The Integrated Aerobiology Modeling System Applied to the Spread of Soybean Rust into the Ohio River Valley during September 2006

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Abstract. Soybean rust (*Phakopsora pachyrhizi*) has recently invaded North America and has the potential to be the most destructive foliar disease of soybean. As part of the response to this threat, the Integrated Aerobiology Modeling System (IAMS) was constructed to forecast the aerial movement of this pathogen from subtropical to middle latitude portions of the continent. IAMS simulations have been conducted daily for the past two growing seasons and integrated with information from a nationwide observation network into a decision support system for soybean farmers. After the 2005 season, the United States Department of Agriculture reported that many millions of United States (U.S.) soybean hectares remained untreated for soybean rust in 2005, due to this decision support system. In 2006, soybean rust appeared for the first time in the major U.S. soybean production region over 1000 km from known areas of inoculum production. IAMS predictions of the geographical extent and timing of disease symptom expression were well matched with subsequent observations of the disease in the field.

Key Words. Transport model, soybean rust, invasive species, forecast, aerial movement

Introduction. On 6 November 2004, *Phakopsora pachyrhizi* Sydow, the causal agent of soybean rust was discovered for the first time on the North American continent (Schneider 2005). Soybean rust was originally identified during the early 20th century in Japan and by mid-century, it had spread extensively within the soybean production regions of southeastern Asia, Australia, and India (Bromfield 1984). During the mid-1990s, the rust appeared in central Africa and within five years had expanded throughout soybean growing areas in the southern and western portions of the continent. Soybean rust infections were found in the Rio Parana valley of South America during 2001 (Miles et al. 2003). Over the subsequent three years, the disease remained south of the equator spreading to soybean production regions in northern Argentina, Paraguay, Uruguay, and throughout much of Brazil (Yorinori et al. 2005). In June 2004, soybean foliage from a location north of the equator in Colombia tested positive for the pathogen. Aerobiological model simulations suggested that soybean rust spores were blown from northwestern South America to the southeastern United States (U.S.) in September 2004 (Isard et al. 2005).

Soybean rust is caused by two fungal species: *Phakopsora meibomiae* and *P. pachyrhizi,* with the latter being considerably more aggressive than the former. *P. meibomiae* has only been found in the Western Hemisphere and it is not known to cause severe yield losses in soybean (Miles et al. 2003). *P. pachyrhizi* has the potential to be the most serious foliar disease of soybean in the U.S. (Sinclair and Hartman 1996). Soybean rust has reduced yields significantly in many Asian countries with losses as high as 40% in Japan (Bromfield 1984) and 80% in Taiwan (Yang et al. 1992). Yield reductions in commercial crops ranged from 60-80% in Zimbabwe and from 10-80% in South Africa

(Caldwell and Laing 2001). During 2003, the pathogen was detected in 90% of the soybean fields in Brazil with yield losses equivalent to US$759 million and an additional US$544 million was spent on fungicide applications to control the disease (Yorinori et al. 2005).

Shortly after soybean rust was identified in South America, the U.S. Department of Agriculture (USDA) began to assess the potential for transport of *P. pachyrhizi* into North America. As part of this effort, they funded the development of the Integrated Aerobiology Modeling System (IAMS) to assess the risk that viable spores could be blown to the U.S., probable atmospheric transport pathways for the pathogen, and when and where deposition of spores was most likely to occur (Isard et al. 2005). Output from the IAMS became the basis for the USDA Economic Research Service assessment of the potential impact of soybean rust on U.S. agriculture (Livingston et al. 2004), which in turn stimulated an unprecedented effort by the USDA to prepare for the incursion of *P. pachyrhizi* (Roberts et al. 2006).

IAMS simulations, conducted immediately after the North American discovery of soybean rust, showed that winds associated with Hurricane Ivan had the potential to transport rust spores from northern South America, including the infected Rio Cauca source area in Colombia, to the southeastern U.S. (Isard et al. 2005). A map showing the IAMS prediction of where viable spores were deposited in rainfall was provided to the USDA Soybean Rust Rapid Response Team in early November 2004, to guide field scouting sorties for the disease. Within three weeks of the initial discovery, *P. pachyrhizi* was confirmed in diseased plant tissue from late-planted soybean fields and wild kudzu (*Pueraria lobata*) plants at multiple locations within or immediately adjacent to the region of spore deposition predicted by the IAMS (see Fig. 5 in Isard et al. 2005).

