Weather-Based Assessment of Soybean Rust Threat to North America
Final Report to APHIS

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Executive Summary

The USDA Animal and Plant Health Inspection Service (APHIS) is preparing for the entry of soybean rust *Phakopsora pachyrhizi* in the conterminous United States. The belief is that aerial transport to the U.S. is a probable pathway for the initial entry of soybean rust and that the likelihood of aerial dispersal to our country will increase as the pathogen expands its range towards North America. The project, funded through a cooperative agreement between APHIS/USDA and North Carolina State University, brought together a group of soybean rust experts, aerobiologists, and information technologists to provide a highly visible, weather-based assessment of the soybean rust threat to North America.

The project produced four deliverables and a report on schedule. (1) A web site through which APHIS provided stakeholders with information on the aerial dispersal of soybean rust. (2) Maps of soybean rust source areas in Africa and South America. (3) Simulations of aerial soybean rust dispersal into South and North America using the HYSPLIT atmospheric transport model. (4) Simulations of aerial soybean rust dispersal into South and North America using the newly developed Integrated Aerobiology Model System framework. This report also includes information to support assessments of risk of aerial incursion of soybean rust into the U.S. by stakeholders.

The most important findings of the research project are:

(1) Opportunities for aerial transport of *P. pachyrhizi* spores from infested soybean growing areas in eastern Asia to Hawaii in 1994 and from southern and western Africa to South America in 2001 existed 1 to 2 months prior to the first discovery of soybean rust epidemics in these regions. Airborne spores would have had to remain viable for 1 to 2 weeks to have caused the new infestations.

(2) There is a substantially higher risk of aerial transport of *P. pachyrhizi* spores to the U.S. from the current infestation region in South America than Africa.

(3) The risk of a soybean rust epidemic in the U.S. due to aerial transport of *P. pachyrhizi* spores from south of the equator in South America is low.

(4) If the pathogen has spread into soybean growing regions north of the equator in South America than the risk of soybean rust incursion into the U.S. during 2004 has increased. Presence of soybean rust north of the equator has not been confirmed by Brazilian scientists.

(5) Once soybean rust epidemics occur in the northern South American soybean growing region winds will likely transport the spores within the Intertropical Convergence Zone (ITCZ) to Central America during the same growing season.

(6) Tropical cyclones have the potential to transport *P. pachyrhizi* spores from the northern South American soybean growing region directly into the southern U.S.

(7) In the event that *P. pachyrhizi* becomes well established around the Caribbean/Gulf of Mexico basin, aerial transport of soybean rust spores into the continental interior of North America is likely to occur each spring.

The Integrated Aerobiology Modeling System (IAMS) produced by this project is a first step toward a long-term solution for the operational prediction of the aerial incursion of invasive pests, weeds, and diseases into the U.S. A recommendation for the future development of an aerobiological modeling system as an operational tool for APHIS is described.

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INTRODUCTION

Soybean rust is caused by the fungi *Phakopsora meibomiae* and *Phakopsora pachyrhizi*. *P. pachyrhizi* is the more aggressive of the two species and is currently in Asia, Australia, Africa, and South America. Once introduced into an agricultural area, *P. pachyrhizi* can devastate a soybean crop typically causing yield losses of 50-60% and complete losses are possible where early infection and environmental conditions favor epidemics (Kloppers 2002).

P. pachyrhizi was detected in the Western Hemisphere during 2001. The first reports were from the Rio Parana region in Paraguay and southern Brazil (Miles et al 2003). Sources in Nigeria (western Africa) and Zimbabwe (southern Africa) are considered strong candidates for the South American outbreaks. Over the past three years, the rust disease has spread throughout South America between 30^{o}S latitude and the equator wherever soybean has been planted. There are unconfirmed reports that the pathogen has recently crossed the equator, infesting soybean fields in the Roraima State of Brazil (Yang 2004). Likely entry points into North America include these rust infested soybean production regions of South America and Africa. A recent USDA Economic Research Service (ERS) report concludes that $640 million to $1.3 billion in net economic losses are expected during the first year of the pathogen's establishment in the U.S. (Livingston et al. 2004).

The USDA Animal and Plant Health Inspection Service (APHIS) is preparing for the entry of soybean rust in the conterminous U.S. (USDA APHIS 2004). As part of that effort, this project, funded through a cooperative agreement between APHIS and North Carolina State University, brought together a group of soybean rust experts, aerobiologists, and information technologists to provide a highly visible, weather-based assessment of the soybean rust threat to North America. The approach is to develop an Integrated Aerobiology Modeling System (IAMS) that incorporates aerobiological theory with state-of-the-art meteorological models. The goal of the application IAMS to soybean rust is to quantify the risk of *P. pachyrhizi* dispersal in the atmosphere to the U.S. under sets of increasingly complex assumptions regarding the spatial and temporal distributions of the pathogen and its exposure to environmental conditions. Team members from the North American Plant Disease Forecast Center (NAPDFC) used the NOAA ARL HYSPLIT model to hindcast historical movements of soybean rust. Comparisons were made between outputs from the two contrasting modeling approaches. Trajectories were calculated from potential source areas in South America and Africa during the grant period to identify atmospheric transport events with potential to bring rust spores to North America.

This project is a stepping-stone to a modeling system for predicting aerial incursions of plant pathogens, insect pests, and weeds into the U.S. In the long-term, APHIS seeks an operational system which can quantify, integrate, and predict the impact of biological, meteorological, geographical, and anthropogenic processes on movements of invasive organisms. This report summarizes progress toward that goal and identifies further steps that are needed to create an aerial dispersal forecast system that can be linked to existing APHIS information systems.

PROJECT OBJECTIVES

Soybean rust, like most fungal diseases, is aerially transported by spores (Bromfield 1984). Isard and Gage (2001) have identified the processes that characterize the movement of these microorganisms in the air. They are spore production, canopy escape, turbulent (atmospheric) transport, dilution in the atmosphere, survival while airborne, deposition into a receptor crop, and colonization with sporulation.

This weather-based assessment of soybean rust threat to the U.S. was organized around the processes affecting the aerial movement of fungal spores. A dearth of information regarding: 1) the biology of the *P. pachyrhizi,* 2) important interaction with its many hosts, and 3) the impact of environmental factors on spore survival in the air, currently require a number of assumptions based on information in the literature about other aeriallytransported plant pathogens. An ongoing USDA-funded field measurement project in the soybean rust infested region of Paraguay is addressing important deficiencies in the existing *P. pachyrhizi* knowledge base (Isard et al. 2004).

