THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF METEOROLOGY

THE DEVELOPMENT AND SPREAD OF SOYBEAN RUST IN 2013: AN ANALYSIS OF THE WEATHER PATTERNS AND THEIR IMPACT ON MARKET PRICES

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ABSTRACT

Many industries are affected by meteorology, but few areas are impacted more by day-to-day variations in the weather than agriculture. Soybean rust, which plagues soybean (*Glycine max*) crops worldwide, is a dangerous spore-based disease that is highly reliant on weather for transport. Caused by the pathogen *Phakopsora pachyrhizi*, soybean rust was first introduced to the Americas from Asia in 2001, making the well-established soybean crop vulnerable to the disease. The light spores are easily picked up by the wind and carried long distances to infect new crops; additionally, because the plant's leaves must be wet to become infected, rain often deposits these spores. Since the disease is often difficult to spot until deep into the infection cycle, farmers rely heavily on weather forecasts to decide whether or not to spray expensive fungicides to prevent infection. Failure to prevent infection of soybeans can result in harsh reductions of harvest yield, as infected soybean plants are essentially lost for the year; this also impacts price fluctuations in the soybean commodity market. Data taken during the 2013 United States growing season support each of these assertions. The intention of this study is to highlight weather's role in the development and spread of soybean rust in addition to potential solutions to the disease while focusing on cases occurring in the United States, Brazil, and Argentina. The results of this analysis indicate that soybean rust is being carefully confined to the Southeast, but the disease still has important effects on crop yield and price.

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ACKNOWLEDGEMENTS

I would like to thank Bill Syrett for notifying me of and giving me the opportunity to serve as a soybean rust and pool use forecaster this past summer. My time forecasting this past year has expanded my meteorological knowledge and forecasting skills greatly and learning about weather’s effects on crop diseases essentially provided me with the subject of this thesis.

I would also like to thank Chris Forest for serving as my honors adviser for the past four years. His great advice and support has helped me to complete my meteorology and honors curriculum in four years despite spending my first semester in the College of Engineering and my fourth semester studying abroad in Ireland.

Finally, I would like to thank Paul Knight for serving as a teacher, project head, thesis supervisor, and overall guide throughout the past year. Before beginning the soybean rust project, I really had not even thought about the interaction between weather and crop diseases; nine months later, I am completing a comprehensive study on the topic. Without his knowledge and support, this thesis would not have been possible.

Chapter 1

Introduction

1.1: What is soybean rust?

Soybeans and soybean products are a well-known alternative source of food and drink for people with dietary restrictions, but soybean production and consumption go well beyond providing lactose-free nutrients. An estimated record of 287.7 million metric tons of soybeans will be harvested by the end of the 2013/14 growing season, representing nearly 57% of the total world production of oilseeds; about two-thirds of this production will be used as feed for livestock, particularly in China, which is consistently the world's top importer of soybeans (WASDE 2014). Of these 287.7 million tons of soybeans, nearly 234 million will have been produced in the United States, Brazil, and Argentina where warm, wet summers allow the crop to flourish (WASDE 2014).

Although each of these countries has a climate extremely well-suited to growing the cash crop, soybeans in these areas are also very susceptible to diseases. Most dangerous among these diseases are *Phakopsora pachyrhizi*, which causes Asian soybean rust, and *Phakopsora meibomiae*, which results in American soybean rust. Of the two, Asian soybean rust is much more aggressive and consequently much more of a threat to the soybean crops of the Americas (Rupe and Sconyers 2008). Each disease infects its

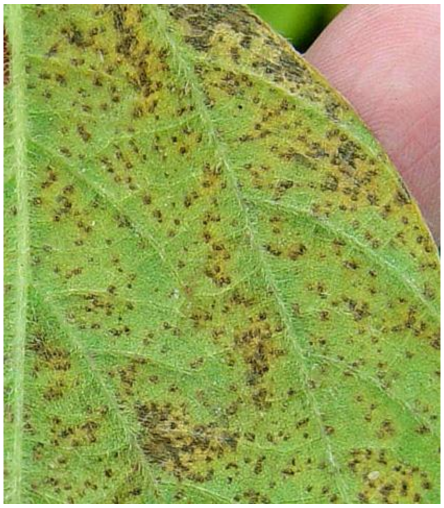
Figure 1: Leaf infected with soybean rust

hosts primarily through the production and deposition of spores, which are easily spread from region to region by the wind. Once a plant is infected, the disease is virtually undetectable for up to eight days; rust is only truly evident when lesions begin to form on plant leaves (Dorrance et al. 2014). These lesions begin to fill with spores after about ten days of infection, and spores are released to infect other hosts about three weeks after the disease's onset (Dorrance et al. 2014). Spores are released continuously as long as conditions remain moist and moderate and the host remains living (Dorrance et al. 2014).

The combination of Asian soybean rust's ability to escape detection for the first week of infection and its quick production of light, fast-traveling spores makes epidemics of rust possible if it is left unchecked. Before the disease was brought to the United States, the threat of destruction posed by a soybean rust epidemic led the government to include *P. pachyrhizi* on its list of "select agents" in the 2002 Bioterrorism Act; this act designated the pathogen as a having the potential to be used in bioterrorism (Rupe and Sconyers 2008). The severity of such a rust epidemic has been seen in Brazil and Paraguay, which were affected by a series of epidemics in the early-2000s. As seen in Figure 2, soybean rust affected all but five states in Brazil in 2003, leading to over $750 million in lost soybean revenue (Yorinori et al. 2005). That year also featured the first widespread use of fungicides to fight the

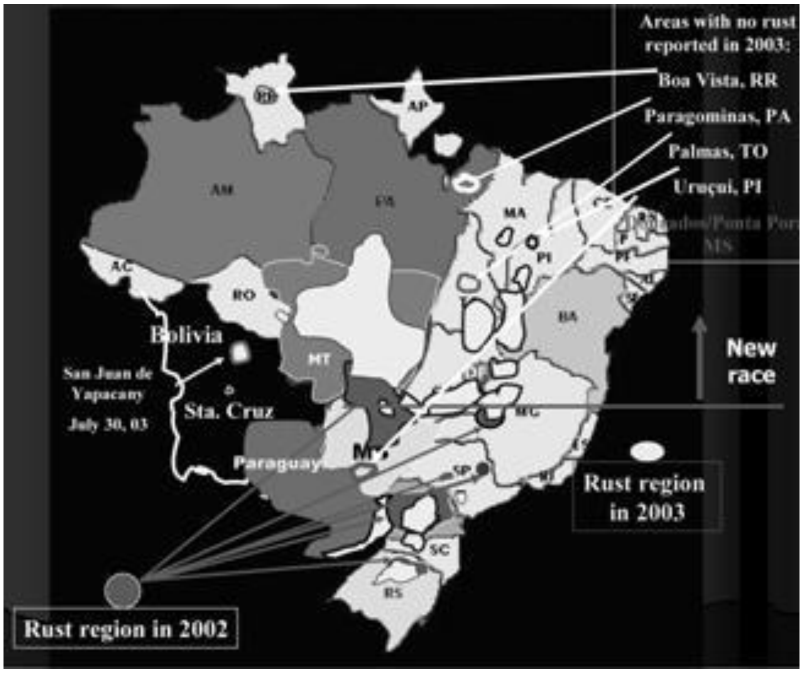

Figure 2: 2003 Spread of soybean rust in Brazil

disease, but even this preventative measure cost Brazil nearly $600 million to employ, due to the wide area (14.8 million hectares) sprayed and the cost ($40/hectare) of the product (Yorinori et al. 2005). Due to the possibility of a multi-billion dollar epidemic such as this, the United States uses weather forecasting combined with prompt application of fungicide in favorable rust development conditions to prevent the disease's spread.

