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Rust diseases in Canada

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Summary
Rust diseases are among the most dangerous that attack food crops, and historically have caused devastating yield losses worldwide. Rust pathogens produce prodigious amounts of spores in a short period of time, which are rapidly wind-dispersed over a large area for subsequent re-infection of the crop. This characteristic of rust diseases allows for several cycles of infection in a short period of time during the growing season and over a large geographical area, and can cause total yield losses under epidemic conditions. This paper describes rust diseases occurring in Canada and the various management practices used to control each disease.

General Characteristics of Rust Diseases
Rust diseases are caused by fungi and are distinct in that they are biotrophic, requiring a living plant host for their nutrients. They are highly specialized, both on the hosts they attack (known as *formae speciales*, or f. sp., e.g. wheat leaf rust cannot attack oat, and vice-versa) and for the cultivars they attack. The latter are known as physiological races, where rust strains vary in their virulence to specific resistance genes, and can attack some varieties but not others[1]. Rust diseases are extremely dangerous because they cycle very rapidly on the plant (reproduce from infection to new spores in 8-10 days), produce prodigious numbers of spores (1 trillion stem rust spores per acre at moderate infection levels), and are transported long distances by wind. Soybean rust was introduced into North America from Africa via hurricane transport across the Atlantic Ocean, and wheat stem rust has migrated from South Africa to Australia across the Indian Ocean on westerly winds. The rust diseases that occur in Canada are stem, leaf, and stripe rust of wheat, stem rust of barley, crown and stem rust of oat, flax rust, sunflower rust, and soybean rust. Discussion of each disease will be presented below.

Wheat stem rust (*Puccinia graminis* f. sp. *tritici*)
This disease caused many epidemics in Canada and the United States in the early 1900s, culminating in a series of major epidemics from 1953-1955 causing hundreds of millions of dollars in losses[2]. Stem rust can cause complete crop loss within a few weeks in a seemingly healthy-looking crop, due to tremendous water loss from large pustules that rip open the epidermis on the stems and subsequent plant collapse (Figure 1). Stem rust over-winters in the south-central USA and moves northward into Canada on winds during the cropping season on the "Puccinia pathway" (Figure 2). The life cycle of stem rust (Figure 3) in North America is now mainly asexual, but has an alternate host (*Berberis* spp.) that functions as the sexual host. The role of barberry in the rust life cycle has been almost entirely eliminated due to the eradication programs that started in Canada and subsequently in the USA around 1916[3,4]. Eradication of ornamental barberry was critical because it resulted in: 1) elimination of initial spore inoculum coming from the barberry bushes that can directly infect emerging wheat crops; and 2) reduced the ability of the fungus to recombine into new virulent races. Since the last major epidemics in the 1950s, no epidemics of wheat stem rust have occurred on spring wheat in Canada. There also has been less race variation in the population of *P. graminis* f. sp. *tritici* in North America in recent years[5]. Annual virulence surveys are conducted in Canada and the USA to monitor changes in the rust population and to detect dangerous new races[6]. Stem rust is controlled by cultural practices, host resistance, and chemical methods. Cultural methods involve removing barberry bushes as mentioned above, and early planting to avoid infection of spores migrating from the USA. Using resistant cultivars is the primary method to control stem rust, which are listed in provincial seed guides. Durable resistance that has lasted over 50 years in Canada has been achieved by stacking effective resistance genes into modern wheat varieties. Most Canadian spring wheat varieties are

resistant to common stem rust races found in North America, but are susceptible to a new strain known as Ug99 that was recently detected in Africa[7]. However, some Canadian wheat varieties are resistant to Ug99, and wheat breeding programs are incorporating new genes that are effective against Ug99 to develop new resistant varieties. Finally, fungicides can be used to control stem rust. The most common foliar fungicides used are the triazoles, which have a systemic mode of action. A list of foliar fungicides is available from provincial websites. Fungicide use results in added input costs, may have long-term environmental consequences, and with continual use may result in development of fungicide-resistant strains of stem rust.

