A CONTINUING SAGA: SOYBEAN RUST IN THE CONTINENTAL UNITED STATES, 2004 TO 2013

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Keywords: soybean rust, SBR, *Phakopsora pachyrhizi*, soybean, kudzu

Distribution of soybean rust in the U.S. since 2004

Soybean rust (SBR), caused by the fungus *Phakopsora pachyrhizi* (Figure 1) is a significant disease of soybean (*Glycine max*) throughout the world. SBR was first described from Japan in 1902 (Hennings, 1903) and was later observed in several countries in Asia followed by Australia in 1934 (Bromfield, 1984). The disease was first reported in Africa in the mid-1990s and subsequently detected in South America in 2001. SBR was first detected in the United States in Hawaii in 1994 (Kilgore & Heu, 1994), but was not detected in the continental U.S. until 2004 in Louisiana (Schneider et al., 2005). Soybean rust is believed to have been carried to the continental U.S. on Hurricane Ivan (Isard et al., 2005; Isard et al., 2006). The initial detection of SBR set in motion a chain of events that continues to be one of the largest plant disease monitoring efforts to date.

Following the discovery of SBR in the continental U.S., a major collaborative effort to monitor the spread and distribution of the disease was initiated by the U.S. Department of Agriculture, Land-grant universities, agricultural industry personnel, and local, regional and national soybean check-off boards (a support group within each state as well as a national organization that is supported by small amounts of money collected from every bushel of soybean harvested). In 2005, strategically planted soybean monitoring plots, termed "sentinel plots", were established throughout the U.S. and Canada to serve as an early warning system for SBR. Information on the location of the disease was made available to the public via the SBR – Pest Information Platform for Extension and Education (SBR-PIPE) website. In addition, a password-protected restricted website on the SBR-PIPE platform, for uploading SBR observations by county or parish, provided predictive models regarding the spread and development of SBR based on the previously provided disease observations. The sentinel plot system, in conjunction with the SBR-PIPE, allowed farmers to make management decisions based on SBR's location and the potential risk to their crop. As a result of this monitoring effort SBR has been detected in a total of 20 states in the U.S. since 2004, as well as Canada and Mexico (Table 1).

In addition to SBR infecting soybean and several other lesser legumes, kudzu (*Pueraria montana* var. *lobata*) (Sikora, 2014c), serves as the primary overwintering host of the pathogen in the U.S. Kudzu, a perennial vine, has been observed in 26 states and in Ontario, Canada (Figure 2) and covers an estimated 2.9 million hectares within the U.S. The major concentration of kudzu occurs in the southern U.S. where some states (e.g., Alabama, Georgia and North Carolina) report every county infested with the invasive weed. Kudzu