1.2: History of the Disease

The origins of *Phakopsora pachyrhizi* can be ascertained from the disease's common name: Asian soybean rust. First reported in Japan in 1902, *P. pachyrhizi* has existed in Asia and Australia for over a century and was confined to those continents until the late twentieth century (Rupe and Sconyers 2008). In 1997, Asian soybean rust was first spotted in Africa; after originally appearing in Uganda, the disease quickly spread to Zimbabwe in 1998 and South Africa in 2001 (Rupe and Sconyers 2008). In 2001, the disease was also spotted for the first time in Paraguay and spread to Argentina and Brazil by 2002, causing particularly severe epidemics in Brazil (Yorinori et al. 2005). By 2004, rust had been reported in sections of northern Colombia and Venezuela; in mid-September of that year, Hurricane Ivan, then a Category 5 storm, passed north of Venezuela and is believed to have picked up *P. pachyrhizi* spores in its updraft (Dorrance et al. 2014). These spores accompanied Hurricane Ivan, as seen in Figure 3, through the Caribbean and Gulf of Mexico and were ultimately deposited in the United States after the storm made landfall (Rupe and Sconyers 2008). The disease was first spotted in November 2004, but cold air prevented its survival and limited its spread (Isard et al. 2014).

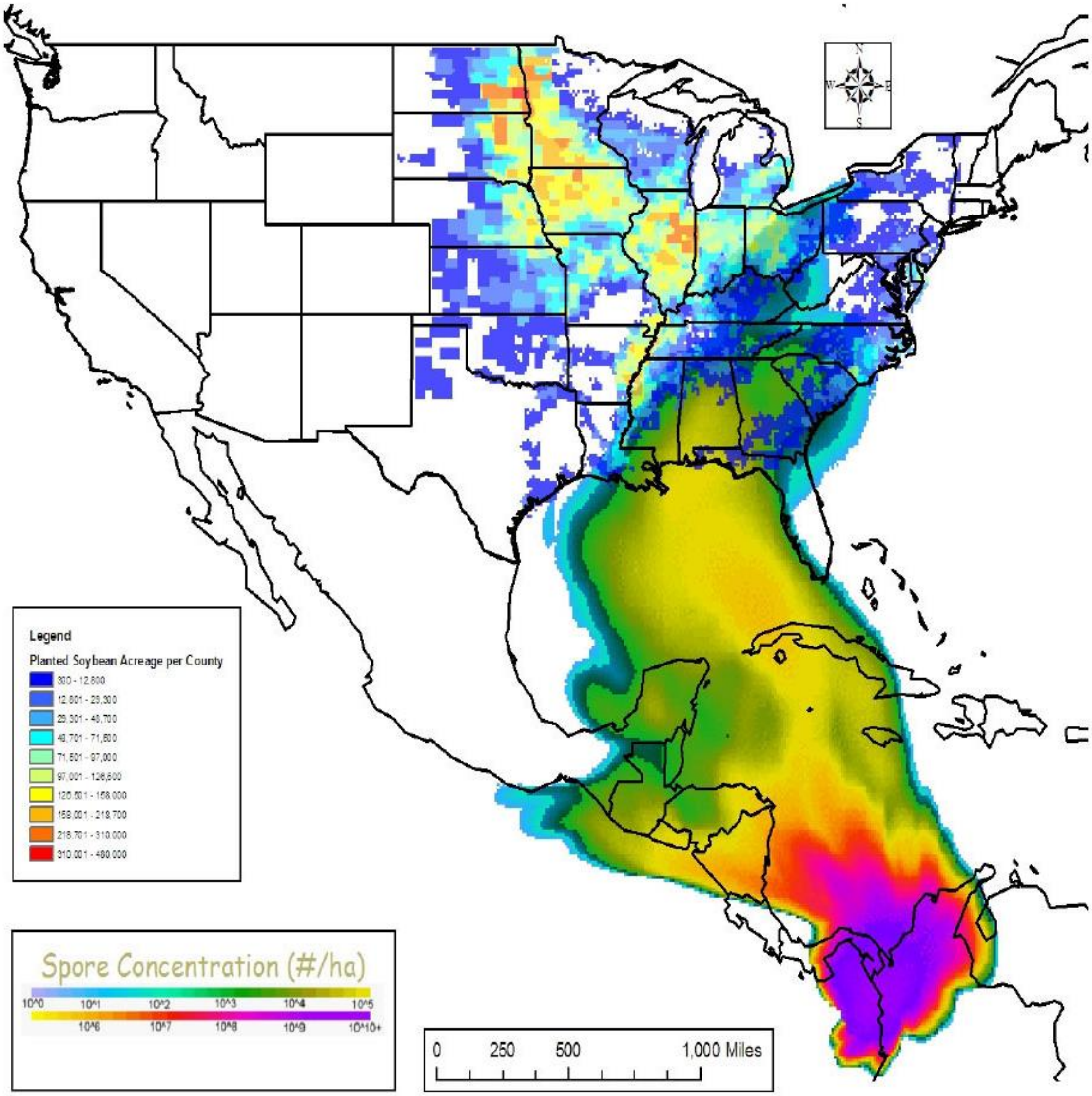

Figure 3: Transport of Soybean Rust by Hurricane Ivan

Although air was too cold to allow soybean rust to survive on soybeans themselves, the disease was able to overwinter in the warmer climate of the Florida Peninsula by infecting a species of vine called kudzu (Rupe and Sconyers 2008). Over the next three years, soybean rust would steadily spread throughout the Southeast and into the soybean-heavy Midwest (Rupe and Sconyers 2008). This spread can be tracked in Figure 4, which documents the extent of soybean rust at the end of each growing season in November. A combination of early season heat and drought in each of these seasons limited the spread of the disease until the late season, when soybeans were less likely to be affected, but the alarming speed of its spread led to increased efforts by scientists to study and prevent the disease (Rupe and Sconyers 2008). Among other methods, scientists have implemented sentinel stations, which consist of soybean plants that are planted a few weeks before commercial crops and are deliberately left unguarded against the disease; since soybean rust takes about a week to become visible, farmers will have adequate time to respond to reports of the disease in the area (Rupe and Sconyers 2008). If soybean rust is in the area, the government also distributes foliar fungicides which protect a plant for seven to twenty days (Isard et al. 2014). Although soybean rust continued to spread during each growing season and has yet to be prevented, outbreaks have been increasingly confined to the Southeastern United States due to a combination of better preventative measures, more favorable weather (such as a lack of hurricane landfalls), and increased accuracy in spread forecasting (Ariatti 2011).

