Development and implementation of the BlightPro Decision Support System for potato and tomato late blight management

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A web-based decision support system (DSS) for potato and tomato late blight management has been developed which links several models into a system that enables prediction of disease dynamics based on weather conditions, crop information, and management tactics. Growers identify the location of their production unit of interest (latitude and longitude of field) and the system automatically obtains observed weather data from the nearest available weather station, and location-specific forecast weather data from the National Weather Service – National Digital Forecast Database. The DSS uses these weather data along with crop and management information to drive disease forecasting systems and a validated mechanistic model of the disease to generate location-specific management recommendations for fungicide application. An integrated alert system allows users to receive notification of upcoming critical thresholds via e-mail or text message. This system provides producers, consultants, researchers, and educators with a tool to obtain management recommendations, evaluate disease management scenarios, explore comparative epidemiology, or function as a teaching aid. In field and computer simulation experiments, DSS-guided schedules were influenced by prevailing weather and host resistance and resulted in schedules that improved the efficiency of fungicide use and also reduced variance in disease suppression when compared to a weekly spray schedule. In situations with unfavourable weather, the DSS recommended fewer fungicide applications with no loss of disease suppression. In situations of very favourable weather, the DSS recommended more fungicide applications but with improved disease suppression. The DSS provides an interactive system that helps users maximize the efficiency of their crop protection strategy by enabling well-informed decisions.

Additional keywords: plant disease management, decision support system, late blight, plant disease epidemiology, crop management, forecasting, potato, tomato

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1. Introduction

Late blight, the plant disease caused by *Phytophthora infestans* (Mont.) de Bary, is a major constraint to potato and tomato production worldwide. A conservative estimate of the total global cost of the disease to potato production is 6.7 billion USD per year in yield losses and costs of late blight control measures (Haverkort et al., 2008). Unexpected late blight epidemics have resulted in major economic losses to growers for whom potatoes or tomatoes are the major income source (Fry et al., 2013; Fry and Goodwin, 1997). Although the disease is more problematic in rain fed agriculture such as in the northeastern USA, sporadically it can also be serious in drier production areas such as the Pacific Northwest (largest potato production area in the USA) (Johnson et al., 2000). For example the cost of managing a potato late blight epidemic in the Pacific Northwest in 1995 was estimated at 30 million USD (Johnson et al., 2000). The disease can be equally devastating to tomato producers. The most recent example occurred in 2009 when infected tomato transplants were distributed via national large retail stores who obtained transplants from a national supplier (Fry et al., 2013). The ensuing pandemic in the mid-Atlantic and Northeast regions of the U.S. devastated tomato crops for many organic farms and in many, many home gardens (Fry et al., 2013).

Management of late blight typically involves cultural procedures designed to reduce the introduction, survival, or infection rate of *P. infestans*, and the use of fungicides. When developing a late blight management strategy, there are several factors that must be considered including the influence of prevailing weather on the pathogen lifecycle and fungicide residue on the crop, late blight resistance of the cultivar being grown, and pathogen characteristics, such as resistance to highly effective fungicides. The complexity of the interactions between these factors makes rational disease management decision-making difficult, leading to implementation of either inadequate or excessive management measures. The application of disease management measures when they are not necessary is at the very least inefficient, as unnecessary applications entail costs to growers, consumers, and the environment (Fry, 1982). Effective management is achieved by integrating a variety of control measures that may differ in efficacy, duration of effectiveness, and cost (Shtienberg, 2000). This complexity creates an opportunity for a decision support system (DSS) to be used to provide science-based information to assist with this decision making.

Decision Support Systems integrate and organize available information on the pathogen, the influence of observed and forecast weather on the disease, cultivar resistance, as well as fungicide characteristics and efficacy, required to make decisions concerning the management of late blight. Computer-based DSSs can integrate these factors to deliver either general or site-specific information to the users via extension personnel, telephone, fax, e-mail, SMS, PC and websites on the Internet (Cooke et al., 2011). Forecasters such as BLITECAST (Krause et al., 1975), FAST (Madden et al., 1978), and the apple scab predictive system (Jones et al., 1980), are examples of early tools that were designed to assist farmers with decisions relating to management of potato late blight, early blight, and apple scab, respectively (Shtienberg, 2013). Since the 1990s, DSSs have been developed in many countries to assist with the management of plant diseases such as potato late blight, apple scab, cereal leaf diseases, strawberry diseases, and grape downy mildew (Pavan et al., 2011; Shtienberg, 2013). In Europe, several DSSs for late blight have been developed using various disease forecasting systems and models (Cooke et al., 2011). A list of these DSSs can be found on the Euroblight website (a potato late blight network for Europe) (http://www.euroblight.net/EuroBlight.asp). In certain European countries, such as The Netherlands, it has been reported that up to 36% of potato growers use the recommendations of commercially available DSSs to assist with their management of late blight (Cooke et al., 2011).

Under experimental settings, use of DSSs has been shown to improve disease suppression, reduce risk of crop damage, and under many circumstances reduce the quantities of active ingredients used, relative to typical spraying practices (Shtienberg, 2000). The objectives for this study were to develop and implement a web-based DSS for late blight capable of utilizing location-specific weather data to drive disease forecasters and a mechanistic model of the late blight disease, in order to provide real-time (in-season) support for late blight management in the USA.