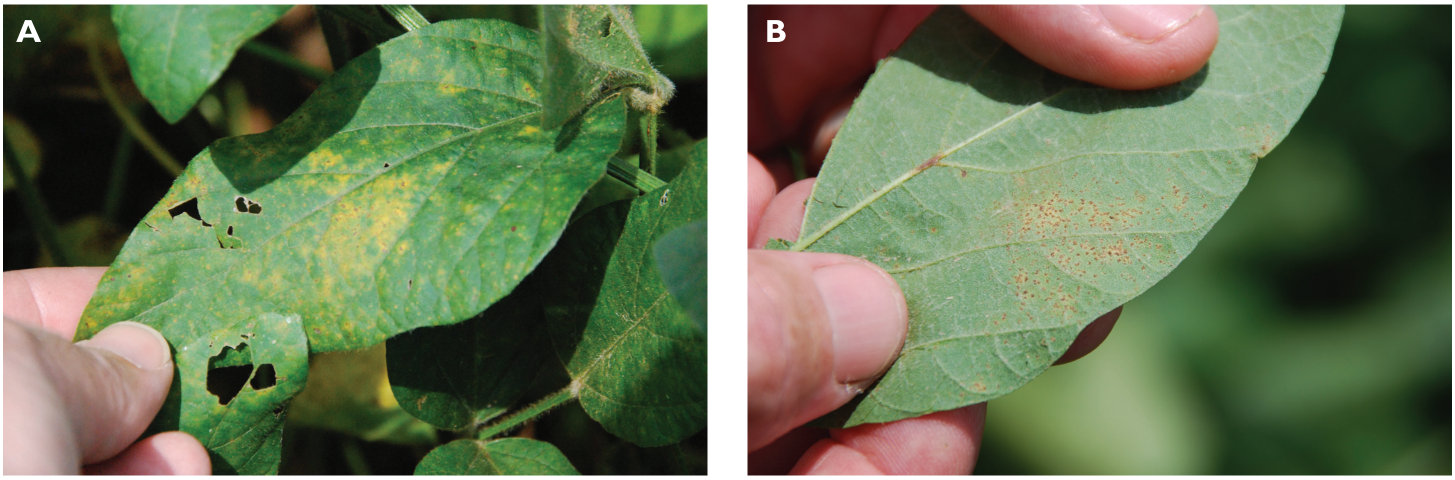

Figure 1. Symptoms of soybean rust on the upper leaf surface (A) as small brownish spots with general yellow chlorosis and (B) the pustules (uredinia) on the underside of the leaf that produce the reproductive structures (urediniospores) that allow for the long-distance dispersal of the fungus.

DOI: 10.1564/v25_apr_05

Table 1. Years when soybean rust positive plant material (kudzu, soybean or other plant) has been observed in a given state or province.

State/Country	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	% years positive [a]
Alabama	X	X	X	X	X	**X**[b]	X	[c]	X	X	90
Arkansas	X		X	X	X	**X**			X	X	70
Florida	X	X	X	X	**X**	X	X	X	X	X	100
Georgia	X	X	X	X	X	**X**	X	X	X	X	100
Illinois			X	X	X	**X**			X	X	60
Indiana			**X**	X		X					30
Iowa				**X**							10
Kansas				**X**		X					20
Kentucky		X	**X**	X	X	X			X	X	70
Louisiana	X	X	X	X	X	X	X	X	X	**X**	100
Maryland				**X**							10
Mississippi	X	X	X	X	X	**X**	X		X	X	90
Missouri	X		X	**X**	X	X					50
Nebraska				**X**							10
North Carolina		X	**X**	X	X	X	X		X	X	80
Oklahoma				**X**	X	X					30
South Carolina	X	X	X	X	X	X			**X**	X	80
Tennessee	X	X	X	X	X	**X**			X	X	80
Texas		X	X	**X**	X	X	X	X	X	X	90
Virginia		X	**X**	X	X	X	X	X	X	X	90
Ontario, Canada				**X**							10
Total positive states/provinces	8	11	15	21	15	17	8	5	13	13	

[a] Percent of years positive was calculated based on a state having found the disease from a given number of years divided by the total number of years (10) soybean rust has been observed in the continental United States.
[b] Bold cells account for the year when soybean rust was observed in the greatest frequency, based on number of counties or parishes, in the particular state or country.
[c] Blank cells account for a year when soybean rust was not observed in that state/country.

serves as the primary host for SBR during the winter months in states along the Gulf Coast including Alabama, Florida, Louisiana, Mississippi, and Texas. In addition, during some years, SBR overwinters on kudzu in southern Georgia in protected areas. Overwintering inoculum is typically greater in years that experience a mild winter (Jurick et al., 2008). Even though kudzu serves as a source of inoculum on an annual basis, the potential of some kudzu populations to be immune or resistant to the fungus is high (Bonde et al., 2009; Jordan et al., 2010). Kudzu has been observed in 989 counties/parishes in the U.S. and in one county in Ontario, Canada (Figure 2). However, even though kudzu has been identified in most of the states where soybean production occurs, not every state has reported observing SBR on kudzu (Table 2). Moreover, since not all kudzu can support an overwintering population of the SBR fungus, kudzu likely only serves as a source of inoculum to initiate disease epidemics on the local scale (Fabiszewski et al., 2010).