Figure 1. Stem rust on wheat.
Photo by T. Fetch, AAFC

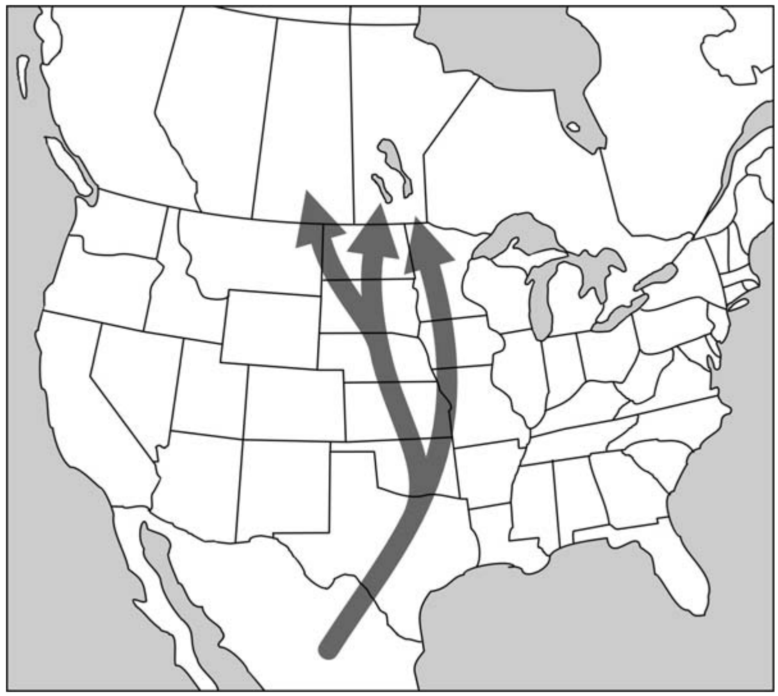

Figure 2. Puccinia pathway of spore movement
Figure by M. Shillinglaw, AAFC

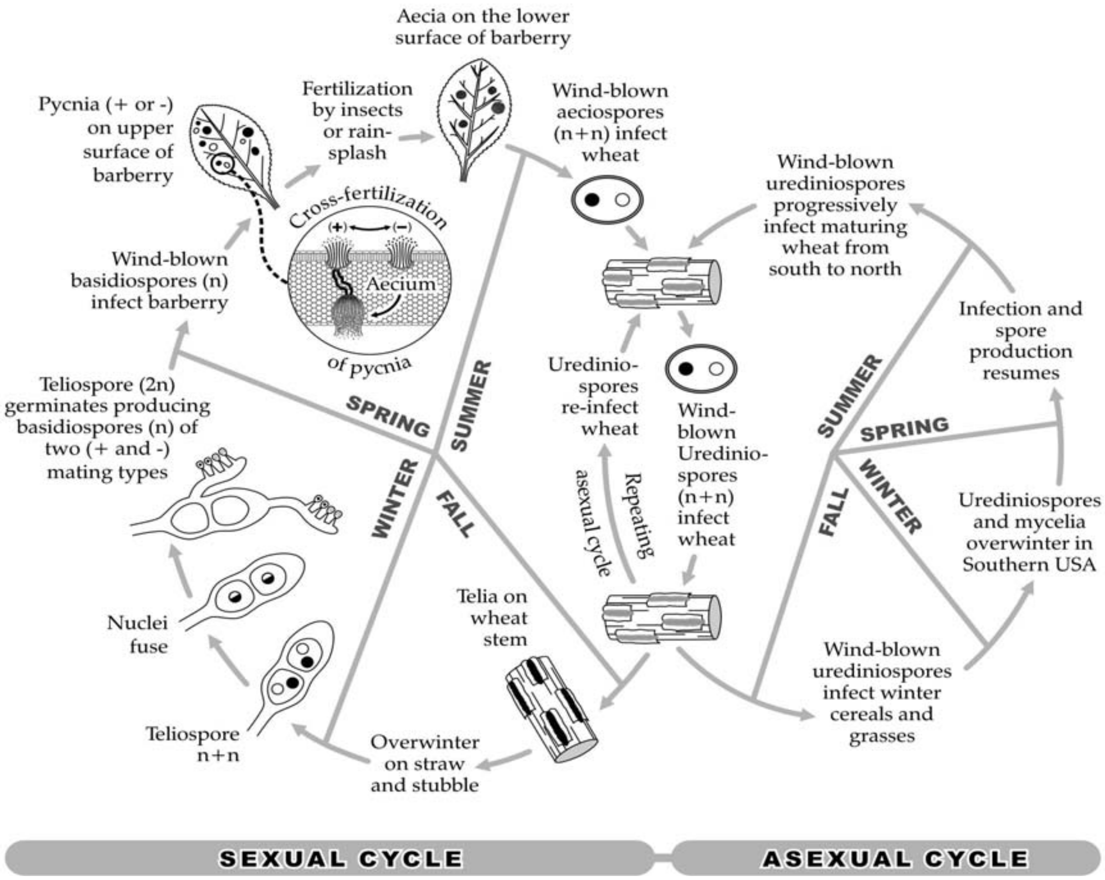

Figure 3. Life cycle of stem rust. Figure by M. Shillinglaw, AAFC

Wheat leaf rust (*Puccinia triticina*)

Leaf rust is one of the most common diseases of wheat worldwide and in Canada[8]. It is characterized by red pustules or uredinia scattered on infected leaves (Figure 4). Disease epidemics occur annually in western Canada, but the severity of the epidemic varies from year to year (Table 1). In most years, susceptible spring wheat cultivars