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NAPPFAST: An Internet System for the Weather-Based Mapping of Plant Pathogens

In recent years, the number of exotic pest introductions has increased rapidly as a result of increased volume of trade (22). The serious and sometimes irreparable ecological and economic damage of exotic pathogens, such as *Cryphonectria parasitica*, *Ophiostoma novo-ulmi*, and *Phytophthora ramorum*, the causal agents of chestnut blight, Dutch elm disease, and Sudden Oak Death, respectively, are amply documented (1,6,42). An estimate of annual losses for exotic plant pathogens is \$21 billion dollars (32). The Plant Protection and Quarantine (PPQ) (Sidebar 1) division within the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) has the goal of safeguarding agriculture and natural resources from the risks associated with the entry, establishment, and spread of exotic pathogens.

Two important components of the APHIS-PPQ mission are risk analysis and pest detection. A key goal of the risk analysis program is to identify exotic pest pathways and to assess the risks these exotic pests pose to plants and plant products as well as to the environment. Three types of risk assessments that evaluate the probability of the introduction and establishment of exotic plant pests are pathway analysis, organism pest risk assessment, and commodity risk assessment. The PPQ pest detection program and its state coop-

erators provide a continuum of pest surveillance, from offshore preclearance programs through port inspections, to surveys in rural and urban sites across the United States. The Center for Plant Health Science and Technology (CPHST) and the Cooperative Agricultural Pest Survey (CAPS) programs are instrumental in APHIS-PPQ's pest detection programs. CAPS is responsible for supplying a means of detection, documentation, and rapid dissemination of information regarding the survey of regulated significant plant pests and weeds in the United States. The survey information gathered by CAPS is entered into a central database known as National Agricultural Pest Information System (NAPIS). CPHST, headquartered in Raleigh, NC, is a multi-program scientific support organization for PPQ. One way CPHST scientists help facilitate the

APHIS-PPQ activities of risk analysis and pest detection is by mapping the potential introduction and establishment of exotic pathogens in the United States. These maps are the result of pathogen-specific information analyses, including climate, pathogen distribution, host distribution, and trade.

Given its influence on pest phenology, reproduction, dispersion, and overwintering survival, climate is a critical component for the geographic assessment of potential pathogen distribution. A large number of climate-based risk mapping systems, such as CLIMEX, BIOCLIM, and GARP, have been used for pest risk analysis (3,10,38,44). Literature typically focuses on the development and/or evaluation of the best modeling techniques (10); however, often the quality of the inputs, including biological parameters, weather

Sidebar 1. List of acronyms

Acronym	Definition
APHIS	Animal Plant Health Inspection Service
CAPS	Cooperative Agricultural Pest Information System
CLIMEX	A tool for climate matching developed by CSIRO, Australia
CPHST	Center for Plant Health Science and Technology
CSREES	Cooperative State Research Education and Extension Service
DSS	Decision Support System
L-PIPE	Legume Pest Information Platform for Extension and Education
NAPIS	National Agricultural Pest Information System -- database used for CAPS
NAPPFAST	NCSU APHIS Plant Pest Forecasting System
NCSU	North Carolina State University
NOAAPORT	The NOAAPORT broadcast system provides a one-way broadcast communication of NOAA environmental data and information in near-real time to NOAA and external users.
NPDN	National Plant Diagnostic Network
USDA-RMA	United States Department of Agriculture - Risk Management Agency
USFS	United States Forest Service
PPQ	Plant Protection and Quarantine

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data, and observed distributions, are likely to be a limiting factor in constructing spatially accurate risk maps. Climate risk mapping tools will use either deductive or inductive mapping approaches (3). Deductive approaches use experimental data to create biological models that predict a pathogen's distribution from weather or climate data. Inductive approaches estimate a pest's potential distribution by comparing the climate in a pest's current range with the climate in areas where the pest is not yet present. Deductive techniques work best when there is adequate information available about the biological requirements (particularly temperature and moisture) of the pest. Some deductive approaches, including degree day or infection models, are advantageous because the models can also be used to predict pest phenology. This may be useful to time survey activities for pest detection programs such as trap placement. Inductive approaches are best when the current pest distribution is well known, but there is a lack of other biological information. Although climatology is a key component for pest risk mapping, other factors may also be important (37). Climate-based modeling may be useful for pathogens that are weather-driven or moisture dependent (14), but not helpful for pathogens that either have broad requirements or are pests of indoor environments, e.g., greenhouses. In addition, crops growing in unique microclimates or grown under irrigation present additional challenges to modelers.