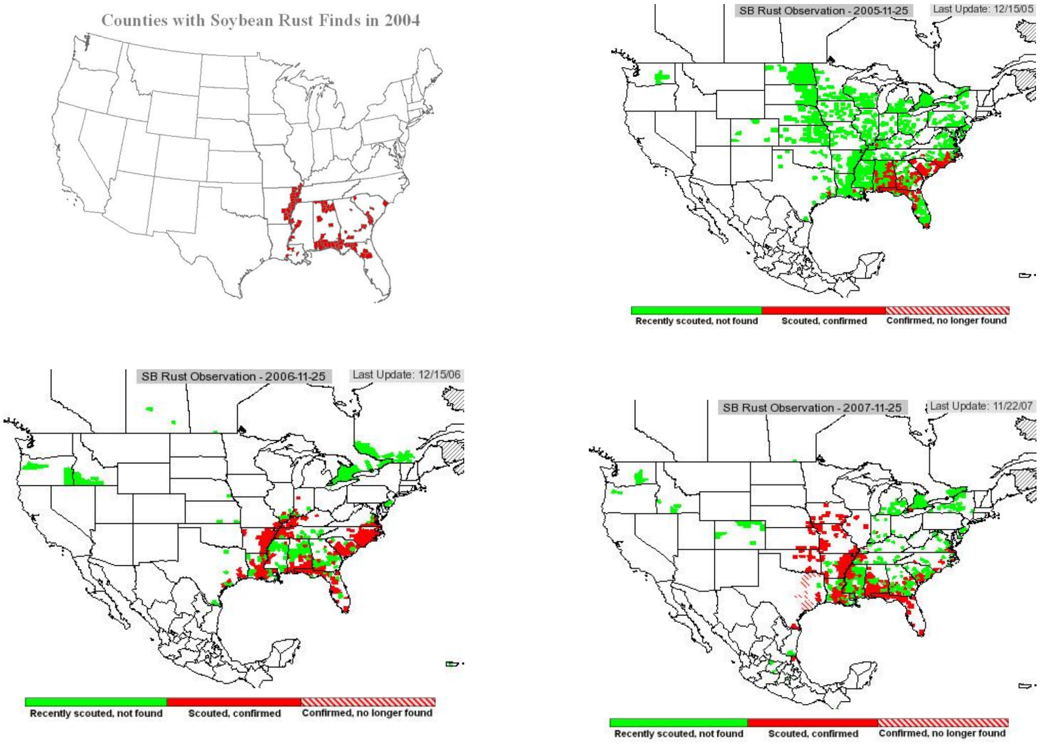

Figure 4: Initial Spread of Soybean Rust in the continental United States (TL: 2004, TR: 2005, BL: 2006, BR: 2007); red indicates counties that have observed the disease on kudzu or soybean plants

1.3: Study on the 2013 Growing Season

In addition to research done on the disease's background and previous outbreaks, substantial attention is given to the 2013 U.S. growing season. As part of an ongoing partnership between Penn State, ZedX, Inc., and the United States Department of Agriculture (USDA), I began providing twice-weekly forecasts of the spread of soybean rust in April 2013 with my partner Josh Markel. We were given access to the USDA's PIPE website, which highlights counties that have reported, suspect, or not found soybean plants affected by soybean rust. Additionally, this website provides graphics which detail the rate of transport and deposition of rust spores across the country. Along with this information, we used forecasts of precipitation probability and amount, wind speed and direction, and cloud cover provided by the Global Forecasting System (GFS), North American Model (NAM), and European Center for Medium-Range Weather Forecasts Model (ECMWF) to forecast where risk of infection was greatest. These forecasts were then sent to Jeremy Zidek, our contact at ZedX, who produces the Field Crop Rust Forecast Bulletin.

The 2013 growing season featured reports of soybean rust in 360 counties in twelve states by November 2, the end of our forecast period. This number was about 15% larger than the previous growing season—during which 312 counties in thirteen states reported soybean rust. Both numbers were much larger than the 2010 growing season (28 counties, 7 states) and 2011 growing season (13 counties, 3 states). However, the 2013 number was smaller than that of the 2008 growing season (392 counties, 16 states) and much smaller than that of the 2009 growing season (513 counties, 16 states). All statistics were obtained from the USDA PIPE website.

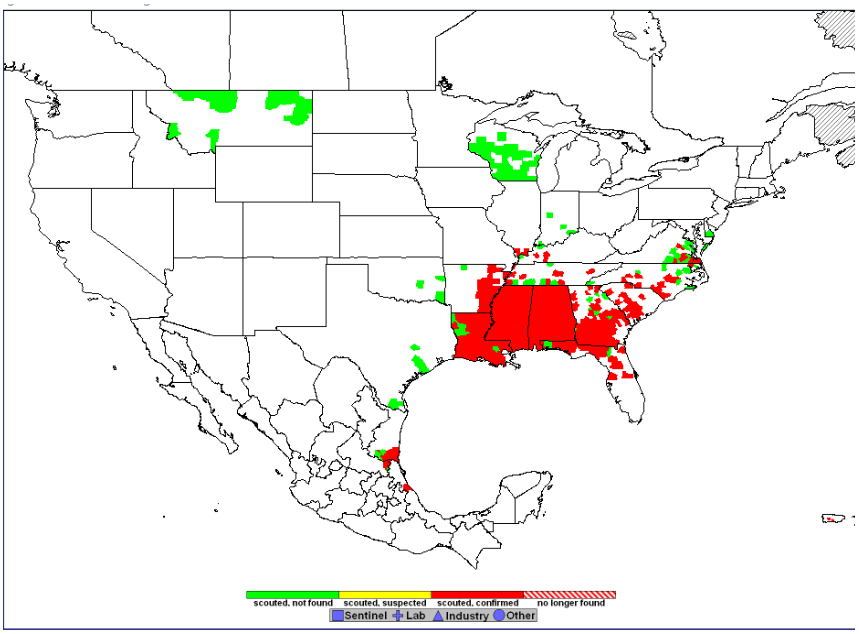

Figure 5: Spread of Soybean Rust through the United States and Mexico on November 2, 2013

Chapter 2

Infection and Development

2.1: Process of Infection and Spore Development

Soybean rust primarily attacks the leaves of its host plant in order to infect it. *P. pachyrhizi* spores enter their hosts by penetrating the cuticle of the relatively strong epidermal cells that cover a plant's leaves; this method of infection is one of the unique features of soybean rust, as most crop diseases infect a plant through its leaves' stomatal openings (Miles et al. 2005). These spores group together on the leaf in a long, thin tube-like structure and begin forming appressoria, flat cells that use microscopic pegs to burrow through the tough leaf surface (Miles et al. 2005). Once the epidermis is penetrated, spores are able to enter the leaf, draw nutrients and water from the host plant, and begin forming small pustules called uredinia after five to eight days (Miles et al. 2005). Reddish-brown lesions filled with one to three uredinia begin to the form on the leaf, usually on its underside (Koenning et al. 2014). Tan or colorless urediniospores are produced in uredinia about four days after uredinia production, or nine to

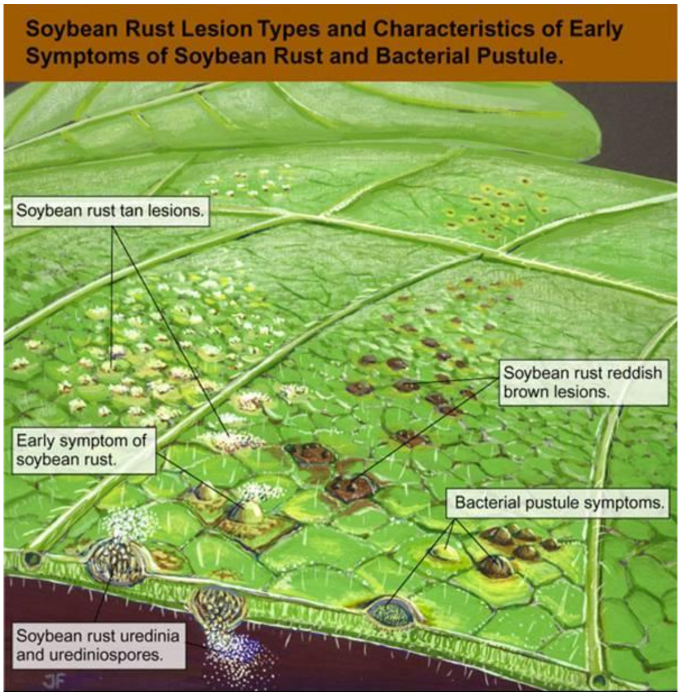

Figure 6: Stages of Soybean Rust Infection

thirteen days after infection; spores continue to be produced for about three weeks, at which point they begin spreading to other plants nearby and fields downwind (Miles et al. 2005). Uredinia will continue to form on the leaf for four to eight weeks, generally near the original tube-like structure formed by the spores, causing the leaf to become heavier and yellower as more spores are produced, eventually causing the leaf to fall off its host plant (Miles et al. 2005; Rupe and Sconyers 2008). However, even though the original infected leaf is now separated from the plant, rust has spread into the stem at this point and can be transported throughout the plant (Rupe and Sconyers 2008). Additionally, as the pustules on a soybean plant age, they begin creating teliospores. These spores do not directly infect healthy soybean plants; instead, their main purpose is to help the disease survive without a living host by creating thick black walls around the pustules, protecting them from the environment (Rupe and Sconyers 2008). This process helps the disease overwinter in the US.

