Wheat Stripe Rust Epidemic and Virulence of *Puccinia striiformis* f. sp. *tritici* in China in 2002

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ABSTRACT

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In China, wheat stripe rust, caused by *Puccinia striiformis* f. sp. *tritici*, is one of the most destructive diseases of wheat and can cause severe yield losses when susceptible cultivars are grown and weather conditions are favorable for the disease. Wheat stripe rust most frequently affects the winter wheat growing areas in Northwest, Southwest, and North China, and the spring wheat growing areas in Northwest China. In the 2001–2002 growing season, a widespread stripe rust epidemic affected about 6.6 million hectares of wheat in 11 provinces: Sichuan, Chongqing, eastern Gansu, southern and western Shaanxi, southern and central Ningxia, Yunnan, Guizhou, Hubei, Henan, southern and central Hebei, and Shandong. The epidemic could be attributed to relatively warm weather from November 2001 to March 2002, high frequencies of stripe rust races CYR31 and CYR32, and widely grown susceptible cultivars. Race CYR31 was virulent on the Chinese differential cultivars Trigo Eureka, Fulhard, Lutescens 128, Mentana, Virgilio, Abbondanza, Early Premium, Funo, Danish 1, Fengchan 3, Lovrin 13, Shuiyuan 11, Lovrin 10, and Hybrid 46. Race CYR32 had all the virulence factors of CYR31, plus virulences on Chinese differential cultivars Jubilejina 2 and Kangyin 655, i.e., CYR32 was virulent on all differential cultivars, except Zhong 4. When tested on the world and European differential and some other resistant genotypes, CYR32 was virulent on Chinese 166 (*Yr1*), Heines VII (*Yr2*, *Yr25*, and *YrHVII*), Vilmorin 23 (*Yr3a* and *Yr4a*), Heines Kolben (*Yr6* and *YrHK*), Lee (*Yr7*, *Yr22*, and *Yr23*), Clement (*Yr9*, *Yr25*, *YrCle*), VPM1 (*Yr17*), Selkirk (*Yr27*), Anza (*YrA*), Carstens V (*YrCV1*, *YrCV2*, and *YrCV3*), Gaby (*YrG*), Strubes Dickkopf (*Yr25*), and Suwon 92/Omar (*YrSO*). Resistance genes in *Triticum spelta album* (*Yr5*), Zhong 4, and Moro (*Yr10* and *YrMor*) were effective against all races identified.

Additional keywords: *Triticum aestivum*, yellow rust

Wheat (*Triticum aestivum* L.) is the second largest stable food crop in China and is grown on over 28 million hectares (17). Winter wheat, which accounts for 95% of the total wheat acreage, is grown mostly in northern China. Stripe (yellow) rust of wheat, caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks., is one of the most damaging diseases of wheat in many areas around the world (29,30). Stripe rust has traditionally been associated with wheat production in the cool, temperate regions of the world, including Asia, Europe, North America, South America, the Middle East, and Africa (21,25,29,42). In terms of acreage affected by stripe rust, China is the largest epidemic region in the world (30). As in other regions, stripe rust is most destructive when susceptible cultivars are grown and the weather is favorable for the disease. The disease occurs most frequently in winter wheat growing areas in Northwest, Southwest, and North China, and the spring wheat growing areas in Northwest China. The most destructive epidemics of stripe rust in China occurred in 1950, 1964, and 1990, which caused yield losses of 6.0, 3.2, and 1.8 million metric tons or 29.3, 13.3, and 1.8% of the national total production, respectively (20).

The same resistance sources have been used in wheat breeding programs throughout China for two decades. By the late 1980s, more than 80% of the released cultivars contained *Yr9*, originally derived from rye through the 1B/1R wheat–rye chromosomal translocation. Since the 1970s, 15% of the wheat cultivars developed were Fan 6 derivatives with resistance from Hybrid 46 (*Yr4b*, *YrH46*). Thus, cultivars with these resistances have been extensively grown in almost all wheat growing regions in China. Plant pathologists and breeders in China realize the danger of using these limited sources of resistance, but have not yet incorporated diverse resistance genes and/or durable types of resistance into wheat cultivars. Consequently, wheat is highly vulnerable to stripe rust (1,25). This threat has become a great concern to wheat growers, breeders, pathologists, and governmental administrators.

In the 2001–2002 growing season, wheat stripe rust caused severe yield losses in many regions of China. The objectives of this paper are to report on the occurrence, distribution, and damage of the epidemic, and discuss the factors causing the epidemic and strategies for sustainable control of stripe rust.

MATERIALS AND METHODS

Field survey. A field survey was conducted during the 2001–2002 wheat growing season. Rust researchers and extension personnel conducted surveys by checking wheat fields and collecting rust samples along major roads throughout the wheat growing areas in Gansu (P1), Shaanxi

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(P3), Sichuan (P4), Yunnan (P6), Hubei (P8), and Henan (P9) provinces (Fig. 1), covering approximately 5,000 km^2.

Trap plots. Trap nurseries consisting of 36 wheat genotypes, either highly susceptible to stripe rust or with various resistance genes, were planted in Gangu, Gansu (P1); Hanzhong, Shaanxi (P3); Xindu, Sichuan (P4); Yuxi, Yunnan (P6); Jingzhou, Hubei (P8); Nanyang, Henan (P9); Wendeng, Shandong (P11); and Linzhi, Tibet (P15) to monitor stripe rust development and virulences, and to determine effectiveness of resistance. The modified Cobb scale (28) was used to determine the percentage of infected tissue (% severity) in the flowering to soft dough stages. Infection types were recorded using the 0 to 9 scale described by Line and Qayoum (23).

Fungicide application and estimation of yield loss. Based on previous studies on fungicide efficacy and usage (3,12), triadimefon was used at 105 to 135 g/ha to reduce yield loss caused by stripe rust in 2002 throughout all areas where stripe rust occurred. Generally, a single application of fungicide was recommended when rust severity (infected leaves) reached 5 to 10% from the stage when flag leaves fully expanded to heading. Acreages of diseased fields were estimated by field survey and by using agricultural statistics for each region through the collaboration of extension personnel in regional plant protection stations. Yields from fungicide-sprayed versus nonsprayed plots in commercial fields and designed experimental plots, which were conducted by plant protection stations in various provinces and regions, were used to estimate yield losses caused by stripe rust and reduction of yield losses due to fungicide application. Data of disease severity, variety, and acreage and models of yield loss (46) were also used to estimate yield loss.

Race identification. Rust collections were sent in paper envelopes to the Rust Disease Research Group, Institute of Plant Protection, Chinese Academy of Agricultural Sciences in Beijing or to the Academies of Agricultural Sciences of Shaanxi, Gansu, and Sichuan and stored at 4°C. These research institutes formed the Chinese National Wheat Rust Collaborative Group (CNWRCG). Date of collection, location, cultivar, severity, acreage, collector, and any other relevant information was recorded for each sample whenever possible.