The environment has been one of the main constraints on spread and distribution of SBR in the U.S. Several papers have presented information on the dispersal of SBR within a single year or between several years (Christiano & Scherm, 2007; Herschman et al., 2011; Mundt et al., 2013; Sutrave et al., 2012). Based on this information it appears that in years with below average winter temperatures along the Gulf Coast, the ability for SBR to overwinter on kudzu is limited. This may result in reduced inoculum levels the following spring which may require the pathogen to build up for at least two years before it becomes a significant problem in southern soybean production systems. Additional environment-related factors such as monthly rainfall, air temperature, and severity and movement of weather systems also play a role in annual SBR development. Early season tropical storm systems emanating from the Caribbean Basin, where SBR readily overwinters (Estévez de Jensen et al., 2013; Sikora, 2011), also have an effect on disease spread and annual epidemic potential.

The development and spread of SBR is also moderated by environmental conditions during the growing season. The disease was observed from the greatest number of states in 2007 (refer to Tables 1 & 2; Figure 3). Environmental conditions encountered early in 2007 included above average rainfall throughout the south, especially Texas, which allowed the disease to initiate earlier than normal as well as occur in some states that had not previously observed the disease (e.g., Iowa, Kansas, Nebraska, Oklahoma). A previously unobserved trend of southerly winds during the growing season moved the disease north and east from the initial points of infection and overwintering sites. From 2007 until 2009, SBR overwintered on kudzu in south Florida and Louisiana. Incidence and spread of SBR increased during the 2008 growing season, and following several winters with above average temperatures, reports of SBR increased dramatically in 2009 (Figure

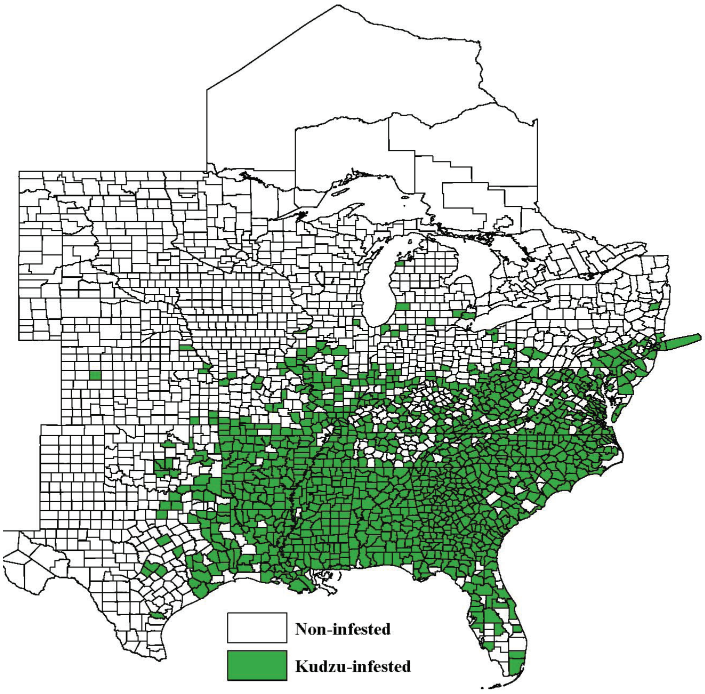

Figure 2. Map of counties and parishes in soybean producing states in the U.S. and Canada that contain kudzu, an additional host for the soybean rust fungus. Portions of the information obtained for this map were derived from the USDA Plants Database on kudzu, the Early Detection & Distribution Mapping System (EDDMapS, 2014), various herbaria resources from each major state, personal observations, and soybean rust observations from 2005–2013 accessed on the SBR-PIPE website.

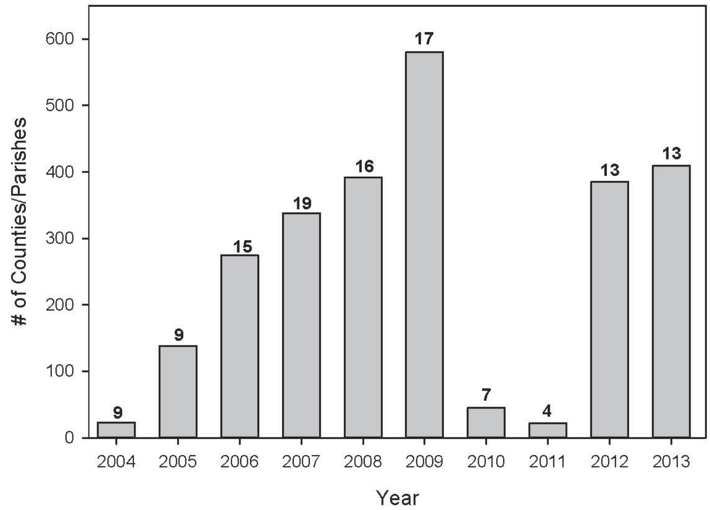

Figure 3. Overall number of soybean rust infected counties and parishes from each year. Numbers presented above bars in bold indicate the number of states that reported soybean rust for each given year.