2. System development

The BlightPro DSS for potato and tomato late blight management (http://blight.eas.cornell.edu/blight/) was developed to integrate pathogen information (mefenoxam sensitivity and host preference), the effects of weather, host resistance and fungicide on disease progress in order to improve in-season disease management. A secondary design objective was to develop a version of the system that could be used with archived weather data to explore disease management scenarios, for comparative epidemiology, or function as a teaching aid.

2..1 Weather data

Each user defines the location of his/her management unit of interest (field) via an interactive geographic information system in the form of a Google Maps API. This provides an easy method to obtain the necessary latitude and longitude information required for the DSS (Fig. 1). The system then automatically identifies the nearest five weather stations to the grower's location, with the closest station serving as the default source for observed weather data, and utilizes the grower location to obtain the weather forecast. The weather station may be a privately owned station (connected to a meteorological network) on the grower's farm, or a publicly accessible station e.g. an airport station. If the user intends to use a private station, the station must be capable of uploading data to a meteorological network such as NEWA (Network for Environment and Weather Applications) in the Northeastern USA http://www.newa.cornell.edu/, or FAWN (Florida Automated Weather Network) in Florida http://fawn.ifas.ufl.edu/. Data from these networks can be accessed by the Northeast Regional Climate Center (NRCC) http://www.nrcc.cornell.edu/.

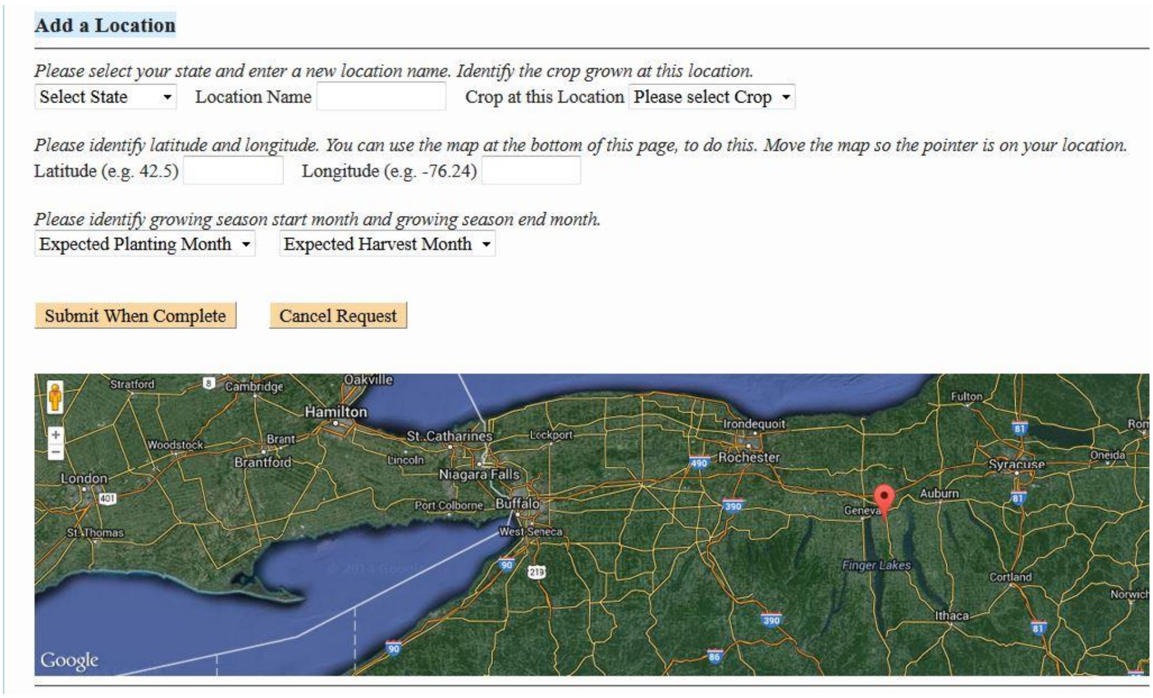

Fig. 1. Interface for definition of new locations. A google API interface allows users to identify their location with the aid of a map. The latitude and longitude of the location is obtained automatically.

The NRCC works cooperatively with the National Climatic Data Center, the National Weather Service, state climate offices, and interested scientists in the Northeast to acquire and disseminate accurate, up-to-date climate data and information. Regional Climate Centers (RCCs) are a federal-state cooperative effort (DeGaetano et al., 2010). The National Oceanic and Atmospheric Administration (NOAA) – National Climatic Data Center (NCDC) manages the RCC Program. The six centers that comprise the RCC Program are engaged in the production and delivery of climate data, information, and knowledge for decision makers and other users at the local, state, regional, and national levels. Weather data are accessed via the Applied Climate Information System (ACIS) developed by the NOAA – RCCs (DeGaetano et al., 2015). A number of weather variables including temperature, relative humidity, precipitation, wind speed and direction are monitored and archived in real time.