Diseased plant materials were incubated on water-soaked tissue paper in petri dishes in the dark at 4°C for 10 to 15 h. Following incubation, and prior to testing isolates on the differential set, urediniospores were multiplied on the susceptible wheat cultivar Mingxian 169. For all seedling tests, seeds were planted in 10-cm-diameter pots containing a mixture of commercial peat moss and soil, and grown in a rust-free greenhouse. About 10 days after planting, seedlings at the two-leaf stage were inoculated with fresh urediniospores using a spatula. Inoculated plants were kept in a dew chamber at 10°C for 24 h and then placed on greenhouse benches with temperatures between 15 and 18°C. Metal halide lights were used to supple-

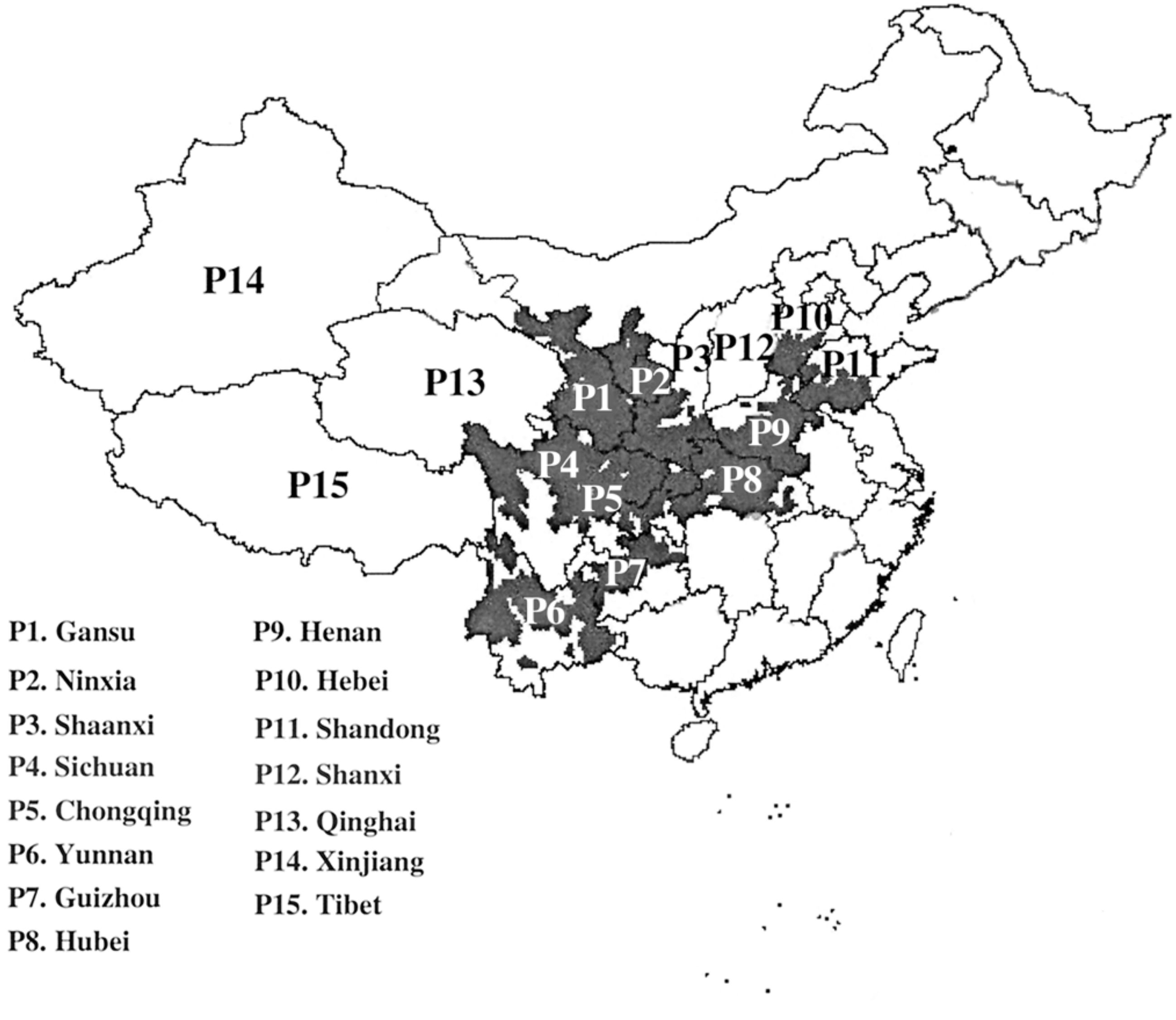

Fig. 1. Distribution of the wheat stripe rust epidemic (shaded area) in China in the 2001–2002 growing season. Provinces that are mentioned in the text are marked.

ment the natural daylight and to extend the photoperiod to 16 h. Inoculated plants were placed in glass booths to prevent cross contamination. The same method was used for inoculating isolates on the set of differential genotypes. Seventeen wheat genotypes (Table 1) were used to differentiate Chinese races of *P. striiformis* f. sp. *tritici*. If an initial isolate showed a mixture of races on the 17 genotypes, spores were collected from one or more differential genotypes to obtain subisolates. The subisolates were tested again on the 17 differential genotypes and often repeated several times to obtain pure isolates for race designation. For new races, single-pustule isolates were used. Tests for all isolates were repeated, except for a few isolates that were pure and clearly resembled previously characterized races.

Races were determined by the infection types (IT) based on the 0 to 9 scale described by Line and Qayoum (23). Infection type data were recorded 15 to 20 days after inoculation. An isolate was considered avirulent (A) on a differential cultivar when it did not produce any visible symptoms (IT 0) or produced necrotic flecks (IT 1), necrotic areas without sporulation (IT 2), necrotic and chlorotic areas with restricted sporulation (IT 3), or moderate uredinia with necrosis and chlorosis (IT 4-6). An isolate was classified as virulent (V) if it produced abundant uredia with chlorosis (IT 7-8) or without chlorosis (IT 9).

Table 1. Wheat genotypes used to differentiate races of *Puccinia striiformis* f. sp. *tritici* in China

Differential		
No.	**Genotype**	***Yr* gene**[a]
1	Trigo Eureka	*Yr6*
2	Fulhard	–
3	Lutescens128	–
4	Mentana	–
5	Virgilio	–
6	Abbondanza	–
7	Early Premium	–
8	Funo	*YrA*
9	Danish 1	*Yr3*
10	Jubilejina 2	–
11	Fengchan 3	*Yr1*
12	Lovrin 13	*Yr9*
13	Kangyin 655	–
14	Suwon 11	–
15	Zhong 4	–
16	Lovrin 10	*Yr9*
17	Hybrid 46	*Yr4b, YrH46*

[a] The *Yr* genes were based on Chen et al. (4), McIntosh et al. (27), Roelfs et al. (28), and Stubbs (29). – = indicates genes unknown.