Soybean rust generally must infect soybean plants before the R3 growth stage—when soybean pods are just beginning to grow off the leaf—to be a major threat to crop yield (Koenning et al. 2014); R3 stage tends to occur in August/September in North America and February/March in South America. Additionally, infection is usually not possible until the plant

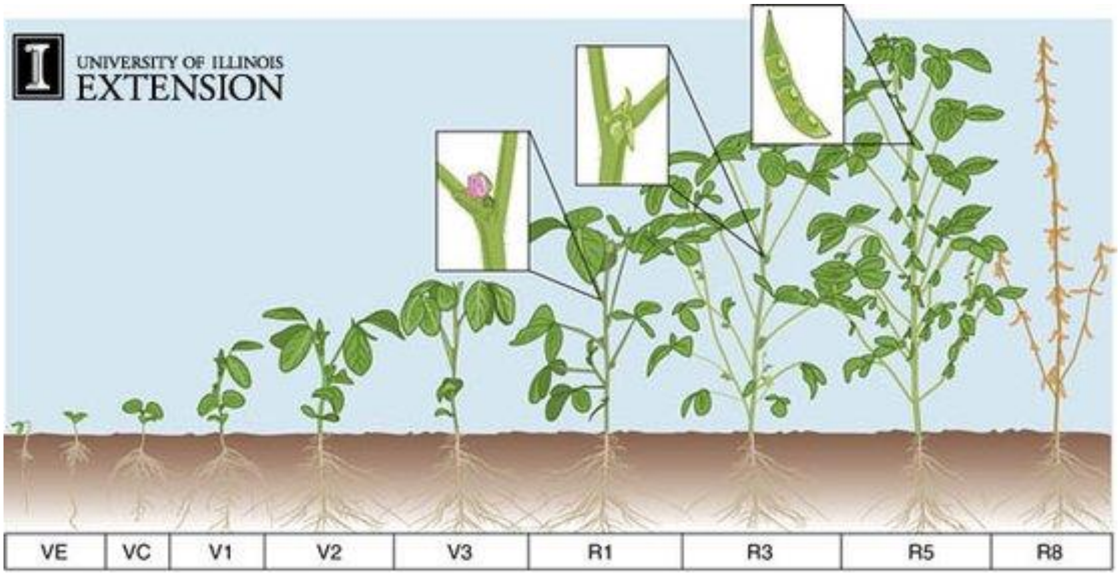

Figure 7: Growth stages of the Soybean Plant (Glycine Max)

actually begins to flower—also known as the R1 stage, which begins in July in North America and mid- to late-January in South America (Rupe and Sconyers 2008). Since spores generally attach themselves to the underside of the plant leaf, it is fairly difficult for infection to develop until that plant leaf has matured. As a result, this gives *P. pachyrhizi* a relatively short time window to infect soybean plants. However, the disease is able to survive in regions by attacking a leafy vine called kudzu, which is very common to the southeastern United States.

2.2: Favorable Weather Conditions for Infection and Development

Two weather variables most affect plant vulnerability to infection: moisture and temperature. In order for spores to be able to attach themselves to a leaf, soybean plant leaves must be wet for an extended period of time; six hours of access to water that has not been absorbed by leaves—also known as free moisture—is the minimum necessary time for host infection while infection is maximized at ten to twelve hours of free moisture (Miles et al. 2005). As a result, soybean rust infection happens most often after showers and thunderstorms. Recent rainfall does not ensure infection, however; ambient temperature must also be in a specific range for spores to survive. The air must be between 8˚C (46.4˚F) and 28˚C (82.4˚F) for infection to occur; plants are most vulnerable when the temperature is between 20˚C (68˚F) and 23.3˚C (74˚F) while infection is severely limited above 30˚C (86˚F) (Rupe and Sconyers 2008). Additionally, though it is not as important as moisture and temperature, cloud cover is associated with increased rates of infection. A broken or overcast cloud deck limits the spores' exposure to sunlight, decreasing evaporation of free water and also moderating temperatures.

The weather patterns and climate common to North America contribute to the spread of soybean rust. As a result of the temperature restrictions, *P. pachyrhizi* cannot survive the North American winter and is generally limited to kudzu vines in Florida; the limited extent of the disease allows for somewhat of a reset for fields at the beginning of each growing season since spores are no longer in the area. The frequency of diurnal thunderstorms and warm, humid weather in the Southeast also explains why soybean rust is most common in that region. As diurnal thunderstorms are less prevalent north of the Gulf Coast states, soybean rust tends to be found in the wake of synoptic-scale features outside of the Southeast. Warm fronts and anabatic cold fronts, which both usually feature sustained periods of rain, cloudiness, and moderate temperatures, are most dangerous in these areas. Outbreaks of soybean rust are most possible in the presence of hurricanes and tropical storms. The sustained combination of heavy rain, total cloud cover, and moderated temperatures found in tropical systems makes infection likely across large distances in the storm path. However, since a major hurricane has not hit the United States since Hurricane Wilma in 2005, infection due to tropical disturbances has been somewhat limited.

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Chapter 3

Spread

3.1: Process of Spore Spread and New Infection

Since soybean rust is a spore-based disease, it relies heavily on weather events to spread. Individual spores are microscopic in size and are thus transported very easily by the wind. However, spores are also highly sensitive to ultraviolet radiation, which means that unless they are protected in some way, the sun's rays will kill them (Rupe and Sconyers 2008). Consequently, most transport of *P. pachyrhizi* spores occurs in cloudy conditions, which limit exposure to direct sunlight. Small-scale spread can occur if only cloudy, damp, and breezy conditions exist, but large-scale spread from state to state often requires the presence of a mesoscale or synoptic feature, such as a squall line, tropical system, or front.

Small-scale spread of soybean rust depends primarily on the wind, as long as cloudy, damp, and mild conditions are present. Uredinia on the soybean leaf fill themselves with spores so that any minor force will cause spores to be expelled into the environment (USDA 2014). Steady winds pick up spores from diseased plants and disperse them over downwind fields (Dorrance et al. 2014). Once deposited over downwind fields, spores begin infecting plants as described in Section 2.1. This method of spread caused mainly by the wind is known as transport.

Large-scale spread of soybean rust depends highly on the presence of the mesoscale and synoptic features described early. As a disturbance passes through diseased fields, updrafts—areas of vertical motion found in areas of instability—pick up urediniospores. These urediniospores are taken up into a cloud, where they mix with water droplets and remain (Keever

2005). As the disturbance moves across the region, these water droplets become larger and fall as rain, taking spores with them as they fall (Keever 2005). When raindrops hit plant leafs, spores are deposited onto the plant and begin the process of infection. This process is also known as wet deposition.