P. pachyrhizi is an obligate parasite that requires green tissue to survive and reproduce (Bromfield 1984). Although the pathogen is known to have many alternative hosts (Lynch et al. 2006), outside of experimental plots in the U.S., it has only be found on soybean (*Glycine max L.*) and kudzu (*Pueraria montana*) (USDA 2007). Consequently in winter, soybean rust is restricted to coastal zones of states bordering the Gulf of Mexico (Gulf Coast), and in the Caribbean basin, Mexico, and Central America where either kudzu retains its foliage or soybeans are grown year-round (Pivonia and Yang 2004, 2005, 2006). To cause significant yield losses in North America, *P. pachyrhizi* uridineospores must be blown from these areas into the major soybean production region in the continental interior between early May and August, at a time when the crop is susceptible to the disease (Livingston et al. 2004).

During the 2004/2005 winter, an Information Technology (IT) platform was constructed to integrate soybean rust monitoring, databasing activities, IAMS output, and communications to stakeholders into a state-of-the-art cyberinfrastructure (Isard et al., 2006b). The level of cooperation among USDA agencies, state Departments of Agriculture, universities, industry, and grower organizations, in support of the resulting USDA Soybean Rust Information System was unique for an invasive agricultural pest in the U.S., enabling the deployment of a pest information system with an exceptional level of utility and credibility. Fortunately, weather conditions during late winter and spring in the overwintering area along the Gulf Coast were not favorable for soybean rust. As a result, inoculum production was low in southeastern U.S. during the early 2005 growing season, and the pathogen did not spread into the major continental interior soybean production region that year. IAMS simulations were conducted daily and along with information from a nationwide observation network provided the basis for communications by plant pathologists to farmers. After harvest, the USDA Economic Research Service reported that many millions of U.S. soybean hectares that would have received at least one unnecessary fungicide spray remained untreated for soybean rust in 2005, due to this application of aerobiology and advanced IT for Integrated Pest Management (IPM) of soybean rust. In that year alone, the information disseminated through the USDA Soybean Rust Information System increased the profits of U.S. soybean producers by between \$11 and \$299 million (\$0.40 to \$10.18 per ha) at a cost that was only a small fraction of the return (Roberts et al. 2006).

During 2006, soybean rust appeared for the first time in the major U.S. soybean production region. IAMS simulations showed that large scale southerly air flows associated with a middle latitude cyclone that traversed the North American continent from west to east between 22-26 September, advected spores from an active inoculum source region in Louisiana more than 1000 km northward (Isard and Russo 2006). Abundant precipitation in the lower Ohio River Valley washed the spores out of the air causing infections that appeared in 36 counties beginning about two weeks later (USDA 2007). This manuscript presents the Integrated Aerobiology Modeling System and its application to the spread of soybean rust into the lower Ohio River Valley during September 2006.

Methodology

Soybean Rust Observation Network. In 2006, a network of 753 soybean rust sentinel plots was established across 35 U.S. states and 5 Canadian provinces. The vast majority of the plots were planted to soybean (650) with 64 established in kudzu and 30 in other leguminous crops (Giesler 2006). Cultivars, planting date, and scouting frequency varied throughout the network in accordance to the USDA sentinel plot protocol. The plots were generally planted with two soybean cultivars, one from the maturity group typically used in the surrounding area and the second from an earlier maturing cultivar group. Planting dates were generally one to two weeks earlier than those in the surrounding commercial soybean fields and multiple plantings occurred at some of the locations. For the most part, 100 leaves were collected from the lower to middle canopy on a weekly basis, although scouting was often less frequent early in the growing season. In some sentinel plots, the leaves were inspected for soybean rust by trained plant pathologists in the field. However in the majority of the cases, especially later in the growing season, the leaves were incubated for 24-48 h and examined in the laboratory using a microscope (Gielser 2006). The first positive find of soybean rust in each state as well as many of the additional positive identifications were confirmed by the USDA National Plant Diagnostic Network laboratories using polymerase chain reaction assay (Harmon et al. 2005, Lamour et al. 2006). The sentinel plot network was augmented by mobile scouting conducted by plant pathologists and agricultural extension specialists in areas threatened by the disease. Overall, 17,797 observations were submitted to the national soybean rust database in 2006 from approximately 2000 different geographic locations throughout the U.S. and southern Canada.