such as 'AC Barrie' or 'Superb' will suffer significant yield losses in the rust area (southern Manitoba and eastern Saskatchewan) if they are not protected by foliar fungicide application. Control measures include foliar

Table 1. Average proportion (%) of infected flag leaves with leaf rust in Manitoba and Saskatchewan 2000-2010

Year	Manitoba	Saskatchewan
2000	3.0	1.0
2001	10.0	3.0
2002	18.0	5.0
2003	2.5	2.0
2004	7.0	2.0
2005	20.0	22.0
2006	10.2	5.3
2007	15.7	4.9
2008	1.1	0.1
2009	0.1	0.1
2010	25.0	5.0
Average	10.2	4.6

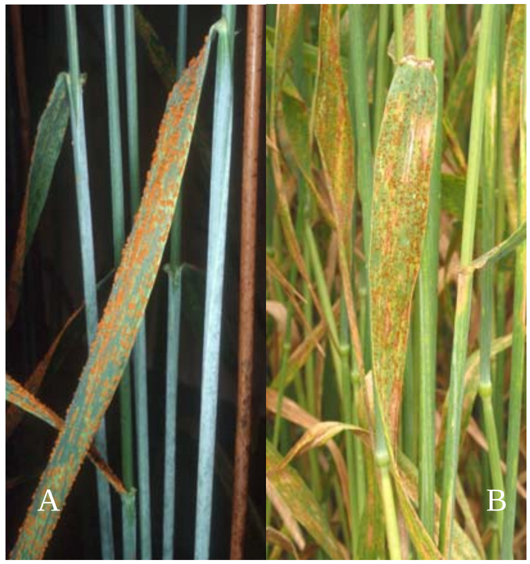

Fig 4. Wheat leaf rust on greenhouseplants (A) and in the field (B). Photos by B. McCallum, AAFC