The present soybean rust assessment project was structured to create four interrelated products. (1) A web site through which APHIS is providing stakeholders with information on the aerial dispersal of soybean rust. (2) Maps of soybean rust source areas in Africa and South America were compiled from information obtained from literature sources, colleagues who recently visited the infected areas, and overseas scientists. The maps were updated whenever new distribution information becomes available. (3) Historical and forecast simulations of soybean rust aerial dispersal into South and North America were conducted for individual days using an established weather-based trajectory modeling approach. (4) Maps of soybean rust dispersal to the U.S. were created from historical and climatic simulations of intercontinental soybean rust transport based on the IAMS approach that combines biological with meteorological information. This report summarizes the important findings of the project, provides information to support spatial and temporal assessments of the risk of aerial soybean rust incursion into the U.S., and outlines further steps toward an aerial dispersal forecast system for invasive species that can be linked to existing APHIS information systems.

The project extended from 1 August 2003 to 31 July 2004. Preliminary results of the analyses were presented in numerous forums including a joint ERS/APHIS meeting in November 2003 and the annual meetings of the American Soybean Association in February 2004. On 4 March 2004, project participants formally presented the research results to CPHST/APHIS.

DELIVERABLES

Project web site. A web site to provide stakeholders with information on the aerial dispersal of soybean rust was developed by Illinois project researchers and constructed by ZedX programmers in October 2003. Public access is: http://soybeanrust.zedxinc.com/. The web site is updated whenever new information on the rust becomes available. It contains an animated description of soybean rust life cycle, an assessment of risk from incursion of soybean rust into the U.S., maps of the South American and African source areas, and links to important sources of soybean rust information on the Internet.

Demarcation of soybean rust source areas. Color-coded maps of soybean rust source areas in Africa and South America were compiled using information obtained from literature and collaborating scientists in the Brazil, Paraguay, Nigeria, Zimbabwe, and the U.S. The maps (Fig 1) contain information on known source regions and unconfirmed but likely source regions; they have been updated periodically when new information on soybean rust became available. They are available for public viewing on the project web site.

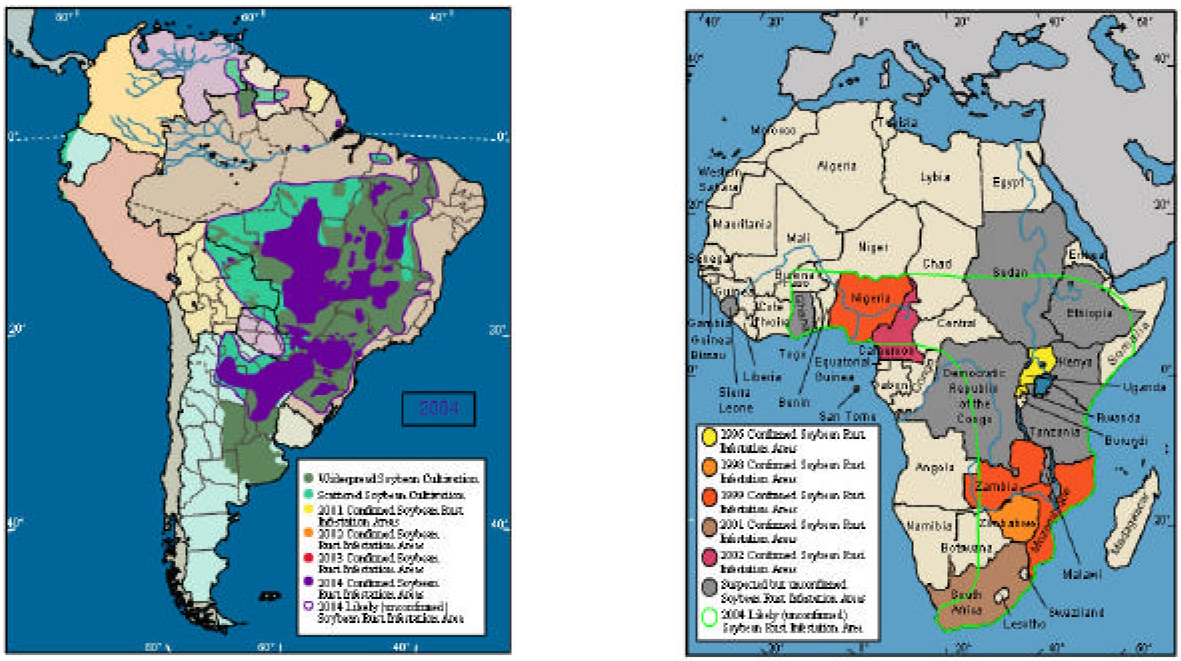

Figure 1. Soybean rust source area maps for South America and Africa. Maps can be accessed on the project's web site at http://soybeanrust.zedxinc.com/. Detailed description of the information sources used to compile the maps is provided. The South American source area map is animated.

Calendars of *P. pachyrhizi* spore production were created for major soybean growing regions in South America and Africa. Although the pathogen has almost 100 alternative hosts (Miles et al. 2003), it is assumed that the vast majority of the spores are produced on soybean. South of the equator in both Africa and South America, soybean is usually planted in late November and December (USDA FAS 2004) and spore production in infested fields can be substantial between late January and April. A second and much smaller peak of spore production may occur in July and August where a second soybean crop is sown. Soybean production north of the equator in South America occurs coincident with the U.S. growing season, with planting in May-June and harvesting during late September-October (USDA FAS 2004). If this area becomes infested with soybean rust, spore release to the air will likely peak in July-August. Most African soybean is grown in Nigeria, Uganda, Zimbabwe and South Africa (FAOSTAT 2004). Soybean rust outbreaks in southern Africa tend to occur in the months of January-April. *P. pachyrhizi* was confirmed in Nigeria during March

1999, infesting the early season seed soybean; subsequently, disease outbreaks have occurred sporadically in Nigeria, usually between July-September in the main soybean crop (ProMED 2001).

Simulations using HYSPLIT atmospheric trajectory models. NAPDFC researchers used the HYSPLIT atmospheric transport model maintained by the NOAA Air Resources Laboratory (ARL) in Silver Spring, MD to hindcast historical movements of soybean rust. For each day during the winter and spring 2004, they also created HYSPLIT model forecast trajectories from current soybean rust source areas in South America and Africa to monitor for atmospheric flows with potential to blow *P. pachyrhizi* spores to North America.