Integrated Aerobiology Modeling System (IAMS). The IAMS is configured in a modular format and includes spore release and escape from the plant canopy, atmospheric transport, mortality due to exposure to solar radiation, wet and dry deposition of spores, host development at destinations, and disease progress on these hosts. Together the modules predict the progression and intensity of an epidemic in an impacted region and when the spatial unit becomes a source of *P. pachyrhizi* spores for further atmospheric spread. The domain of the model for this application is 7.5 - 50 ^{o}N latitude and 60-130 ^{o}E longitude with a grid resolution of 0.083 degrees (~ 10 km) and a vertical resolution defined by the standard pressure levels (1000, 950, 900, 850, 800, 700, 600, 500 hPa). Thus there are as many as eight, 3-dimensional “airscape units” or air layers above each grid cell on the ground. The time step for model simulations is 1 h. The wind speed and direction, air temperature, humidity, and cloud cover data used in IAMS simulations are output from U.S. National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP) models including the Rapid Update Cycle Forecast (Benjamin et al. 2004), North American Mesoscale (Rogers et al. 2005), and the Global Forecast System (Kanamitsu 1989, Kanamitsu et al. 1991). Hourly precipitation data are obtained from the U.S. National Weather Service (NWS) NEXRAD Stage IV radar precipitation model (Lin and Mitchell 2005).

Spore release and canopy escape. Information on the geographic location and extent of individual inoculum source areas, the developmental stage of infected host plants, and the severity of the disease on hosts was obtained from the extensive network of USDA- and industry-funded “sentinel” soybean and kudzu plots as well as from mobile scouting in commercial fields and wild kudzu patches. The monitoring data from locations reporting soybean rust were used to determine percent of grid cell surface area that was infected, leaf area index (LAI) of the host, and a disease severity index (0-100%). For maximum disease severity and maximum LAI, the model uses a release rate of 5×10^{10}spores ha^{-1} d^{-1}. Spore release from an infected soybean or kudzu canopy is assumed to occur over a six-hour period between 0900-1500 local time. Escape of spores from a canopy, as a fraction of spores released, is calculated as a function of surface wind speed (WS). Escape fraction (EF) is assumed to be zero whenever the precipitation rate is ≥ 2.54 mm h^{-1} or wind speed is ≤ 1 m s^{-1}; and EF has a maximum value of 0.15. Otherwise,

$$EF = 0.15(1.0-e^{-0.333WS}). \tag{1}$$

Consequently, a wind speed of 3 m s^{-1} allows for the canopy escape of 0.095 (63.2% *x* 0.15) of the released spores.

Atmospheric transport. All spores escaping the canopy enter the atmosphere from the entire grid cell area at the surface pressure level (surface airscape unit, usually 1000 hPa unless the ground elevation above sea level is high). During subsequent time steps, the spores spread out from the airscape unit in a 15 degree arc centered on the mean wind vector for the hour. The arc is subdivided into 40 radii, separated by equal angular intervals. The distance of the arc from the source airscape unit is the wind run for the hour. An equal number of spores travel along each radial vector of this distance. The IAMS does not include the effect of turbulence on the aerial transport of spores. The combination of the 1-h time step and the 10 km^2 grid cell area results in an average wind speed that smoothes out any contribution due to turbulence in the spore transport process. Vertical movement of spores occurs in the direction of the vertical wind vector and is a function of the air vertical velocity (v in hPa h^{-1}) and the thickness of the pressure level (T in hPa). The fraction of the spores that move vertically between airscape units (VMF) in the hour time period is given by:

$$VMF = 0.9*T/v \tag{2}$$

and is constrained to a maximum value of 0.75. Downward vertical movement from the lowest pressure level is considered dry deposition and is discussed below. The number of spores in each destination airscape unit is the sum of the contributions from all other airscape units for the preceding hour interval.