RESULTS

Stripe rust occurrence. During the rust survey from fall 2001 to spring 2002, stripe rust was detected earlier than in previous growing seasons throughout China. In Sichuan (P4) province where stripe rust can sporulate during winter, the disease was observed on 13 November 2001 in Shehong County. In Mianyang, Sichuan, the disease was found on 21 November 2001. Subsequently, the disease was observed in most of the wheat growing areas in Sichuan 20 to 50 days earlier than normal dates relative to stripe rust observations in the past 50 years (36,39–41). In Yicheng of Hubei (P8) Province, stripe rust was found on 24 December 2001, while normally the disease could not be found until March. In Henan (P9) Province, the eastern wheat growing region in China, the disease was first found on 7 February 2002 in Xiping and Queshan counties, about 40 days earlier than normal dates for finding the disease, in late March. In Tianshui of Gansu (P1) Province, overwintered stripe rust was first observed in the middle of February 2002, which was 25 to 30 days earlier than normal based on rust records in the last 50 years.

Stripe rust developed and spread rapidly in the 2001–2002 growing season. In Tianshui, Gansu (P1), infected plants increased from 0.01 to 5% between 18 to 20 March and 5 to 6 April 2002, and infected wheat fields increased from 520,000 to 800,000 ha. In Yicheng, Hubei, the percentages of fields diseased were 24% on 5 March, 50% on 10 March, 85% on 15 March, and 89% on 25 March. In Nanyang of Henan (P9), 29% of the wheat fields were infected by stripe rust on 8 April 2002. In Miangyang of Sichuan (P4), infected fields reached 13,330 ha by late December 2001, 36,670 ha by 15 January 2002, and 70,000 ha by 22 March, which accounted for 61% of the total wheat acreage in that region. The first detection of stripe rust in Ningxia (P2) Province was on 7 May 2002 in Pengyang as a single diseased leaf, and during the survey conducted on 26 to 30 May, stripe rust was common and most fields reached the control threshold of 4.5% infected plants (38). In the eastern wheat growing provinces, where wheat is harvested from late May to mid-June, diseased leaves continued producing fresh urediniospores until early May due to higher rainfall and lower temperatures than in previous years, which extended stripe rust infection and damage. Large areas were affected by the quick development and spread of rust inoculum, which produced more inoculum, resulting in a typical exponential phase of disease progress.

Stripe rust occurred on 6.6 million hectares in 11 provinces (Fig. 1, Table 2), resulting in the largest epidemic of the past three decades. These regions include the over-summering areas in Northwest China, mainly eastern Gansu (P1) and northwestern Sichuan (P4), and important wheat growing areas in eastern China: Henan (P9), Shandong (P11), Hebei (P10), and Hubei (P8). Wheat acreage and percentage of total fields infected for these provinces are shown in Table 2. The total yield loss was estimated to be about 1.31 million metric tons (1.4%) nationwide, which was the biggest yield loss of the last decade. As shown in Table 2, it was estimated that 6.2 million hectares were sprayed with the fungicide triadimefon and that 1.9 million metric tons of yield losses were prevented by fungicide applications based on yield data from fungicide nurseries.

Virulence of *P. striiformis* f. sp. *tritici* in 2002. In 2002, 37 different virulence

Table 2. Total wheat acreage, estimated infected acreage, acreages of fungicide application, estimated yield losses, and yield protected by fungicide application for each of the 11 provinces in 2002

Province		Wheat acreage	Estimated infected acreage		Acreage of fungicide application	Estimated yield loss		Yield protected by fungicide application
No.	**Name**	**(1,000 ha)**	**(1,000 ha)**	**%**	**(1,000 ha)**	**%**	**(1,000 ha)**	**(1,000 tons)**
P1	Gansu	479	479	100	479	2.8	90	180
P2	Ningxia	215	215	100	215	4.5	45	175
P3	Shaanxi	912	621	68.1	545	3.0	124	184
P4	Sichuan	1,220	1,015	83.2	1,220	6.8	336	600
P5	Chongqing	105	105	100	105	3.6	35	32.65
P6	Yunnan	319	278	87.1	533	21.2	360	–[a]
P7	Guizhou	191	140	73.3	191	1.1	10	18.9
P8	Hubei	659	659	100	498	5.6	90	162.3
P9	Henan	4,171	1,523	36.5	1,249	0.6	137	240.5
P10	Hebei	2,356	558	23.7	569	0.1	13	56.1
P11	Shandong	3,180	1,000	31.4	582	0.5	70	255
	Total		6,593		6,186	1.9	1,310	1,904.45

[a] Data not available.

patterns were detected from 926 stripe rust samples (Table 3). Of the 37 virulence patterns, only one race, CYR17, was first detected before 1970; six races (CYR18, CYR21, CYR22, CYR23, CYR24, and CYR26) were first detected in the 1970s; 10 races (CYR27, CYR28, CYR29, Lov10-3, Lov10-5, Lov13-2, Lov13-3, Lov13-8, SY11-1, and SY11-2) were first detected in the 1980s; and the remaining 20 were first detected in the 1990s. None of the races were virulent on Zhong 4 (differential 15). All but races CYR17 and CYR18 were virulent on Fulhard, Lutescens 128, Abbondanza, Early Premium, and Fengchan 3. Race CYR17 had the narrowest virulence spectrum, and race CYR32 had the widest virulence spectrum. Race CYR32 had a combination of virulences to differential genotypes Lovrin 10, Lovrin 13, Hybrid 46, and Shuiyuan 11, which have been used as group "pathotypes" (34,36).

Frequencies of 30 races detected with more than 0.5% in 2002 were compared with their frequencies from 1997 to 2001 (Fig. 2). Race CYR32 with a frequency of 34.6% was the most predominant in 2002 (Table 3). Races with frequencies above 5% included CYR31 (6.6%), SY11-4 (6.1%), and SY11-14 (8.8%). Race CYR32 had the most dramatic increase from 1997 to 2002 and played a major role in causing the widespread epidemic in 2002.

Because race CYR32 had the widest virulence spectrum and was the most predominant race in 2002, the typical isolate of CYR32 and isolates collected in 2002 from Hennan, Sichuan, and Yunna provinces representing the rust populations from a wide geographic area were tested on the world and European differential sets and other genotypes with reported resistance genes (Table 4). These isolates were avirulent on Moro, *Triticum spelta album*, and Merring*/K733 and virulent on Chinese 166, Lee, Suwon 92/Omar, Heines Peko, Nord Desprez, Heines VII, Sonalika, Lovrin 10, Maris Huntsman, Anza, Gaby, Selkirk, Nugaines, Avocet S, and Mingxian 169. The typical isolate of CYR32 and the isolate (also CYR32) from Yunnan were virulent on Vilmorin 23 while the isolates from Henan (SY11-4) and Sichuang (SY11-14) produced intermediate reactions on Vilmorin 23.

