Race Composition of *Puccinia striiformis* f. sp. *tritici* in Tibet, China

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Abstract

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In Tibet, China, wheat stripe rust (caused by *Puccinia striiformis* f. sp. *tritici*) has recently become one of the most destructive diseases on winter wheat. To identify races of the pathogen in Tibet, 261 isolates were obtained in 2010 and tested on seedlings of a standard set of 19 wheat indicator genotypes. Of the 261 isolates, 248 were identified as members of 19 known races (CYR17, CYR20, CYR21, CYR22, CYR23, CYR29, CYR31, CYR32, CYR33, Lov13-6, Su11-1, Su11-2, Su11-3, Su11-4, Su11-5, Su11-6, Su11-7, Su11-8, and Su11-13), and 13 identified as representatives of 4 new races. CYR32 and CYR33 were the most predominant. The number of races and their frequencies in Tibet were more similar to the fungal populations in Sichuan and Gansu provinces than to those in Yunnan, Qinghai, and Shaanxi provinces. The results suggest that Tibet is also a possible center of inoculum source and genetic variation for the stripe rust pathogen in addition to Sichuan and Gansu.

Wheat stripe rust (yellow rust), caused by *Puccinia striiformis* f. sp. *tritici* Erikss., is one of most destructive diseases in many wheat-growing regions worldwide (2,6,11,20,21), including China (2,4,5). It was estimated that severe rust epidemics in China caused yield losses of 6.00, 3.20, 2.65, and 1.40 million metric tons in 1950, 1964, 1990, and 2002, respectively(5,12).

Host resistance genes have been deployed to manage stripe rust in China but are often overcome by the pathogen. New races capable of overcoming single-gene conferred resistance often render corresponding resistance genes ineffective within 5 years of deployment in commercial wheat cultivars (3,14,15). Since the 1950s, wheat cultivars have been changed eight times on a large scale in order to keep up with the pace of emergence of new *P. striiformis* f. sp. *tritici* races. In recent years, resistance to *P. striiformis* f. sp. *tritici* in more than 95% of Chinese cultivars has been overcome (13). Understanding the pathogen race composition in time and space is important for breeding cultivars with effective resistance genes (2,7,10,14,15). The Chinese National Wheat Rust Collaborative Group (CNWRCG) has been monitoring *P. striiformis* f. sp. *tritici* races since 1957. To date, 33 Chinese yellow rust (CYR) races have been named; in addition, there are more than 40 unnamed races that have already been identified (1).

Tibet Autonomous Region is situated in the southwest of China bordering Sichuan, Yunnan, Qinghai, and Xinjiang provinces (Fig. 1) and also India, Burma, Bhutan, and Nepal. The average altitude of Tibet is over 4,000 m. Wheat is the second most important food crop in Tibet, second only to barley. Winter wheat accounted for nearly 77% (28,000 hectares) in 2010, primarily in Lasha, Shannan, Linzhi, Rikeze, and Changdu regions (Fig. 1). Wheat-growing areas in Tibet can be classified into three cropping zones. The first zone consists of the winter wheat areas in low-elevation valleys in the southeast of Tibet, including Caou, Caya, Basu, Mangkang, Bomi, Linzhi, Milin, and Yadong counties. These areas are located in the warm and humid plateau, with an average altitude below 3,000 m and minimum temperatures usually above –2°C. The second zone covers the winter and spring wheat areas in the cool and semiarid plateau, with altitudes between 3,000 and 4,000 m, including the Changdu, Lasa, Shannan, and Rikeze regions. The third zone consists of the spring wheat areas in the cold and wet or semiarid plateaus of northwestern and southwestern Tibet, with altitudes over 4,000 m. Wheat stripe rust mainly occurs on winter wheat in the first two zones, where the climatic conditions are generally conducive to stripe rust development and enable the pathogen to complete its life cycle (17). Because susceptible cultivars have been grown during the last decade in Tibet, wheat stripe rust has gradually become a limiting factor for winter wheat production, particularly in Linzhi. Information on *P. striiformis* f. sp. *tritici* races in Tibet is limited, hampering effective deployment of resistant cultivars.