<u>Spore exposure to solar radiation.</u> Spores experience exposure to incoming solar radiation after transport during each time step. Mortality by UV radiation is proportional to surface incoming solar radiation (SRad in MJ m^{-2}) provided by the NAM and GFS models. For this application, spores in a column of air regardless of their altitude receive

the same radiation exposure. The surviving fraction of spores (SF) in an airscape unit is calculated from Isard et al. (2006) as:

$$SF = -0.0307SRad + 1.0084. \quad (3)$$

Deposition of spores. Spore deposition is computed after spore mortality. Dry deposition occurs when it is not raining and there is downward vertical motion. Only spores in the lowest airscape unit experience dry deposition. The dry deposition fraction (DDF) for an hour time step is estimated as a linear function of vertical velocity (v in hPa hr^{-1}) and the thickness of the surface pressure level (T in hPa) from:

$$DDF = 0.125T/v \quad (4)$$

and is constrained to a maximum value of 0.25. Spores throughout airscape units above a grid cell can be deposited by rain. The wet deposition fraction (WDF) is a function of the surface precipitation rate (Precip in mm h^{-1}) for the grid cell according to:

$$WDF = 1.0-e^{-Precip/33.1} \quad (5)$$

A precipitation rate of 33.1 mm h^{-1} (1.5 in h^{-1}) results in a wet deposition of 63.2% of the spores in the air column. In simulations where spores are transported across multiple grid cells during a 1 h time step, deposition may occur in the intermediate grid cells according to equations 4 and 5.

Host development. IAMS incorporates a soybean plant module driven by growing degree day calculations to compute LAI and phenological growth stage. The model 1) uses a 10 ^{o}C base temperature with lower and upper thresholds of 10 ^{o}C and 30 ^{o}C, 2) assumes that LAI reaches a maximum value (which can not exceed 4 for soybean) at peak development, and 3) follows the Hanway scheme for soybean phenological stages (Richie et al. 1994). County-level data on number of hectares planted to soybean were obtained from the USDA National Agricultural Statistical Service (NASS 2007) and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA 2007) and assigned to the grid cells within each county based on U.S. Geological Survey, National Land Cover Data 1992 (Vogelmann et al. 2001).

For each grid cell, computations of accumulated heat were correlated to Normalized Difference Vegetation Index values from the Advanced Very High Resolution Radiometer (Goward et al. 1991) using data collected over a 5-year period to create grid cell specific "greening" functions. Soybean planting dates for spatial units in which the crop is prominent were also estimated as a function of accumulated heat. Beginning in January of a forecast season, the IAMS accumulates heat using temperature data and computes the greening function for each grid cell daily to determine whether kudzu foliage is available for *P. pachyrhizi* colonization and to initiate soybean planting. The model assumes that soybean fields in a grid cell are planted as seven cohorts equally spaced in time. The start and end of the planting season and thus the time interval between planting dates is determined from NASS and OMAFRA data. A normal distribution is used to allocate the number of soybean hectares in each grid cell to the seven planting dates. The model also assumes that the soybeans planted in each grid cell are from a maturity group typical of those used in the county. The start and length of the emergence period for each soybean cohort is predicted as a function of soil-degree days where the 5 cm depth soil temperature is approximated from the air temperature (Curran et al. 2004).

Disease progress on hosts. A soybean rust disease module is coupled to the soybean growth model and kudzu greening function and is initialized once spore deposition occurs in a grid cell containing a susceptible host. Disease progress is estimated as a function of temperature and humidity using data from field experiments conducted in Taiwan (Tchantz 1984). Infection level is expressed as a percent of leaf area occupied by pustules. A disease progression weather favorability index (DPWF), ranging from 0 to 4, is calculated for each day as a function of air temperature and leaf wetness, with the latter estimated from humidity and precipitation data. These values are accumulated after spore deposition on a host. Soybean rust progresses from the latent phase to the sporulation phase once 25 DPWF index values have accumulated. Thereafter, the percent leaf area covered by pustules progresses linearly from 0 to 100% as DPWF index values increase from 25 to 75. The foliage senesces and sporulation ceases when the entire leaf area is covered by pustules. Prolonged dry conditions (100 consecutive hours of zero leaf wetness) halt the progress of the disease in the model, including the release of spores into the air. Once moisture becomes available again, disease progress is reinitiated at the start of the latent period.

