Epidemiology and Chemical Control of Soybean Rust in Southern Africa

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ABSTRACT

Levy, C. 2005. Epidemiology and chemical control of soybean rust in Southern Africa. Plant Dis. 89:669-674.

Phakopsora pachyrhizi was discovered on soybeans in Uganda in 1996. This was the initial confirmation of the pathogen on soybeans in Africa, although there had been earlier unsubstantiated listings on other legumes. Thereafter, it was wind-dispersed southward to Rwanda, Zimbabwe, and Zambia in February 1998, where it severely damaged commercial plantings. It also devastated small-scale fields in eastern Nigeria at about this time. Rust continued its southward movement to southern Mozambique in early 2000, and into eastern South Africa in March 2001. By early 2003, substantial losses were being reported from western Cameroon. Scientists in Zimbabwe and South Africa have coordinated their research to combat the pathogen and have developed a strategy based on the effective, economical use of fungicides and the development of resistant germ plasm. The chemical and spraying recommendations resulting from field studies are discussed in relation to their practicalities, and a preliminary analysis of the meteorological data recorded will show the fundamental factors that influence the development of an epidemic.

Phakopsora pachyrhizi Syd. & P. Syd. was first reported to affect soybeans in Japan in 1902 (9), and during the twentieth century, soybean rust spread throughout Southeast Asia, China, India, Sri Lanka, Indonesia, the Philippines, Papua New Guinea, Australia, and other Australasian islands, where it became endemic and caused infrequent but severe production losses (1,15,16).

Epidemiology in Africa

Central and West Africa. The arrival of *P. pachyrhizi* into Africa is unknown. Recent speculation is that its spores were blown from western India into the eastern coastal areas by the moist, northeast monsoon winds (13). It has been known to affect legumes other than soybean in several Central and West African countries since the 1960s (1); Sudan, Uganda, Tanzania, Zaire, Ghana, Sao Tome, and Sierra Leone are listed (4), presumably from specimens submitted to the Commonwealth Mycological Institute. Later, this pathogen was mentioned in Togo (11), in Nigeria on cowpea (*Vigna unguiculata* (L.) *dekintiana* (Harms) Verdc.) (1), in Zambia on soybeans (7) (a highly doubtful report), and unconfirmed presences in

Ethiopia (16) and Egypt (13). Bromfield (1) doubts whether this pathogen was the same form *specialis* as those found in Southeast Asia and in the Americas (*P. meibomia* (Arth.) Arth.), as it never infected soybeans growing in the affected areas.

In late 1996, rust (presumed to be *P. pachyrhizi*), however, caused severe, widespread damage to soybeans in field trials and on small-scale farms in Uganda, and to a lesser extent, in Kenya (8); these observations were confirmed by Dashiell, Int. Inst. Trop. Agric., Nigeria, who later visited the affected areas. Rust was confirmed on soybeans in Rwanda in late 1998, and by this time, it had become a limiting factor to Ugandan small-scale production (P. Tukumuhabwa, *personal communication*). Communication with these researchers has since become erratic, and the current situation in West and East Africa is unclear. Recently in February 2003, soybean rust was reported as causing major problems to commercial soybean production in the western highlands of Cameroon (B. Nguimgo, *personal communication*); however, details of the losses and area affected were not available.

Zimbabwe. In late February 1998, a leaf spotting, which resembled the bacterial pustule disease, on several experimental soybean lines at the Rattray Arnold Research Station (RARS), Enterprise, was diagnosed as rust, and it was confirmed to be caused by *P. pachyrhizi*. About a week later, numerous reports of soybean rust were received from the north-central and northwestern growing regions, with the

first outbreaks occurring in the northern parts. The disease very rapidly defoliated and killed plants. Fungicide sprays were generally ineffectual, being applied after significant damage had been done, and a widespread 40 to 80% yield loss resulted. By the end of the season (late March), rust was present in fields to the southwest of Harare, but this late infection had little impact.

The spread of rust in Zimbabwe in 1998 mirrored the southward movement of the Inter-tropical Convergence Zone (ITCZ) from East Africa during mid- to late-January. It was supposed that vast numbers of *P. pachyrhizi* spores were blown into the country by these rain-bearing winds at a time when the crop was at its most susceptible.