An ideal APHIS-PPQ risk mapping system for exotic pests should have the following specifications: an interactive web-based interface; access to high-quality and

high-resolution daily weather data sets for the United States and the world; simple interactive modeling tools supporting deductive and inductive techniques; and capabilities to overlay multiple geographic data sets, including those for host distribution, pest interception and distribution, trade, and survey. This type of risk mapping system has application for three types of APHIS personnel: pest survey specialists, program managers, and risk analysts. Pest survey specialists implement surveys and require state or regional risk maps, in addition to the optimum time to conduct the survey(s). Program managers have national and/or regional responsibilities and are primarily concerned with the allocation of resources using national or regional risk maps. Risk analysts require risk maps to assess the potential establishment for high-risk pathways, commodities, or pests. Risk maps may also be useful in delimiting surveys or for managing pest eradication. In 2002, APHIS-PPQ, in partnership with North Carolina State University (NCSU) and ZedX Inc., began developing the NCSU-APHIS Plant Pest Forecasting (NAPPFAST) system. This project was initially the concept of the late Jack Bailey, an NCSU plant epidemiologist. ZedX Inc. is an agricultural information technology company with experience in building Decision Support Systems (DSS) for plant protection, including E-weather (36), GUI-ADS, and the Pest Information Platform for Education and Extension (PIPE) (17). NAPPFAST is a customization of a generic ZedX Inc. product known as the Data-Gorilla. The Data-Gorilla allowed users to mine and map large weather databases. NCSU li-

censes access to the NAPPFAST interface and online databases through a cooperative agreement with APHIS.

Components of the NAPPFAST System

In this paper, we will give an outline of the tools used for model and map creation, and discuss model validation. We also present several prominent case studies, including soybean rust (*Phakopsora pachyzyi*) and Sudden Oak Death (*Phytophthora ramorum*). In the final pages, we identify potential developments of the NAPPFAST system and its sister products used for survey, detection, and eradication.

Climate databases. The NAPPFAST system uses a web-based graphic user interface to link climatic and geographic databases with templates for biological modeling (Fig. 1). ZedX Inc. maintains climatic data sets from 1978 onwards. The global dataset (Climate Research Unit, Norwich, UK) (29) encompasses a monthly 0.5 degree (~55 k) resolution of nine meteorological variables (Sidebar 2). The data set includes both observed and derived variables. The derived variables, including leaf wetness, evaporation, and soil temperature, are calculated using proprietary algorithms. The algorithms used for leaf wetness have been validated elsewhere (12,13,19,25). The other climate data set is related to North America and consists of daily data for nine meteorological variables (Sidebar 2). Thirty years of weather data are available for both data sets. The North American database compiles observations from approximately 2,000 stations (Fig. 2) supplied by government and commercial sources, includ-

Fig. 1. View of the web interface for NAPPFAST showing the history section for map creation and viewing.

ing the NOAAPORT (36). ZedX Inc. uses a series of proprietary quality control algorithms for error checking and filling-in missing values. The licensing agreement with ZedX Inc. allows users to export model output but not model input, i.e., weather data.

Biological templates. Templates provide a rapid method to create models. Usually there is little lead time for research and development when APHIS-PPQ program managers realize they have a new exotic pest outbreak or a high-risk pathway that requires a risk map. There may also be times when there is little to no information about an exotic pest's epidemiology; as a result, there is a need for a system to create "first guess" pest risk maps from models with few biological inputs (26). The interactive templates in NAPPFAST include an infection template for plant pathogens; a generic template with canned (preprogrammed) equations for creating empirical models; and a degree-day template, primarily for arthropod or weed phenology modeling.