No stripe rust occurred in the trap nursery in Wendeng of Shandong (P11), and only a trace of rust was present in Linzhi of Tibet (P15) and Yuxi of Yunnan (P6) provinces (Table 5). In contrast, stripe rust was severe in Gansu (P1), Sichuan (P4), southern Shaanxi (P3), southern Henan (P9), and Hubei (P8) provinces. Adult plants of Cappelle-Desprez, Clement, Heines Kolben, Hybrid 46, Maris Huntsman, Mega, Moro, Strubes Dickkopf, Spaldings Prolific, *T. spelta album*, Vilmorin 23, VPM 1, and Zhong 4 were moderately or highly resistant. Cultivars with *Yr1* such as Chinese 166 and Fengchan 3, and those with *Yr9* such as Kavkaz, Lovrin 10, Lovrin 13, and Neuzucht, were susceptible. Wheat genotypes such as Jubilejina 2, Abbondanza, Funo, and Fan 6, which have been widely used as resistance sources (20), also were susceptible.

Table 3. Races of *Puccinia striiformis* f. sp. *tritici* and their first year of detection, frequency in 2002, and virulence (V) and avirulence (A) on Chinese differential genotypes

Race[a]	Year first detected	% in 2002	Virulence (V) and avirulence (A) of races on differential genotype[b]																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CYR17	1965	0.7	VA	V	A	VA	A	VA	V	A	A	A	AV	A	A	A	A	A	A
CYR18	1972	0.3	A	A	V	AV	A	V	AV	AV	V	A	AV	A	A	A	A	A	A
CYR21	1975	1.5	VA	V	V	VA	A	V	V	VA	VA	V	V	A	A	A	A	A	A
CYR22	1975	1.6	V	V	V	VA	A	V	V	V	VA	V	V	A	V	A	A	A	A
CYR23	1978	0.8	V	V	V	V	A	V	V	V	V	A	V	A	A	A	A	A	A
CYR24	1978	1.3	VA	V	V	V	A	V	V	V	A	A	V	A	A	A	A	A	A
CYR26	1978	0.3	VA	V	V	A	A	V	V	V	V	A	V	A	A	A	A	A	A
CYR27	1980	0.1	V	V	V	V	V	V	V	V	V	V	V	A	V	A	A	A	A
CYR28	1983	1.2	V	V	V	V	V	V	V	V	V	A	V	A	A	A	A	V	A
CYR29	1985	1.5	V	V	V	V	V	V	V	V	V	A	V	V	A	A	A	V	A
CYR30	1991	3.2	V	V	V	V	V	V	V	V	V	A	V	V	A	A	A	V	V
CYR31	1993	6.6	V	V	V	V	V	V	V	V	V	A	V	V	A	V	A	V	V
CYR32	1994	34.6	V	V	V	V	V	V	V	V	V	V	V	V	V	V	A	V	V
Lov10–3	1986	0.1	A	V	V	V	A	V	V	V	V	A	V	A	A	A	A	V	A
Lov10-5	1988	0.9	V	V	V	V	A	V	V	V	V	A	V	A	A	A	A	V	A
Lov10–6	1991	0.5	V	V	V	VA	A	V	V	V	V	V	V	A	A	A	A	V	A
Lov13–2	1985	0.7	V	V	V	V	A	V	V	V	V	A	V	V	A	A	A	V	A
Lov13–3	1985	0.9	V	V	V	V	V	V	V	V	V	V	V	V	V	A	A	V	A
Lov13-8	1988	0.1	V	V	V	V	V	V	V	V	V	V	V	V	A	A	A	V	A
H46–4	1994	0.5	VA	V	V	V	V	V	V	V	V	V	V	A	V	V	A	A	V
H46–5	1995	2.1	V	V	V	V	VA	V	V	V	V	V	V	A	V	V	A	V	V
H46–6	1996	0.7	VA	V	V	V	V	V	V	VA	VA	A	V	A	A	V	A	A	V
H46–7	1996	2.1	A	V	V	V	VA	V	V	V	V	V	V	V	V	V	A	V	V
H46–8	1996	2.5	VA	V	V	V	VA	V	V	V	V	V	V	V	A	V	A	V	V
H46–9	1996	0.3	V	V	V	V	V	V	V	V	V	V	V	A	V	V	A	A	V
SY11–1	1982	0.1	V	V	A	A	A	A	V	A	A	A	A	A	A	V	A	A	A
SY11-2	1985	0.8	V	V	V	V	V	V	V	V	V	A	V	A	A	V	A	A	A
SY11–3	1993	2.1	VA	V	V	V	V	V	V	V	V	V	V	A	V	V	A	A	A
SY11–4	1995	6.1	AV	V	V	V	A	V	V	V	V	V	V	A	V	V	A	V	A
SY11–5	1995	2.9	V	V	V	V	VA	V	V	V	V	AV	V	A	A	V	A	V	A
SY11–7	1995	2.3	V	V	V	V	VA	V	V	V	V	A	V	V	A	V	A	V	A
SY11–8	1996	1.4	V	V	V	V	A	V	V	V	V	A	V	A	A	V	A	A	A
SY11–10	1996	1.1	A	V	V	V	A	V	V	V	V	A	V	A	A	V	A	A	A
SY11–11	1996	0.9	V	V	V	V	A	V	V	V	V	V	V	A	V	V	A	A	A
SY11–12	1996	1.7	A	V	V	A	A	V	V	V	V	A	V	A	A	V	A	V	A
SY11–13	1997	0.9	V	V	V	V	A	V	V	V	V	V	V	A	A	V	A	A	A
SY11-14	1997	8.8	AV	V	V	V	VA	V	V	V	V	V	V	V	V	V	A	V	A

[a] CYR indicates races of Chinese Yellow Rust; Lov10-X, Lov13-X, H46-X, and SY11-X indicate different "pathotypes" within race groups virulent on Lovrin 10, Lovrin 13, Hybrid 46, and Shuiyuan 11, respectively.

[b] Chinese differential genotypes: 1 = Trigo Eureka, 2 = Fulhard, 3 = Lutescens 128, 4 = Mentana, 5 = Virgilio, 6 = Abbondanza, 7 = Early Premium, 8 = Funo, 9 = Danish 1, 10 = Jubilejina 2, 11 = Fengchan 3, 12 = Lovrin 13, 13 = Kangyin 655, 14 = Shuiyuan 11, 15 = Zhong 4, 16 = Lovrin 10, and 17 = Hybrid 46. V = virulent, A = avirulent, and AV and VA indicate varied reactions.

DISCUSSION

The stripe rust epidemic in the 2001–2002 growing season was one of the four most damaging epidemics recorded in Chinese history. It affected 6.6 million hectares, which is comparable to the 8.3, 8.0, and 5.6 million hectares affected in 1950, 1964, and 1990, respectively (20,46). Damage of the 2002 epidemic (1.3 million metric tons) was much less than the damage in 1950 (6.0 million metric tons), 1964 (3.0 million tons), and 1990 (1.8 million metric tons) epidemics because of the wide use of fungicides.