3) with 580 counties/parishes reporting the disease. However, the overall number of reports decreased in 2010 following a much colder winter. Kudzu was killed back further south limiting the number of overwintering sites for the pathogen and the overall number of SBR reports decreased by 92% the following growing season. A relatively cold winter in 2011 also appeared to help reduce the incidence of the disease during the 2011 season. However, reports of SBR increased during the 2012 (94% increase between 2011 and 2012)

Table 2. Total number of kudzu counties/parishes within each state/country and observations of soybean rust on kudzu from each state where soybean rust has been reported since 2004.

State/Province (# of kudzu counties/parishes)	Year of soybean rust report [a,b]									
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Alabama (67)	0	15	18	26	15	26	3	---	39	41
Arkansas (73)	0	---	0	1	30	30	0	---	2	0
Florida (43)	1	13	19	23	26	24	13	15	6	20
Georgia (159)	0	8	10	43	62	75	5	2	66	82
Illinois (46)	---	---	0	0	0	0	0	---	0	0
Indiana (30)	---	---	---	---	---	---	---	---	0	---
Iowa (0)	---	---	---	---	---	---	---	---	---	---
Kansas (6)	---	---	---	---	---	---	--	---	---	---
Kentucky (57)	---	1	2	0	0	0	0	---	0	0
Louisiana (53)	0	1	6	17	9	29	4	0	26	29
Maryland (9)	---	---	---	---	0	---	---	---	---	---
Mississippi (81)	0	1	2	7	4	8	4	---	7	10
Missouri (35)	0	0	0	1	0	0	0	0	---	---
Nebraska (1)	---	---	---	---	---	---	---	---	---	---
North Carolina (100)	---	0	2	0	0	0	0	0	0	0
Oklahoma (15)	---	---	---	7	0	0	---	---	---	---
South Carolina (35)	0	1	0	0	2	0	0	0	0	0
Tennessee (59)	0	---	0	0	0	0	0	0	1	0
Texas (41)	---	1	4	2	2	2	0	0	0	3
Virginia (77)	---	---	0	0	0	0	0	0	0	0
Ontario (1)	---	---	---	0	---	---	---	---	---	---
TOTAL = 989	1	41	63	127	150	194	29	17	147	185

[a] "---" indicates a year when soybean rust was not reported from that state/country.
[b] "0" indicates a year when soybean rust was reported from the state/country, but soybean rust was not reported from kudzu.

Table 3. Most commonly used fungicides labeled for the management of soybean rust in the continental United States.

Fungicides			
Class	**Active ingredient (%)**	**Trade name**	**Rate/A (fl oz)**
QoI Strobilurins	azoxystrobin (22.9%)	Quadris 2.08 SC	6.0-15.5
Group 11	fluoxastrobin (40.3%)	Aftershock 480 SC	2.0-5.7
		Evito 480 SC	
	picoxystrobin (22.9%)	Approach 2.08 SC	6.0-12.0
	pyraclostrobin (23.6%)	Headline 2.09 EC/SC	6.0-12.0
DMI Triazoles	cyproconazole (8.9%)	Alto 100SL	2.75-5.5
Group 3	flutriafol (11.8%)	Topguard 1.04 SC	7.0-14.0
	propiconazole (41.8%)	Tilt 3.6 EC	2.0-4.0
		multiple generics	
	prothioconazole (41.0%)	Proline 480 SC	2.5-4.3
	tetraconazole (20.5%)	Domark 230 ME	4.0-5.0
MBC Thiophanates Group 1	thiophanate-methyl	Topsin-M	10.0-20.0
		multiple generics	
Mixed modes of action	azoxystrobin (18.2%)	Quadris Top 2.72 SC	8.0-14.0
	difenoconazole (11.4%)		
Group 3 + 11	azoxystrobin (7.0%)	Avaris 1.66 SC	14.0-20.5
and	propiconazole (11.7%)	Quilt 1.66 SC	
Group 7 + 11		HM-0812 1.66 SC	
	azoxystrobin (13.5%)	Quilt Xcel 2.2 SE	10.5-21.0
	propiconazole (11.7%)		
	fluoxastrobin (18.0%)	Evito T 3.99	4.0-6.0
	tebuconazole (25.0%)		
	picoxystrobin (17.94%)	Approach Prima 2.34 SC	5.0-6.8
	cyproconazole (7.17%)		
	pyraclostrobin (28.58%)	Priaxor 4.17 SC	4.0-8.0
	fluxapyroxad (14.33%)		
	trifloxystrobin (11.4%)	Stratego 250 EC	10.0
	propiconazole (11.4%)		
	trifloxystrobin (32.3%)	Stratego YLD 4.18 SC	4.0-4.65
	prothioconazole (10.8%)		