In this application, a HYSPLIT trajectory represents the pathway that a hypothetical spore-laden parcel of air starting at a specified altitude and geographic location would most likely follow on the given day and time. The trajectory can be viewed as the centerline of a moving cloud of spores that spreads out becoming less concentrated through time. Trajectories were constructed forward-in-time from release sites (forward trajectory) and backward-in-time from destinations (back trajectory). They were run with historical weather data and with forecast model output from Numerical Weather Prediction models. These weather data sets have 6 hr resolution. The maximum trajectory duration for historical and forecast trajectories are 315 hr (13 d) and 180 hr (7.5 d), respectively. Both historical and forecast forward trajectories were initiated for 1000 local time (peak spore release) and altitudes of 100, 200, and 500 m above ground level (AGL). When results were particularly interesting, additional trajectories were initiated at 1, 10, 50, 1000, and 1500 m AGL. Once periods of favorable conditions for aerial movement of *P. pachyrhizi* spores from Africa to South America were identified, back trajectories were initialized for 00Z and 12Z UTC from the Rio Parana Valley. The HYSPLIT model, weather data sets, and the methodology are explained in detailed on the ARL web site (www.arl.noaa.gov).

Transport Events from Africa to South America, Nov 2000 - February 2001. Zimbabwe (17.0°S, 30.0°E), Nigeria (7.0°N, 10.0°E), and Sierra Leone (8.0°N, 12.0°W) were selected as African soybean rust source areas for this analysis. The first two are important soybean production regions that have experienced rust epidemics since the late 1990s, while Sierra Leone is located close to South America and may currently represent the westward extent of soybean rust in Africa (Levy, personal communication). Forward trajectories were generated from the three sites for each day during the four months previous to the February 2001 discovery of *P. pachyrhizi* in South America.

The trajectories from Africa vary widely in direction and speed for this period. The large majority of them are unremarkable with regards to the potential introduction of soybean rust to South America. However, the trajectories initiated in Africa for days between 30 December 2000 and 2 January 2001 traverse the South Atlantic Ocean and terminate in South America.

Hypothetical air parcels released from Sierra Leone during this 4 day period reach the northeastern Brazilian coastline in as little as 8 days and penetrate far into the interior of the continent. Those initiated at the higher altitudes in the air encountered strong winds and reach South America sooner than those released closer to the Earth. Nearly all trajectories from Sierra Leone during this period follow similar paths both in the horizontal and vertical planes, indicative of uniform large-scale flow in the lower atmosphere.

The most noteworthy of the Sierra Leone trajectories are those initiated for 30 December 2000 (Fig 2). The hypothetical spore-laden air parcels curve to the southeast and then south after crossing the South American coastline. The 1500 m trajectory crosses the Rio Parana Valley between days 12 and 13, while the 1000 m trajectory reaches northern Paraguay after 13 days. Many of trajectories initiated from Nigeria and Zimbabwe for the 30 December 2000 to 2 January 2001 period also terminate over South America. Forward trajectories from Zimbabwe generally extend westward reaching the east coast of Brazil near 15^{o}S latitude (Fig 3).

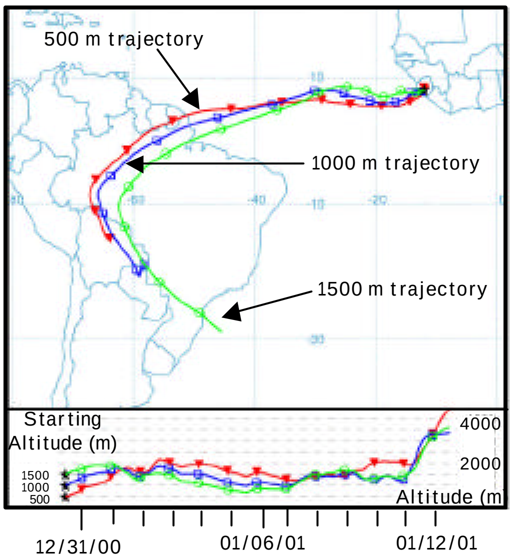

Figure 2. Forward trajectories from Sierra Leone on 30 December 2000. The trajectories begin at heights of 500 m (**red triangles**), 1000 m (**blue squares**), and 1500 m (**green circles**).

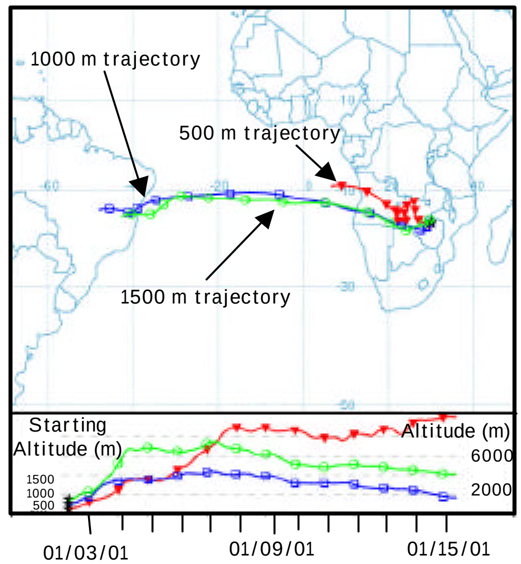

Figure 3. Forward trajectories from Zimbabwe on 2 January 2001. The trajectories begin at heights of 500 m (**red triangles**), 1000 m (**blue squares**), and 1500 m (**green circles**).

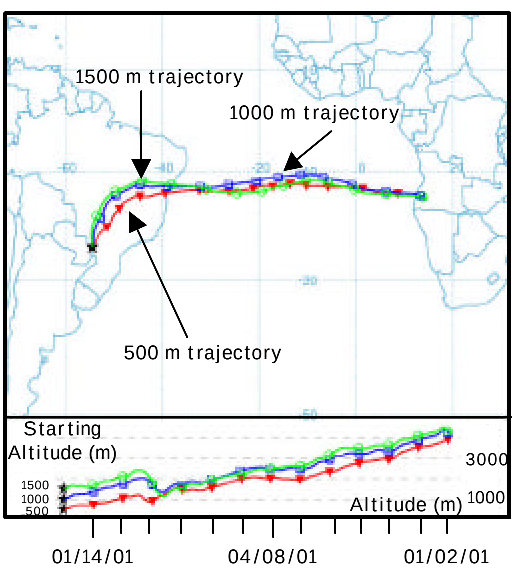

Figure 4. Backward trajectories from the Rio Parana Valley region for 13 January 2001. The trajectories begin at heights of 500 m (**red triangles**), 1000 m (**blue squares**), and 1500 m (**green circles**).

Backward Trajectories from South America to Africa, January 2001. A series of backward-in-time trajectories were initiated from the Rio Parana Valley for days between 10 and 17 January 2001. This time window corresponds with the arrival dates of potentially spore-laden air parcels that left Africa during the 30 December 2000 - 2 January 2001 period and reached South America (see Figs 2 and 3).

The back trajectories regress from the Rio Parana Valley to southern Africa, reaching the coast on 2 - 3 January 2001 (Fig 4).

Again, there is very good clustering in the horizontal and vertical directions, confirming the presence of stable, uniform easterly flow across the South Atlantic Ocean.