To fill this knowledge gap on *P. striiformis* f. sp. *tritici* races in Tibet, we have collected 376 *P. striiformis* f. sp. *tritici* samples from Tibet and identified races using a standard set of wheat genotypes that have been used to differentiate *P. striiformis* f. sp. *tritici* races in China (1). Frequencies of *P. striiformis* f. sp. *tritici* races in Tibet were compared with those from other major stripe rust epidemic areas in China, including Sichuan, Yunnan, Qinghai, Gansu, and Shaanxi provinces (9). This information on race composition is valuable for understanding pathogen dispersal among different regions, and for breeding and deploying resistant cultivars to manage wheat stripe rust in Tibet and other provinces.

Materials and Methods

Collecting stripe rust samples. In total, 376 *P. striiformis* f. sp. *tritici* samples were randomly collected from adult plants in Miling, Lingzhi, Gongbujiangda, and Bomi counties in Lingzhi, Tibet in June 2010 (Table 1; Fig. 1). Leaves with sporulating stripe rust lesions were kept in an envelope inside a desiccator at room temperature for a maximum of 7 days before inoculum multiplication.

Multiplying urediniospores. Leaf samples were incubated on water-soaked tissue paper in petri dishes in the dark at 4°C for 15 to 18 h to produce fresh urediniospores, which were used to inoculate seedlings of susceptible 'Mingxian 169' to multiply inoculum. Seed were sown in pots of 10 cm in diameter containing cow dung compost and soil. Ten days after sowing, seedlings with two leaves

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were inoculated with fresh urediniospores of a single isolate using a spatula. A single urediniospore was obtained with a needle under ×200 magnification (BX51 Olympus microscope). Immediately after inoculation, the seedlings were kept in a dew chamber at 10°C for 24 h and then placed on greenhouse benches with temperatures of 14 to 17°C and a photoperiod of 10 to 14 h. The plants were covered with a transparent plastic cylinder to prevent cross contamination. Fresh urediniospores produced on these inoculated seedlings were then collected, vacuum dried, and kept at –80°C until used to test on differential cultivars.

Differential genotypes. The 19 standard wheat genotypes (1) were used to differentiate *P. striiformis* f. sp. *tritici* races. These (together with their corresponding resistance genes) are Trigo Eureka (*Yr6*), Fulhard (unknown), Lutescenes 128 (unknown), Mentana (unknown), Virgilio (*YrVir1*, *YrVir2*), Abbondanza (unknown), Early Piemium (unknown), Funo (*YrA*, other unknown), Danish (*Yr3*), Jubilejina (*YrJu1*, *YrJu2*, *YrJu3*, *YrJu4*), Fengchan 3 (*Yr1*), Lovrin 13 (*Yr9*, other unknown), Kangyin 655 (*Yr1*, *YrKy1*, *YrKy2*), Suwon11 (*YrSu*), Zhong 4 (unknown), Lovrin 10 (*Yr9*), Hybrid46 (*Yr3b*, *Yr4b*), *Triticum spelta album* (*Yr5*), and Guinong 22 (unknown).

Identifying races. The standard protocol as previously described (1,12) was used to determine races for the isolates. If the test data suggested that an isolate was composed of more than one race, spores were collected from one or more differential genotypes to obtain subisolates; these subisolates were then tested again on the 19 differential genotypes. Sometimes, several cycles of subisolating and testing were necessary to assign a relatively pure subisolate for identifying it to a single race.

Determination of races was based on the infection type (IT) recorded 15 to 20 days after inoculation on a scale of 0 to 9 (8). An isolate was considered avirulent on a particular genotype when its IT score was in the range of 0 to 6 (0: no visible symptoms; 1: necrotic flecks; 2: necrotic areas without sporulation; 3: necrotic and chlorotic areas with restricted sporulation; 4–6: moderate uredinia with necrosis and chlorosis). Otherwise, an isolate was classified as virulent; that is, resulting in production of abundant uredia with chlorosis (IT 7 and 8) or without chlorosis (IT 9). All experiments were carried out in Shaanxi Taibai Key Field Observation Experimental Station of Wheat Stripe Rust, the Ministry of Agriculture, China.

