURE 5
Dr. Srđan G. Aćimović of Virginia Tech using the PATHMAP app tool in the field to document *Schizophyllum commune* basidiocarps on a tree trunk.

The PATHMAP app is the ideal venue for integrating related applications. The platform can be used to house or inform fruit industry alert systems, such as disease outbreak alerts or movement of insect pests into a region. The Network for Environmental and Weather Applications (NEWA: https://newa.cornell.edu/) and Enviroweather (https://enviroweather.msu.edu/) are two notable platforms housing numerous predictive models that provide guidance for diseases, insect pests, and horticultural management decisions in fruit and other crops. These two are frequently cited by growers in the Northeast and Upper Midwest as extremely valuable to their pest management strategy and reducing pesticide use (Carroll et al. 2017). In other cases, a DSS has been developed separately for specific diseases, such as the USABlight DSS, which provides unique application and flexibility (Small et al. 2015). PATHMAP has the potential to house data contributing to DSSs such as NEWA and Enviroweather and/or to house separate models where appropriate. PATHMAP also offers a way to track spatiotemporal distribution of fruit-related pests in a public space. Distribution data are invaluable for identifying locations of concern and the rate/direction of spread of biotic pests. Furthermore, describing the distribution and potential spread of pesticide resistance is integral to deploying appropriate management tactics and alerting the at-risk locations. Examples include pathogen resistance to pesticides in tree fruit systems, such as streptomycin resistance in the fire blight pathogen of apples and pears, *Erwinia amylovora* (Sundin and Wang 2018; Sundin et al. 1995; Wallis et al. 2021) and sterol demethylation inhibitor fungicide resistance in the apple scab pathogen, *Venturia inaequalis* (Pfeufer and Ngugi 2012).

Accurate maps will be valuable in plant pathogenic studies as they will enable traceback efforts to locate the point source of an outbreak. Such practices have become extremely important for human pathogens and conducting tracebacks of foodborne illness, enabled by the FDA GenomeTrakr tool and database (Allard et al. 2016). This tool also includes genomic information on the pathogen to connect strains of a pathogen and to link specific strains to sources. Adding genomic data to PATHMAP in the future will give it the potential to offer this same service to the agricultural industry. This would therefore aid the tree fruit industry and consumer by reducing food loss and waste.

The detailed information included in each observation gives PATHMAP the potential to be used beyond visual diagnosis and mapping outbreaks. The database will become a paradigm-shifting resource for data mining, model creation and research.

This can be achieved once parameters such as wind, leaf wetness, vapor pressure, relative humidity, solar radiation, and temperature are integrated into the pest and pathogen map of a given area. Weather data, coupled with disease incidence and severity, have been utilized to build models in programs for a variety of crops and diseases, including SOYRUST (Del Ponte et al. 2006), SOYGRO (Hoogenboom et al. 1992), Maryblyt (Lightner and Steiner 1992), and CougarBlight (Smith 1999), among others. Databases and sensors from federal sources (National Oceanic Atmospheric Administration, National Weather Service), universities (Florida Automated Weather Network), and state-run and satellite-based weather stations will be fed directly into PATHMAP (Newlands et al. 2018). Data can then be compiled and mined to calculate degree days and other critical weather data that correlate with field observations tailored specifically for a disease of interest (e.g., bitter rot of apple caused by *Colletotrichum* spp.). We envision that this toolset will be instrumental in developing additional disease forecasting models and epidemiological tools in combination with artificial intelligence.

The PATHMAP app and dashboard have real-world utility with significant impact, evident in the capability to increase communication amongst industry professionals, serve as a data repository for field observations, and potentially map the incidence and spread of tree fruit pests and disorders. Looking ahead, integrating weather data, algorithms, and artificial intelligence with PATHMAP can result in pest management and disease monitoring tool development programs for existing and emerging plant production problems. PATHMAP is a unique concept and will serve as a guide for other commodities and systems to help track and monitor diseases, pests, and physiological disorders that might emerge. We envision that the future of this platform will continue to evolve to meet stakeholder needs, help report information to other groups (e.g., government agencies), impact policy and reform, and shape food systems to reduce food waste and loss while reducing and optimizing inputs to combat pests and diseases.

LITERATURE CITED

Agnello, A., Brown, B., Carroll, J., Cheng, L., Cox, K., Curtis, P., Dunn, A., Helms, S., Robinson, T, and Sosnoski, L. 2022. Cornell Pest Management Guidelines for Commercial Tree Fruit Production. PMEP Cornell University, Ithaca, NY.

Allard, M. W., Strain, E., Melka, D., Bunning, K., Musser, S. M., Brown, E. W., and Timme, R. 2016. Practical value of food pathogen traceability through building a whole-genome sequencing network and database. J. Clin. Microbiol. 54:1975-1983.

Carroll, J., Weigle, T., Agnello, A., Reissig, H., Cox, K., Breth, D. Robinson, T., Loeb, G., Wilcox, W., Eggleston, K., DeGaetano, A., Olmstead, D., Grant, J., Gibbons, J., and Petzholdt, C. 2017. NEWA (Network for Environment and Weather Applications) provides fruit IPM and production tools from 400 weather stations. Fruit Quart. 25:6.