The observed data are combined with high-resolution forecast data (2.5 square km grid) for the location of interest, obtained from the National Weather Service – National Digital Forecast Database (NWS-NDFD) using access routines provided by the NRCC. The NWS-NDFD short-term weather forecasts are provided in a grid format and include sensible weather elements (e.g., temperature, relative humidity, sky cover). The NDFD contains a seamless mosaic of digital forecasts from NWS field offices working in collaboration with the National Centers for Environmental Prediction (NCEP). The weather data and forecasts are updated 8 times per day. The frequency of updates depends on the rate at which new forecasts are generated by the NWS and processed by the NRCC. As weather forecasts are updated, the outputs of the DSS will change to reflect the most recent weather data.

2.2. Cultivar resistance database

A database providing information on late blight resistance in potato and tomato cultivars was generated for the DSS using a combination of published literature and field experiments. Information on potato cultivar resistance to late blight was obtained from published plant disease management reports and field experiments (Forbes et al., 2005; Fry, 1998; Fry and Apple, 1986; Inglis et al., 1996; Jenkins and Jones, 2003; Parker et al., 1992; Stevenson et al., 2007). Field experiments to investigate potato cultivar resistance to late blight were conducted at the Homer C. Thompson Vegetable Research Farm in

Freeville NY in 2011, 2012 and 2013 (Small et al., 2013). The system was initially developed for late blight of potato but extension of the system is underway to enable its use for late blight of tomato. Information on tomato cultivar resistance to late blight was obtained from published plant disease management reports (McGrath et al., 2013) and field trials (Hansen et al., 2014). A list of cultivars evaluated is available on the DSS. Currently (May 2015), there are more than 60 potato cultivars and more than 50 tomato cultivars that have been classified for their resistance to late blight. These numbers will increase as experimental data is obtained.

2.3. Disease forecasting tools

The DSS provides a platform to run late blight forecasting systems. Two systems are currently implemented: Blitecast, which is a forecast system developed to predict the initial occurrence of late blight in northern temperate climates, as well as the subsequent spread of late blight (Krause et al., 1975); and Simcast, which is a forecasting system that integrates the effect of host resistance with the effects of prevailing weather on late blight progress and the effect of prevailing weather on fungicide weathering (Fry et al., 1983). Simcast does not predict the initial occurrence of late blight (the need for a first fungicide application), but may be used to schedule subsequent applications. A user might schedule his/her initial fungicide application based on the accumulation of 18 Blitecast severity values, or a particular growth stage, and then use Simcast to schedule subsequent applications. Critical thresholds for Simcast were originally validated in field experiments using chlorothalonil as a fungicide. In order to accommodate for the variety of fungicides used by producers, thresholds were established for several of the most commonly used fungicide active ingredients e.g. copper hydroxide, cyazofamid, cymoxanil, mancozeb, mandipropamide, mefenoxam, propamocarb hydrochloride, and others. Thresholds for fungicide active ingredients (and combinations of active ingredients) were established based on field experiments, published fungicide efficacy data, and expert opinion.

2.4. Late blight disease simulator

A mechanistic model of the late blight disease on potato (Andrade-Piedra et al., 2005) is available on the system and can be used in real-time with the observed and forecast weather to predict disease dynamics and fungicide weathering and loss. The model was validated for late blight on potato and fungicide weathering on a potato canopy. Validation of the model for its ability to predict late blight of tomato and fungicide residue on tomato canopy is yet to be accomplished. The simulator may be used to evaluate disease management scenarios, or to quantify the effects of host resistance and/or fungicide. The fungicide sub-model is based on chlorothalonil, a widely used protectant fungicide (Bruhn and Fry, 1982a; Bruhn and Fry, 1982b).

2.5. System output

The DSS generates several reports, including reports on prevailing weather, disease forecast information, and late blight simulator outputs. The weather data report includes graphs illustrating 7 days of observed and 7 days of forecast weather (hourly relative humidity, hourly temperature, six-hourly precipitation). The disease forecast reports include information from: 1) Blitecast – observed and forecast daily severity values; and 2) Simcast – observed and forecast daily blight units and fungicide units. Blitecast severity values indicate the favorability of the prevailing weather for late blight progress and represent specific relationships between duration of relative humidity periods ≥ 90 % and average temperature during those periods, and their impact on late blight (Krause et al., 1975). Similarly, Simcast blight units represent the favourability of the prevailing weather for late blight progress and are also calculated based on the relationships between duration of relative humidity periods ≥ 90 % and average temperature during those periods. However, in Simcast, the calculation of blight units is influenced by the cultivar resistance to late blight with different thresholds for cultivars of different resistances. Simcast fungicide units represent the impact of prevailing weather (including precipitation) on fungicide weathering. Critical thresholds for both blight units and fungicide units are determined according to cultivar resistance (Fry et al., 1983). The reports generated by the late blight simulator are based on observed and forecast weather data and include information on: 1) simulated disease progress data; and 2) simulated fungicide residue on crop.