and 2013 (6% increase between 2012 and 2013) production seasons following mild winters in the south that allowed the pathogen to survive more readily on kudzu in Alabama, Florida, and Louisiana. Subsequently, significant economic damage in commercial soybean fields was reported in 2012 and 2013 from at least one state.

SBR management and yield loss in the South

The vast majority of the commercially available soybean varieties in the U.S. are susceptible to SBR. However, at least one new variety will be commercially available in 2014 per Asgrow (a Monsanto Company) company literature. Monitoring soybean fields for SBR is a suggested practice throughout the growing season; however, farmers should also follow the real-time information presented on the public SBR-PIPE (Hershman, 2011). Early detection of SBR and properly timed fungicide applications are the best method available to avoid yield loss. In addition, fungicides can reduce damage from other foliar diseases such as aerial blight (*Rhizoctonia solani*), anthracnose (*Colletotrichum truncatum*), Cercospora blight (*Cercospora kikuchii*), frogeye leaf spot (*Cercopsora sojina*), and pod and stem blight (*Diaporthe phaseolorum* var. *sojae*). Currently a number of foliar fungicides that include different active ingredients as well as modes-of-action are available for general soybean disease management and more specifically for SBR management in the U.S. (Wise, 2013) (Table 3). Factors such as recent environmental conditions, proximity to sources of SBR inoculum, cost of available products, soybean growth stage at time of disease observation, and an estimate of the crop's yield potential should be considered when determining a fungicide program (Sikora et al., 2009).

Data suggest that fungicide applications prior to bloom (R1 growth stage) are not economical for SBR management (Miles et al., 2003a, b). In general, farmers should consider an initial fungicide application when the crop is between bloom and full seed (R6) when SBR has been detected in the immediate area and environmental conditions favor development and spread of the disease. If farmers wait for the disease to appear in their fields before applying a fungicide, there is an increased likelihood that the fungicide program will not be as effective and a yield loss will result. In some cases, a second fungicide application 2 to 4 weeks after the first application may be necessary depending on the growth stage of the crop and presence of SBR. Research has determined that a two-fungicide sequential spray program to manage SBR may be

Figure 4. Aerial image of a soybean field infected with soybean rust during the 2009 season in Noxubee County located in eastern Mississippi. The large, brown areas consisted of soybean plants that were defoliated as a result of the disease.

needed and profitable in some years (Sikora et al., 2009). Applying a fungicide after R6 is not suggested due to lack of a yield response, plus limitations due to pre-harvest intervals by the fungicide manufacturer.

Yield losses between 60 and 100% have previously been reported from Paraguay, Brazil and South Africa during the early 2000s (Caldwell & McLaren, 2003; Yorinori et al., 2005). However, losses attributed to SBR in the U.S. have typically not been as great as those reported from other countries. In fungicide efficacy trials comparing sprayed and unsprayed plots, yield losses from SBR as great as 19% from Texas (Isakeit & Scott, 2008), 29% from Louisiana (Schneider et al., 2007), 35% from Georgia (Mueller et al., 2006), and 43% from Alabama (Sikora et al., 2009) have previously been reported. The greatest yield reduction was recorded from an experimental trial in Florida in 2008 when a 65% loss was observed (Douglas et al., 2009).