With favorable weather conditions, 30 to 60 days are required for the disease to progress from an initial rust infection to a wide spread infestation in a soybean crop (Tschanz 1984). The combination of evidence given by the forward and backward trajectory analyses clearly indicates that opportunities for aerial movement of *P. pachyrhizi* spores from infested soybean growing areas in Africa to South America existed 1 - 2 months prior to the initial discovery of a rust epidemic in the Rio Parana Valley.

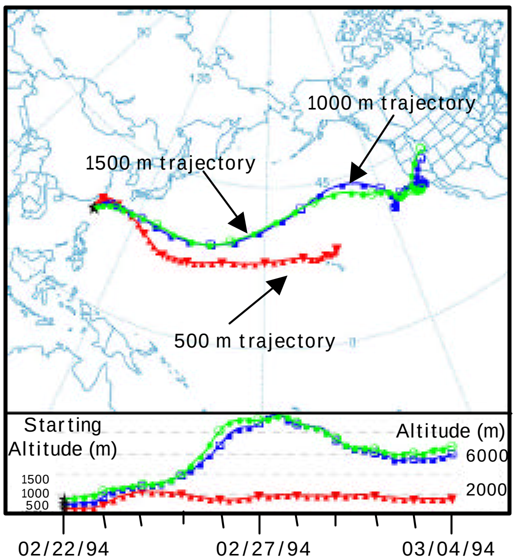

Figure 5. Forward trajectories from Taiwan on 22 Feb 1994. The trajectories begin at heights of 500 m (**red triangles**), 1000 m (**blue squares**), and 1500 m (**green circles**).

Forward Trajectories from East Asia to Hawaii, January - April 1994. Forward trajectories were run from Taiwan (23.5°N, 121.0°E) for all days at the beginning of 1994 (Fig 5). A rust infestation was identified in soybean on the Hawaiian islands in early May 1994 at time when *P. pachyrhizi* was present in east Asian soybean fields (Sinclair and Hartman 1996). Although the pathogen may have been transported to the island by human actions, if aerial transport was responsible for starting the soybean rust epidemic in Hawaii then the spores likely landed in the fields during the previous March. Our analysis reveals that there was a period of 10 days in late February and early March 1994 when winds over Hawaii blew from the east coast of Asia. These simulations coupled with the HYSPLIT trajectories showing potential spore movement from Africa to South America suggest that if aerial transport was responsible for starting the soybean rust infestations in Hawaii and the Rio Parana Valley then *P. pachyrhizi* must have the capability of remaining viable in the air for at least 1 - 2 weeks.

Comparison of Historical Trajectories for China and the U.S., May and June 2000-2003. In terms of latitude and geographic position, the eastern U.S. is similar to eastern China. However, unlike eastern Asia with its high plateaus and east-west mountain ranges, the interior of the North American continent has no significant obstruction to air movement, and the absence of east-west barriers allows air masses from the Gulf of Mexico to sweep for 1000s of kilometers northward across the interior plains (Johnson 1995, Barry and Chorely 1998). *P. pachyrhizi* over-seasons south of 37°N in eastern Asia and comparative climate model simulations suggest that conditions in the Caribbean, Mexico, and along the U.S. Gulf Coast are also conducive for over-seasoning of the pathogen (Yang et al. 1991, Pivonia and Yang 2003, Magarey 2003). In the past, China has experienced epidemics of soybean rust at frequencies and intensities that vary from south to north (Yang 2003). Severe and frequent epidemics have been observed equatorward of 30°N. Between 30 and 37°N epidemics are frequent but not severe, while poleward of 37°N epidemics are infrequent. Since *P. pachyrhizi* does not over-season poleward of 37°N, it is thought that the pathogen is occasionally blown to northern China (Tan 2001).

To compare and contrast the directions of the airflows impacting eastern China and the eastern U.S. at the beginning of the growing season, backward trajectories were created for days from late-May through mid-June 2000 - 2003 for each country. The trajectories were initiated for the 500 m altitude at 2000 local time from locations in each nation's major soybean production regions (southern Heilongjiang, northwestern Henan, and central Shandong provinces in China and northern Iowa, west-central Indiana, southern Missouri, and northeastern Maryland in the U.S.). Fig 6. displays the back trajectories for each day during the last week in May 2002. The patterns are representative of those for the other weeks and are indicative of the differences between the airflows above eastern China and the eastern U.S. Although southwesterly winds bring both plant pathogens and insects to northern China in spring and summer (Chen et al. 1995, Tan 2001), the dominant pattern of airflow in the region during late May and early June is from the dry region to the northwest. In contrast, the frequency and intensity of large-scale southerly flows in eastern North America during this period is much greater than in eastern Asia. A week during Spring in the major U.S. soybean-growing region without severe weather events (e.g., thunderstorms and tornadoes) caused by large-scale advection of warm moist air from the subtropics is rare. In the event that *P. pachyrhizi* becomes well established along the Gulf Coast, on Caribbean islands, and in Mexico, aerial transport of soybean rust spores into the continental interior of North America is likely to occur each spring.

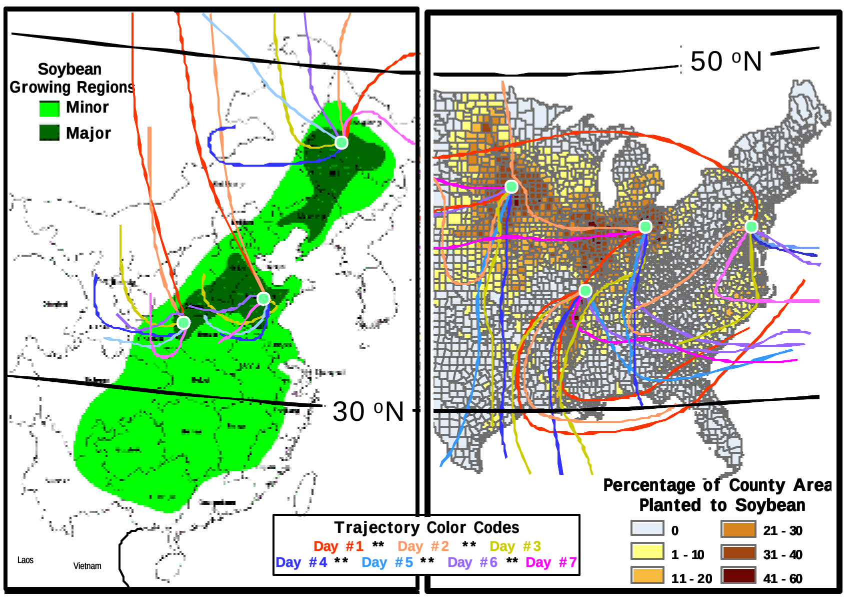

Figure 6. Backward trajectories initalized at a 500 m altitude for soybean growing regions in China and U.S. for individual days during the 4th week of May 2002. The winds in the China soybean growing region were generally from the northwest while southerly airflow was present on many of the days in the U.S. soybean growing region.