2.5.1. Weather data

A weather report provides users with the ability to inspect recent observed weather and forecast weather. The report contains graphs of hourly temperature and relative humidity and six-hourly precipitation, for 7 days of recent observed and 7 days of forecast weather data (Fig. 2). Decision-makers might find this information useful to verify that weather data are accurate for their location and to understand the association between prevailing weather and favorability of the weather for late blight. In addition to the detailed weather data, the system conducts an automatic check for missing weather data and a summary table indicating the number of hours of missing data for any of the relevant weather variables is presented. Since the reliability of the outputs from the disease forecasts and disease model are dependent on accurate and complete input weather data, the system has a missing-weather backup feature. If more than 6 hours of missing temperature or relative humidity data occur, the system substitutes missing data with archived forecast information for that specific location. The archived weather data consists of the first 24 hr of forecast weather, which are saved daily. For missing precipitation data, the system substitutes missing data with high resolution precipitation data generated by the NRCC. Alternatively, the user has the option to select one of the other four nearest stations as a source for the observed data.

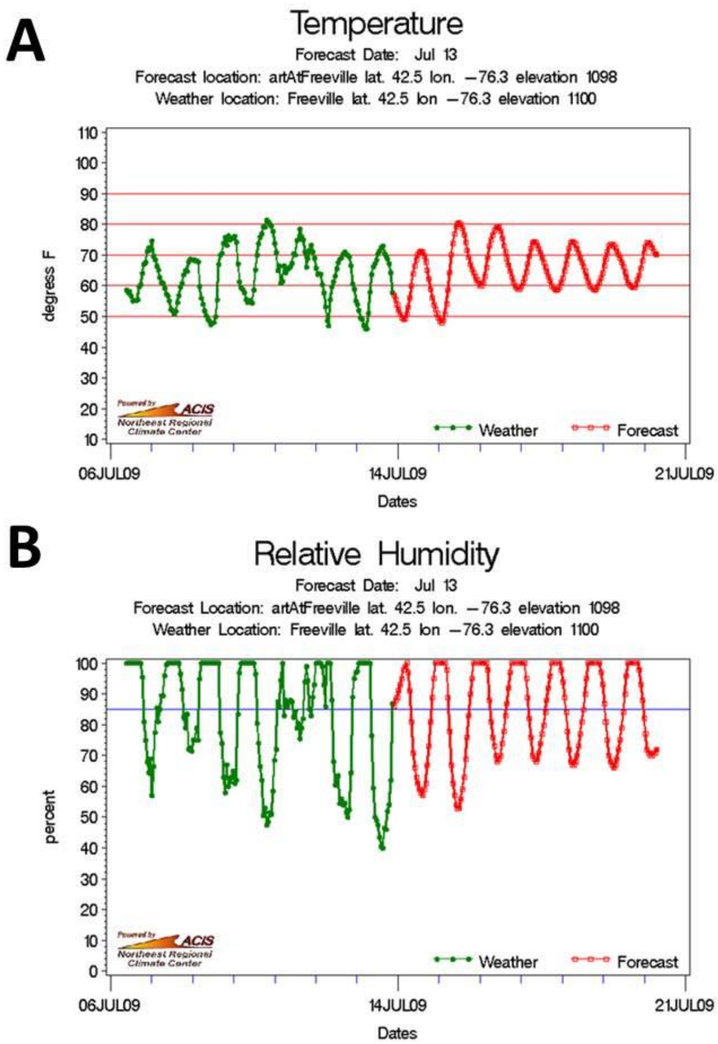

Fig. 2. Examples of weather reports. **A**. Hourly temperature data for a defined location. **B**. Hourly relative humidity data for a defined location. Seven days of observed (green series) and 7 days of forecast (red series) weather data are represented on each report.

2.5.2. Disease forecast reports

The system generates a detailed report for each disease forecasting system, Blitecast and Simcast. The detailed Blitecast report provides daily information about wet period duration and average temperature during each wet period (Fig. 3). This information is used to calculate a daily severity value, the cumulative severity value since last fungicide application, as well as the seasonal cumulative severity value (based on the Blitecast system). The detailed Simcast report provides daily information on wet period duration and average temperature during each wet period, as well as daily precipitation/irrigation (Fig. 4). This information is used to calculate daily blight units and daily fungicide units. Blight units indicate the favorability of the prevailing/forecast weather for late blight and fungicide units represent the influence of prevailing/forecast weather, or irrigation, on fungicide weathering. For blight units and fungicide units the daily value is presented along with the cumulative value since last fungicide application and seasonal cumulative value. A colour coding system distinguishes information based on forecast weather data from observed weather data (Fig. 4). Critical thresholds for fungicide application are automatically indicated on the reports.

6/10/2010 Blitecast Report
Weather Location: Freeville 5/30/2010 to 6/10/2010
Forecast Location: freevilleFarm 6/10/2010 to 6/16/2010
Replacement for missing weather: not applicable

	Wet Period				Severity Values		
Fungicide Date	**start**	**end**	**hrs.**	**Ave. Temp. (F)**	**daily**	**accum since last fung. appl.**	**season accum.**
	6/15 4am	6/15 7am	3	54	0	19	19
6/14							
	6/13 7pm	6/14 9am	14	64	2	19	19
6/13							
	6/12 9pm	6/13 1pm	16	69	3	17	17
6/12							
	6/11 10pm	6/12 10am	12	61	1	14	14
6/11							
	6/10 8pm	6/11 9am	13	52	0	13	13
6/10							
	6/10 10am	6/10 11am	1	62	0	13	13
6/9							
	6/9 11am	6/10 9am	22	57	4	13	13
	6/8 9pm	6/9 8am	11	48	0	9	9
6/8							
	6/7 11pm	6/8 9am	10	52	0	9	9

Fig. 3. Detailed Blitecast report. Daily severity values are calculated based on wet period duration and average temperature during each wet period. Information based on observed weather data has a white background and information based on forecast weather data has an orange background. When the cumulative daily severity value has exceeded a critical threshold, this is indicated by red font colour.