Spread of Soybean Rust in North America, February 2005 - September 2006.

Although soybean rust had been identified in nine states following the transport event associated with Hurricane Ivan (CERIS 2005), freezing temperatures during the 2004-2005 winter defoliated kudzu plants causing the disappearance of the disease throughout most of the southeastern U.S. (USDA 2007). A concerted effort to scout for soybean rust in February identified infected kudzu foliage at only two locations in central Florida (Figure 1a). Over the next two months, soybean rust was found on kudzu at three other Florida sites. Volunteer soybeans infected with the disease were discovered in southern Georgia during late April and immediately destroyed. The next finds did not occur until June, when the disease was identified on soybean and kudzu plants in isolated locations in northern Florida, southern Alabama, and southern Georgia. Perhaps the hot temperatures and dry weather during this period reduced infection efficiency and slowed the rate of the epidemic (Scoyners et al. 2006). However, the disease continued to spread very slowly in June and July despite seasonably cool temperatures and abundant precipitation throughout the region, weather conditions considered favorable for disease development (Kochman 1979). It was not until August, when soybean plants entered their mid-reproductive growth stages that detections began to increase. Overall, 121 additional counties in Alabama (30), Georgia (29), South Carolina (24), North Carolina (18), Florida (15), Louisiana (2), Texas (2), and Kentucky (1) reported first 2005 observations of soybean rust between August and November (USDA 2007). The geographic spread throughout this period was gradual (Figure 1a). The 2005 Atlantic hurricane season was the most active in recorded history with eight tropical cyclones making landfall between June and October in or near rust infected areas of the southeastern U.S. (NCDC 2006). However, no single weather event appeared to be more instrumental than any other in spreading the disease.

Cold air temperatures again caused defoliation of kudzu across much of the southeastern U.S. in December 2005. During January 2006, numerous kudzu patches known to be infected by soybean rust the previous year were surveyed. Soybean rust was found in 12 counties in Florida (10), Alabama (1), and Georgia (1) at this time (Figure 1b). A prolonged period with subfreezing nighttime temperatures in February defoliated the infected kudzu vines except at sites in southern Florida and in sheltered, sunny locations in urban areas. In February, a late-planted soybean field was found to be infected with soybean rust in extreme southern Texas and immediately harvested. Although soybean rust had been found in 23 counties during the 2005-2006 winter, by the beginning of March the disease was no longer discernable or just barely apparent at these sites (USDA 2007). Conscientious efforts to scout for the disease during spring throughout the southeastern states led to the discovery of soybean rust in only one additional county until mid-June.

The slow spread of soybean rust within the southeastern U.S. during spring and summer 2006 was most likely due to an extensive drought that prevailed in much of the region (Le Comte 2007). At the end of August, ample precipitation associated with Tropical Cyclone Ernesto relieved the drought conditions along the southeastern coastline of the U.S. September through November in this region was characterized by ample rainfall and decreasing daytime temperatures with the approach of autumn. A concomitant poleward spread of soybean rust was observed during this period with the states of South Carolina, North Carolina and Virginia reporting first 2006 observations of soybean rust in 2, 26, 44, 10 additional counties during the months of August, September, October, and November respectively (Figure 1b).

Precipitation along the Gulf Coast west of the Mississippi River also began to increase during August and September 2006, ending the summer drought (Le Comte 2007). By mid-September, soybean rust had been found in 18 Louisiana counties. Many kudzu patches throughout the south and central portions of the state were heavily infected and soybean rust severity levels were moderate in some commercial fields (USDA 2007). At this time, soybean rust had not been reported during 2006 in northern Louisiana, Arkansas, northern Mississippi, northern Alabama, and northwest Georgia, areas all greatly impacted by the spring and summer drought.

Spread of Soybean Rust into the Lower Ohio River Valley, Late September 2006.