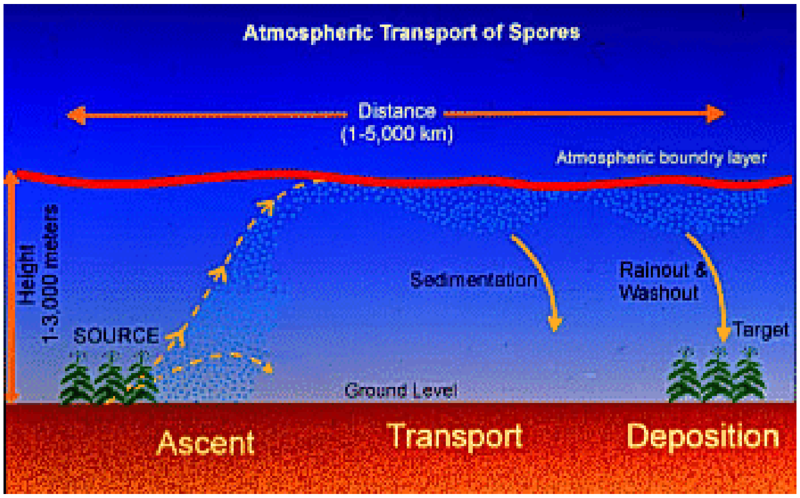

Figure 8: Methods of Soybean Rust Spread

3.2: Favorable Weather Conditions for Spread and New Infection

Favorable weather conditions for small-scale spread and infection are very similar to those described for development. Skies must be broken or overcast, conditions must be damp from recent rain or other free moisture for at least six hours (ideally twelve), and temperatures must be between 8˚C and 28˚C (ideally between 18˚C and 28˚C). During the 2013 growing season, winds of ten knots tended to be strong enough to initiate small-scale transport. Single-cell thunderstorms also can cause small-scale transport—even in areas that do not receive rain—through the creation of gusty winds.

Large-scale spread of soybean rust relies more on a combination of wet deposition and transport. Bands of multi-cell thunderstorms often last long enough to cause large-scale spread of urediniospores; this is particularly enhanced by the diurnal nature of southeastern U.S.

thunderstorms, which deposit spores on plants just before sundown, giving spores enough time without direct sunlight to infect a plant. Large-scale spread of soybean rust more frequently results from cold fronts, particularly anabatic cold fronts. Vertical motion ahead of cold fronts picks up spores and transports them over large areas. In the case of anabatic cold fronts, which feature a wide area of precipitation and cloud cover behind the front, spores have plenty of free moisture to use and avoid direct sunlight for the necessary amount of time. This wide area of precipitation and cloud cover stems from the undercutting nature of surface wind flow from the northeast; this is in contrast to katabatic cold fronts, which feature long and narrow bands of precipitation ahead of the front and clearing skies behind it. Lastly, the most dangerous catalysts of large-scale spread of soybean rust are tropical disturbances, such as hurricanes and tropical storms. These storms often feature intense upward motions, very strong low-level winds (speeds greater than 35 knots), an abundance of moisture and precipitation, and sustained periods of overcast skies. The strong organization of tropical systems also enables spores to be transported to areas deep in the storm’s track and far away from diseased fields. Fortunately, no major hurricane has hit the United States since 2005.

Chapter 4

Development and Spread during the 2013 U.S. Growing Season

Purely taking into account reports of soybean rust, the 2013 U.S. Growing Season was an active year for soybean rust; however, of the 360 counties and 12 states affected during growing season, only the Gulf Coast states of Louisiana, Mississippi, Alabama, and Georgia were strongly affected, with over forty counties in each state reporting rust; Virginia, Kentucky, Tennessee, the Carolinas, and Florida all had a few counties report the disease while Arkansas failed to see disease development until very late in the growing season. The disease was kept well away from important soybean producing regions in the Upper Midwest and Great Plains, which provide about 80% of the country's annual production.

The season started ominously with reports of severe soybean rust in winter nurseries in Puerto Rico; additionally, warm air allowed soybean rust to overwinter in parts of Florida, Louisiana, and interior Alabama, which marked the farthest north soybean rust had overwintered in the United States. During March and April, rust was reported in several other counties in these states as well as Georgia, resulting in a total of 20 counties in which the disease was present by

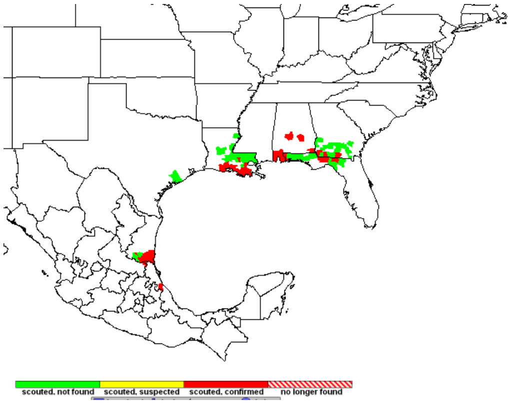

Figure 10: Spread of Soybean Rust through April 29, 2013

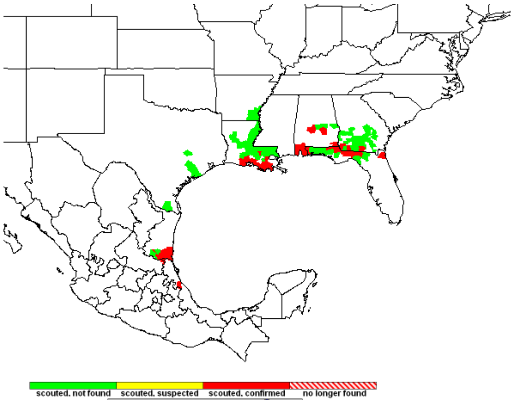

Figure 9: Spread of Soybean Rust through May 30, 2013

April 29, the beginning of our forecast period. A relatively dry month of May limited spread of soybean rust to only five more counties and no new states by May 31.

A spring of near-normal precipitation and temperatures well below average was followed by a very wet and fairly mild summer in the Southeast (NCDC 2013). Despite this increased precipitation, soybean rust only spread to two new counties—one in Florida and one in Georgia—in June. Spread picked up a bit in July, when most beans were reaching the R1 stage, as 17 new counties, including five counties in Mississippi, reported soybean rust; these reports, including the first report of rust in a commercial soybean field in 2013, were concentrated toward the end of the month, likely stemming from stormy periods in early- and mid-July, which helped locations like Atlanta collect over 9 inches of rain for the month. August was similarly stormy, resulting in the spread of soybean rust to 64 new counties, including locations in South Carolina and far southern Arkansas. Meteorological summer ended with a total of 109 counties in seven states

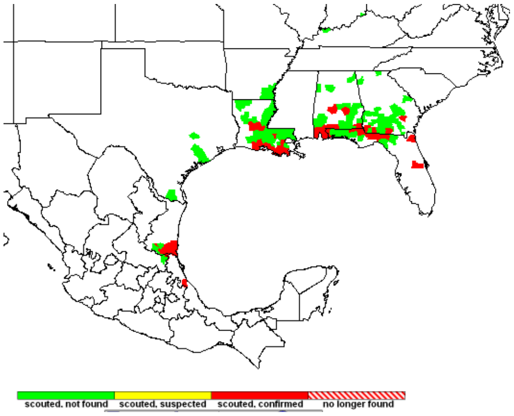

Figure 12: Spread of Soybean Rust through July 1, 2013

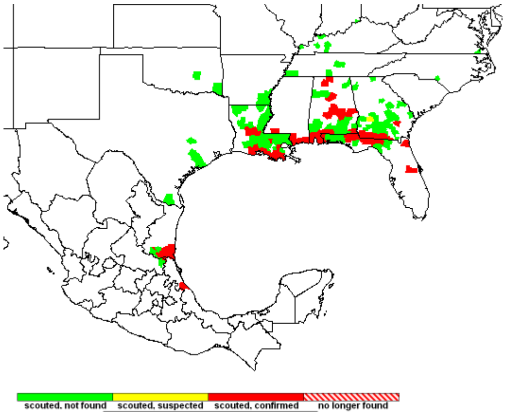

Figure 13: Spread of Soybean Rust through July 31, 2013

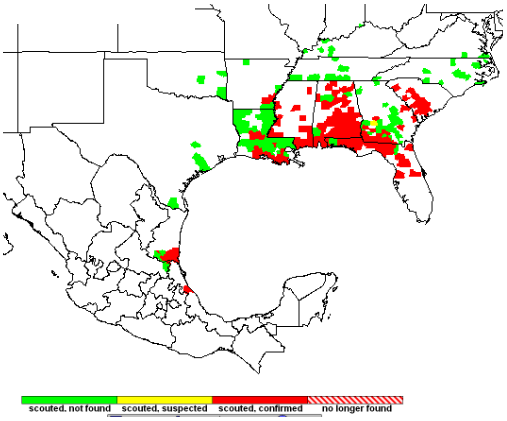

Figure 11: Spread of Soybean Rust through August 31, 2013

affected by the disease.