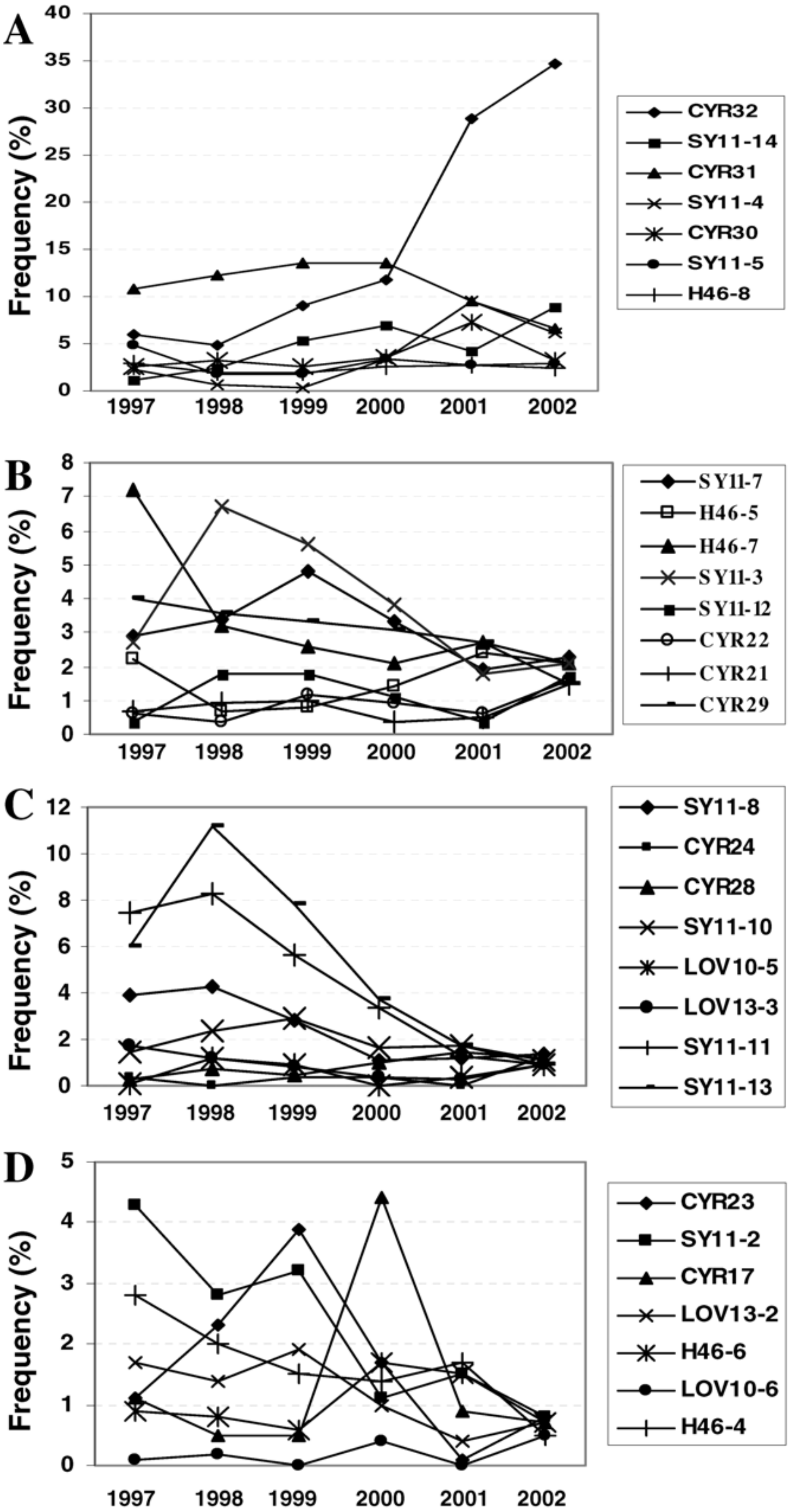

Fig. 2. Frequencies of races of *Puccinia striiformis* f. sp. *tritici* from 1997 to 2002. **A,** Predominant races occurring at frequencies from 2.5 to 35%, **B,** races at frequencies from 1.5 to 2.3%, **C,** races at frequencies from 0.9 to 1.4%, and **D,** races at frequencies from 0.5 to 0.8% in 2002. Races that had frequencies less than 0.5% are not shown.

Widely distributed virulent races, cultivars with ineffective race-specific resistance, and rust-favorable weather were major factors contributing to the 2002 epidemic. The relatively warm winter and early spring in 2001–2002 was favorable for overwintering and development of rust. The temperatures were ≥1°C higher than average during the late winter and early spring across China in 2002. For example, monthly average temperatures from December 2001 to March 2002 in Kunming, Yunnan, were 11.4, 10.6, 14.1, and 15.5°C, respectively, which was 1.5 to 3.4°C higher than means of monthly average temperatures (9.2, 9.1, 10.7, and 13.8°C, respectively, for these months) from 1982 to 2002. In Chengdu, Sichuang, the average monthly temperature was 11.3°C for February and 14.7°C for March 2002, while the mean of the average monthly temperature from 1982 to 2002 was 8.0°C for February and 11.8°C for March. In Laohekou, Hubei, the winter average monthly temperatures were 6.6, 9.4, and 18.3°C in January, February, and March 2002, respectively, which were 2.2 to 4.8°C higher than means of the average monthly temperatures (3.8, 7.2, and 13.5, respectively) from 1996 to 2002. In most areas of Sichuan and in some areas in northern Hubei and southern Shannxi provinces, the pathogen infected crops, reproduced, and spread during the 2001–2002 winter season. Precipitation was also higher than average during the 2002 growth season. For example, Guiyang, Guizhou, had 64.6 mm of precipitation in February 2002, 30.6 mm more than the average for that month from 1982 to 2002. In March 2002, Chongqing; Laohekou, Hubei; and Zhengzhou, Henan had 50.6, 56.4, and 24.6 mm of precipitation, which was 12, 121, 186% more than the averages (45.1, 25.5, and 8.6 mm), respectively, for these locations from 1982 or 1996 to 2002. The higher rainfall was associated with a decrease in temperature during the late spring.