The generic template contains a series of equations used to build empirical models. The equations include logical relationships (e.g., "X and Y", "X or Y"), polynomials,

and logistic or exponential functions. Once an equation is selected, users can choose a variable (Sidebar 2) from a pick list and set limits. The generic template allows for a quick and easy creation of a variety of models. Common examples include models that predict the survival of organisms or their hosts based on maximum or minimum temperatures. The generic template can be used with daily and monthly data. Soybean rust overwintering survival is a NAPPFAST example that uses a generic template.

The generic infection template (Fig. 3) is based on a temperature-moisture response function (26), using daily weather data as its input. The temperature-response function, commonly used to model crop growth, is scaled to a pathogen's surface wetness requirement to create a simple infection model. Model parameters include the date and cardinal temperatures, leaf wetness requirements (hours per day), rain splash requirement, and degree day initiation. Parameter information can be obtained in crop compendia, primary literature, culture studies, or by comparison with related organisms (26). Some pathogens have rain splash requirements; for example, ascospores of *Uncinula necator*,

the grape powdery mildew, must be splashed from the bark to the susceptible new host growth (11). Degree day and date range options allow models to target a susceptible host growth stage either by date or by a degree day trigger. The template includes a color ramp selection for customizing map or graph outputs. Examples of pathogens that have infection models in NAPPFAST include *Phytophthora ramorum* (causal agent of Sudden Oak Death), *Phakopsora pachyrhizi* (soybean rust), *Phragmidium violaceum* (blackberry rust), and *Elsinoe australis* (sweet orange scab).

The generic degree day template was developed to model insect pests, but it can also be used for modeling phenological development of other organisms or crops based on degree days. This template is dynamic and allows users to select the number of phenological stages and the number of generations. Users must provide the temperature base and the upper threshold for the pest, as well as the degree day requirements for each phenological stage. *Popillia japonica* (Japanese beetle) and *Cydia pomonella* (codling moth) are among the variety of models created in NAPPFAST. A simple climate matching capability has recently been added to the system, so risk maps can be created from an observed pathogen distribution using inductive techniques (3).

Numerical output. Following the creation of a NAPPFAST model, a numerical model output can be exported in the form of graphs or maps. The raw weather data cannot be exported from the system. NAPPFAST can create raster or grid-based maps using a Barnes interpolation at a 10-km² resolution (4). The Barnes analysis is widely used in meteorology and can produce a grid from a weighted average of irregularly spaced observations. The graphing function is commonly used to verify model performance by plotting model output and raw weather data for selected locations and histories. More commonly, NAPPFAST creates map output in the form of historical or probability maps. A historical map is useful for comparing pest observations against specific years or to compare years. A probability map request tool allows a user to create a map showing the frequency of years meeting specific criteria as defined by model inputs or outputs. The criteria might be a specific number of favorable or unfavorable days occurring between two dates based upon 10, 20, or 30 years of weather data. Predictive maps for over 30 pests are available at a public site, including models for some pests on the CAPS 2004, 2005, and 2006 target pest lists.

NAPPFAST has simple GIS viewing capabilities, allowing users to see reference layers (ESRI shapefiles) as overlays or masks. For instance, users have the option to overlay crop/host distributions

Sidebar 2. Variables in the NAPPFAST pest forecasting system

North American daily data set	International monthly data set
Daily mean temperature (°C)	Daily mean temperature (°C)
Daily minimum temperature (°C)	Daily minimum temperature (°C)
Daily maximum temperature (°C)	Daily maximum temperature (°C)
Total hours of leaf wetness per day*	Daily temperature range (°C)
Average daily relative humidity (%)	Frost day frequency (per month)
Average daily wind speed (k/h)	Precipitation (mm)
Precipitation (mm)	Wet day frequency (days per month)
Average soil temperature 5 cm (°C)*	Vapor pressure (hectapascals)
Evaporation (mm)*	Cloud cover (%)

* Derived variables.