After a summer of seasonal to slightly below-average temperatures, the eastern half of the Southeast had a drier-than-average fall while the western half had wetter conditions than normal; temperatures in both areas hovered around average (NCDC 2013). Likely as a result of the excess soil moisture from the wet summer and lower-than-average temperatures, soybean rust spread very quickly in September, reaching 159 new counties and four new states (Tennessee, Kentucky, North Carolina, and Virginia). However, spread of soybean rust remained virtually nonexistent in Arkansas and north of the Ohio River, protecting the most important soybean-producing regions. Continuing wet conditions in the Mississippi River Valley allowed soybean rust to spread further, reaching a total of 94 new counties and one new state (Illinois). However, by this point, most soybean plants across the country were too mature to lose much yield to soybean rust infection. Our forecast period ended on November 2 with a total of 360 soybean rust reports in twelve states.

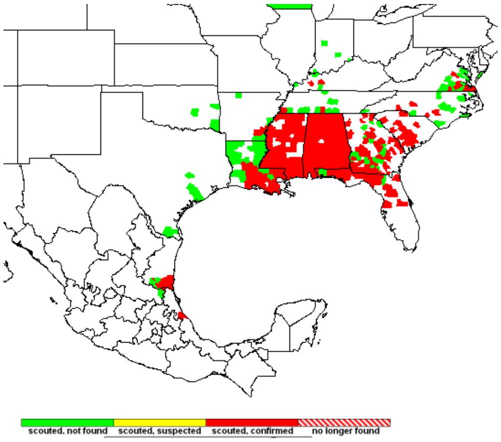

Figure 14: Spread of Soybean Rust through September 31, 2013

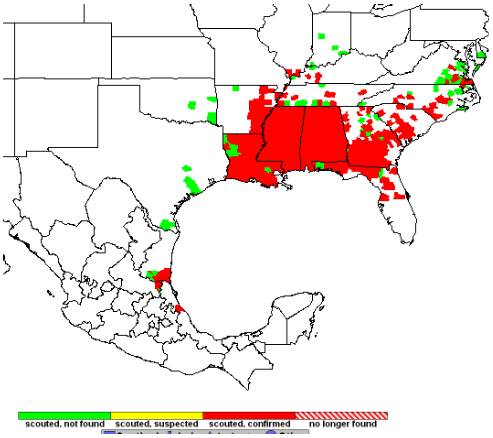

Figure 15: Spread of Soybean Rust through November 2, 2013

Chapter 5

Market Effects

5.1: Background on World Soybean Market

Roughly 287.7 million metric tons of soybeans are projected to be harvested during the 2013/14 growing season, representing about 57% of the world's total oilseed production (WASDE 2014). Soybeans and their oil have a number of uses, including food and biodiesel fuel, but roughly two-thirds of these soybeans are used in feed for livestock (WASDE 2014). As a result of its importance in world agriculture, soybeans are traded much like any commodity on the financial market.

The soybean market is dominated by four countries: the United States, Brazil, and Argentina on the production side and China on the demand side. About 78% (227 million metric tons) of the world's 287.7 million metric tons of soybeans have been harvested in the United States, Brazil, and Argentina this past growing season; meanwhile, due to its sharply increased consumption of meat and resultant need for feed, China alone consumes 23% of the world's soybeans (WASDE 2014). As a result of this unbalanced relationship, factors that increase or decrease supply of soybeans in North and South America and/or demand of soybeans in China lead to massive fluctuations in price. One of the most critical factors that affect the world's supply of soybeans is weather. Soybeans require certain conditions—mild and wet conditions during germination and growth, dry conditions at harvest—to maximize yield (NSRL 2014). The conditions best for soybean growth are also conducive to disease, however; soybean rust epidemics can have severe effects on soybean yield and the world's supply of soybean. Additionally, South American transportation infrastructure and labor strikes can have strong effects on soybean prices. Workers in South American ports recognize their importance in the world soybean market and occasionally use this influence by striking to increase their pay (Thompson 2013). This problem can be exacerbated by the poor port structure in South America, particularly Brazil, which can result in soybean-carrying trucks waiting for weeks in lines up to ninety miles long. Forced to wait extra days to receive soybean shipments, China uses this delay as an excuse to cancel contracts with Brazilian and Argentinian governments in exchange for more favorable deals (Thompson 2014). Even if no supply concerns exist, the actions of the Chinese can result in fluctuations of soybean price. As recently as March 2014, China occasionally finds themselves with a surplus of soybeans and will cancel contracts, citing port delays, a mix with genetically-modified plants, or other reasons (McFerron 2014). These cancellations cause the price of soybeans to decrease as a result of increased supply and decreased demand in the short-term.

5.2: Analysis of Soybean Rust Risk

With 227 million metric tons, or 8.34 billion bushels, of soybeans located in areas vulnerable to the disease, soybean rust represents a massive risk to the world's soybean market. Using a price of $13 per bushel—the price at the beginning of 2014—$108 billion worth of soybeans is in a high-risk area for soybean rust. As a result, reductions in yield due to soybean rust can have devastating effects on the world soybean market. Although it is unlikely that both North and South American crops would sustain catastrophic losses in yield, hundreds of millions to billions of dollars have been lost due to past epidemics in Brazil and Paraguay (Yorinori et al. 2005), and the United States has been fortunate to avoid a major hurricane, which would likely cause substantial losses in yield due to both crop destruction and spread of soybean rust, over the past eight years. Additionally, if fungicide-resistant strains of *P. pachyrhizi* were to develop, previous risk analyses have suggested that 10% of yield could be lost in any U.S. growing region and as much as 50% could be lost in the Southeast (Isard 2014). Previous estimates have stated that such an epidemic would result in losses of $7 billion in the U.S. economy (Isard 2014). Given the increased reliance on soybeans today—world production has increased 20% since just 2011/12 (WASDE 2014)—world economies would likely suffer even more from a soybean rust epidemic.

5.3: Effects of Past Epidemics on Market

The most severe soybean rust epidemics seen in the Americas came after the disease's introduction in South America in 2001. During the 2001/02 growing season, soybean rust was found on all Paraguayan soybean plants and 60% of Brazilian plants, resulting in 30-75% of yield losses in the important southern states and 0.5 million metric tons—valued at US$125.5 million (Yorinori et al. 2005). This epidemic would only get worse in 2002/03, when soybean rust caused losses of 3.4 million metric tons—valued at US$759 million—in Brazil (Yorinori et al. 2005). As seen in Figure 16, the combination of these two epidemics contributed to an over 50% increase in the price of soybeans (from $4 to over $6). As fungicides began to be developed for the disease, another epidemic during the 2003/04 growing season led to both severe decreases in South American soybean supply and increased concerns over the possibility of the disease spreading to North America (Good 2004; Koenning et al. 2014); this resulted in a sharp spike in soybean prices ($5.50 to $10.50) that can be seen in Figure 17.