<u>*Forecast Trajectories from South America and Africa to North America, January - April 2004*</u>. To monitor for transcontinental movement of rust spores to the U.S. during the project, forward trajectories using forecast weather data were run for all days between 1 January and 30 April 2004 from the Zimbabwe, Nigeria, and Sierra Leone locations in Africa (specified above) and sites in four states throughout the soybean growing regions of Brazil:

Mato Grosso (10.5°S, 58.0°W), Maranhao (4.5°S, 45.5°W), Goias (16.0°S, 48.0°W) and Roraima (3.9°N, 61.0°W).

The forward forecast trajectories for all sites exhibited a wide diversity of directions and speeds. However, movement toward the west within the Intertropical Convergence Zone (ITCZ) was the most dominant pattern, especially for the trajectories from Sierra Leone in Africa and Roraima in far northern Brazil.

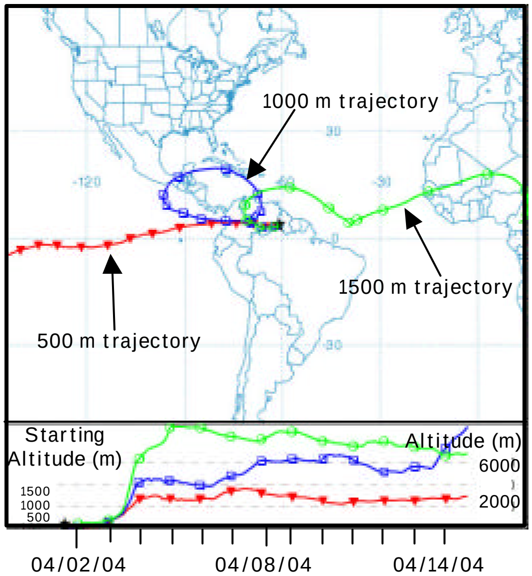

Figure 7. Forward trajectories from northern Brazil for 1 April 2004. The trajectories begin at heights of 500 m (**red triangles**), 1000 m (**blue squares**), and 1500 m (**green circles**).

Although the vast majority of the trajectories were unremarkable with regards to the potential introduction of soybean rust to North America, the analysis indicates that winds blowing from Roraima State in northern Brazil may have transported spores northward into Central America during the first few months of 2004. A typical trajectory from this region starts westward and encounters the Andes Mountains within a few days (Fig 7). As a result, the hypothetical spore-laden air parcels are forced up to great heights. Many trajectories then continue west, some curve back to the south, while others veer to the north. Those that swing south or north usually turn back eastward as the air parcels encounter high altitude westerly winds that generally blow over the tropics (e.g., the 1000 m trajectory in Fig 7). If rust spores were involved in these transport events, they would have been transported over Central America and the Caribbean islands. However as noted above, most of the soybean north of the equator in South America is planted in late May and June (USDA FAS 2004). As summer progresses and the ITCZ moves farther to the north, the frequency of transport events with potential to carry spores from northern South America to Central America, the Caribbean, and perhaps the southern U.S. will amplify. In addition, the quantity of airborne soybean rust spores above the Roraima source region and capable of being blown toward the U.S. may increase if the pathogen spreads within the maturing soybean crop.

Simulations using the IAMS parcel-box model. The IAMS parcel-box model was constructed by ZedX programmers accounting for spore release and canopy escape in source areas, mortality due to exposure to solar radiation during atmospheric transport, and wet deposition in destination regions. The model assumes no dry deposition (spores are suspended until rained out). The domain of the model extends from 130°W to 50°E longitude and from 50°S to 50°N latitude, including most of the continents of North and South America, Africa, and Europe. Computations are conducted on a 0.125 by 0.125 degree grid (~ 14 x 14 km) throughout the model domain using a 6-hr time step. Spore density is computed on a per ha per day basis according to the number of hectares in a grid cell and presented as number of spores/ha/day on maps. For computational efficiency, a grid cell with less than 0.5 spore/ha/day is considered empty.

Spore release and escape from the crop canopy in a source area is computed using the following assumptions: (1) 25% of the soybean crop is heavily infected with soybean rust (personal communications with South American growers and researchers), 2) 6 million spores are released per day per heavily infected soybean plant (Melching et al. 1979, Yang et al. 1990), 3) planting density is 500,000 soybean plants/ha (personal communications with South American growers and researchers, 4) 33% of soybean rust spores are released during the late-morning to noon optimal transport period (applicable for *Peronospora tabacina* spores, Aylor 1986, Davis and Main 1989), and 5) 15% of spores released escape from the soybean canopy (applicable for *Peronospora tabacina* spores, Aylor and Taylor 1983). Using the Brazilian State of Roraima with 15,000 ha planted to soybean as an example, the number of spores that are released and escape from the canopy into the atmosphere during a heavy soybean rust epidemic is 3.7×10^{10} spores/ha/day.

The model spreads the spores that have escaped from the soybean canopy first in the horizontal or down wind direction, and then vertically. Horizontal transport is computed for a 15^{o} arc (dispersion angle) centered on the wind vector from each point source (grid cell center). A 15^{o} dispersion angle approximates an increase in spore cloud radius with travel time (Heffter1980, Aylor 1986, Davis and Main 1989). The distance of the arc from the point source is the average wind speed multiplied by the model time step (6-hr). Each arc is subdivided into 40 radii and the spores associated with the grid cell during the previous time step are allocated equally among them. The wind-determined horizontal transport distance is the same along each radius and is used to calculate destination grid cells. The computations are conducted separately for 6 standard pressure levels (1000, 925, 850, 700, 600, and 500 mb). After the horizontal transport computations are complete, the spores are moved vertically (up or down) between pressure levels using vertical wind vectors. This procedure is followed for each point source (grid cell containing spores). After the trajectories from each grid cell containing spores are computed, the spores arriving (A) at each grid cell and pressure level (potentially from multiple point sources) are summed in preparation for the solar radiation mortality and wet deposition computations. The proportion of airborne spores that are eliminated from the model at each time step due to mortality from radiation exposure and wet deposition are equal for the six pressure levels.