Fig. 2. Weather stations archived in the NAPPFAST North American Database.

from the National Agricultural Statistics Service (NASS) (41) or other reference layers, such as interstate highways. Maps at a 10-km² resolution created in NAPFAST can be exported as geo-tiff images, and then imported into most GIS software programs for further analysis. A common application combines an infection (or phenology model) with hot or cold temperature exclusion, and then overlays it with a commodity map; this represents the potential establishment maps required by CAPS and other APHIS-PPQ groups.

Model validation. The lack of national and international observations of pest incidence can make model validation a major challenge. This is true both for exotic and indigenous pests. Pest records found in crop compendia, herbaria records, or national databases, such as the CAPS database (NAPIS) and the NPDN database, may have poor spatial and temporal resolution. Records with poor spatial and temporal resolution may be helpful for defining the presence or absence of a species but are not as helpful for establishing the frequency at which a pest may cause economic injury. These records do not contain detailed collections of disease observations; those with such observations have only a few sites and seasons. Combining data from multiple studies is tedious and difficult due to different methods used in disease assessment. In addition to these issues, a current limitation with the NAPFAST model is the lack of daily international weather data within the system to create models for exotic plant pathogens with observations from outside North America.

An approach we are testing with NAPFAST is the comparison of models with different complexities at different temporal and spatial scales. In one study, R. D. Magarey and C. L. Thayer (unpublished data) compared three apple scab models for the continental United States. Each model was used to predict the frequency of years favorable for apple scab infection during April. The first was a commercial model (ZedX Inc., Bellefonte, PA) that ran hourly data at a 1-km² resolution. Results show the frequency of all hours over the 10-year period falling in and between the classes "very low" and "very high" (Fig. 4A). The second model was created in NAPFAST using the generic infection template using daily data at a 10-km² resolution. Results show the frequency of years in which April has five or more days suitable for apple scab (Fig. 4B). The third model was made with the generic template using a logical statement; it was based on the monthly average maximum and minimum temperature, precipitation, and rain days at a 55-km² resolution. Results show the frequency of years where the month of April was classified as suitable for apple scab (Fig. 4C). Although there is a marked loss in resolu-

tion, this preliminary result demonstrates that simple and coarse resolution models can provide useful information for pest risk mapping. A more thorough analysis is being conducted using this technique, and results will be published elsewhere. Consequently, it is not clear if this will prove to be a useful validation technique.

Case Studies

Sudden Oak Death. Sudden Oak Death, caused by *Phytophthora ramorum* (S. Werres, A.W.A.M. de Cock, & W.A. Man in't Veld), is an important disease of some species of oak, rhododendron, and camellia (35,43). Regulations control the movement of nursery stock and plant material from 12 infested counties in California and an area under eradication in Oregon. In 2003, PPQ program managers required a risk map to help conduct a national survey following shipment of infected nursery stock from a number of West Coast nurseries to nationwide outlets. The first risk layer of the NAPFAST *P. ramorum* risk map was based on an infection model using cold temperature exclusion, and on a host match based on forest density data. The infection model for *P. ramorum* used the temperature and moisture requirements for zoospore infection. The temperature thresholds (minimum, optimum, and maximum) for *P. ramorum* infection were 3, 20, and 28°C, respectively (30,40,43). The moisture requirement was at least 12 h when describing zoospore infection of *Umbellularia californica* leaves (15). At least 60 favorable days for infection was arbitrarily chosen as a useful indicator of climatic risk. For each 10-km² pixel, a day was assigned a value

between 0 (unfavorable for infection) and 1 (favorable for infection); these values were accumulated over the year. The resulting layer represents the frequency of years that have a sum of at least 60 favorable days over the entire year.

The second risk layer was constructed using the generic template and represented survival based on extreme low soil temperatures. This was less than -25°C; extreme low temperatures reduce the survival of *P. ramorum* sporangia and chlamydospores in laboratory tests (9). Snow cover may provide insulation, but it is not considered in the model; additional cold temperature survival data are necessary in order to better define the northern extent of the disease. Areas that had -25°C in one or more years in 10 were given a risk value of zero.