As in 1950, 1964, and 1990, a single cultivar or cultivars with the same source of resistance, grown over large acreage, was the major cause of the widespread epidemic in 2002. Two major groups of cultivars, *Yr9* and Fan 6 derivatives, have been grown in more than 80% of the wheat acreage in recent years. The *Yr9* derivatives, which include genotypes that have Lovrin 10, Lovrin 13, Aurora, Kavkaz, Neuzucht, Predgornaya, and other 1BL/1RS genotypes in their pedigrees, have been used in breeding programs throughout the country since the 1960s. Cultivars with *Yr9* include the Yumai series (e.g., Yumai 10, Yumai 21, Yumai 36, Luozhen 1, and Yunong 118) in Henan Province, the Lumai series (e.g., Lumai 1, Lumai 14, and Lumai 15) in Shandong, the Jimai series (e.g., Jimai 24) in Hebei, the Jinmai series (e.g., Jinmai 49) in Shanxi, and the Ermai series (e.g., Ermai 1) in Hubei. These cultivars also have been grown in other provinces. The second group of cultivars includes those developed from Fan 6, containing the Hybrid 46 resistance. Fan 6 has been used by breeders since the 1970s and gave rise to Miannong 4, Mianyang 11, Mianyang 19, Mianyang 25, Mianyang 26, Mianyang 28, Mianyang 29, Chuanmai 22, Chuanmai 25, Chuanmai 26, Chuanmai 28, Chuanmai 29, Chuanyu 12, and Chuanyu 24. Most of these cultivars became susceptible to races CYR31 and CYR32, which were first detected in the early 1990s (34) in western China (Gansu, Sichuan, and Qinghai) and subsequently spread to other regions.

In 1991, virulence on Hybrid 46 (*Yr4b*, *YrH46*), the resistance source for all Fan 6 derivative cultivars, was first detected in Sichuan and Yunnan provinces, and these isolates, with virulence to 13 of the 17 differential genotypes, were designated race CYR30 (31,38). Race CYR31, with similar virulence to CYR30, and Shuiyuan 11 were detected in 1993. The most virulent race, CYR32, with virulence on all differentials except Zhong 4, was detected first in 1994 and was recognized as H46-3 until the new designation in 2002 (36). Race CYR32 combines all previous virulences, especially those on *Yr9*, Hybrid 46, and Shuiyuan 11, that have been the major resistance sources since the 1960s. In 2002, this race was virulent to *Yr1*, *Yr2*, *Yr3*, *Yr4*, *Yr6*, *Yr7*, *Yr9*, *Yr17*, *Yr22*, *Yr23*, *Yr27*, *YrA*, *YrCV1*, *YrCV2*, *YrCV3*, *YrG*, *YrSD*, and *YrSO*. Race CYR32 can be considered race 239E175 in the world and European race nomenclature (18). Evaluation of wheat cultivars showed that more than 80% of the currently grown cultivars were susceptible to CYR31 and CYR32 (data not shown).

Races CYR30, CYR29, SY11-4, and SY11-14 had relatively high frequencies in the 2002 growing season. An isolate from Sichuan was virulent on Compair, which has resistance genes *Yr8* and *Yr19* (4), and was virulent on Clement with *Yr9* and *YrCle* (8). Isolates with combined virulences on *Yr8* and *Yr9* were reported in the United States in 2000 (9) and in Australia in 2002 (43).

Fang (14) published the first paper on the identification of stripe rust races in China in 1944. Using the wheat genotypes Carstens V, Heines Kolben, Vilmorin 23, 9 H 77, Hybrid 128, Carina, and Michigan Amber and barley genotype Heil's Franken as differentials, Fang identified nine races (C1 to C9) from 43 stripe rust samples in Southwest China. In 1955, Fang and Chen (15) detected five races from 18 samples in eastern China using the same differentials. In 1956, Lu et al. (24), using Gassner and Straib's (16) 14 differentials, reported 16 races from 50 samples. Although changes among differentials were made several times, the race nomenclature system has been relatively formal and continually used since 1957 (34,41,45). The current Chinese differential set consists of 17 wheat genotypes (Table 1) (20,31,34,36). Traditionally, the major virulence patterns were named as races with CYR (for Chinese Yellow Rust); and similar virulence patterns, especially virulence on some key differential genotypes like Lovrin 10, Lovrin 13, Hybrid 46, and Shuiyuan 11, were considered "pathotypes" (34,36,40,41). So far, 32 CYR races and 35 "pathotypes" of *P. striiformis* f. sp. *tritici* have been identified in China. All of the 67 virulence patterns should be considered races based on their avirulence/virulence formula on the 17 differentials. The population structures of the pathogen based on virulence have varied with the corresponding resistance changes in wheat cultivars. The annual surveys of *P. striiformis* f. sp. *tritici* have provided the information on virulence variability of the pathogen in China, and those results have been previously published (34,39–41,45).

In China, prediction of the frequency of occurrence of new races with relatively better parasitic fitness (i.e., wider virulence spectrum, high frequency, virulent to larger number of cultivars) is considered important. Although progress has been made, improvement in stripe rust monitoring and race identification is still needed. The current race identification system has two major drawbacks: the differential genotypes are used only in China, and most of

Table 4. Infection types (IT) produced by race CYR32 and some 2002 representative isolates of *Puccinia striiformis* f. sp. *tritici* collected from Henan, Sichuan, and Yunnan provinces on the world, European, and supplemental differential genotypes

		IT produced by isolates of *P. striiformis* f. sp. *tritici*[b]			
Differential genotype	***Yr* genes[a]**	**CYR32 (typical)**	**SY11-4 (Henan, P9)**	**SY11-14 (Sichuan, P3)**	**CYR32 (Yunnan, P6)**
World differentials					
Chinese 166	*1*	9	7-9	7-8	9
Lee	*7, 22, 23*	9	7	7-8	9
Heines Kolben	*2,6*	9	2-3	3	9
Vilmorin 23	*3a,4a*	9	4-6	3-6	9
Moro	*10,Mor*	0	0	0	1
Strubes Dickkopf	*SD,25*	9	2-3	7	9
Suwon 92/Omar	*4,Su*	9	7-9	8-9	9
Clement	*2,9,25,Cle*	9	7-9	9	9
Triticum spelta album	*5*	0	0	1	1
European differentials					
Hybrid 46	*4b*	9	3	1, 7	9
Reichersberg 42	*7,25*	7-9	3	2, 5	9
Heines Peko	*2,6,25*	8-9	7-9	8-9	9
Nord Desprez	*3a,4a*	9	9	8-9	9
Compair	*8,19*	1	0	8-9	1
Carstens V	*Cv*	9	2-3	8, 5	7
Spaldings Prolific	*Sp*	0	7-9	9	1
Heines VII	*2,25,HVII*	9	7-9	9	9
Supplemental differentials					
Sonalika	*2,A*	9	9	8-9	7-9
Lovrin 10	*9*	9	9	8-9	9
Lovrin 13	*9*	9	3-5	8-9	9
Aurora	*9*	8-9	3-6	7, 5	9
Mega	*3a,4a*	7	1	3, 7	7
Maris Huntsman	*2,3a,4a*	9	7-8	9	9
Hobbit	*3a,4a*	9	2	9	9
VPM1	*17*	7	6-7	6	3
Anza	*A*	9	6-7	7-9	9
Merring*/K733	*24*	1	2	1	2
Gaby	*G*	9	8-9	6	9
Selkirk	*27*	7-9	7-8	7	7
Synthetic=Altar 84/ *T. tauschii* W-219	*28*	2, 5	9	2	2-3
Nugaines	?	9	8-9	7-9	9
Avocet S	Control	9	7-8	9	9
Mingxian 169	Control	9	9	7-9	9

[a] The *Yr* genes were based on McIntosh et al. (26).