Spore mortality due to UVB radiation exposure in the atmosphere is proportional to cloud-adjusted, surface total incoming solar radiation (Aylor 1999). Total incoming radiation ranges between a clear, sunny day (0% cloud cover, 75% of the total radiation at the top of the atmosphere) to an overcast day (100% cloud cover, 25% of the total radiation at the top of the atmosphere). Observed percent cloud cover between 0 and 100% was used to adjust the amount of radiation between the two radiation limits. In model iterations, spores are exposed to incoming solar radiation after transport to the destination point and before wet deposition. The expired fraction (E_f) is calculated as a function of incoming solar radiation (Rad) in megajoules (MJ) using:

$$E_f = 1.0 - e^{-Rad/14.0} \quad .$$

A solar radiation level of 14.0 MJ/m^2 results in a mortality of 63.2% of the exposed spore population. This value represents the mean of the critical doses of solar radiation for survival for *P. tabacina* and dry bean rust *Uromyces appendiculatus* (Table 1 in Aylor 1999). The number of expired spores (E, spores/ha/day) is the total number of spores arriving at a grid cell multiplied by the expired fraction for that destination:

$$E = E_f A \quad .$$

Wet deposition of viable spores after transport to a destination point is proportional to the observed surface precipitation total (Precip) in inches for the grid cell and time step. The wet deposition fraction (WD_f) is calculated from:

$$WD_f = 1.0 - e^{-Precip} \quad .$$

A precipitation total of 1.0 inch results in a wet deposition of 63.2% of the spore population. The number of spores deposited on the ground by precipitation (WD, spores/ha/day) is the difference between the total number of spores arriving at a grid cell and the number of expired spores multiplied by the wet deposition fraction for that destination:

$$WD = WD_f \, (A - E) \quad .$$

Consequently, the number of spores posed to move during the next iteration of the model (S, spores/ha/day) is the total number of spores that arrived minus the sum of those that expired and were deposited during the previous time step:

$$S = A - E - WD \quad .$$

For display purposes, total daily values of S, E, WD are obtained by integrating the spore concentrations over the pressure levels in the air column above each grid cell. Wet deposition is also accumulated through time for each grid cell and release date(s) for mapping.

The IAMS was constructed in two stages to provide access to model output for decision making during the project. The software interface built during stage 1 has been available on the Internet since February 2004, enabling simulation of soybean rust aerial dispersal based on 23 years of historical meteorological data. Users specify a soybean rust source area (South Africa or South America) and select single or multiple weeks from individual or sets of years for analysis. This initial interface provides a weather-based assessment of aerial dispersal of soybean rust spores that is useful for estimating potential pathways and transit times associated with the movement of air parcels that potentially could transport spores long distances. The results of the simulations run by project team members were used in the USDA-ERS analysis (Livingston et al. 2004) and in numerous presentations for survey planning.

The second interface incorporates the set of complex assumptions regarding pathogen exposure to environmental conditions as defined above. This interface enables Internet users to select single or multiple source areas and create analyses for spore releases on individual or sets of days from single or multiple years between 1999 and 2003. The model simulations are summarized in daily time steps, providing users with vivid images of potential spore movement including aerial concentrations of viable spores, deposition of viable spores for individual days, and cumulative viable spore deposition along the transport route. Because this IAMS interface integrates biological parameters and meteorological information, the resulting simulations provide a more realistic basis for assessing the likelihood of aerial dispersal of soybean rust spores to the U.S.

Preliminary IAMS Calibration Studies.
A preliminary analysis was conducted to explore the sensitivity of IAMS model output to both input parameters and model spatial resolution as well as to test the hypothesis that Africa was the likely source of soybean rust spores transported to South America. The spore source areas for this study included Nigeria, Uganda, and Zimbabwe in Africa. Four model runs were conducted in 6-hr time steps for each daily cohort released during the months of December 1999, January 2000, December 2000, and January 2001.

The model runs were executed in an iterative fashion by increasing the solar radiation parameter from 14.0 to 16.0, 18.0 and 20.0 MJ/m^2 in combination with the precipitation parameter of 1.0 and 1.5 inches. The combination of 20 MJ/m^2 and 1.5 inches appears to work best in that it results in viable spores being transported from Africa and deposited in rainfall within South America for the December 1999 and January 2000 simulations (Figs 8 and 9). It interesting to note that in the December 1999 run the spores ended up in northern Brazil and neighboring countries, while in the January 2000 simulation, the spores were deposited in central and northern Brazil. Unlike the first two runs, spore transport from Africa and deposition in South America was not evident in the simulations for December 2000 and January 2001. The simulations indicate that favorable transport conditions can vary from year-to-year for the same time period. They also suggest, that if soybean rust spores from Africa were responsible for initiating the epidemics in South America, they more likely originated from western than southern Africa. Strong subsidence and the associated clear skies that prevail over the Kalahari and Namib deserts and Benguela current curtailed transport of viable spores eastward even when wind conditions as indicated by the HYSPLIT trajectory model were favorable (Figs 3 and 4).

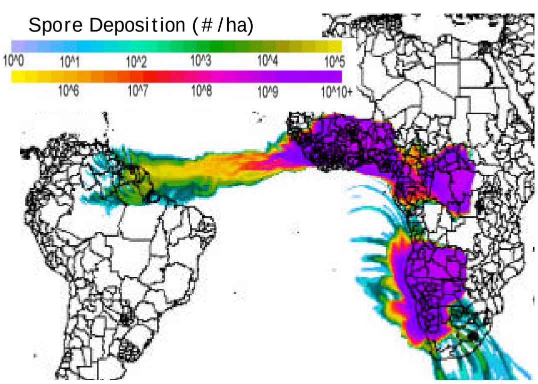

Figure 8. Cumulative wet deposition of *P. pachyrhizi* spores from African soybean-growing region for a hypothetical December 1999 release.

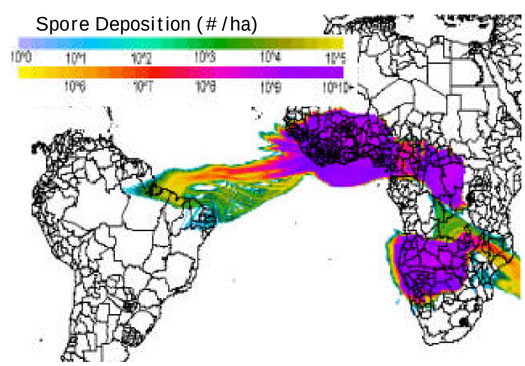

Figure 9. Cumulative wet deposition of *P. pachyrhizi* spores from African soybean-growing region for a hypothetical January 2000 release.

These simulations also revealed the influences of the model starting conditions. First, the location and size of pathogen sources in Africa greatly influence the number of viable spores transported to South America. That is, the larger the soybean rust source area, the greater the likelihood that viable spores could be successfully transported across the South Atlantic Ocean and deposited in South America when winds were favorable. Second, the time of year chosen also greatly influences the number of spores transported to South America. Like source areas, the addition of more "release days" improves the likelihood that more spores will be successfully transported from Africa to South America. Third, the dispersion angle has a significant influence on spore transport. The larger this angle, the greater the geographic extent of the transported spores. This increase in area is due to the fact that as spores spread out they experience a greater range of air motion in the atmosphere.