The third risk layer was susceptible host density based on USFS data (Fig. 5) (45). Hardwood forests were assigned a value of 1.0 and mixed forest was assigned a value of 0.5 to eliminate coniferous trees, which are predominantly nonhosts. The model had good agreement with reported observations of the disease in California and also with other risk models created for *P. ramorum* for the contiguous United States (R. D. Magarey, unpublished). In the future, model improvements include a rain splash requirement and the influence of high temperatures on spore survival (9).

Asian soybean rust. Asian soybean rust (*Phakopsora pachyrhizi* H. Sydow & Sydow) is one of the most serious exotic pest threats for U.S. agriculture. It was first detected in the continental United States in the fall of 2004, spread, most likely, as a result of spore deposition during Hurricane

The screenshot shows the 'Model Setup' window for 'http://aphis.zedxinc.com - Model Setup - Microsoft Internet Explorer'. The 'Model Name' is 'lrdm-sod-infection', the 'Template' is 'Generic Infection 1', and the 'Pest' is '-'. The 'Model Setup' section includes fields for 'Begin Day (mm-dd)' (01-01), 'End Day (mm-dd)' (01-31), 'Infection Level Lower Limit' (0), and 'Infection Level Upper Limit' (1). The 'Degree Day Initiation' section has a table with columns: Method, Unit, Base, Max, Init, Term. The 'Setup Variables' section has a table with columns: Variable, Unit, Min, Opt, Max. The 'Setup Output' section has a table with columns: Name, Infection Level, Level +, Level -, Accumulate, Low, High, Text, Color, R, G, B.

Variable	Unit	Min	Opt	Max
Air Temperature	C	3	20	28
Leaf Wetness	hrs	12		
Precipitation	mm			

Name	Infection Level	Level +	Level -	Accumulate	Low	High	Text	Color	R	G	B
1.	>	<=	0.9999	=>	Nil				0	0	255
2.	>	<=	0.9999	=>	Yes				255	0	0

Fig. 3. Infection template model parameterized for *Phytophthora ramorum*.

Ivan (16). To prepare U.S. agriculture to appropriately respond to soybean rust, research groups developed models based on the aerobiological transport of spores from South America (16,31); as these studies progressed, NAPPFAST was used to

prepare risk maps for overwintering survival and risk of infection. The estimated overwintering survival is based on the death of leguminous hosts when the temperature falls below -2°C . Model results indicate that in most years soybean rust

can overwinter in southern Florida and parts of California (Fig. 6A). In other areas, i.e., southern portions of Texas and Louisiana, soybean rust may overwinter in some, but not most years. Another research group obtained a similar result using the CLIMEX system (33).

The second model estimated the climatological frequency of seasons favorable for serious epidemics based upon an infection model. Soybean rust infection occurs between 10 and 28°C , with an optimum temperature between 20 and 25°C ; it requires at least 6 to 8 h of leaf wetness (27,28). The period from 1 April to 30 September was selected as the time during which the soybean crop is susceptible to infection (this is applicable throughout the nation). For a serious epidemic it is likely that four or five cycles of disease multiplication may be required. Since the fungal latent period is 5 to 8 days (27), epidemic development may take place over a period between 20 and 40 days. It could reasonably be expected that where 15 favorable days occur, serious epidemics may occur by presenting numerous opportunities for the infection cycle to be repeated. The model was run from 30 years of weather data.

The model output indicated that climatic conditions are favorable for serious epidemics in most U.S. soybean regions (Fig. 6B). States east of the Mississippi have favorable conditions almost every year that could trigger epidemics; however, states west of the Mississippi have less favorable conditions for soybean rust, although serious disease epidemics could still occur most years. Currently, international daily data are unavailable in NAPPFAST, making it impossible to properly validate the model using international observations of soybean rust. In 2005, this soybean rust map was used in extension talks. The model also was used in a 2004 USDA Economic Research Service risk assessment (23).