The frequencies of *P. striiformis* f. sp. *tritici* races in Tibet were compared with those in other major stripe rust epidemic provinces of China (Gansu, Qinghai, Yunnan, Sichuan, and Shaanxi) in 2010 (9)m and χ^2 tests based on the maximum likelihood test were used to determine whether the frequencies of virulences against major resistance genes differed among the six regions (Gansu, Qinghai, Yunnan, Sichuan, Shaanxi, and Tibet).

Results

Of the 376 samples collected from Miling, Linzhi, Gongbujiangda, and Bomi, 261 isolates were recovered and identified for their respective *P. striiformis* f. sp. *tritici* races. In total, 248 of the 261 isolates were identified as 19 previously reported races (Table 2). Among them, CYR32 (31.8%) and CYR33 (24.1%) were the most prevalent races, whereas the other 17 races had frequencies less than 7%. The other 13 isolates were identified as four new races that differed in their virulence on four differential genotypes (Mentana, Early Premium, Fengchan 3, and Suwon11; Table 2).

More races of the early-CYR series (prior to CYR28) were detected in Tibet than in other major provinces (Table 3), except in Gansu. CYR17, CYR20, CYR21, and CYR23 were detected in

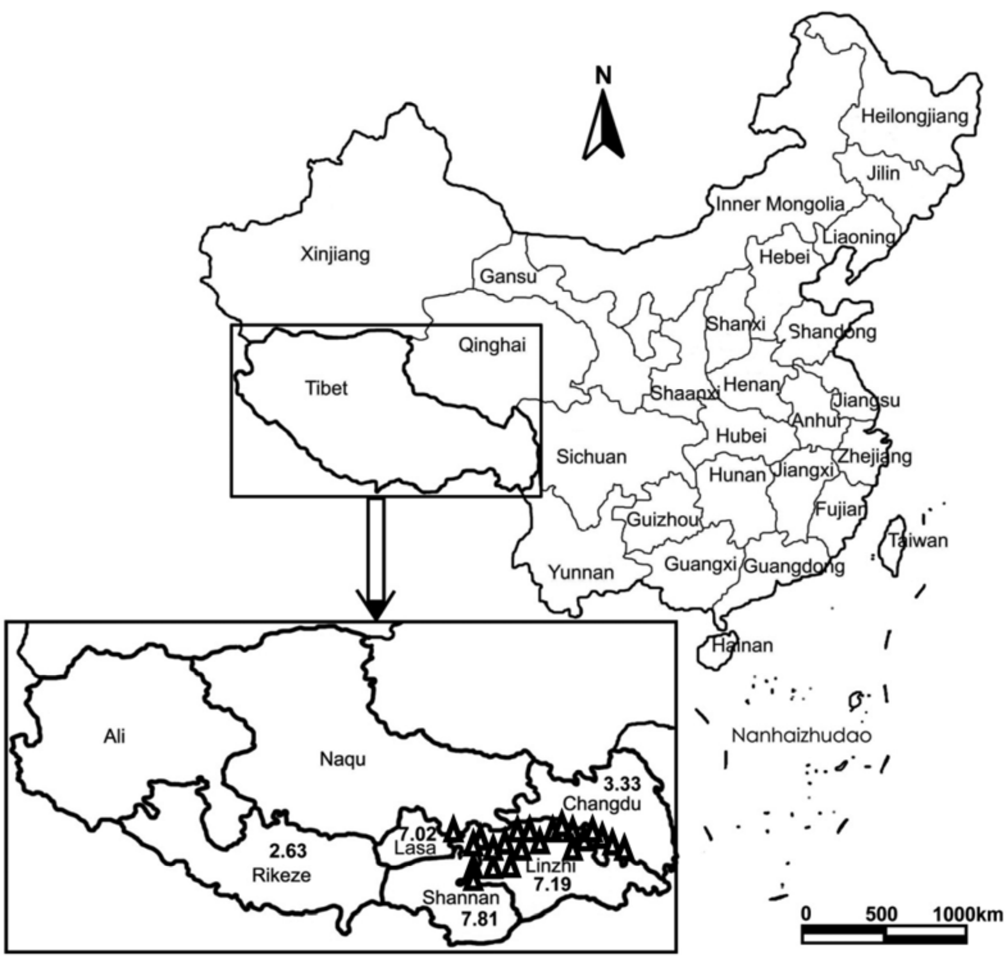

Fig. 1. Winter-wheat-growing areas in Tibet in 2010. Open triangles represents sites that were sampled for *Puccinia striiformis* f. sp. *tritici* in 2010. Number next to the site name is the winter wheat area (in thousand hectares) in the corresponding locations.

both Tibet and Gansu; the frequency of these races in Gansu was lower than in Tibet (Table 3). Fewer races were detected in Qinghai and Yunnan than in the other four provinces, possibly due to fewer samples (Table 3). Although Spearman's rank correlation indicated that prevalent races were similar in most sampled regions, the race composition in Tibet was similar to only those of Sichuan and Gansu ($P < 0.05$) based on Lin's concordance correlation coefficient. CYR32 and CYR33 were the most common races in Tibet, Gansu, and Shaanxi (Table 3). Only races CYR32 and CYR31 in the Hybrid 46 group were found in Tibet, which was similar to Qinghai. In contrast, more races were found in the Hybrid 46 group in other regions (Table 3). More races in Suwon 11 group were found in Tibet, Sichuan, Gansu, and Shaanxi than in Qinghai and Yunan. Overall, relative frequencies of races in the five groups differed significantly among the six provinces ($P < 0.001$; Fig. 2). Races in Tibet, Sichuan, and Shaanxi were dominated by races in the Hybrid 46 and Suwon 11 groups whereas, in Gansu, races in the Suwon 11 and others groups dominated.