fungicide application, early seeding, and genetic resistance. The cultivar 'Thatcher' was predominant from 1939 to the 1960s, was very susceptible to leaf rust, and suffered high yield losses[9]. This led to breeding for resistance against leaf rust, and single resistance genes such as *Lr13* in 'Manitou', 'Neepawa', and 'Katepwa' or combinations of resistance genes such as *Lr10*, *Lr14a*, and *Lr16* in 'Selkirk'[10] were incorporated. The most common leaf rust genes in western Canadian spring wheat cultivars are *Lr1*, *Lr10*, *Lr13*, *Lr14a*, *Lr16*, *Lr21*, *Lr22a* and *Lr34* [8,9]. Genes *Lr1*, *Lr10*, *Lr13*, and *Lr14a* are no longer effective, but *Lr21* and *Lr22a* condition nearly complete resistance to all known races[11]. *Lr21* and *Lr22a* were discovered by Rowland and Kerber[12] and have been deployed in many Canadian cultivars. They also have closely linked molecular markers[13,14]. *Lr21* has also been extensively deployed in the northern USA. Genes *Lr16* and *Lr34* condition a partial level of leaf rust resistance. *Lr16* does not have an adequate level of resistance by itself (e.g. 'AC Barrie'), but contributes to resistance in combination with other genes, particularly *Lr34*. *Lr34* was first deployed in western Canada in the Canada Western Extra Strong (CWES) cultivar 'Glenlea', registered in 1972. It has conferred moderate resistance to leaf rust in 'Glenlea' and other cultivars which carry this gene. *Lr34* also enhances the expression of other resistance genes in a synergistic manner, so cultivars that carry *Lr34* in combination with other resistance genes are nearly immune to leaf rust[15]. The resistance conditioned by *Lr34* has never been overcome by virulence changes in the *P. triticina* population in Canada or in any other country where it has been deployed. Therefore, it provides 'durable' resistance because it has been effective for many years in numerous cultivars grown worldwide. In addition to controlling leaf rust, *Lr34* is also completely linked with the *Yr18* stripe rust resistance gene[16] (Singh, 1992). *Lr34* also confers resistance to stem rust[17], powdery mildew[18], and barley yellow dwarf virus[19]. Approximately half of the spring wheat cultivars in western Canada carry *Lr34*. Diagnostic molecular markers within the coding sequence of this gene facilitate the incorporation of *Lr34* into new wheat cultivars[20]. The use of *Lr34* and other effective resistance genes such as *Lr16*, *Lr21*, and *Lr22* accounts for most modern cultivars being resistant or moderately resistant to wheat leaf rust.

Wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*)

Stripe rust of wheat is a perennial production problem in southern Alberta. Stripe rust was first reported in Manitoba and eastern Saskatchewan in 2000, when it also caused damage in the southern and central Great Plains region of the United States[21]. New races with adaptation to higher environmental conditions were identified[22], which may be from exotic introduction into North America. Stripe rust has been detected annually in this region since 2000, although the only serious wide-spread epidemic occurred in 2005 near Regina[23]. Stripe rust infection appears as a chain of yellow-orange uredinia that run parallel to the leaf veins (Figure 5). The development of *P. striiformis* is favoured by cool (7-20°C) environmental conditions. At higher temperatures, development of the fungus slows and it switches from producing orange wind-dispersed urediniospores to black teliospores that are tightly attached to the leaf (Figure 6). The life cycle of *Puccinia striiformis* was recently described by Jin et al.[24] and has barberry as the alternate host, as described earlier for stem rust. Stripe rust infection can be confused with leaf rust, but is distinguishable by the pattern and the colour of the uredinia (Figure 7).

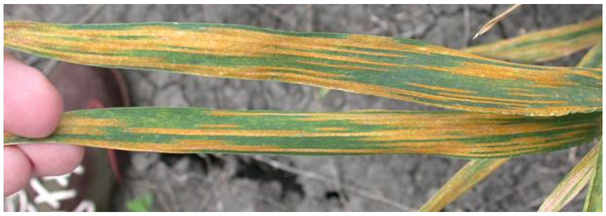

Figure 5. Wheat stripe rust on winter wheat, Winnipeg MB 2006 Photo by T. Fetch, AAFC

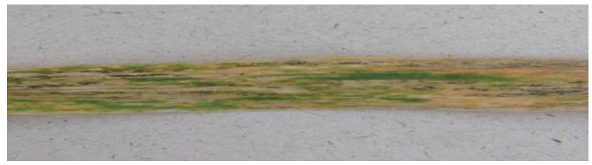

Figure 6. Black teliospores of *Puccinia striiformis* on infected wheat Photo by B. McCallum, AAFC

Figure 7. Wheat leaf rust and wheat stripe rust co-infecting a wheat leaf, Brandon MB 2010. Leaf rust appears as red uredinia scattered on the leaf, whereas stripe rust uredinia are yellow-orange and appear as a chain of pustules running parallel to the leaf veins. Photo by B. McCallum, AAFC