In 1999, rust was first reported in two small eastern border areas in late January. Thereafter, the pathogen moved slowly westward to affect the main central Mashonaland growing region. The weather pattern differed from the previous season. The ITCZ entered the country in late November to early December 1998, in advance of the main rust sporulation in East Africa, and had remained static over Zimbabwe. Very hot, dry conditions were present in East Africa at that time, and consequently, relatively few spores were produced during the latter part of 1998. Only when a cyclone developed off the Kenyan coast in mid-January and moved down the Mozambique Channel, were the rust spores brought southward. Although the epidemic was far more widespread in Zimbabwe during that summer, major yield losses were contained by extensive spraying.

In subsequent seasons, soybean rust appeared to have become endemic within

Table 1. Fungicides and their rate of application for the control of *Phakopsora pachyrhizi*, as approved by the Zimbabwe Chemical Registration Authority

Chemical name	Application rate (g ha ⁻¹) (single spraying)
Carbendazim-flusilazole	87.5 + 43.75 or 125 + 62.5 ^a
Cyproconazole	30
Difenoconazole	75 or 125 ^a
Flutriafol	100
Tebuconazole	250
Triadimenol	125
Triforine	281

^a Lower rate is for ground application; higher rate is for aerial application.

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Accepted for publication 8 December 2004.

Zimbabwe, its appearance unrelated to any complementary movement of the ITCZ from Central Africa. Rust can now be found throughout all soybean growing regions of the country, but the incidence differs greatly, with the hotter, drier southern areas least affected.

Zambia and Mozambique. Zambia was the only other southern African country to record soybean rust in 1998; it affected soybean crops growing around Lusaka and in the Mkushi area late in the season (13). Thereafter, it became widespread, but the losses incurred were relative to whether spraying was done and when the sprays were applied. Little accurate commercial yield loss data are available, but field results suggested that the severity on untreated plants was similar to that in Zimbabwe (J. S. Tichagwa, *personal communication*).

Little is known of the impact of rust on the small-scale production in Mozambique, and it is very difficult to obtain any reliable information. Early infection of the Zimbabwean eastern and southeastern border crops in 1999 is logically linked to sources of spores being present within Mozambique. Rust was identified on plants in scattered farm plots in the southern Maputo Province just prior to the extensive flooding caused by Cyclone 'Eline' in February 2000 (M. A. Smit, *personal communication*).

South Africa. Soybean rust was first noticed near Vryheid, in northern KwaZulu-Natal Province, South Africa, on 1 March 2001, and 2 days later in the central growing area of the province (10; J. M. J. Ward, *personal communication*). Rust spores, produced by affected crops in southeastern Zimbabwe and southern Mozambique, are likely to have been blown southward by a

cyclonic depression, which moved down the Mozambique Channel about 2 weeks earlier. The disease was reported from several growing areas beyond these foci by the end of the season.

Most South African farmers reacted immediately, and sprayed their crops. Yield losses were minimized (15 to 17% in the northern areas; 7 to 10% in the central areas) due to the late arrival of the pathogen, its confined incidence, and the extensive spraying (14); however, Caldwell and Laing (2) report 10 to 80% estimates, with some complete losses where soybean monocropping was practiced. Disease severity has subsequently been low in the KwaZulu-Natal Province, probably due to hotter, drier weather prevailing and widespread spraying being done by the farmers (E. D. du Preez, *personal communication*).

Shortly after the arrival of soybean rust in southern Africa in 1998, several mul-

Fig. 1. Severity of soybean rust on soybean cv. LS666, either sprayed with one of six fungicides at three rates or left unsprayed at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa during 2001–02. log AUDPC: area under the disease progress curve (log-transformed) based on a 0 to 9 scale. CON: unsprayed; TEB: tebuconazole; DIF: difenoconazole; FLU: flusilazole; FLU+CARB: flusilazole-carbendazim mix; CARB+FLU: carbendazim-flusilazole mix; TRI: triadimenol; M-45: mancozeb. 50, 100, and 200%: rate of fungicide applied relative to that approved for commercial use by the South African Chemical Registration Authority.

Fig. 2. Yields ($t\ ha^{-1}$ at 12.5% moisture) of soybean cv. LS666, either sprayed with one of six fungicides at three rates or left unsprayed at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa during 2001–02. CON: unsprayed; TEB: tebuconazole; DIF: difenoconazole; FLU: flusilazole; FLU+CARB: flusilazole-carbendazim mix; CARB+FLU: carbendazim-flusilazole mix; TRI: triadimenol; M-45: mancozeb. 50, 100, and 200%: rate of fungicide applied relative to that approved for commercial use by the South African Chemical Registration Authority.