On 21 September, a low pressure system drifted eastward across the Rocky Mountains and intensified over the High Plains in Colorado. IAMS simulations showed that warm air advecting from over the Gulf of Mexico ahead of the low during the next few days likely picked up spores from infected soybean fields and kudzu patches in southern and central Louisiana and carried them northward within the Mississippi River valley. Dense cloud cover protected the spores from the detrimental effects of UV radiation. A strong cold front developed accompanied by ample precipitation on 23 September and swept across the central U.S. (Figure 2). The IAMS predicted deposition of large numbers of viable spores in an area centered on the confluence of the Ohio and Mississippi Rivers, approximately 1000 km from the Louisiana source area (Figure 3). A second zone of heavy precipitation and predicted spore deposition occurred in northern Mississippi and eastern Arkansas. By 24 September, the low pressure system had passed to the east of the region.

Fortunately for soybean growers in the central U.S., the vast majority of the 2006 crop was approaching harvest at the end of September. Likewise, the simulated plants in the IAMS had progressed to maturity bringing the soybean rust disease forecasting season to a close. Notwithstanding, IAMS simulations were conducted for the 23 September to mid-October period in the lower Ohio River valley to predict areas of deposition and the subsequent appearance of soybean rust disease symptoms. It was assumed that soybean plants were present in every county in an early reproductive development stage and susceptible to infection (Figure 4a). The plants in the model became infected with soybean rust in counties where the IAMS predicted wet deposition of viable spores (Figure 4b). The model simulated the progression of the disease through its latent period using NWS daily temperature and moisture data for each county (Figures 4c – 4e). Extended periods of leaf wetness accompanied by temperatures of 15-28 ^{o}C favor soybean rust development and under these conditions, uredinia can develop in lesions 5 to 8 days after infection (Marchetti et al. 1975). Air temperatures in the lower Ohio River valley from 23 September until 11 October were greater that 17 ^{o}C for part of each day and only exceed 32 ^{o}C on a single day. On 13 of these 19 days, the mean daily air temperature was in the optimal range.

The IAMS predicted that soybean rust disease symptoms would first become apparent in the lower Ohio River valley on 4 October, 11 days after spore deposition. Two days later on 6 October, soybean rust was found in a corner of an otherwise mature soybean field in Caldwell County, Kentucky (Figure 4c). Over the subsequent week, soybean rust was identified in 22 additional counties in Kentucky and in extreme southern portions of Illinois and Indiana (Figure 4d). The severity of the disease at these sites was uniformly low, indicating that a large number of spores likely had been blown into the region by a single weather system a few weeks earlier (Hershman 2006). By the end of the following week, the disease had been found on soybean plants in 36 counties in the lower Ohio River valley (Figure 4e) as well as on a single leaf in an experimental field in north central Indiana.

It is conceivable that soybean rust spores were blown into the lower Ohio River valley prior to the 23 September transport event causing the infection that appeared in early October. Reports from the infected area in Louisiana indicate that both soybean rust incidence and severity were low until 18 September when extremely high disease levels began to be reported from commercial soybean fields (USDA 2007). The following day it was reported that due to ideal environmental conditions, rapid development and spread of the disease was expected (USDA 2007). An examination of IAMS model output for each day in the preceding month revealed that southwesterly air flow could have transported spores from the infected area to the lower Ohio River valley on 18 and 19 September 2006. Model output for these days shows that the heaviest wet deposition of viable soybean rust spores likely occurred in Arkansas, western Tennessee, and northwest Mississippi. Predicted deposition (spores/ha) further north in the lower Ohio River valley was two orders of magnitude less for the 18-19 September event than for the transport event that occurred 5 days later. Disease observations from Arkansas, western Tennessee and northwestern Mississippi were not included in the analysis (Figure 4) because of the 18-19 September potential transport event and because scouting for the disease in these states ceased in early September and did not resume until 18 October.

In general, the IAMS predicted that lesions would become visible on soybean leaves before disease symptoms were observed by scouts in the field. The model also predicted that soybean rust would be found uniformly across the lower Ohio River valley. There are a number of plausible reasons for discrepancies between IAMS predictions and field observations. IAMS simulations used soybean plants in an early reproductive stage of development. At this growth stage, the disease progresses rapidly on soybean plants. In contrast, the vast majority of the soybean plants in the counties had matured and scouts could find very few, if any, green soybean plants to inspect. There was also a lack of urgency to look for soybean rust in the field since it was far too late in the crop's development for the disease to reduce yield. As a result, scouting by plant pathology specialists occurred on only a few days during October and not all of the counties in the lower Ohio River valley were visited. Figure 4f shows the difference in days between the IAMS prediction of symptom expression and the discovery of soybean rust in the field for the 35 counties in which there were positive disease identifications. About 70% of the IAMS predictions were early, with a maximum difference of 12 days. The mean difference between model predictions and field observations of soybean rust was 5 days.