7/15/2010 Simcast Report for susceptible cultivar
Weather Location: Freeville 6/13/2010 to 7/15/2010
Forecast Location: freevilleFarm 7/15/2010 to 7/21/2010
Replacement for missing weather: not applicable

		Wet Period				Blight Units				Fungicide Units		
Date	Fungicide (epa number)	start	end	hours	Ave. Temp. (F)	daily	since last fung. appl.	season accum.	Rainfall (& irrigation) (inch)	daily	since last fung. appl.	season accum.
7/21										-1	-19	-19
		7/20 23	7/21 9	11	64.4	6	55	196				
7/20										-1	-18	-18
		7/19 22	7/20 9	12	66.2	6	49	190				
7/19										-1	-17	-17
		7/19 1	7/19 9	9	66.2	5	43	184				
7/18									0.01	-1	-16	-16
		7/18 0	7/18 8	9	66.2	5	38	179				
7/17									0.26	-4	-15	-15
		7/16 20	7/17 8	13	68.0	7	33	174				
7/16									0.08	-3	-11	-11
		7/15 23	7/16 9	11	69.8	6	26	167				
7/15									0.00	-1	-8	-8
		7/14 20	7/15 9	14	66.2	7	20	161				
7/14									0.00	-1	-7	-7
		7/13 20	7/14 11	16	71.6	7	13	154				

Fig. 4. Detailed Simcast report for a defined location. The Simcast report provides daily information on wet period duration and average temperature during each wet period, as well as daily precipitation/irrigation. This information is used to calculate daily blight units and daily fungicide units. The report is divided into three sections based on background colour: white background is observed weather data used for calculations; orange background is forecast temperature, relative humidity, and precipitation; and yellow background is forecast temperature and relative humidity. Longer term precipitation forecast (beyond three days) is excluded due to high variability.

In addition to the detailed reports, a simple summary graphic is presented which clearly indicates whether or not a critical threshold is expected to occur within the upcoming 7 days, based on forecast weather (Fig. 5).

Simcast Summary

Date	7/15	7/16	7/17	7/18	7/19	7/20	7/21
Blight Units	20	26	33	38	43	49	55
Fungicide Units	-8	-11	-15	-16	-17	-18	-19

Key	
	Below Threshold
>=30	Blight Unit Threshold Exceeded
<=-15	Fungicide Unit Threshold Exceeded

Fig. 5. Seven-day forecast summary. A summary graphic is generated which presents key forecast information for the upcoming 7 days. Daily information is represented as columns with rows showing the accumulated blight/fungicide units. Background colour of each cell indicates whether a critical threshold has been exceeded. A key shows the applicable critical thresholds accompanied by their respective background colour.

2.5.3. Simulator reports

Three outputs are generated by the simulator: 1) a graph indicating simulated disease progress based on observed and forecast weather, cultivar resistance, and fungicide use (Fig. 6); 2) a graph indicating simulated average fungicide residue on the potato canopy, based on observed and forecast weather and fungicide application information (Fig. 7); and 3) a table containing a detailed numerical listing of several model outputs calculated for each day, such as disease severity and fungicide residue (Fig. 8).