The series of runs conducted for Africa also revealed the influence of the spatial and temporal resolutions of the model. The chosen spatial resolution of 0.125 degree (approximately 14 km) greatly affected the simulated precipitation patterns. That is, the cruder the resolution, the greater the precipitation coverage, which favors an accelerated wet deposition of spores. Consequently, the final distance of spore transport may be shorter that actually observed. An increase in the precipitation parameter from 1.0 to 1.5 inches helped to offset this factor. Similar arguments could be made for the solar radiation. Cloud cover, like precipitation may have been too extensive due to the chosen spatial resolution and the crude 6-hour time step. Like the precipitation parameter, the radiation parameter was increased from 14 to 20 MJ/m^2 to account for this limitation. It should be noted that the choice of the spatial and temporal resolutions was dictated by the initial resolution (2.5 degrees) of the NCEP weather data, the quality of the data, storage requirements for the data, and the long, computation times for the model runs.

In the analysis that follows, the parameter values as presented in the model description above were used in the runs. Although, larger values of the critical dose of solar radiation and critical amounts of precipitation for deposition appear to allow for transoceanic movement, survival, and deposition of soybean rust spores from Africa to South America, the original values extracted from the literature are more conservative. This sensitivity analysis clear points out the need for both: 1) field studies to measure the survival of soybean rust spores in the air with increasing exposure to solar radiation and 2) a concerted effort to validate the IAMS model with historical data such as those collected by the NAPDFC on the blue mold disease of tobacco.

<u>Evaluation of Africa as a Potential Source for Soybean Rust Aerial Incursion to the U.S.</u> As discussed above, soybean rust has been present in western Africa since March 1999 (ProMed 2001). Because sugarcane rust apparently crossed the Atlantic Ocean from Africa (Purdy et al. 1985) and numerous culturable bacteria and fungi from African sources have been recently collected in the Caribbean (Griffen et al. 2001, 2003), it is possible that *P. pachyrhizi* spores will be blown from the western Africa to North America.

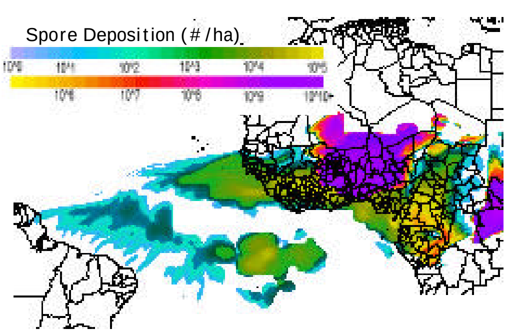

Figure 10. Cumulative wet deposition of *P. pachyrhizi* spores from Nigerian soybean-growing region for a hypothetical 07-22 July 2003 release.

IAMS simulations were created using the major Nigerian soybean production region as the rust source area and weather data for weeks in July from 1999-2003. Soybean rust outbreaks have been observed in the main soybean crop during this period. In some of the runs, the hypothetical spores were able to cross the Atlantic Ocean (Fig 10), but they were generally confined to the ITCZ and were deposited before reaching the Caribbean Sea.

Nigeria harvested 680,000 ha of soybean in 2003, approximately 61% of the total soybean production area on the African continent. This production area is equivalent to only 2% of the soybean hectares harvested in South America (FAOSTAT 2003). The relatively low source strength of *P. pachyrhizi* in western Africa coupled with the high dominance of winds that converge into the ITCZ at this time of year suggest that the current potential for spore movement from Africa to North America is low when compared to the likelihood of aerial rust transport from South to North America. Purdy et al. (1985) and Griffen et al. (2001 and 2003) suggest that the western Sahara region is the source area for the microorganism that are blown across the Atlantic Ocean to Caribbean. If the *P. pachyrhizi* were to expand its range to include the moist western African coastal region between Liberia and Senegal, the likelihood of soybean rust spores being blown across the Atlantic to the Caribbean would increase.

Historical Analysis of Potential Aerial Pathways for Soybean Rust from Northern South America to the U.S., 1999 - 2003. IAMS simulations were created for all days between 7 July and 3 September during the past 5 years to evaluate likely aerial pathways for spread of the pathogen from the South American soybean production area north of the equator. As previously mentioned, unconfirmed reports in 2004 suggest that the pathogen has extended its range to this region that includes portions of Venezuela, Roraima State in Brazil, Guyana, and Suriname. Since planting and harvesting usually begin in May and September respectively in this region (USDA FAS 2004), if soybean rust epidemics occur this year, spore production will likely peak between mid-July and late August. The vast majority of the model simulations for this source region during July and August 1999-2003, resulted in wet deposition of spores in Central America. Figure 11 shows a typical pattern of spore deposition for runs initiated on days in mid-July. As the summer progresses and the ITCZ shifts further north, the deposition region extends to southern and eastern Mexico including the Yucatan peninsula (Fig 12).

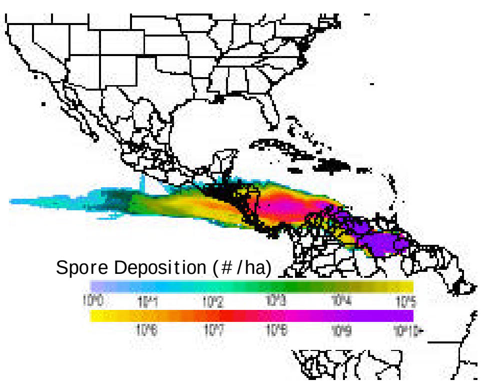

Figure 11. Cumulative wet deposition of *P. pachyrhizi* spores from northern South America soybean-growing region for a hypothetical 10 July 2003 release

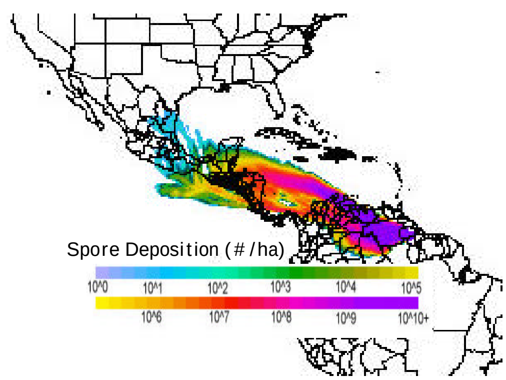

Figure 12. Cumulative wet deposition of *P. pachyrhizi* spores from northern South America soybean-growing region for a hypothetical 19 August 2001 release

<u>*Historical Analysis of Potential for Tropical Cyclones to Transport Soybean Rust from Northern South America to the U.S., 1999 - 2003*</u>. Simulations indicate that tropical cyclones in the Caribbean Sea and Gulf of Mexico during August are able to quickly transport rust spores directly to the U.S. from the South American soybean-growing region north of the equator. One example is Hurricane Bret that formed in the Bay of Campeche on 18 August 1999, tracked north, and dissipated in southern Texas seven days later. Had the soybean fields in northern South America been heavily rust infested at that time, model simulations suggest that wet deposition of viable *P. pachyrhizi* spores would have occurred throughout much of the southern U.S. (Fig 13). Similarly, had rust infested soybean fields in the same region been sporulating at the end of August 2003, it would have been likely that Tropical Depression #9 would have provided a mechanism to transport *P. pachyrhizi* to Florida and Texas (Fig 14).