The overall frequencies of virulence types against *Yr1* (Fengchan 3), *Yr3* (Danish 1), and *YrA* (Funo) were similar across

Table 1. Information on the sites in Tibet from which wheat leaves with stripe rust lesions were sampled in 2010

Site	Latitude and longitude	Elevation (m)	Severity (%)[a]	Incidence (%)[b]	Number of samples
Dongru village, Bayi town, Linzhi county	N29°38′12.0″ E94°20′53.6″	3,000	20–30	100	10
Jiemai village, Bayi town, Linzhi county	N29°34′15.5″E94°25′19.4″	2,962	15–20	85	16
Bujiu town, Linzhi county	N29°28′40.1″ E94°25′1.5″	2,943	20–30	100	17
Bangna village, Bujiu town, Linzhi county	N29°28′30.8″ E94°26′41.4″	2,943	10–50	100	15
Meeting rivers, Linzhi county	N29°25′59.1″E94°27′9.6″	2,938	10–20	75	13
Gengzhang villiage, Linzhi county	N29°45′17.1″E94°1′50.3″	3,102	10–20	100	21
Baiba villiage, Linzhi county	N29°48′18.0″E93°48′1″	3,174	5	1	6
Gangga village, Milin county	N29°16′47.6″E94°18′45.4″	2,934	5–15	80	32
Near airport, Langduo town, Milin county	N29°21′46.2″E94°26′1.6″	2,931	20–30	100	20
Milin village, Nanyiluoba town, Milin county	N29°11′20.3″E94°10′41.9″	2,960	10–20	100	29
Mini village, Qiangna town, Milin county	N29°22.7′10.7″E94°33′59.7″	2,936	20–30	100	28
Langga village, Danniang town, Milin county	N29°26′36.6″E94°42′11.1″	2,960	10–20	70	27
Bahe village, Gongbujiangda county	N29°54′21.8″E93°36′45.8″	3,249	5	1	8
Longya village, Zamu town, Bomi county	N29°45′32.8″ E95°58′5.3″	3,074	10–30	70	19
Gala village, Sunzong town, Bomi county	N29°48′37.7″ E95°48′14.8″	2,812	30–50	85	22
Genni village, Sunzong town, Bomi county	N29°44′47.7″ E96°5′7.5″	3,046	30–70	100	18
Kada village, Palongzangbu, Bomi county	N29°54′10.5″ E95°38′46.6″	2,720	20–50	60	13
Zhongsha village, Gu town, Bomi county	N29°54′38.3″ E95°29′9.2″	2,648	5–10	30	7
Suotong village, Gu town, Bomi county	N29°59′49.1″ E95°18′32.5″	2,448	20–50	80	19
Zibu village, Gu town, Bomi county	N29°33′27.2″ E94°30′4.1″	3,190	5	10	9
Mirui town, Linzhi county	N29°29′35.7″ E96°36′38.6″	3,086	30–50	70	14
Zhamu town, Bomi county	N29°50′35.4″ E95°46′42.7″	2,755	10–20	40	13