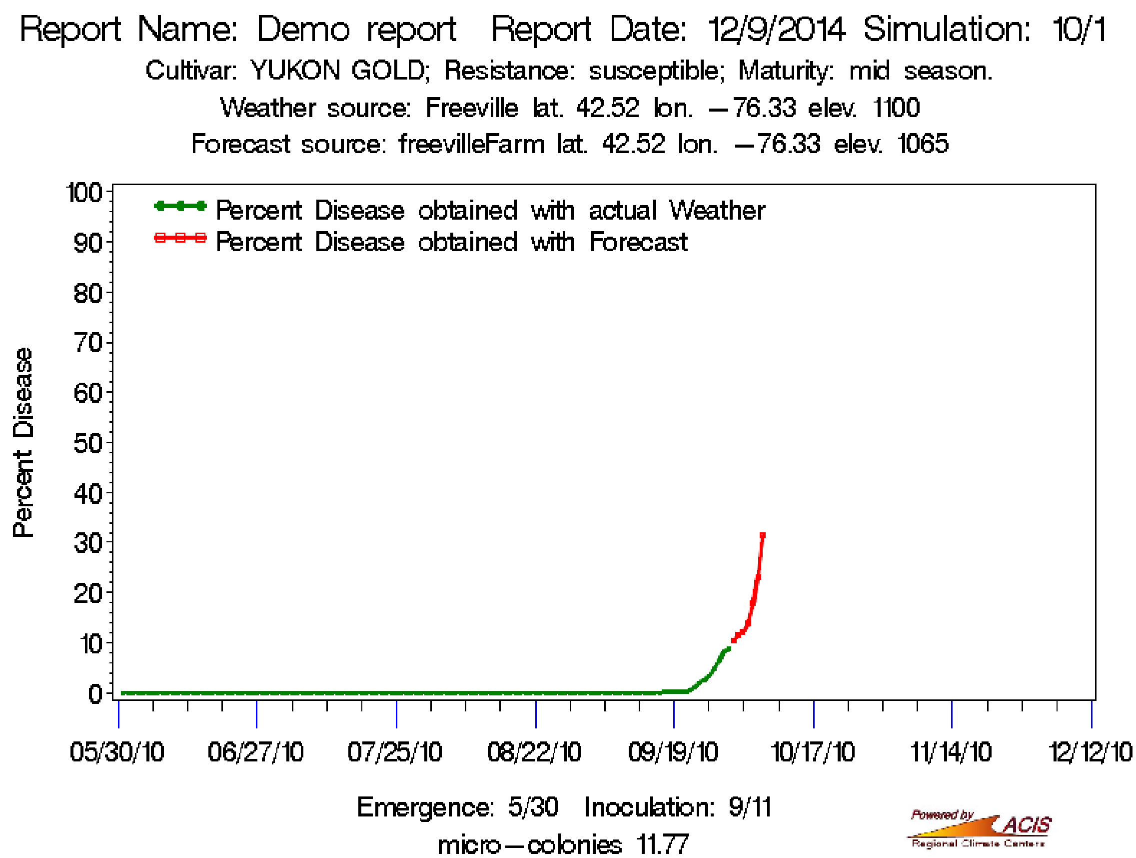

Fig. 6. Graph showing simulated disease progress on potato. A validated mechanistic model can be used to simulate daily disease severity based on observed (green series) and forecast (red series) weather data, presence and severity of observed disease, cultivar resistance, and fungicide use.

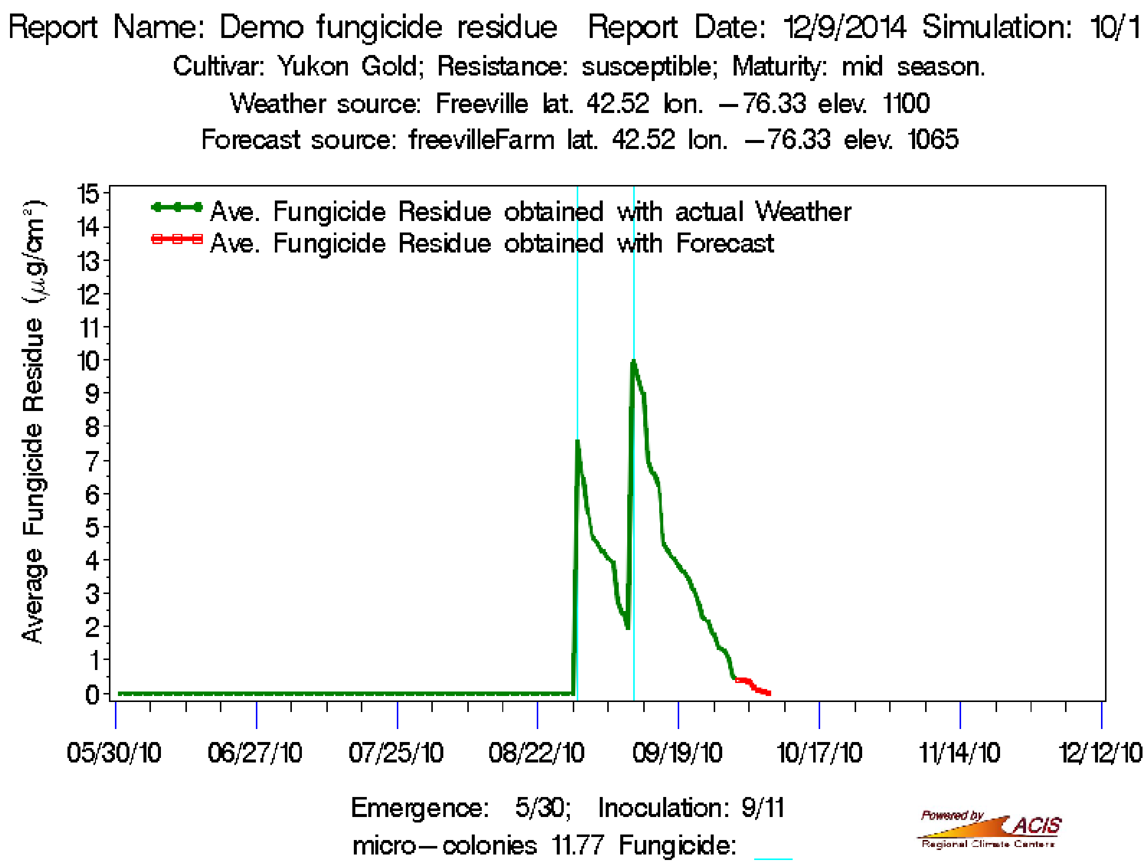

Fig. 7. Simulated fungicide residue on potato. The predicted average fungicide residue on the plant canopy can be simulated using a validated mechanistic model for the protectant fungicide chlorothalonil on potato. Fungicide residue predictions are based on observed (green series) and forecast (red series) weather data, as well as information about fungicide applications made.