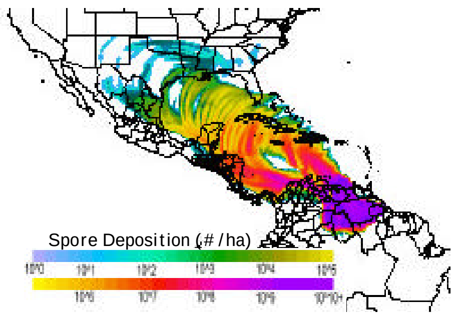

Figure 13. Cumulative wet deposition of *P. pachyrhizi* spores from northern South America soybean-growing region for a hypothetical 21-27 August 1999 release.

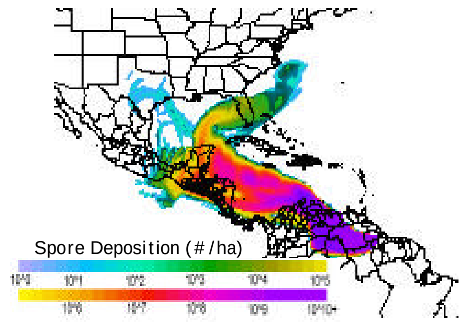

Figure 14. Cumulative wet deposition of *P. pachyrhizi* spores from northern South America soybean-growing region for a hypothetical 22-29 August 2003 release.

In July 1970, a tropical cyclone transported corn leaf blight from the heavily infested Gulf Coast states up the Mississippi River Valley to Kentucky, Ohio, Indiana, and Illinois. By September, the pathogen had spread locally in these states and to Wisconsin, Minnesota, and southern Canada reducing U.S. corn yields by 15%, at a cost of about $1 billion (Tatum 1971). Clearly tropical cyclones also represent a likely transport mechanism for soybean rust once it enters the Caribbean and Gulf of Mexico basins. However, until it spreads beyond the Roraima area in northern South America, the likelihood of direct transport to the U.S. by a tropical cyclone is low; IAMS simulations show soybean rust transport from Roraima to the U.S associated with only two July-August tropical weather systems in the five-year record.

TOWARD INTEGRATION OF THE SOYBEAN RUST AEROBIOLOGY MODELING SYSTEM WITH NAPPFAST

This project has taken the first step toward a modeling system for predicting aerial incursions of plant pathogens, insect pests, and weeds into the U.S. Clearly, the introduction of non-indigenous species to North America by completely natural means today is rare; almost all introductions are assisted by human activities. Soybean rust might represent an exception to this generalization, but only time will tell. Although aerial transport alone is seldom responsible for the introduction of non-indigenous species, the capability to use the atmospheric for rapid spread within the U.S. in large parts determines the "invasive potential" of organisms once they are introduced. Failure to consider spread by atmospheric transport in concert with human-mediated dispersal can lead to inappropriate and inefficient uses of containment and control strategies for invasive species.

In the long-term, APHIS seeks an operational system that can quantify, integrate, and predict the impact of biological, meteorological, geographical, and anthropogenic processes on movements of invasive organisms. The next step toward this objective should be to incorporate the IAMS soybean rust model into the North Carolina State University (N) APHIS (A) Plant (P) Pest (P) Forecasting (FA) System (ST) (NAPPFAST) system so that observed and forecast weather data could be used as input into simulations. The resulting modeling system could predict on a daily basis: 1) *P. pachyrhizi* source strength in soybean growing regions throughout the Western Hemisphere, 2) atmospheric transport from sporulating source areas to potential receptor regions, and 3) soybean rust epidemic development at destinations. An online version of the simplified transport model would allow users to establish biological and geographic parameters prior to a simulation. Like other existing models in NAPPFAST, user-set alerts could be assigned to the model output.

This modeling framework has potential for predicting the aerobiological invasion of other organisms. Such models are vital because they allow the USDA to evaluate the probabilities of biotic dispersal using the atmospheric pathway relative to the many human-mediated pathways for invasive species (Aylor 2003). USDA programs to contain and control the current wave of invasive species are generally very expensive, so it is important that the potential for aerial spread be considered in the planning processes to ensure that adopted strategies are as efficient and effective as possible. For example, the current version of the IAMS model allows users to estimate how far, for how long, from where, and when *P. pachyrhizi* can move in the air to the U.S., providing useful information on whether space and time render insignificant its impact on 2004 crop yields in U.S. agricultural regions.

OUTREACH

Results from this project have been communicated on numerous occasion reaching a diverse audience. For example, Isard and Magarey made presentations at the USDA-ERS meeting on soybean rust held in November, 2003. As a result of this interaction, aerobiological and climatological maps produced by these researchers were incorporated into the USDA-ERS economic evaluation of soybean rust. These maps also have been distributed upon request to a number of universities and agricultural industry representatives. Magarey participated in the USDA-OPMP soybean rust working group organized by Kent Smith and presented the project findings at the Southern Region IPM soybean rust workshop. He also made a presentation on soybean rust at the Infectious Diseases Informatics Working Group (IDIWC) meeting held in March in Ballston, VA. Isard has made presentations on aerial dispersal of rust spores at soybean industry meetings held in Missouri in January and Illinois during March. On multiple occasions, Hartman and Miles have also communicated the results of the simulations to Midwest soybean producers. Finally, Russo, Magarey, and Main are scheduled to make one poster and three oral presentations on soybean rust at the August 2004 American Phytopathological Society national meeting in Anaheim.

Project scientists have made a concerted effort to engage APHIS staff and programs. The group briefed the APHIS Pest Detection and Management Programs staff in February. Isard also participated in discussions aimed at incorporating aerobiology into a soybean rust response plan. Team members briefed CPHST on preliminary project results during early March. In addition to these activities, an article featuring the results of the project has appeared in the Associated Press.

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