Figure 16: Price of Soybeans from January 2001 to August 2003

Figure 17: Price of Soybeans from January 2002 to January 2006

Despite the introduction of soybean rust to North America in 2004, soybean prices did not rise too sharply, reflected by a two dollar price range in contrast to the previous year's five dollar range. As soybean rust spread up the Mississippi and Ohio Rivers in 2006 as shown in

Figure 18, soybean prices began to steadily rise; the acceleration of this increasing trend also coincides with the spread of soybean rust into the Great Plains and Upper Midwest 2007, where most soybean production occurs. Incidence of soybean rust continued to increase in 2008 and 2009, which is not reflected by the soybean prices present in Figure 19; the likely cause of this dissimilarity is the lack of soybean rust in the Great Plains and Upper Midwest. Quickly increasing prices late in 2010 and early in 2011 did not coincide with widespread soybean rust on either continent, and a drop in soybean prices late in 2011 can likely be attributed to the scarcity of soybean rust in the United States. The 2011/12 South American growing season, however, saw the fiercest outbreak of soybean rust in Brazil since 2003/04. The yield losses and fungicide cost due to this epidemic contributed to another sharp price spike in mid-2012, when soybeans reached their highest price ($17.90 in July) in the past 25 years.

Figure 18: Price of Soybeans from January 2005 to January 2009

Figure 19: Price of Soybeans from January 2007 to January 2013

5.4: Analysis of Effects on 2013 Soybean Market

The 2013 U.S growing season featured reports of soybean rust in 360 counties across twelve states by November 2, the end of our forecast period; following this date, 48 more counties reported signs of soybean rust, but soybean crops were too mature to lose much yield due to rust. Despite this relatively large area covered by soybean rust, soybean prices failed to increase drastically; instead, they actually decreased from $16.10 in July to $12.72 in November.

Several rust-related explanations exist for such a bearish market. July prices may have been fueled by predictions of an active hurricane season, represented by NOAA’s prediction of 7-11 hurricanes and 3-6 major hurricanes (NOAA 2013a); an active hurricane and, by extension, soybean rust season, combined with ever-present demand of soybeans by China, would have led to a disparity between supply and demand. The price of soybeans dropped by about 20% in late-

July and early-August, but once again began to rise throughout August; the beginning of this rise coincides with the August 8, 2013 release of NOAA's revised hurricane season forecast, which still predicted an above-average season of 6-9 hurricanes and 3-5 major hurricanes (NOAA 2013b). Prices rose from $13.30 on August 8 to $14.96 on September 5, during which time three tropical storms formed. However, by September 10, the usual peak of hurricane season, still no hurricanes had formed—Tropical Storm Humberto did become a weak hurricane one day later. After September 12, the price of soybeans fell for the rest of September and remained fairly steady in October at $12.65. The 2013 Atlantic hurricane season ended up being one of the weakest on record in terms of accumulated cyclone energy and posed little threat to soybeans in the United States.

Another explanation for the drop in soybean prices is the confinement of soybean rust to the Southeast, particularly when soybean plants are at their vulnerable flowering stage. By September 28, by which point many soybean plants were too mature to be affected by soybean rust, the disease was still confined to the Gulf States and a few counties in Virginia and the Carolinas. It was only after the first week of October—when most, if not all, soybean plants across the country were well past the stage of vulnerability to rust—that the disease spread into Arkansas, which harvests 3.2 million acres of soybeans (Hightower 2013). Since soybean rust failed to come close to affecting soybean harvests in the Upper Midwest and Great Plains, supply was bolstered by record soybean production in the United States (WASDE 2014), and the market remained relatively bearish.

A combination of these two hypotheses likely best explains the bearish market. A weak hurricane season helped keep *P. pachyrhizi* spores confined to the Gulf States for the majority of the growing season. This, combined with favorable weather for growing soybeans in soybean-rich areas far from the Southeast, led to very good plant yield and record U.S. production. With increased supply and no offsetting increased demand, soybean prices went down.

Chapter 6

Short-Term and Long-Term Prevention

6.1: Short-Term Methods of Prevention

Currently, there are no varieties of the soybean plant that are resistant or immune to *Phakopsora pachyrhizi*; as a result, fungicides are by far the most effective method of combatting the spread of soybean rust today (Main and Keever 2007). Application of fungicides are recommended in the United States if soybean rust has been reported upwind of a field of soybean plants in the R1 to R5 growth stages and conditions are conducive to spread; in South America, similar recommendations are made even in the V2 and V3 stages due to increased vulnerability (Rupe and Sconyers 2008). If conditions remain favorable—i.e. temperatures remain mild and precipitation frequently occurs--for development of soybean rust for the next 10-21 days, it is recommended that a second preventative spray of fungicides be made (Main and Keever 2007). When the plant is in the R6 growth stage, yield is not likely to be affected by soybean rust, and fungicides are no longer economical (Rupe and Sconyers 2008).

Since soybean rust cannot be discovered without careful scouting and is difficult to control once established, timing of fungicide application is crucial. As a result of this, many farmers rely on sentinel plots to give them an early warning of when soybean rust is in the area. These small sentinel plots, established in state-by-state networks by state governments and universities, consist of soybean plants or kudzu vines that are planted a few weeks before commercial soybean crops; as a result, these plants flower weeks before the commercial crop (Purdue 2005; Rupe and Sconyers 2008). If soybean rust is present in the area, it will begin affecting these unprotected sentinel plots after they flower. By the time commercial soybean plants are ready to flower and become vulnerable to soybean rust, the disease will be visible in the sentinel plots, and farmers can confidently decide whether or not to spray preventative fungicides (Purdue 2005).

The fungicides used to protect soybean plants against rust can be categorized two different ways. One way to classify these fungicides is by their function: preventative or curative (Main and Keever 2007). Preventative fungicides—as their name suggests—are effective in protecting a plant from infection by *P. pachyrhizi* spores. Curative fungicides, in addition to having preventative properties, can eradicate some existing infection in a field exposed to soybean rust. In addition to the function classes, fungicides are more commonly divided into three groups, each named by its dominant chemical compound: nitrile, strobilurin, and triazole (Main and Keever 2007). Nitrile and strobilurin fungicides are preventative in nature while triazole fungicides are both curative and preventative. Additionally, a mix of strobilurin and triazole fungicides is sometimes implemented for maximum effectiveness, as seen in Figure 20. Strobilurin and triazole fungicides are more commonly used than nitrile fungicides, which must be applied more frequently to be effective (Rupe and Sconyers 2008). Furthermore, although triazole fungicides have curative properties not present in the strobilurin fungicides, overuse of triazole fungicides may result in resistant strains of *P. pachyrhizi* spores developing (Main and Keever 2007). For that reason, farmers generally account for soybean rust present in early stages in the area by applying

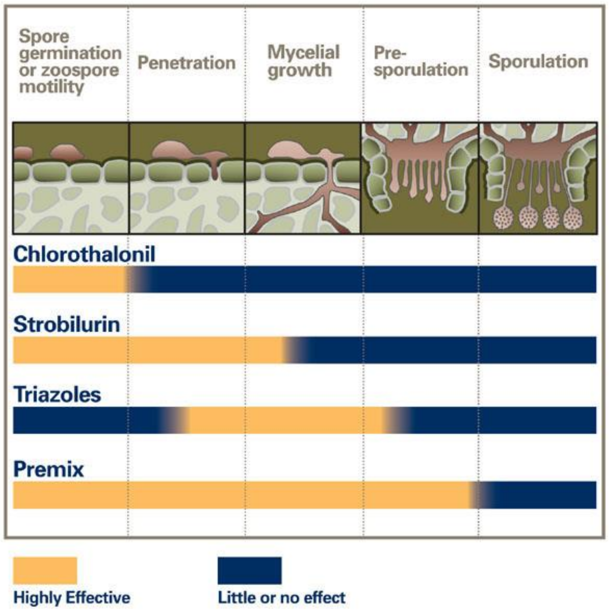

Figure 20: Effectiveness of Different Fungicide Classes

triazole fungicides, followed by a strobilurin spray and, if necessary, a nitrile spray (Main and Keever 2007). Of these three sprays, several individual brands exist, as seen in Table 1.