Yield loss has been observed in commercial soybean fields in Alabama, Florida, Georgia, and Louisiana, and to a lesser extent in Mississippi and Texas (unpublished data). However, determining a number associated with the yield loss in commercial settings is difficult. Yield loss estimates of 25% were reported from commercial fields in Mississippi in 2009 (Figure 4). In this case one field received a well-timed fungicide application between beginning pod (R3) and full pod (R4) whereas a neighboring field went untreated (Figure 4). Even though the fungicide treated field had soybean rust present in the lower plant canopy the fungicide prevented defoliation in the upper plant canopy and protected yield. Plants in the untreated field defoliated and became susceptible to additional plant diseases such as charcoal root rot (Macrophomina phaseolina) that was extensively observed in the field at the time of the photograph (approximately R6).

Excessive yield losses as a result of SBR were documented from commercial fields from Alabama in 2012. SBR was estimated to have reduced yield by up to 60% in over 200 hectares of poorly managed soybeans (Sikora et al., 2013). Fields with the greatest yield loss either received a fungicide application too late or did not receive a fungicide. These losses are the greatest reported from commercial fields in the U.S. as a result of SBR, and are equivalent to losses observed in South America (Morel & Yorinori, 2002; Yorinori et al., 2005). Farmers that lost yield claimed they did not apply a fungicide because the disease was not problematic during the two previous years; years that were dominated by prolonged drought conditions, often considered to be unfavorable for SBR development. The farmers also did not react to warnings provided early in the production season regarding the high probability of SBR activity in the area, or suggestions to apply fungicides in a preventive program to avoid yield loss. Estimated economic losses were upwards of $135,000 to farmers who failed to apply a fungicide (ACES, 2013).

Losses from SBR in commercial fields were also observed in Alabama during 2013 (Sikora et al., 2014a). Yield losses up to 40% were estimated in some unprotected or poorly protected soybean fields based on a fungicide application. Greater losses appear to have been avoided by properly timed fungicide applications along with a late summer drought that slowed the progress of the pathogen.

SBR monitoring efforts and continued funding potential

When the sentinel plot network was implemented in 2005, the concept of intense scouting for an important plant disease was not new, but the concentrated monitoring effort that followed could not be maintained. Efforts had previously been outlined in other parts of the world to develop a simplified, accurate process of determining the presence of SBR at the earliest possible soybean plant growth stages. The process used in Brazil (sentinel plots) was implemented in the U.S. during the 2005 growing season. The sentinel plot system involved the early planting of one or more soybean maturity groups in an area no less than 15.2 × 15.2 meters, approximately three weeks prior to commercial soybean plantings in the area. The number of sentinel plots within a state varied for a variety of reasons such as overall number of hectares planted to soybean, geographic location within the U.S. and personnel availability for scouting. Sentinel plots were scouted and leaf samples were collected weekly for microscopic examination for SBR. In addition to monitoring sentinel plots, mobile scouting of commercial soybean fields as well as kudzu was also conducted.

In the initial phases of the monitoring program it was realized that such a system would be travel- and labor-intensive as well as expensive. The initial funding for the monitoring system, conducted in 35 states, and the SBR-PIPE platform development came from the USDA – Animal Plant Health Inspection Service (USDA-APHIS). After two years, APHIS decided to cease funding due to their specific mission of dealing with relatively new invasive pests. In response to the loss of funds, the USDA's Risk Management Agency (RMA) continued funding the program for two additional years, but added the requirement that the participating states provide a series of training sessions regarding SBR and its impact on the industry. The main role of the USDA-RMA was to respond to damage from SBR from an insurance standpoint. After SBR failed to develop into a nationwide epidemic, RMA ceased funding at the end of 2008.