Fig. 3. Severity of soybean rust on soybean cv. LS666, either sprayed with one of five fungicides at three rates or left unsprayed at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa during 2001–02. log AUDPC: area under the disease progress curve (log-transformed) based on a 0 to 9 scale. CON: unsprayed; AZO: azoxystrobin; TRI: triforine; FLUT: flutriafof; FLUS+CARB: flusilazole-carbendazim mix; STRO+TRIA: experimental strobilurin-triazole mix. 50, 100, and 200%: rate of fungicide applied relative to that approved for commercial use by the South African Chemical Registration Authority.

Fig. 4. Yields ($t\ ha^{-1}$ at 12.5% moisture) of soybean cv. LS666, either sprayed with one of five fungicides at three rates or left unsprayed at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa during 2001–02. CON: unsprayed; AZO: azoxystrobin; TRI: triforine; FLUT: flutriafof; FLUS+CARB: flusilazole-carbendazim mix; STRO+TRIA: experimental strobilurin-triazole mix. 50, 100, and 200%: rate of fungicide applied relative to that approved for commercial use by the South African Chemical Registration Authority.

tisectoral meetings were held in Zimbabwe and South Africa to share knowledge on soybean rust and to develop national control strategies. Farmer education on disease recognition, symptom development, and the need for control was viewed as a priority. An integrated approach for control was developed that combined public awareness, monitoring, possible disease avoidance, the appropriate use of fungicides, and breeding for resistance. Success in this program has resulted from the cooperation developed among scientists, industry, farmers, and agricultural extension workers, in the coordination of research and other activities. Throughout, there has been a general awareness that equipment and chemical stocks have to be "on-farm" or readily available to achieve efficient control.

While the strategies adopted have been multifaceted, this paper presents the research done on the chemical control of *P. pachyrhizi* in southern Africa and a preliminary analysis of the meteorological factors that influence initial field infection.

Chemical Control

Research into the control of *P. pachyrhizi* by fungicides in southern Africa has focused on several aspects: the screening of chemicals for efficacy, the optimum rate of their application, the number and timing of sprays, the persistence of the chemicals, and the use of adjuvants to possibly enhance control.

Fungicide screening. Shortly after the arrival of rust in Zimbabwe in 1998 and South Africa in 2001, fungicides were field-tested for their ability to control the disease. In Zimbabwe, it was agreed that the local agrochemical companies would be responsible for evaluation and promotion of suitable products; different rates of each chemical were compared as a normal procedure in these screenings. As a result, the Chemical Registration Authority approved seven fungicides as controls of *P. pachyrhizi*: five triazoles, a benzimidazole-triazole mix, and a morpholine (Table 1). The results of these experiments are proprietary and have not been published. The Commercial Oilseeds Producers Association, however, independently compared the registered fungicides at several sites between 1998 and 2001. While these assessments confirmed the efficacy of these products, the need for the correct timing of their application was evident.

In South Africa, a different policy was adopted. Although the agrochemical companies have field-tested their products, an independent fungicide evaluation was made by the KwaZulu-Natal Department of Agriculture & Environmental Affairs on behalf of the National Soybean Rust Task Force. The South African Chemical Registration Authority has similarly relied upon triazoles to control *P. pachyrhizi* under temporary licensing, at rates higher than in Zimbabwe, until research shows otherwise.

Under the independent evaluation, chemicals were tested by du Preez and van Rij (5) at 50, 100, and 200% of the levels temporarily approved by the Registration Authority. The fungicides were applied to selected plots at 63 days after planting (DAP) (R2 growth stage), 84 DAP (R4

growth stage), and 105 DAP (late R6 growth stage). While the fungicides reduced infection (Fig. 1) and most were associated with significant yield increases (Fig. 2), plants sprayed with triadimenol produced yields only marginally better than those left unsprayed. Increasing the

Fig. 5. Severity of soybean rust on two soybean cultivars, Sonata (black bar) and Soprano (white bar), either left unsprayed or sprayed with a carbendazim-flusilazole mix at the Rattray Arnold Research Station, Zimbabwe during 1999–2000. AUDPC: Area under the disease progress curve based on the 1 to 4 scale of the International Rust Working Group (12).

Fig. 6. Yields (t ha^{-1} at 11% moisture) of two soybean cultivars, Sonata (black bar) and Soprano (white bar), either left unsprayed or sprayed with a carbendazim-flusilazole mix at the Rattray Arnold Research Station, Zimbabwe, during 1999–2000.

rate of application did not further improve the control or the yields.