Table 1: List of Common Fungicides

Brand Name	Common Name	Fungicide Class	Function	Oz required/acre
Various	Chorothalonil	Nitrile	Preventative	24.0-38.4
Quadris	Azoxystrobin	Strobilurin	Preventative	6.2-15.4
Headline	Pyraclostrobin	Strobilurin	Preventative	6.0-12.0
Tilt, PropiMax, Bumper	Propiconazole	Triazole	Curative + Preventative	4.0-8.0
Folicur	Tebuconazole	Triazole	Curative + Preventative	3.0-4.0
Laredo	Myclobutanil	Triazole	Curative + Preventative	4.0-8.0
Domark	Tetraconazole	Triazole	Curative + Preventative	4.0-6.0
Stratego	Propiconazole + Trifloxystrobin	Triazole + Strobilurin	Curative + Preventative	10.0
Quilt	Propiconazole + Azoxystrobin	Triazole + Strobilurin	Curative + Preventative	14.0-20.0
Headline SBR	Pyraclostrobin + Tebuconazole	Triazole + Strobilurin	Curative + Preventative	7.8

6.2: Long-Term Methods of Prevention

Although fungicides have proven to be a very effective way of preventing soybean rust epidemics in the United States, they are not without two main problems. First, fungicides require very precise applications; if a strip of the crop is missed by sprays and goes untreated in an environment where urediniospores are present, that area is left completely vulnerable to the disease and will likely be lost, as seen in Figure 21. The larger issue that makes fungicides only a short-term solution is their cost. Fungicide spray costs can range from $10-35 per acre per application (Dorrance et al. 2008). 76.5 million acres of soybeans are set to be planted in the 2014 U.S. growing season, roughly 15% (11.475 million acres) of which will be planted in the

Figure 21: Strip of Soybean Crop Not Sprayed With Fungicide

rust-heavy Southeast (WASDE 2014; Ash 2012); consequently, each fungicide spray of this area would cost $114.75-401.63 million. It is unlikely that this entire area will have to be sprayed with fungicides, but such costs are not out of the ordinary; after consecutive years of rust epidemics, Brazilian soybean producers spent an estimate $1 billion in fungicide application in their 2003/04 growing season (Dorrance et al. 2008). As a result of these huge expenses, scientists and farmers are currently developing and testing long-term methods of prevention.

Currently, farmers are making changes to the ways soybeans are planted and cultivated. Because soybean rust spread north from the Gulf Coast takes time to develop, some farmers have begun planting soybeans earlier in the season (Smith 2008). By planting earlier in the seasons, farmers hope to mature their soybeans more quickly and help them reach the harvest stage before soybean rust can reach the area. On the opposite end of the spectrum, some farmers are delaying crop planting to account for climatically drier periods in the growing season (Rupe and Sconyers 2008); by allowing plants to reach their vulnerable flowering stage during dry weather unconducive to soybean rust spread, the crop can be protected while also lessening the need for fungicides. Lastly, modifying potassium and phosphorous levels in soil to increase plant resistance to the disease has been proposed; however, research on this method is still ongoing (Rupe and Sconyers 2008). While these methods may not be able to prevent soybean rust on their own, they can increase the soybean plant's resistance to the disease.

The North and South American soybean plant is extremely vulnerable to soybean rust because it has not had time to build up resistance to the Asian disease; scientists are trying to change this weakness by developing resistant strains of *Glycine max*. Since the disease's introduction to the United States, infected plants have produced tan lesions, red-brown lesions, or none at all (Rupe and Sconyers 2008). As described in Chapter 2, tan lesions are filled with many pustules and can result in the production of millions of spores while red-brown lesions are filled with comparatively few pustules and urediniospores. Scientists believe that this response is determined by four dominant genes, termed *Rpp1* (Resistance to *Phakopsora pachyrhizi* 1) to *Rpp4* (Rupe and Sconyers 2008). Although these genes are fairly easy to inject into soybean plants and their soil, they are not effective against all strains of *P. pachyrhizi*, and often following growing seasons see the development particularly harmful strains that attack this gene (Rupe and Sconyers 2008). However, research is currently being done by the USDA on these genes in the Southeast; the objective of this study—scheduled to end in June of 2014—is to identify resistant plants and their respective genes and transfer these genes to new soybean plants (ARS 2014). Another experimental method, known as moderate resistance, combines the identification of resistant genes with changes in cultural practices. This method, which has been developed in Asia, takes resistant genes and combines them to boost resistance against many strains of the disease (Rupe and Sconyers 2008). However, the use of moderate resistance often decreases yield and is tough to adapt to current soybean plants (Rupe and Sconyers). As a result, although it can be effective, this method is unlikely to be used as the primary method of long-term disease prevention.

Chapter 7

Conclusion

Although soybean rust has not had the devastating effect on North and South American soybean production as predicted in the early-2000s, it still poses an extremely important problem for world agriculture. The vast majority of the world's soybeans remain in high-risk areas for the disease, and significant yield loss due to infection would have severe effects on the world's agricultural economy while also straining supply of other crops, such as corn, that are used as animal feed.

Soybean rust relies on specific conditions to develop and spread to other fields, but North and South America both represent hospitable environments for the disease. Spores are able to overwinter in warmer areas of each continent, such as the American Gulf Coast, and the ability of the disease to survive the 2013 winter as far north as northern Alabama is concerning. However, soybean rust also has not been able to spread into important soybean-producing areas like the Upper Midwest and Great Plains since 2007, mitigating its negative effects on the United States' soybean crop. This lack of spread can be partially attributed to relative weak hurricane seasons in recent years, and a major hurricane carrying soybean rust striking the U.S. would still prove to be very costly for the country's supply of soybeans.

The 2013 U.S. growing season illustrated these trends very well. Soybean rust was able to overwinter in many places along the Gulf Coast and even inland areas. Spread was limited early in the growing season by relatively dry weather and even at the beginning of a very wet summer. This limited initial spread and lack of a land-falling hurricane helped shield the nation's soybean crop from the disease until they were mature enough to withstand it.

Soybean rust theoretically could have a large effect on the world soybean market, and examination of price trends generally confirms this. The introduction of soybean rust in South America and later North America combined with a quickly increasing demand has helped prices rise steadily over the past decade. Variations in price correlate well with past variations in the extent of soybean rusts, particularly in the record price seen in July 2012 after a severe South American epidemic. Additionally, week-to-week variations in price can be attributed at least partially to variations in forecasts and reports of soybean rust.

The confined spread of soybean rust in recent years can be attributed largely to the success of short-term solutions such as fungicides, which have proven to be very effective combatting *P. pachyrhizi* spores in both North and South America. However, the high cost of these fungicides makes this method of prevention economically imprudent as a long-term solution. Instead, changing cultural practices and research on genes resistant to soybean rust represent the future of disease prevent and should continue to be implemented.

Weather has a profound effect on soybean rust, soybeans, and agriculture as a whole. Forecasts of weather conducive to and unfavorable to soybean rust spread help provide both farmers and financial traders with reliable advice that can be used in each field. This continued integration of weather with finance, industry, and other sciences will ensure that the field of weather risk management will continue to grow.

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