Delgado, J. A., Vandenberg, B., Kaplan, N., Neer, D., Wilson, G., D'Adamo, R., Carter, J., O'Gan, L., Grow, N., Marquez, R., Arthur, D., Eve, M., Del Grosso, S. J., Johnson, J. M. F., Karlen, D. L., Durson, L., Finley, J., Acosta-Martinez, V., Knaebel, D. B., Harmel, D., and Derner, J. 2018. Agricultural Collaborative Research Outcomes System (AgCROS): A network of networks connecting food security, the environment, and human health. J. Soil Water Conserv. 73:158A-164A.

Del Ponte, E. M., Godoy, C. V., Li, X., and Yang, X. B. 2006. Predicting severity of Asian soybean rust epidemics with empirical rainfall models. Phytopathology 96:797-803.

Environmental Protection Agency. 2021. August 21. Integrated Pest Management (IPM) principles. https://www.epa.gov/safepestcontrol/integrated-pest-management-ipm-principles

Hoogenboom, G. Jones, J. W., and Boote, K. J. 1992. Modeling growth, development, and yield of grain legumes using Soygro, Pnutgro, and Beangro: A review. Trans. ASAE 35:2043-2056.

Isard, S. A., Russo, J. M., Magarey, R. D., Golod, J., and VanKirk, J. R. 2015. Integrated Pest Information Platform for Extension and Education (iPiPE): Progress through sharing. J. Integr. Pest Manag. 6:15.

Khodadadi, F., González, J. B., Martin, P. L., Giroux, E., Bilodeau, G., Peter, K., Doyle, V., and Acimovic, S. 2020. Identification and characterization of *Colletotrichum* species causing apple bitter rot in New York and description of *C. noveboracense* sp. nov. Sci. Rep. 10:11043.

Lightner, G. W., and Steiner, P. W. 1992. MARYBLYTTM: A computer model for predicting of fire blight disease in apples and pears. Comput. Agric. Electron. 6:1-15.

Martin, P. L., Krawczyk, T., Khodadadi, F., Acimovic, S. G., and Peter, K. 2021. Bitter rot of apple in the Mid-Atlantic US: Causal species and evaluation of the impacts of regional weather patterns and cultivar susceptibility. Phytopathology 111:966.

Newlands, N. K. 2018. Model-based forecasting of agricultural crop disease risk at the regional scale, integrating airborne inoculum, environmental, and satellite-based monitoring data. Front. Environ. Sci. 6:63.

Pfeufer, E. E., and Ngugi, H. K. 2012. Orchard factors associated with resistance and cross resistance to sterol demethylation inhibitor fungicides in populations of *Venturia inaequalis* from Pennsylvania. Phytopathology 102:272-282.

Sadler, E. J., Steiner, J. L., Hatfield, J. L., James, D. E., Vandenberg, B. C., and Tsegaye, T. 2020. STEWARDS: A decade of increasing the impact of Agricultural Research Service watershed research programs. J. Soil Water Conserv. 75:50A-56A.

Small, I. M., Joseph, L., and Fry, W. E. 2015. Development and implementation of the BlightPro decision support system for potato and tomato late blight management. Comput. Electron. Agric. 115:57-65.

Smith, T. J. 1999. Report on the development and use of Cougarblight 98C—A situation-specific fire blight risk assessment model for apple and pear. Acta Hortic. 489:429-436.

Sundin, G. W., Monks, D. E., and Bender, C. L. 1995. Distribution of the streptomycin-resistance transposon Tn *5393* among phylloplane and soil bacteria from managed agricultural habitats. Can. J. Microbiol. 41: 792-799.

Sundin, G. W., and Wang, N. 2018. Antibiotic resistance in plant-pathogenic bacteria. Annu. Rev. Phytopathol. 56:161-180.

Tancos, K. A., and Cox, K. D. 2016. Exploring diversity and origins of streptomycin-resistant *Erwinia amylovora* isolates in New York through CRISPR spacer arrays. Plant Dis. 100:1307-1313.

Vaghefi, N., Kikkert, J. R., Hay, F. S., Carver, G. D., Koenick, L. B., Bolton, M. D., Hanson, L. E., Secor, G. A., and Pethybridge, S. J. 2018. Cryptic diversity, pathogenicity, and evolutionary species boundaries in *Cercospora* populations associated with Cercospora leaf spot of *Beta vulgaris*. Fungal Biol. 122:264-282.

Wallis, A., Yannuzzi, I. M., Choi, M. W., Spafford, J., Fenn, M., Ramachandran, P., Timme, R., Pettengill, J. B., Cagle, R., Ottesen, A., and Cox, K. D. 2021. Investigating the distribution of strains of *Erwinia amylovora* and streptomycin resistance in apple orchards in New York using clustered regularly interspaced short palindromic repeat profiles: A 6-year follow-up. Plant Dis. 105:3554-3563.

Whitlock, M. C., McPeek, M. A., Rausher, M. D., Rieseberg, L., and Moore, A. J. 2010. Data archiving. Amer. Naturalist 175:145-146.

Wise, J. C. 2022. Michigan Fruit Management Guide, Extension Bulletin E-154. Michigan State University Bookstore, East Lansing, MI.