Eucalyptus rust. The inclusion of *Eucalyptus* rust as a case study demonstrates the potential of using the monthly international weather data set. *Eucalyptus* rust (also known as Guava rust) is caused by *Puccinia psidii* G. Winter. The first serious outbreak of *P. psidii* on a *Eucalyptus* sp. occurred in the Brazilian province of Espirito Santo in 1973; as a result, large-scale losses occurred in nurseries and young plantations of *E. grandis* originating from South African seed sources (8). Currently, *P. psidii* is a serious threat to eucalyptus plantations worldwide, particularly in Australia, where eucalypts are native. Of the economically important tropical tree crops, *Eucalyptus* spp. are most significant, comprising over eight million hectares of forest plantations in the tropics and subtropics (8). The disease is widespread in South America, and is also present in southern Florida and Hawaii (7,18).

Fig. 4. Comparison of apple scab models at three temporal and spatial scales for predicted frequency of years favorable for apple scab infection based on 10 years of weather data: A, Commercial model (ZedX Inc.) at hourly and 1 km^2 resolution showing the frequency of all hours in April falling in and between the classes “very low” and “very high”; B, NAPPFAST generic infection model at 10 km^2 and daily resolution showing the frequency of years with five or more favorable days in April; and C, NAPPFAST generic model at monthly resolution and 55 km^2 showing the frequency of years where April was favorable.

The Eucalyptus rust model was developed in collaboration with colleagues at the Australian Department of Agriculture Food and Forestry, Canberra, Australia. The parameters for the model using monthly data are: average daily maximum temperature less than or equal to 33°C; average daily minimum temperature greater than 13°C (8); and at least five, but fewer than 25, wet days per month. The assumption was that if three or more months in the year met these conditions, then the climate would be suitable for the pathogen. The model was run with 10 years (1993–2002) of weather data. The frequency of favorable years was high in tropical South America and the Caribbean, areas that currently have the disease (Fig. 7). In Australia, the predicted climate match was limited to the north and central-east coast. A climate-match model developed by the Australian Government Research Group ENSIS, Canberra, Australia, also indicated that the eastern and north-eastern coast was the most at risk (5). Although the models made with the generic template and the international monthly data sets are relatively crude, they have the advantage of using simple biological inputs.

Future Outlook

At present, NAPPPFAST has limited utility for those working on issues related to the day-to-day forecasting, modeling, or management of endemic plant pathogens. This is because NAPPPFAST's modeling capability is limited and its spatial (10 km²) and temporal (days/months) resolu-

tions are relatively coarse. Consequently, it is best suited for use with exotic pests where models are needed for a first-guess estimate of a pest's establishment potential. However, as NAPPPFAST matures, we expect to see continued development with contributions from university, industry, and government plant pathologists. Plant pathologists may provide more specialized and better validated models to replace the simple model templates currently used in the system. They may also assist in research that relates to the implementation of models including quantification of uncertainties associated with modeling, filling gaps in epidemiological data, and improved methods to communicate with stakeholders. As daily international data are added to the system, this will be an opportunity to work with overseas plant pathologists. We hope the system will provide a means to test and share disease forecasts for exotic pests that might eventually threaten U.S. agriculture. We anticipate the need for more advanced climate matching capabilities in NAPPPFAST, and this may be developed by collaboration with other researchers who have experience in this area.

An important part of cooperation with plant pathologists in developing a risk mapping system is the need to include real-time survey and diagnostic data. This is not only for model validation but also for the purpose of real-time pest tracking. A system needs to support data collection, integration, and sharing. The potential for this effort was well-illustrated by the development of the Legume Pest Information

Platform for Extension and Education (L-PIPE), partially based on NAPPPFAST architecture (17). The L-PIPE was initially created in response to the incursion of soybean rust; this collaborative project was first funded and managed by APHIS, and later transferred to the CSREES Regional IPM centers with funding from the USDA Risk Management Agency. The purpose of the tool is to provide the public with a web-based platform for extension and risk management of soybean rust. The L-PIPE system includes a map and calendar format, but has additional menu selections for management guidelines, educational material, and training opportunities. Moreover, the PIPE includes tools for data collection via PDA, online forms, or uploadable spreadsheets. The L-PIPE system allows its users to integrate data collected from diverse sources, including federal and state governments, universities, and industry.