Discussion. Plant pathogens, such as soybean rust, that move through the air create some of the most interesting disease management problems because their populations can increase dramatically, often without warning and seemingly independent of conditions within fields and the surrounding landscape (Irwin, 1999; Jeger, 1999). The advent of IPM programs for reducing reliance on chemical control of diseases in agricultural systems has created an increased need to forecast when, where, and which plant pathogen populations are likely to increase rapidly and require control. Where long distance dispersal is critical to the dynamics of populations, the realization of this demand requires information on the movements of pathogens into and out of agricultural fields and the degree to which fields throughout entire continents are interconnected by these flows (Isard and Gage, 2001). Advances in our ability to gather, verify, store, share, process, visualize, and communicate information have increased our capability to understand and monitor diseases in agricultural fields, and to track the phenological progression of their causal agents and hosts. The rapid progress in information technology (IT) has also opened new frontiers for integrating near real-time biological and meteorological information gathered at high spatial and temporal resolution to forecast plant diseases. The IAMS demonstrates the utility of coupling a system for forecasting the aerial spread of an important plant pathogen at the continental scale with an extensive monitoring system on a state-of-the-art IT platform to provide real-time communications and IPM decision support. In 2005, many millions of soybean hectares in North America that would have received at least one fungicide application remained untreated for soybean rust due to this platform for IPM of soybean rust (Roberts et al. 2006).

The development of a comprehensive understanding leading to the capability to forecast aerial movements of pathogens and other organisms is in its infancy. The application of the IAMS to predict the spread of soybean rust into the lower Ohio River valley region illustrates the potential to anticipate and assess movement of organisms on a continental scale. It highlights the importance of an aerobiological framework to forecast and respond rapidly to threats from pathogens and other pests that utilize the atmosphere to spread.

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Figure Captions

Figure 1. Maps showing the spread of soybean rust in the southeastern U.S. for 2005(a) and 2006(b). Fill colors correspond to months when soybean rust was first identified in counties during each year.

Figure 2. Radar reflectivity images for 800, 1000, 1200, and 1400 local time depicting the progression of the cold front through the lower Ohio River valley on 23 September 2006. Red and orange colors indicate areas of most intense precipitation. Red circle in images indicate likely source area for *P. pachyrhizi* spores. State abbreviations in the figure are: AL–Alabama, AR–Arkansas, GA–Georgia, KY–Kentucky, IL–Illinois, IN–Indiana, LA–Louisiana, MS–Mississippi, MO–Missouri, OH–Ohio, and TN–Tennessee. Images provided by Weather Services International Corporation and National Aeronautics and Space Administration though the Global Energy and Water Cycle Experiment Continental-Scale International Project (NCDC 2007)

Figure 3. IAMS output showing deposition of viable *P. pachyhrizi* spore on 23 September 2007. Green colors ($>10^2$ spores ha^{-1}) indicate areas of spore deposition dense enough to cause disease in the few remaining fields in the region where soybean plants were still green and susceptible to infection.

Figure 4. Maps showing output from IAMS simulations of disease severity for 23 September to mid-October in the lower Ohio River valley overlayed with field

observations of soybean rust. The model simulations assumed that soybean plants were present in every county in an early reproductive development stage and susceptible to infection (a). Soybean plants became infected with soybean rust on 23 September (b) in counties where the IAMS predicted wet deposition of viable spores (see Figure 3). The model simulated the progression of the disease through its latent period when disease symptoms are not visible. Panels c, d, and e show disease progression on 6, 13, and 20 October, respectively. Counties in which symptoms of soybean rust were observed by scouts are dark red. Panel f shows the difference in days between the IAMS prediction of symptom expression and the discovery of soybean rust in the field for the 35 counties in which the disease was identified.