Beginning in 2009, the North Central Soybean Research Program began funding the monitoring effort for all states who participated in the sentinel plot system. Most of the funding was directed to Gulf Coast states because of the high probability of observing SBR. Additional states on the edges of the Gulf Coast states (Arkansas, Georgia, Oklahoma, and South Carolina) were added to increase the chances of early warning. In 2011, a decreased level of funding was obtained from the United Soybean Board (USB) only to support states in the southern U.S. Additional funds for monitoring were secured from Qualified State Support Boards (check-off boards); this included states in the Midwest that continued to monitor for the disease on a limited basis. At present, funding for six states (Alabama, Florida, Georgia, Louisiana, Mississippi, and Texas) comes exclusively from the USB. The board has been generous with the participating states, but the funding level has dropped from $2.3 million in 2005 for SBR monitoring and development of the SBR-PIPE internet platform to less than $200,000 for 2014 to monitor for SBR, a 91% decrease in funding since 2005. Additionally, participating states have expanded the scope of scouting to include diseases in addition to SBR. Adding additional diseases, as well as important topics such as scouting for fungicide-resistant pathogens such as those responsible for aerial web blight, Cercospora blight, and frogeye leaf spot aided in funding approval. At present, funds are no longer available for the SBR-PIPE internet platform development, maintenance, or predictive modeling.

Reduced funding has resulted due to the lack of an epidemic of SBR affecting the Midwest soybean crop. Although the Midwest has been spared, the southern soybean crop, representing approximately 5% of the U.S.'s total soybean hectares, has been affected annually with the level of disease dependent on environment both during the winter and the current crop year. Even though substantial reductions in funding have occurred since 2005 the level of scouting conducted in the southern U.S. appears sufficient on an annual basis to protect the U.S. soybean crop. However, an associated 69% reduction in the personnel who scout for SBR occurred between 2004 and 2012 as a result of the decrease in funding (Sikora et al., 2014b). In addition, since many states have not observed a yield reduction as a result of SBR, the disease continues to pose a risk for soybean farmers, particularly in the southern U.S.

Future of the monitoring effort

The SBR-PIPE system is an on-line, limited-access database for following and cataloging information on SBR distribution and development in North America as well as modeling disease spread and development over time. Currently, there is a proposal to shift the data storage, presentation, and predictive disease model development from the SBR-PIPE to a new platform defined as the Integrated Pest Information Platform for Extension and Education (iPiPE) (Isard et al., 2013). Industry has been encouraged to support/fund the new iPiPE platform. In the iPiPE format, some information will be derived from unbiased sources through university cooperators, but access to data on the restricted website will be sold to additional third-party cooperators. In addition, third-party cooperators in the form of members of the agricultural service community will have the ability to upload observations on a limited number of plant diseases, defined by each state's Extension coordinator, using a mobile form of the software platform for use on smartphones and additional mobile devices. Funding from additional sources may cover the cost of the iPiPE platform, but it will not fund the Land-grant university-based programs to monitor for SBR and additional yield-limiting diseases of soybean or provide those data to the soybean community to aid in disease management decisions.

A survey of consultants regarding their use of the SBR-PIPE suggested the continued importance of the monitoring network as well as the unbiased internet platform for reporting disease distribution to the soybean community (Bradley et al., 2010). Unfortunately, the infrastructure of the sentinel plot data collection system viewed so favorably over the years is now on the verge of being lost due to severe funding cuts. Even though the emphasis of the system has shifted from focusing on SBR to scouting for all soybean diseases as well as providing information regarding the presence of fungicide-resistant organisms, this might not be enough to maintain the continued future of the program or the previously unbiased data collection. If the infrastructure of the sentinel plot system is lost, an additional loss of unbiased information from Land-grant institutions across North America will likely follow. Losing university-based support of the program will greatly impact the reliability of the information provided to the public regarding SBR and other economically important diseases of soybean. Maintaining the monitoring network will require a continued source of funding to support the scouting efforts as well as maintaining an unbiased computer database/platform that consultants and farmers can rely on for effective disease management suggestions.

Acknowledgments

The authors wish to acknowledge gratefully the countless individuals at the local, state, regional, and international level that contribute time to protecting soybean farmers from yield-limiting diseases such as soybean rust. More specifically, the authors are greatly indebted to the agencies responsible for providing funds to allow us to continue to protect soybean farmers throughout North America. The USDA-APHIS, USDA-RMA, North Central Soybean Research Program, United Soybean Board, the Grain Farmers of Ontario, and many local Qualified State Support Boards (state check-off funds) have graciously supported these tremendous efforts since 2005. The authors also wish to recognize the support of the Directors of the Experiment Station Section of Association of Public and Land-grant Universities and the USDA National Institute of Food and Agriculture for their continued support.

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