Stripe rust can be controlled with fungicide application or genetic resistance. Prior to 2000, the level of stripe rust resistance in western Canadian wheat cultivars was largely unknown, since they were not tested for this trait during the registration process. Selected Canadian spring wheat cultivars, representing each major bread wheat class, were tested for stripe rust resistance in areas of the world where the disease is endemic[25]. Most western Canadian wheat cultivars were susceptible to stripe rust, many had an intermediate level of resistance, and a few were more resistant. Many of the cultivars with intermediate to moderate resistant were known or hypothesized to carry the *Yr18* gene. This appears to be the major source of stripe rust resistance in Canadian wheat, although other genes may be involved. In contrast to other wheat classes, resistance breeding and screening for stripe rust has been applied to Soft White Spring (SWS) wheat cultivars, which could have combinations of effective resistance genes. Wheat breeders are encouraged to incorporate *Lr46/Yr29* or *Lr67/Yr46* to improve stripe rust resistance, which act like the *Lr34/Yr18* locus in conditioning resistance to both leaf and stripe rust[26].

Barley stem rust *(Puccinia graminis* f. sp. *tritici*, *Puccinia graminis* f. sp. *secalis*)
Although leaf and stripe rust also infect barley, stem rust (Figure 8) is the primary concern for Canadian barley growers. While wheat is only attacked by f. sp. *tritici* and rye is only attacked by f. sp. *secalis*, barley is attacked by both *formae species*. Stem rust epidemics on barley occurred in 1935 and 1937, but have been controlled using host resistance (gene *Rpg1*) since 1947. However, in 1988 a race (QCC) with virulence on *Rpg1* was detected in the prairie region[27]. The resistance gene *rpg4* is effective against QCC, but no varieties with *rpg4* have been released to date. Race QCC was virulent on the popular winter wheat varieties grown in the United States in the late 1980s, which provided ample inoculum to infect barley. However, susceptible winter wheat cultivars were quickly replaced around 1990 with ones resistant to QCC, thus greatly reducing the inoculum for infection of spring-planted barley. Since the early 1990s, stem rust has not caused any economic losses in barley production. Early planting is an effective control measure, as barley matures quickly and often escapes infection. Foliar fungicides can also be used to control barley stem rust, similar to wheat.

Figure 8. Severe stem rust infection on barley in the field. Photo courtesy of B. Steffenson, University of Minnesota

Oat stem rust (*Puccinia graminis* f. sp. *avenae*)
There have been several epidemics of oat stem rust in Canada, most notably in 1935, 1977, and recently in 2003[6]. Oat stem rust (Figure 9) has barberry as its alternate host, over-winters in the southern USA, and moves north on the "Puccinia pathway" like wheat stem rust, but is a different f. sp. (*avenae*) than wheat, barley, and rye. Unlike wheat stem rust, there are few resistance genes available to provide control of oat stem rust. Resistance in oat cultivars in Canada has utilized only five genes (*Pg1*, *Pg2*, *Pg4*, *Pg9*, *Pg13*), and cultivars considered as having an intermediate resistance in provincial seed guides likely possess the *Pg2* + *Pg13* combination[28]. This combination was effective against the oat stem rust races in North America until 1998, when a new race (NA67, now known as race TJJ[29]) was identified[30]. Efforts to find new sources of resistance to race NA67 were conducted, and were unsuccessful in hexaploid oat but did identify some resistance in diploid species[31]. Races virulent to *Pg2* + *Pg13* (TJG, TJJ, TJS) are now common in the Canadian oat stem rust population[5]. All currently grown cultivars in Canada are susceptible to races TJJ and TJS, but the effective resistance genes *Pg10*, *Pg11*, *Pg16*, and the *Pg-a* complex are being utilized in AAFC breeding programs. One cultivar ('Stainless') with *Pg-a* resistance has been released, but is

susceptible to race TJS. As previously described, early planting can be used to avoid infection and fungicide application is an effective method to control oat stem rust.

Figure 9. Stem rust infection on oat in the field in the 2003 epidemic. Photo by T. Fetch, AAFC

Oat crown rust (*Puccinia coronata* f. sp. *avenae*)

Crown rust is arguably the most important disease of oat in Canada. It can cause yield losses of 10 to 40% in the rust prone areas of Quebec, Ontario, Manitoba, and eastern Saskatchewan. The pathogen is favoured by mild to warm (20 to 25°C) sunny days and mild nights (15 to 20°C) with adequate moisture for dew formation. Losses result from damage to leaves (particularly the flag leaf), which leads to reduced photosynthesis and transport of carbohydrates to the developing grain. This causes shriveled grain and reduced grain quality. Heavily rusted oat plants will also be less tolerant of drought. The symptoms of oat crown rust are the presence of orange pustules (uredinia) on the upper and lower surfaces of leaves (Figure 10).