Report Name: Demo fungicide residue   Report Date 12/9/2014
Cultivar: Yukon Gold; Resistance: susceptible; Maturity: mid season.
weather: Freeville lat. 42.52 lon. -76.33 elev. 1100
forecast: freevilleFarm lat. 42.52 lon. -76.33 elev. 1065

Date	Day of Season	Num. Sporangia	Cumulative Disease Severity	Germinated Zoospores	Germinated Sporangia	New Infections	Percent Disease	Fungicide Residue
10/07/10	130	0.00	10.46	181390.38	1312.67	584.38	2.35	0.02
10/06/10	129	1671554.06	8.50	86542.56	0.00	721.58	1.56	0.05
10/05/10	128	730447.43	7.15	0.00	0.00	0.00	1.15	0.10
10/04/10	127	0.00	6.13	0.00	0.00	0.00	0.89	0.19
10/03/10	126	0.00	5.29	0.00	0.00	0.00	0.79	0.38
10/02/10	125	0.00	4.51	17919.06	0.00	78.40	0.76	0.40
10/01/10	124	233023.03	3.78	14852.65	0.00	98.75	0.70	0.42
09/30/10	123	892091.72	3.12	2320.48	6253.76	566.71	0.62	0.45
09/29/10	122	1144541.83	2.51	0.00	0.00	0.00	0.60	1.04
09/28/10	121	0.00	1.97	62769.89	704.16	197.00	0.48	1.30
09/27/10	120	602146.91	1.54	16381.90	1014.44	140.49	0.38	1.37
09/26/10	119	282489.27	1.21	0.00	0.00	0.00	0.29	1.73

Fig. 8. Example listing of model (LB 2004) outputs. A numerical listing of several model outputs is provided in a report. Information about pathogen lifecycle stages, disease severity, and fungicide residue is provided for each day of the season. The report is divided into three sections based on background colour. The white background is observed weather data used for calculations.The beige background is forecast temperature, relative humidity, and precipitation The yellow background is forecast temperature and relative humidity.

2.6. Alert system

Optional automated alerts about upcoming critical thresholds for intervention are available to users via sms (short messaging system) text message or e-mail. An initial alert is sent out when a critical threshold is exceeded within the first 72 hr of forecast. Messages for all locations with upcoming critical thresholds are compiled into text and/or e-mail form and sent once a day to avoid multiple messages. SMS technology has been successfully used in other disease alert systems such as the Strawberry Advisory System (Pavan et al., 2011). The alert systems have been tested since 2012 to evaluate their value to the user and received positive feedback from extension personnel and producers.

2.7. Teaching tool

A training/teaching version of the system was developed that provides access to archived weather data (observed and forecast) from multiple locations and has a function that allows the user to navigate through the season by changing the ‘current’ date to any date in the season, enabling the user to explore the system outputs under different scenarios, or to use it to teach epidemiological principles. This provides producers, consultants, researchers and educators with a tool to evaluate disease management scenarios, explore comparative epidemiology, develop forecasting models, or function as a teaching aid.

2.8. Information technology

The system was developed using a multilayered programming approach. The layers consist of a web-based interface for the user, with programs and databases in the background. The overall system runs on a server hosted by the NRCC at Cornell

University that has Quixote and CORBA installed. Password protected account information is stored in databases consisting of SQL Light tables. Disease forecasting tools, written in Python, and a mechanistic model of the disease, written in SAS, utilize input information stored in the database to generate outputs. Outputs are presented via a web interface, in HTML format, and are also generated in portable document format (pdf) using a program written in SAS. The web interface was generated using JQuery and Javascript. A tab-based interface was developed to separate sections of the DSS, such as inputs, simulator, alert setup, and irrigation input. This tab-based approach is intended to simplify the addition of other forecasts and models and to enable personalization of access to specific tabs for certain groups (basic user/consultant/extension educator/researcher). Access to certain tabs can be user-specific, as set by the administrator. An example of a reason to provide user-specific access might be based on geographic location (state), allowing the system to provide the most appropriate disease forecasting tools and models for that region.

Python programs are used to obtain observed and forecast weather data. These programs are automatically processed by Unix scripts, called "cronjobs" and executed several times a day. Complete weather records of observed and forecast weather are generated for each location (field) defined on DSS. These records are utilized by the DSS disease forecasting tools and the disease simulation model.

Disease forecasts are executed on a daily basis, or upon user request, to provide users with rapid access to results and to identify any upcoming critical thresholds that might trigger recommendations for management intervention. If a critical threshold is forecast (up to 72 hr into the future) then an automated alert will be sent to the user (if alerts have been requested).

2.9. Evaluation of the system recommendations

A preliminary version of the system has been available to extension educators and producers in NY since the 2010 cropping season. The system was evaluated by researchers in field experiments conducted each year from 2010 -2014 (Small et al., 2013) and in computer simulation experiments, as well as by extension personnel, crop consultants and commercial farms (potato and tomato). Field experiments have been conducted for both potato and tomato. In multiple field experiments, the average number of fungicide applications per season recommended for a susceptible cultivar was equivalent to a calendar-based (7-day) schedule (range: -36% to +12%, relative to a 7-day schedule). For moderately susceptible cultivars, an average reduction of 25% (range: -28% to -10%) fungicide application was achieved, relative to a 7-day schedule. For moderately resistant cultivars, an average reduction of 40% (range: -50% to -37%) fungicide application was achieved, relative to a 7-day schedule (Small et al., 2013). These experiments demonstrated that fungicide usage can be reduced by up to 50% through the use of the DSS when conditions are not favourable for late blight, while maintaining successful disease suppression. Under favourable conditions for the disease, the DSS recommended up to 12% increase in fungicide applications, relative to a 7-day schedule (Small et al., 2013).