[a] Percentage of leaf area with uredia.
[b] Percentage of diseased plants.

Table 2. Races of *Puccinia striiformis* f. sp. *tritici* and their first year of detection, frequency in 2010 in Tibet, and virulence and avirulence on 19 Chinese differential genotypes

Race[b]	Year[c]	2010 (%)	Virulence (V) and avirulence (A) of races on differential genotype[a]																		
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CYR17	1965	4.60	VA	V	A	VA	A	VA	V	A	A	A	AV	A	A	A	A	A	A	A	A
CYR20	1968	4.60	AV	V	AV	AV	A	A	A	V	A	A	V	A	A	A	A	A	A	A	A
CYR21	1975	0.77	VA	V	V	VA	A	V	V	VA	VA	V	V	A	A	A	A	A	A	A	A
CYR22	1975	0.38	V	V	V	VA	A	V	V	V	VA	V	V	A	V	A	A	A	A	A	A
CYR23	1978	3.83	V	V	V	V	A	V	V	V	V	A	V	A	A	A	A	A	A	A	A
CYR29	1985	1.15	V	V	V	V	V	V	V	V	V	A	V	V	A	A	A	V	A	A	A
CYR31	1993	5.36	V	V	V	V	V	V	V	V	V	A	V	V	A	V	A	V	V	A	A
CYR32	1994	31.80	V	V	V	V	V	V	V	V	V	V	V	V	V	V	A	V	V	A	A
CYR33	1997	24.14	AV	V	V	V	VA	V	V	V	V	V	V	V	V	V	A	V	A	A	A
Lov13-6	1987	0.38	VA	V	V	V	V	V	V	VA	VA	A	V	A	A	V	A	V	A	A	A
Su11-1	1982	4.60	V	V	A	A	A	A	V	A	A	A	A	A	A	V	A	A	A	A	A
Su11-2	1985	0.38	V	V	V	V	V	V	V	V	V	A	V	A	A	V	A	A	A	A	A
Su11-3	1993	0.38	VA	V	V	V	V	V	V	V	V	V	V	A	V	V	A	A	A	A	A
Su11-4	1995	1.92	AV	V	V	V	A	V	V	V	V	V	V	A	V	V	A	V	A	A	A
Su11-5	1995	2.30	V	V	V	V	VA	V	V	V	V	AV	V	A	A	V	A	V	A	A	A
Su11-6	1995	6.90	V	V	V	AV	A	V	V	V	V	V	A	V	A	V	A	A	A	A	A
Su11-7	1995	0.38	V	V	V	V	VA	V	V	V	V	A	V	V	A	V	A	V	A	A	A
Su11-8	1996	0.38	V	V	V	V	A	V	V	V	V	A	V	A	A	V	A	A	A	A	A
Su11-13	1997	0.77	V	V	V	V	A	V	V	V	V	V	V	A	A	V	A	A	A	A	A
Unnamed	2010	0.38	A	V	A	A	A	A	V	A	A	A	V	A	A	A	A	A	A	A	A
Unnamed	2010	3.83	A	V	A	A	A	A	V	A	A	A	A	A	A	A	A	A	A	A	A
Unnamed	2010	0.83	A	V	A	V	A	A	V	A	A	A	A	A	A	A	A	A	A	A	A
Unnamed	2010	0.38	A	V	A	A	A	A	A	A	A	A	A	A	A	V	A	A	A	A	A