[b] The infection types (IT) were described by Line and Qayoum (23): 0 = no visible signs or symptom, 1 = necrotic and/or clorotic flecks; no sporulation, 2 = necrotic and/or chlorotic blotches or stripes; no sporulation, 3 = necrotic and/or chlorotic blotches or stripes; trace sporulation, 4 = necrotic and/or chlorotic blotches or stripes; light sporulation, 5 = necrotic and/or chlorotic blotches or stripes; intermediate sporulation, 6 = necrotic and/or chlorotic blotches or stripes; moderate sporulation, 7 = necrotic and/or chlorotic blotches or stripes; abundant sporulation. 8 = chlorosis behind sporulating area; abundant sporulation, 9 = no necrosis or chlorosis; abundant sporulation.

their resistance genes are unknown. Because different genotypes are used as differentials, it is difficult to compare the Chinese stripe rust populations with those in other countries. Among the differentials, only Fengchan 3 (*Yr1*), Danish 1 (*Yr3*), Hybrid 46 (*Yr4b*, *YrH46*), Trigo Eureka (*Yr6*), Lovrin 10 (*Yr9*), Lovrin 13 (*Yr9*), and Funo (*YrA*) have identified resistance genes (5,26,27,29). Based on differential reactions to races such as CYR28, H46-5, and SY11-12, differential genotype Lovrin 13 should have a different gene in addition to *Yr9*. Studies are underway to analyze the resistance genes in the Chinese differentials. Another approach to solving this problem is to use near-isogenic lines (NILs) for *Yr* genes. Currently, we are using the *Yr* NILs developed in the Plant Breeding Institute at the University of Sydney, Australia, for monitoring virulences of the stripe rust pathogen. *Yr* NILs for the resistance genes in the Chinese differential genotypes are under development.

In Northwest and Southwest China, annual climatic conditions, geographic characteristics, and cropping systems are favorable for stripe rust every year in some parts of Gansu, Sichuan, Shaanxi, and Yunnan provinces. The environment and cropping systems provide ideal conditions for the survival, mutation, and development of races of the stripe rust pathogen. Especially in southeastern Gansu and northwestern Sichuan, the pathogen can survive and reproduce year-round (19). These regions appear to be major centers of stripe rust diversity and also provide inoculum and new races for other regions in China. Furthermore, almost all Chinese races and pathotypes were first detected in these regions (34,39–41,45). Historically, every resistance “breakdown” event occurred first in these regions.

Despite the less frequent occurrence of favorable weather conditions in North China, especially the lower part of the Yellow River Valley (Shanxi, Henan, and Shandong provinces), which is one of the major wheat producing areas, stripe rust has the potential to cause significant yield losses, as witnessed in 1950, 1964, 1990, and 2002 in this region. Although the focus of stripe rust management in China is mainly in Northwest and Southwest China, attention should be paid to the eastern growing areas as well in case of widespread epidemics.

Migration of stripe rust urediniospores might occur among China, India, Pakistan, Nepal, and other central Asian countries, but this possibility should be very low because of geographic barriers. Geographically, China is relatively isolated in terms of inoculum exchange with other epidemic zones for stripe rust in Asia (30). Several high mountain ranges like Himalaya, Kunlun, and Altai, big deserts like Taklimakan and Gobi, and less wheat cropping land from the Southwest to the Northwest may prevent rust inoculum from moving between China and countries in

Table 5. Stripe rust severities and infection types of wheat cultivars in trap nurseries in various locations in 2002

		Stripe rust severity (%) and infection type (in parentheses) of wheat culitvars at various locations[b]							
Cultivar	***Yr* gene[a]**	**Linzhi Tibet (P15)**	**Gangu Gansu (P1)**	**Xindu Sichuan (P4)**	**Hanzhong Shaanxi (P3)**	**Nanyang Henan (P9)**	**Jingzhou Hubei (P8)**	**Yuxi Yunnan (P6)**	**Wendeng Shandong (P11)**
Alba	?	–	40 (1-5)	15 (6-7)	10 (1-3)	<5 (1-3)	5 (1-3)	0	0
Anza	*A*	<5 (1-3)	80 (6-7)	50 (8-9)	30 (1-3)	<5 (1-5)	65 (6-7)	0	0
Cappelle Desprez	*3a,4a,16*	0	20 (1-5)	5 (1-3)	15 (1-3)	<5 (1-3)	0	0	0
Chinese166	*1*	–	80 (6-7)	80 (8-9)	70 (8-9)	100 (8-9)	10 (4-5))	5 (4-5)	0
Clement	*2,9,25,Cle*	0	20 (6-7)	10 (1-3)	10 (1-3)	10 (1-3)	0	0	0
Compair	*8,19*	–	10 (1-3)	5 (1-3	5 (1-5)	<5 (1-3)	25 (4-5)	0	0
Heines Kolben	*2,6*	0	0	10 (1-3)	<5 (1-3)	0	10 (4-5)	0	0
Heines VII	*2,25,HVII*	25 (6-7)	40 (6-7)	60 (8-9)	20 (1-3)	15 (1-3)	25 (4-5)	0	0
Hobbit	*3a,4a,14*	0	40 (1-5)	0	5 (1-5)	0	0	0	0
Mingxian 169	None	–	80 (6-7)	50 (8-9)	60 (8-9)	50 (8-9)	65 (8-9)	10 (6-7)	0
Hybrid 46	*4b,H46*	0	5 (1-3)	10 (4-5)	<5 (1-3)	–	5 (1-3)	0	0
Joss Cambier	*11*	10 (1-3)	60 (1-5)	15 (6-7)	50 (1-3)	<5 (1-3)	5 (1-3)	0	0
Lee	*7,22,23*	0	20 (6-7)	50 (6-7)	10 (4-5)	<5 (4-5)	40 (6-7)	0	–
Maris Huntsman	*2,3a,4a,13*	0	10 (1-5)	<5 (1-3)	5 (1-3)	5 (4-5)	5 (1-3)	0	0
Mega	*3a,4a,12*	0	20 (1-5)	0	<5 (1-3)	0	5 (1-3)	0	0
Moro	*10,Mor*	0	0	<5 (1-3)	<5 (1-3)	<5 (1-3)	0	0	0
Selkirk	*27*	–	40 (1-5)	<5 (1-3)	20 (4-5)	<5 (1-5)	5 (1-3)	0	0
Strubes Dickkopf	*25,SD*	0	10 (1-5)	0	5 (1-5)	<5 (1-3)	5 (1-3)	0	0
Spaldings Prolific	*Sp*	0	0	0	5 (1-5)	<5 (1-3)	5 (1-3)	0	0
T. spelta album	*5*	<5 (1-3)	0	0	0	–	0	0	0
Vilmorin 23	*3a,4a*	0	10 (4-7)	<5 (1-3)	<5 (1-3)	<5 (1-5)	5 (1-3)	0	0
VPM1	*17*	–	10 (1-5)	<5 (1-3)	10 (4-5)	<5 (1-3)	5 (1-3)	0	0
Abbondanza	?	–	40 (6-7)	30 (8-9)	40 (6-7)	15 (6-7)	25 (6-7)	<5 (6-7)	0
Funo	*A*	–	40 (6-7)	15 (6-7)	40 (4-5)	<5 (6-7)	10 (4-5)	0	0
Fan 6	?	0	40 (6-7)	50 (8-9)	30 (6-9)	–	40 (6-7)	0	0
Fengchan 3	*1*	–	40 (1-5)	40 (6-7)	25 (4-5)	5 (6-7)	40 (6-7)	10 (6-7)	0
CI 12203	?	5 (1-3)	20 (6-7)	50 (6-7)	25 (4-7)	<5 (1-3)	40 (6-7)	5 (4-5)	0
Kavkaz	*9*	–	20 (6-7)	30 (6-7)	20 (4-5)	<5 (1-3)	25 (4-5)	0	0
Lovrin 13	*9*	TR	40 (6-7)	25 (6-7)	20 (6-7)	25 (6-7)	25 (6-7)	0	0
Mentana	?	10 (1-3)	10 (1-5)	50 (8-9)	20 (4-7)	20 (4-7)	25 (4-5)	0	0
Neuzucht	*9*	<5 (1-3)	40 (4-7)	70 (8-9)	20 (6-9)	25 (6-9)	25 (1-3)	0	0
Jubilejina 2	?	–	40 (6-7)	25 (6-7)	20 (6-7)	40 (6-7)	40 (4-5)	<5 (4-5)	0
Early Premium	?	–	40 (6-7)	25 (8-9)	25 (6-7)	10 (1-3)	10 (1-3)	0	0
Zhong 4	?	0	0	0	0	–	0	0	0
Chambord	?	–	20 (6-7)	10 (4-5)	20 (1-5)	<5 (1-3)	5 (1-3)	0	0
Quality	?	–	40 (1-7)	35 (8-9)	10 (6-7)	15 (4-7)	40 (6-7)	5 (4-5)	0