In order to test the system under diverse environmental conditions, field experiments were simulated using historic observed weather (2000 – 2013) from 59 potato/tomato growing locations. The computer model of the late blight disease was used to run 6912 simulations for the equivalent of 768 field experiments. Management recommendations given by the DSS were compared with calendar-based approaches to fungicide scheduling in these simulated field experiments. The average number of fungicide applications per season recommended by the DSS for susceptible cultivars was 24 % higher than a calendar-based (seven-day) schedule (range: -91 % to +91 %). For moderately susceptible cultivars, an average reduction of 15 % (range: -91 % to +36 %) fungicide application was achieved, relative to a 7-day schedule. For moderately resistant cultivars, an average reduction of 35 % (range: -91 % to 0 %) fungicide application was achieved, relative to a 7-day schedule. Simulation experiments demonstrated the potential of the system to reduce fungicide usage by up to 91% (when conditions are not favourable for late blight), while maintaining successful disease suppression. Under favourable conditions for the disease, the DSS has the potential to recommend up to 91% increase in fungicide applications on susceptible cultivars, relative to a 7-day schedule.

3. Discussion

The late blight DSS provides an interactive system that helps users maximize the efficiency of their crop protection strategy by enabling well-informed decisions. In situations with unfavourable weather, the DSS recommended fewer fungicide applications with no loss of disease suppression and, in situations of very favourable weather, the DSS recommended more fungicide applications but with improved disease suppression. The benefit of using this system will be consistent disease control while enabling reduction of fungicide use under conditions that are not favourable for late blight. In addition, the system provides scientifically-based recommendations for reduced fungicide use on partially resistant cultivars. The outputs of the system are meant to aid decisions by the grower or the consultant. The system is not intended to replace grower or consultant decisions.

A large national initiative to combat late blight, USAblight (http://usablight.org/), was established in the USA to reduce losses to potato and tomato late blight by monitoring pathogen populations, developing additional resistant cultivars, and enhancing education and extension. The BlightPro DSS is a key component of this late blight community initiative. Development of an internet-based late blight DSS within the late blight research community in the USA is intended to facilitate implementation of this late blight DSS across the USA and enable future development of the late blight DSS applications by allowing exchange of components and information between partner research groups and institutions. Overall, the current system can be viewed as consisting of core components of an internet-based late blight DSS. As improved, or regionally-specific, forecasting tools become available these can be integrated into this system. A similar collaborative approach, Web-blight, was established in Nordic countries, Baltic countries, and Poland in 1998 (Cooke et al., 2011).

In response to requests for user accounts, the system has been expanded to enable its use in 19 US states. In New York alone, thirteen farms and two consultants working with one vegetable extension specialist, Carol MacNeil, as well as several farmers working independently, successfully used the BlightPro DSS in 2012 and 2013 to more effectively and efficiently control late blight, and time fungicide sprays, on over 4,000 acres of potatoes and tomatoes.

A key aspect of the development of the DSS is that it was constructed in consultation with end users, primarily extension personnel and producers. This ensured that the information provided by the system was relevant to users and that the language and formats used for the interface and outputs were intuitive and appropriate. Development of the system has been ongoing with feedback from users and new developments driving modifications to the system.

The accuracy of the outputs of this system is limited by the availability of accurate and representative weather data. Ideally, weather stations used for a particular location will be located in the crop canopy or close to the production unit of interest, with minimal infield variability. The microclimate within a canopy is likely to play an important part in the variability in performance as would other factors such as damp hollows in fields, tree shading, and differential rates of foliage growth. These all influence the in-field variability of the microclimate. In addition, the forecast information should match the meteorological conditions actually observed in order for accurate advanced decision making.

4. Future research and development

Future research plans include the addition of existing forecasting tools for other important diseases of potatoes and tomatoes, such as early blight. This will provide a tool that will assist decision-makers with the task of understanding the complex interactions between prevailing weather, cultivar resistance to the diseases, fungicide effects and will help integrate this information into management recommendations that are appropriate for both early blight and late blight.

The current system provides recommendations for variable interval fungicide application. In certain production systems there is limited flexibility around application intervals, such as prescheduled aerial applications. To accommodate for systems with limited flexibility around application intervals, research is underway to provide recommendations for variable fungicide dose and/or type of fungicide.

The current version of the simulator is limited to a sub-model of the protectant fungicide chlorothalonil. Plans are underway to include a validated sub-model for the systemic fungicide mefenoxam (metalaxyl-m).

Information regarding the presence/absence and quantity of late blight inoculum is not an integral part of the current system. A planned expansion of the current system involves a new tool to identify the risk of infection for a known source of late blight. The USAblight pathogen monitoring database will be connected with the DSS to provide information regarding pathogen occurrence to drive a new tool that will provide infection risk alerts to users.

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