[a] 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 = Suwon 11, 15 = Zhong 4, 16 = Lovrin 10, 17 = Hybrid 46, 18 = *Triticum spelta album*, and 19 = Guinong 22. V = virulent, A = avirulent, AV = avirulence area > virulence area, and VA = virulence area > avirulence area.
[b] CYR: Chinese yellow rust; Lov13-X and Su11-X: different "pathotypes" within the race groups virulent on Lovrin 13 and Suwon 11, respectively.
[c] Year first detected.

the six regions, all close to 100%. The frequencies of virulence types against *Yr6* (Trigo Eureka), *Yr9* (Lovrin10 and Lovrin13), and *Yr3b/4b* (Hybrid 46) varied greatly among regions, ranging from 49.3% in Shaanxi to 100% in Qinghai, from 26.7% in Yunnan to 100% in Qinghai, and from 27.9% in Qinghai to 73.3% in Yunnan, respectively. Relative frequency of virulence against *Yr1*, *Yr3*, and *YrA* did not significantly vary among the six regions ($P > 0.05$) but relative frequency of virulence against *Yr6*, *Yr9*, and *Yr3b/4b* significantly varied among the six provinces ($P < 0.001$; Table 4).

Discussion

Wheat strip rust has caused huge yield losses about once every decade in China since 1940s (5). Resistance to stripe rust in major wheat cultivars has been regularly circumvented. In China, major resistance genes such as *Yr1*, *Yr3*, and *YrA* appear to be almost completely overcome by all tested *P. striiformis* f. sp. *tritici* isolates. This present survey study suggested that other genes such as *Yr6* and *Yr9* were ineffective against considerable proportions of tested isolates in major wheat-growing areas. Thus, these genes should not all be used in breeding programs.

To monitor the dynamics of *P. striiformis* f. sp. *tritici* races, the CNWRCG has been continuously updating differential genotypes to differentiate *P. striiformis* f. sp. *tritici* races. However, most wheat-growing areas in Tibet have not been covered by the CNWRCG annual survey. Previous studies of wheat stripe rust in Tibet focused on understanding epidemic development (16) and pathogenicity differences among *P. striiformis* f. sp. *tritici* isolates (18,19).

For the first time, we obtained comprehensive information of the identity and composition of *P. striiformis* f. sp. *tritici* races in Tibet in the present study. The number of races detected in Tibet is comparable with those in Sichuan and Gansu, which have been considered as the major sources of inoculum and virulence variation because new *P. striiformis* f. sp. *tritici* races usually first emerged in these two regions and then gradually spread to other regions (5,22). Direct and indirect dispersal of *P. striiformis* f. sp. *tritici* races from Gansu to Tibet is unlikely because Qinghai province lies between Gansu and Tibet and fewer *P. striiformis* f. sp. *tritici* races were observed in Qinghai. Frequent one-way or two-way exchange of *P. striiformis* f. sp. *tritici* urediniospores between Sichuan and Tibet is more likely. Another possibility is that Tibet itself is also a center of *P. striiformis* f. sp. *tritici* sources because *P. striiformis* f. sp. *tritici* can oversummer and overwinter in southeastern Tibet, hence completing its annual life cycle as in Sichuan and Gansu (17). This is supported by the fact that several new races were detected in Tibet. The *P. striiformis* f. sp. *tritici* population in Tibet might be related to the populations in the neighboring countries such as India and Nepal, although this is unlikely given the Himalaya mountain range between the regions.