In a separate experiment, the fungicides again limited disease development (Fig. 3): plants sprayed with flutriafol developed the fewest symptoms, and those sprayed with azoxystrobin, the most. The converse was true upon harvest: plants treated with either azoxystrobin, a flusilazole-carbendazim mix or an experimental strobilurin-triazole mix produced significantly higher yields than those sprayed with tri-

forine or flutriafol, which did not differ from the unsprayed plants (Fig. 4).

Number and timing of sprays. The number and timing of sprays necessary to control *P. pachyrhizi* were determined in two separate replicated experiments planted at several sites in Zimbabwe between 1998 and 2003. In the first, 100 g of carbendazim + 50 g of flusilazole per hectare were sprayed onto two soybean cultivars at 20-day intervals, from 28 to 108 DAP. A treatment schedule of 5 sprays

during the season was included to provide rust control and an estimate of yield potential. The results of the trial planted at RARS in the 1999–2000 season are representative of the control achieved. A rapid sigmoidal increase in disease severity occurred when fewer and later sprays were applied (Fig. 5), and this led to a converse decrease in yield (Fig. 6). Three or more sprays were found necessary to maintain the yield potential, whereas two sprays or a single application, applied during pod-fill, were insufficient to control the disease.

Although this experiment clearly demonstrated that multiple sprays were necessary, it did not indicate when they should be best applied. Therefore, another experiment was devised whereby one, two, or three applications were compared, and the benefits of several early and late combinations could be determined. The disease severity and the yields harvested at the RARS in the 2000–01 summer provide a good example. The 70 DAP treatment gave the best control of the single sprayings (Fig. 7), and this was evident in the yield (Fig. 8), which was similar to the 70 + 90 DAP treatment of cv. Soprano and the multiple sprayings of cv. Sonata. The early single-sprays (50 or 60 DAP) did not adequately protect the plants from late-season reinfection, and the later single-sprays (80 or 90 DAP) did not contain the initial rust development. The benefit of earlier application was also evident in the two-spray treatments: both cultivars sprayed at 50 + 70 DAP had significantly less disease than those sprayed at 70 + 90 DAP, and cv. Soprano treated before 70 DAP produced significantly higher yields.

These two experiments showed that soybean plants needed to be adequately protected from rust from flowering through physiologic maturity (R1 to R7 growth stages) (6) with two or more fungicide sprays applied during early reproductive growth.

du Preez and van Rij (5) also investigated this aspect in South Africa. Soybean cv. LS666 was sprayed either once, twice, or three times with either azoxystrobin or a flusilazole-carbendazim mix at the Cedara Agricultural Research Centre during the 2001–02 season. The initial sprays were done at either the V12 growth stage (58 DAP), at first-flower (R1 growth stage; 65 DAP), upon first sign of rust (86 DAP), or at early pod-fill (R5 growth stage; 94 DAP), and the subsequent sprays were made at 21-day intervals thereafter. Although a low rust severity developed during the season, the plants sprayed at flowering were the least infected (Fig. 9), significantly less than those sprayed at the V12 growth stage and at first sign of the disease. Plants treated at the R5 growth stage were as severely affected as those left unsprayed. Spraying more than once significantly reduced the infection.

Fig. 7. Severity of soybean rust on two soybean cultivars, Sonata (black bar) and Soprano (white bar), either left unsprayed (CON) or sprayed with a carbendazim-flusilazole mix at various days after planting (DAP) at the Rattray Arnold Research Station, Zimbabwe, during 2000–01. AUDPC: area under the disease progress curve based on the 1 to 4 scale of the International Rust Working Group (12). 3 times: 50+70+90 DAP; 4 times: 50+70+90+110 DAP.

Fig. 8. Yields (t ha^{-1} at 11% moisture) of two soybean cultivars, Sonata (black bar) and Soprano (white bar), either left unsprayed (CON) or sprayed with a carbendazim-flusilazole mix at various days after planting (DAP) at the Rattray Arnold Research Station, Zimbabwe, during 2000–01. 3 times: 50+70+90 DAP; 4 times: 50+70+90+110 DAP.

Plants that were sprayed earlier produced yields significantly higher than those sprayed at the R5 growth stage or left unsprayed (Fig. 10). Increasing the number of sprays, however, did not improve yield.

Persistence of fungicides. The persistence of the fungicides used to control soybean rust in Zimbabwe and South Africa has been studied since 2001. In the South African experiment (5), plots of soybean cv. LS666 were sprayed once with one of 11 fungicides after two significant disease assessments had been made (94 DAP); disease development was thereafter monitored twice weekly. The results suggest that the carbendazim–flusilazole mix and flutriafol protect plants for at least 16.5 days (Fig. 11), significantly longer than difenoconazole, azoxystrobin, the experimental strobilurin–triazole mix, and mancozeb, which gave ≤ 14 days protection. Fungicides with translaminar activity persisted for between 14 and 18 days.