[a] *Yr* genes were based on McIntosh et al. (25,26).

[b] The modified Cobb scale (28) was used to determine the percentage of possible tissue infected (% severity) in adult plant stage. The infection types were described by Line and Qayoum (23): 0 = no visible signs or symptom, 1 = necrotic and/or clorotic flecks; no sporulation, 2 = necrotic and/or chlorotic blotches or stripes; no sporulation, 3 = necrotic and/or chlorotic blotches or stripes; trace sporulation, 4 = necrotic and/or chlorotic blotches or stripes; light sporulation, 5 = necrotic and/or chlorotic blotches or stripes; intermediate sporulation, 6 = necrotic and/or chlorotic blotches or stripes; moderate sporulation, 7 = necrotic and/or chlorotic blotches or stripes; abundant sporulation, 8 = chlorosis behind sporulating area; abundant sporulation, and 9 = no necrosis or chlorosis; abundant sporulation.

South and Central Asia. Increasing commercial exchange and travel may increase the possibility of moving urediniospores from other countries, as has been seen with introductions of exotic strains from other regions and/or countries to Australia (42,43) and South Africa (2).

Along with the devastating epidemics in 1950, 1964, and 1990, the 2002 epidemic again demonstrated the importance of stripe rust control in the wheat production of China. With nearly 30 million hectares of wheat that can be affected by stripe rust, China is the largest potential epidemic region in the world (30). Successful control of this disease will positively impact on the economy because China must improve food security and alleviate poverty for its expanding population. The 2002 epidemic and its control provided both valuable experience and lessons in the development of strategies for sustainable control of stripe rust in the future.

Based on cropping systems, weather conditions, and geographic characteristics that influence stripe rust epidemics, wheat growing areas can be separated into the western over-summering region and the eastern epidemic region (20). Strategies for controlling stripe rust can be slightly different for these two regions. Reducing the initial inoculum in the over-summering regions is a key strategy to achieve sustainable control of stripe rust in China (44). The integrated management to control stripe rust in these regions includes (i) diversification of resistance genes, (ii) deployment of resistant cultivars in different regions, (iii) reduction of wheat acreage by planting other crops such as vegetables, fruits, maize, and canola, and (iv) seed treatment with fungicides (11,32). Strategies for controlling stripe rust throughout the rest of the country include use of effective and durable resistance, appropriate use of fungicides, and cultural practices that can reduce stripe rust but do not have significant adverse effects on yield and consequent crops.

Use of resistance is the most cost-effective and environmentally sound method to reduce stripe rust damage. Resistant cultivars developed mainly since the 1950s have greatly reduced the frequency of major epidemics and have contributed to the increase of wheat production in the past 50 years (17,20). However, growing cultivars with few genes for race-specific resistance has selected more virulent races like CYR31 and CYR32, resulting in widespread epidemics like the one in 2002. It is important to seek effective resistance genes, especially genes for durable resistance to be used in breeding programs. Based on data of resistance evaluation in recent years, the resistance genes *Yr5*, *Yr10*, *Yr11*, *Yr12*, *Yr13*, *Yr14*, *Yr16*, and *Yr18* are still effective and can be used in developing new resistant cultivars. Gene pyramiding, gene deployment, and multiline cultivars should be considered in use of genes for race-specific resistance. High-temperature, adult-plant (HTAP) resistance, which has proven to be non-race-specific and durable, has been successfully used in control of wheat stripe rust in the Pacific Northwest of the United States (6,7,21,22). This type of resistance also has been found in Chinese cultivars (33,35). Based on weather conditions and disease development patterns, this durable type of resistance should be effective in the major wheat production regions in China.

Fungicide application, which reduced wheat yield losses in 2002, will be a necessary measure to combat stripe rust in the foreseeable future. Triadimefon (Bayleton) has been the most widely and extensively used fungicide to control stripe rust in China since the late 1970s (10,11) because it is relatively cheap and easy to use compared with other fungicides such as diniconazole, propiconazole (Tilt), and tebuconazole (Raxil), which were equally effective in efficacy tests (3,13,37). Even though stripe rust isolates resistant to triadimefon have not been found (12), it is highly recommended to use other effective active ingredients as alternatives and to develop new highly effective, low-cost, and less environmentally hazardous fungicides.

Forecasting played a positive role in controlling stripe rust in 2002 and will serve as an important component in integrated management by providing information to pathologists, growers, extension personnel, the agricultural chemical industry, and the government for informed decision making. Not only will accurate forecasts prepare growers for the possible need for disease control, predictions based on cultivar resistance, weather, and inoculum will prevent the unnecessary use of fungicides.

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