Race structure of a pathogen population depends largely upon the composition of resistant genes deployed in the region. Given the great number of *P. striiformis* f. sp. *tritici* races, surprisingly, there are only four major wheat cultivars that have been grown for many years in Tibet, which is in contrast to the number of cultivars in other provinces (Sichuan = 14, Yunnan = 19, Gansu = 29, Shaanxi = 14, and Qinghai = 8). This could be due to the complex genetic background regarding resistance to *P. striiformis* f. sp. *tritici* in the four cultivars grown in Tibet (Zangdong 10, Zangdong 20, Shandong 6, and Feimai), which are not currently grown in other regions. It is also possible that the isolates collected from

Table 3. Comparison of frequencies of *Puccinia striiformis* f. sp. *tritici* races in 2010 among the six regions in central western China

	Provinces (region)						
Races	Tibet	Sichuan	Qinghai	Yunnan	Gansu	Shaanxi	Average
CYR17	4.60	0	0	2.11	0.92	0	0.61
CYR20	4.60	1.36	0	9.47	1.84	0	2.53
CYR21	0.77	0	0	0	0.31	0	0.06
CYR22	0.38	0.68	0	0	0	0	0.14
CYR23	3.83	0	0	0	0.92	0	0.18
Lov10 group							
CYR28	0	0.68	0	0	0	0	0.14
Lov13 group							
CYR29	1.15	0.68	0	1.05	0	0.40	0.43
Lov-3	0	0.68	1.79	0	0.31	0	0.56
Lov-6	0.38	0	0	0	0.92	0	0.18
Lov-8	0	0	0	0	0.61	0	0.12
Hybrid 46 group							
CYR31	5.36	3.40	0	2.11	0.61	1.61	1.55
CYR32	31.80	14.29	5.36	33.68	15.64	33.06	20.41
Hy46-4	0	1.36	0	0	0.31	0	0.33
Hy46-6	0	8.16	0	7.37	0.31	0.81	3.33
Hy46-7	0	0.68	0	3.16	0	0	0.77
Hy46-8	0	6.80	0	11.58	0.92	0.81	4.02
Hy46-9	0	0.68	0	0	0	0	0.14
Suwon 11 group							
Su11-1	4.60	0.68	0	0	0	1.21	0.38
Su11-2	0.38	0	0	0	0.61	0.81	0.28
Su11-3	0.38	1.36	0	0	0.92	1.21	0.70
Su11-4	1.92	5.44	7.14	0	4.91	4.03	4.30
Su11-5	2.30	6.12	8.93	0	6.13	1.21	4.48
Su11-6	6.90	14.97	0	0	0.61	0	3.12
Su11-7	0.38	0	0	0	2.15	2.01	0.83
Su11-8	0.38	0	0	0	0	0.81	0.16
Su11-10	0	1.36	0	1.05	0.31	0	0.54
Su11-11	0	4.76	0	0	0	0.81	1.11
Su11-12	0	0.68	0	0	0	0	0.14
Su11-13	0.77	0.68	5.38	0	0.61	1.21	1.58
CYR33	24.14	7.48	48.21	7.37	20.55	40.73	24.87
Others	4.98	17.01	23.21	21.05	39.57	9.27	22.02
Number of samples	261	147	56	95	326	248	…
Number of races	19	22	6	10	21	15	30[a]

[a] Number of races identified in all regions.

Tibet carry additional virulence factors which may not be identified by the currently used differential genotypes; these complex virulence types may be sustained by local cultivars or wild *Hordeum* plants in Tibet.

This study indicated the possibility of Tibet as another center of *P. striiformis* f. sp. *tritici* diversity. If confirmed, it may have significant implications on stripe rust management, including cultivar deployment. Further research is needed to assess this possibility. In particular, further molecular studies are needed to assess differences among *P. striiformis* f. sp. *tritici* populations from Tibet, Sichuan, and Gansu at several key time points in the epidemic within a season. Field-based monitoring of spatio-temporal dynamics of *P. striiformis* f. sp. *tritici* development, including volunteer wheat plants and alternative hosts during the oversummer and overwinter period, and modeling studies should be undertaken to assess the feasibility of large-distance dispersal of *P. striiformis* f. sp. *tritici* between Sichuan and Tibet within a growing season. Finally, efforts should be made to identify the genetic basis of the current wheat cultivars in Tibet, including minor local cultivars and wild *Hordeum* spp., against different *P. striiformis* f. sp. *tritici* races. Through these studies, we may gain better understanding of *P. striiformis* f. sp. *tritici* epidemiology and *P. striiformis* f. sp. *tritici*–host co-evolution for effective management of this disease.