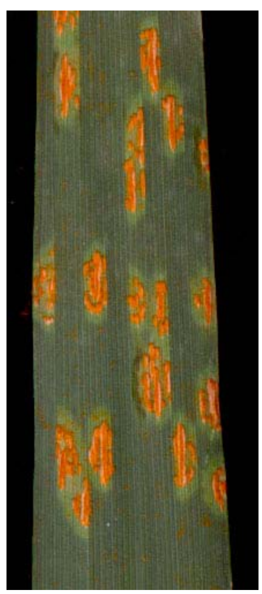

Figure 10. Oat crown rust uredinia on seedling leaves in the greenhouse. Photo by J. Chong, AAFC

Leaf sheaths and glumes may also become infected under severe epidemic conditions. Pustules contain masses of orange urediniospores that are exposed by the rupture of the leaf epidermis. The life cycle of crown rust is similar to wheat stem rust (Figure 3), but the alternate host is buckthorn (*Rhamnus* spp.). Crown rust is named for the shape of the teliospores, which have prong-like projections forming a crown-like structure. Both the asexual and sexual cycles are important in the epidemiology of *P. coronata* f. sp. *avenae* in Canada. Urediniospores do not over-winter in Canada, but migrate from the southern United States along the "Puccinia pathway" (Figure 2) similar to stem rust. In Manitoba and eastern Saskatchewan, buckthorn is not widespread, thus the primary inoculum is urediniospores migrating from the USA. However, buckthorn is spreading, resulting in a greater influence of the sexual cycle in these two provinces. Common buckthorn (*R. cathartica*) is widespread in Ontario and Quebec, where aeciospores are the primary inoculum in the spring and directly infect newly emerging oat plants. Surveys for virulence are conducted annually to describe the variation in the population of *P. coronata* f. sp. *avenae* and detect new dangerous races[32], similar to stem rust and leaf rust. Control of oat crown rust has been achieved mainly through the use of resistant cultivars. Although there are many described resistance genes, few are effective in North America. The functional sexual stage on buckthorn creates many new races through genetic recombination. Thus, resistance genes which were effective at the time of cultivar release eventually are overcome by new pathogen races. Producers can consult provincial seed guides to find resistant oat varieties for their area. Destruction of buckthorn shrubs in shelterbelts is encouraged to reduce the development of new races. Avoid planting oats in fields close to areas suspected of having buckthorn plants to eliminate early infection. The Canadian Food Inspection Agency regulates the importation of buckthorn species that are susceptible to the crown rust pathogen. As with other cereal rusts, early planting is encouraged to avoid infection, and foliar fungicides can also be effectively used to control oat crown rust.

Flax Rust (*Melampsora lini*)

Flax rust is a common disease in North America and worldwide. It has five spore stages (macrocyclic life cycle) similar to stem rust, but does not have an alternate host. All spore stages occur on flax, resulting in a high frequency of sexual recombination and the formation of new races. Local inoculum arises from over-wintering black-colored teliospores (Figure 11), which ultimately produce orange-yellow aeciospores that cause early infection on flax seedlings and volunteer plants[33]. Subsequently, flax is repeatedly infected during the summer by urediniospores, which result in formation of orange-colored uredial infections (Figure 12).

Figure 11. Black telia stage on mature flax stems. Photo by K. Rashid, AAFC

Figure 12. Orange uredinia on flax leaf during growing season. Photo by K. Rashid, AAFC

Rapid disease development can occur, resulting in local epidemics. Temperatures of 10-25°C and 8-12 h of dew are the optimum conditions for urediniospore infection during the growing season. The last flax rust epidemics occurring in North America in the 1970s were caused by new races of the group 370. Flax rust has not been observed in western Canada over the last 30 years due to the immune level of resistance bred into all commercial cultivars. This success story of breeding for disease resistance has saved the Canadian growers and flax industry hundreds of millions of dollars over the last 30 years. Control of flax rust in Canada was primarily accomplished through using resistant cultivars, but other control practices include crop rotation (3 year between flax), eliminating volunteer flax plants in rotational crops and field ditches, and not planting flax adjacent to previously infected crops. Recommended fungicides for flax also can be used and this information is available in provincial fungicide guides.