Recommended spray times. Prior to 2000, spraying was supposed to commence “at the first signs of disease” in Zimbabwe. Experience has shown that it is very difficult to detect the initial symptoms of rust on soybean leaves without the aid of a hand-lens or microscope, and frequently, the disease had become well established before it was visible. The fungicide studies above had also shown that plants needed to be protected from infection throughout reproductive growth to avoid yield loss. Therefore, the following was adopted in Zimbabwe, and provisionally in South Africa, to replace the previous advisory spray program:

- In areas of known high rust severity, three sprays will be necessary to maintain optimum yields. The first should be applied at first-flowering, and the other two at 21-day intervals thereafter;
- In areas of low rust severity, only two sprays are necessary, and these should be applied at first-flowering and 21 days later.

Zimbabwean farmers have opted to modify these recommendations to “50-70-90 DAP” and “50-70 DAP” schedules, respectively. In most situations, the first application will be prophylactic, prior to the arrival of the pathogen. If these recommendations are to be used elsewhere, the effects of day length and spectral composition on flowering and reproductive growth need to be taken into consideration.

Environmental factors influencing initial infection. An analysis has been made of the daily weather data recorded between November and April of 1998 to 2002 at RARS to determine the factors favoring natural rust infection in southern Africa. The environment is inherently drier than in Southeast Asia or coastal Australia, under which several epidemiological studies have been made (3,15,17). As the field trials

Fig. 9. Areas under the disease progress curves (log-transformed) of soybean rust severity on soybean cv. LS666, either left unsprayed (CON) or sprayed with either azoxystrobin (AZO) or a flusilazole-carbendazim mix (FLU+CARB), at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa, during 2001–02. log AUDPC: area under the disease progress curve (log-transformed) based on a 0 to 9 scale.

Fig. 10. Yields (t ha^{-1} at 12.5% moisture) of soybean cv. LS666, either left unsprayed (CON) or sprayed with either azoxystrobin (AZO) or a flusilazole-carbendazim mix (FLU+CARB), at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa, during 2001–02.

Fig. 11. The persistence (days) of 11 fungicides in their control of soybean rust on soybean cv. LS666 at the Cedara Agricultural Research Centre, KwaZulu-Natal, South Africa, during 2001–02. ^z values followed by the same letter are not significantly different according to Duncan’s multiple range test at $P \leq 0.05$.

described above were planted on different dates, the values were also adjusted to the number of days after planting so that prevailing conditions could be directly compared for similar plant growth. A period 30 to 60 DAP (V3 to R2 growth stages) is pertinent to initial infection in Zimbabwe.

Maximum temperatures of 25.5 to 29°C and minimum temperatures of 15 to 17.5°C were present during this period; coincidental temperatures occurred at 38 DAP, 42 DAP, 33 to 44 DAP (late vegetative growth), and 50 DAP (R1 growth stage). Consistent diurnal temperature ranges of 11 to 12°C occurred at 38 DAP, 43 DAP, and 47 DAP, and of 12 to 14°C at 51 DAP. The rainfall and evaporation recorded differed from season to season, without any consistency or trend.

Although dew point temperatures fluctuated between 16 and 19°C at 8:00 A.M., they were roughly coincident at 16.5 to 18°C on 33 DAP, 39 DAP, 41 to 47 DAP, 52 DAP, and 56 to 57 DAP. Dew formed on most days during the period, and its presence did not appear to be the sole determinant of infection. Relative humidities of 70 to 96% were recorded at 8:00 A.M. during the period, but 80 to 92% appears necessary for infection. Atmospheric moisture was coincident at 83% at 34 DAP, 41 to 42 DAP, and 54 to 55 DAP.

To summarize, natural infection by *P. pachyrhizi* is favored by a maximum temperature of 26 to 29°C, a minimum temperature of 15 to 17°C, with a diurnal range of 11 to 12°C in Zimbabwe. Early-morning dew point temperatures of 16 to

18°C and a humidity of over 80% are necessary, being optimal of approximately 85%. Increased relative humidity promotes disease development.

ACKNOWLEDGMENTS

I thank the Commercial Oilseeds Producers Association for funding some of the research; L. Mutemeri, Agricultural Research Trust; J. R. Tattersfield, J. S. Tichagwa, and H. Ndhlovu, Seed Company of Zimbabwe Limited, and their respective technical staff, for assistance with the field experimentation.

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