While the PIPE structure provides an ideal method for sharing forecast model output and survey and diagnostic data on endemic plant pathogens, it is useful to consider what other functionality should be included in PIPE systems for exotic plant pathogens. In order to make spatially and temporally specific risk predictions for exotic plant pathogens, it is necessary to consider data sets other than climate and disease observations. For example, international transport (trade/commerce and travel/tourism) throughout U.S. history has exacerbated the accidental or purposeful introduction of exotic species into the United States (2,21,34,39); international transport is the most important human-

Fig. 5. Relative risk of *Phytophthora ramorum* establishment based upon three variables: infection frequency, extreme cold temperatures, and host range. Maps are based upon 10 years of weather data.

mediated pathway of exotic species (20,24).

APHIS-PPQ recognizes the importance of these data sets and has developed the Hotzone trapping concept to map sites with the highest introduction potential for exotic pests and to successfully provide early detection and eradication of these pests. Three types of hotzones are classified in the program: (i) primary hotzones are sites that receive international shipments or have a recent history of exotic pests, e.g., an import warehouse; (ii) secondary hotzones are sites that receive shipments from a primary hotzone, e.g., a distribution center; and (iii) tertiary hotzones are other suspect sites either by proximity from or similarity to known hotzone sites, e.g., a marina close to a port.

The hotzone program relies upon the manual interrogation of a variety of databases including those from APHIS-PPQ, commercial, customs, and other sources. In some cases, this data is collected manually by a PPQ officer conducting a site survey. After compilation of the data, sites are ranked under each of the three hotzone types using an informal analytical process that is uniquely formulated for each case.

While the Hotzone program is successful and innovative, its implementation may be limited by the labor and technical expertise required to integrate and analyze disparate data sources. Pest survey specialists or program managers may not have the time to integrate and analyze the vast quantities of data required to generate site-specific risk predictions. To overcome this

barrier, CPHST proposes to build on the NAPFAST and PIPE concepts, and create a Pest Detection Web Site (Fig. 8). The proposed Pest Detection Web Site creates site-specific model output using the integration of trade, pest interception information, and multi-source survey data sets in combination with weather and climate modeling. These site-specific predictions can be made for an individual establishment, for example a warehouse or a retail establishment. Like the PIPE system, the Pest Detection Web Site will feature a map and calendar format for easy temporal and spatial navigation. Users will pick from a number of target CAPS lists, such as national, regional, and state lists. After selecting a pest, a user will be able to access more information by using tools in one of

Fig. 6. A, Frequency of years with freezing temperatures ($T \leq -2^{\circ}\text{C}$) during January and February. B, Frequency of years favorable for soybean rust infection based on the NAPFAST infection model. Maps are based upon 30 years of weather data. Hatched areas indicate soybean production areas (41).

three modules: Habitat, Pathways, or Hot-zone. A user could define a pest's habitat by selecting a NAPFAST pest model and overlaying with a host or commodity dis-

tribution. The next step is to identify pathways of entry using data from pest interceptions, trade, cargo, road transportation, and commercial sources (1,44). Currently,

APHIS-PPQ is collaborating with Michigan State University on a USDA-CSREES funded grant to integrate the necessary databases that will analyze the human-

Fig. 7. Frequency of years favorable for Eucalyptus rust spread based upon 10 years of weather data (inset provides observed distribution in the Western Hemisphere [7]).

Fig. 8. Design of the pest detection web site, a proposed map-based resource allocation tool for integrating climate, host, trade, survey, and pest interception databases.

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Dr. Magarey grew up on a pear orchard in the Adelaide Hills, Australia, and developed an early interest in agriculture. In 1989, he earned a B.S. in agricultural science from Adelaide University, and then his Ph.D. with Robert Seem at the New York State Agriculture Research Station (Cornell University). In 2002, Dr. Magarey accepted a postdoctoral appointment in plant pathology at North Carolina State University working with Jack Bailey to develop disease forecast systems. In January 2003, He became a cooperator with APHIS, PPQ, CPHST in Raleigh, NC, through Ron Stinner and the Center for Integrated Pest Management. He continues his work on NAPPFAST and pest tracking systems.