Sunflower Rust (*Puccinia helianthi*)

Sunflower rust is a widespread disease in North America and worldwide. Like flax rust, all five spore stages can occur on sunflower plants[34], resulting in a high frequency of sexual recombination and the formation of new races. Inoculum from over-wintering black-colored teliospores (Figure 13B) ultimately produce orange-colored aeciospores, which causes early infection on sunflower seedlings and volunteer plants. Subsequently, brown-colored uredial infections lead to rapid disease development resulting in local epidemics (Figure 13A). Temperatures of 10-30°C and 6-10 h of dew are optimum conditions for uredial infections and re-cycling of infections during the growing season. Frequent severe local epidemics occurred in North America (including Manitoba) over the last 20 years with a shift in the race structure of the *P. helianthi* population from race-group 100 to the more virulent race-groups 300 and 700. Rust epidemics can reduce the yield up to 60% depending on the susceptibility of sunflower hybrids to the local rust races, the earliness of primary infections, and weather conditions. Sunflower rust is managed in the same manner as flax rust, by i) selecting hybrids with genetic resistance to the prevalent local races, ii) following a 3-year rotation between sunflower crops, iii) controlling volunteer sunflower plants in rotational crops and in ditches around fields, and iv) avoiding sunflower crops planted adjacent to last years rust-infected crops. Foliar fungicides listed in provincial guides can also be used to control rust, starting application at the first appearance of rust on the middle leaves.

Figure 13. Heavily rusted sunflower plant with brown urediniospores (A) and underside of leaf with mature black teliospores (B). Photos by K. Rashid, AAFC

Asian Soybean Rust (*Phakopsora pachyrhizi*)

Asian soybean rust is a new and invasive fungal disease in North America. It was first reported in the United States in November of 2004. The first confirmed soybean infection in Canada occurred in Ridgetown, Ontario in 2007[35]. Currently, soybean rust is not causing economic losses in Canada, but the disease continues to develop in the southern United States and Mexico. Like many "new" diseases, the overall pattern will take a few more years to determine and will vary annually. The threat of soybean rust has led to unparalleled international cooperation. The comprehensive soybean rust "sentinel plot" monitoring program established by the United States Department of Agriculture (USDA) in conjunction with the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), Agriculture and Agri-Food Canada (AAFC), and the Grain Farmers of Ontario (GFO) is one such example. The function of this project is to coordinate soybean rust monitoring efforts in Canada with those of the United States and Mexico and to create an early warning system for the soybean production areas of North America. Ontario's involvement in this initiative requires a series of sentinel plots established from Windsor to Ottawa. Data from Ontario locations were added to 954 sentinel and 1,430 mobile plots established in the United States. The establishment of these plots allows for the surveying of other pests such as Soybean Cyst Nematode, aphids, viruses, and other diseases. These sentinel plots are intensively scouted for soybean rust symptoms by OMAFRA in conjunction with AAFC and industry partners. Scouting results are posted on the USDA ipmPIPE website (www.sbrusa.net) and Grain Farmers of Ontario website (http://www.gfo.ca/Research.aspx). The early warning system is very effective and has saved Ontario and American soybean producers from crop losses, reduced input costs, and lowered environmental and applicator risks. The system in conjunction with education, monitoring, prediction models, and fungicides give producers the tools needed to track and combat this destructive disease and limit yield losses. In 2007, the Canadian soybean rust spore detection network (using rainfall and air sampling equipment) was established at nine Ontario sentinel plot locations. It was expanded in 2006 to Alberta (1), Saskatchewan (1), Manitoba (1), and Quebec (2). The Canadian spore detection data was added to the USDA network and incorporated into soybean rust forecasting models. Soybean rust spores have been detected each year beginning in June. Most of the broad detection events (large geographical areas) corresponded to storm fronts from the United States, which supports long distance transport of soybean rust spores. Soybean rust is primarily controlled by using fungicides, since resistant cultivars have not yet been identified.

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