Born in Portland, OR, Dr. Fowler received a Ph.D. in entomology from North Carolina State University in 1999, where his dissertation focused on identifying potential host resistance mechanisms in Fraser fir against the balsam woolly adelgid. He followed his studies with a postdoctorate at the Forestry Department at North Carolina State University, and he also began working at the Plant Epidemiology and Risk Assessment Laboratory (PERAL), becoming a full time employee with PERAL in 2001. His current projects include GIS predictive modeling of invasive plant pests using the NAPPFAST system and working with the North American Forest Commission to update the Exotic Forest Pest Information System for North America. Dr. Fowler is a member of the pathway analysis team and has worked on quantitative models and associated pest risk assessments for Karnal bunt in U.S. wheat exports and Asian gypsy moth on Japanese maritime vessels.

Dr. Borchert is an entomologist at the Plant Epidemiology and Risk Assessment Laboratory (PERAL), Raleigh, NC. He received his B.S. in plant science from Cornell University and an M.S. and Ph.D. in entomology from North Carolina State University. His graduate work focused on pest management and phenology in apple systems using semiochemicals and reduced risk insecticides. After earning his doctoral degree, he worked as a research associate in cooperation with CPHST developing the NCSU APHIS Plant Pest Forecast system (NAPPFAST) becoming a CPHST employee in October 2004. He is a member of the CPHST GIS virtual team and is involved with creation of maps used by the CAPS program for survey timing and determining areas of establishment for pest risk assessments.

Dr. Sutton is a professor and departmental extension leader in the Department of Plant Pathology at North Carolina State University. He received his B.A. in botany and chemistry from the University of North Carolina at Chapel Hill and his M.S. and Ph.D. degrees from North Carolina State University in 1971 and 1973. He has a joint appointment in research, extension, and teaching. His research and extension activities have focused on the epidemiology, biology, and management of summer diseases of apples and vinifera grapes in the southeastern United States. Through students from Costa Rica, he worked on the biology, epidemiology, and control of several banana diseases. He taught an undergraduate course on fruit disease management, teaches a component of a graduate course on epidemiology and management of plant diseases, and leads the development of a curriculum for students interested in careers in extension or industry.

Dr. Colunga-Garcia is an assistant professor in the Department of Entomology at Michigan State University. His research has focused on understanding the principles for sustainable management of landscapes. He is particularly interested in the ecological interactions between urban environments and agricultural and natural systems, including the assessment of the impact of landscape fragmentation in human-dominated landscapes. He is currently collaborating with the USDA/APHIS/PPQ/CPHST and the US Forest Service in the assessment of the vulnerability of U.S. metropolitan areas to invasive species.

Dr. Simpson works as a mycologist with Biosecurity Australia in Canberra. He grew up on a mixed dairy and meat producing farm in southwestern Victoria, Australia, and from an early age had an interest in native forests and their biota. In 1965, he graduated from Melbourne University with a Bachelor of Agricultural Science. He then moved to Adelaide to undertake postgraduate studies with Jack Warcup at Waite Institute, Adelaide University. In 1970, he joined the Forestry Department in Papua New Guinea where he established the forest pathology unit. In 1981, he accepted a position as forest pathologist with State Forests of New South Wales and moved to Sydney, Australia. Mr. Simpson was president of the Australasian Mycological Society from 1995 to 1998. His current research activity is focused on pest risks associated with international trade in wood and wood products.

mediated pathways of exotic pests into metropolitan areas. Combining the habitat and pathway data layers provides a map that can be used as a resource allocation template in the Hotzone module. When the CAPS list is used at a regional or national scale, a program manager can allocate funds or personnel to the appropriate region. Using the system on a local scale allows a pest survey specialist to set traps near locations that receive foreign cargo at periods when exotic pests are likely to be found.

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