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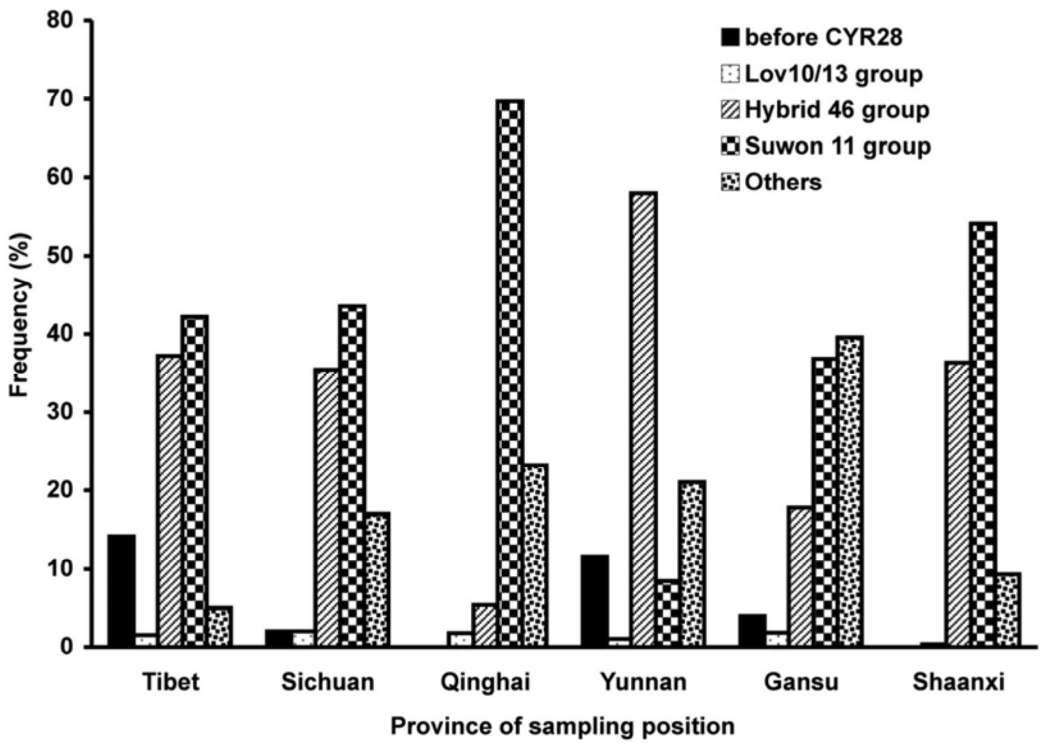

Fig. 2. Frequency of major races or race groups of *Puccinia striiformis* f. sp. *tritici* in the six central western regions of China in 2010.

Table 4. Frequencies of *Puccinia striiformis* f. sp. *tritici* races that overcame a number of selected host resistance genes in the six provinces of China in 2010

	Province					
Host resistance genes (host)	**Tibet**	**Sichuan**	**Yunnan**	**Qinghai**	**Gansu**	**Shaanxi**
Yr1 (Fengchan 3)	95.16	99.18	100.00	100.00	100.00	98.67
Yr3 (Danish)	85.48	97.54	96.00	100.00	95.43	98.67
Yr6 (Trigo Eureka)	95.16	95.08	86.67	100.00	94.68	49.33
Yr9 (Lovrin 13)	70.97	55.74	26.67	100.00	87.31	94.22
Yr3b/4b (Hybrid46)	39.11	42.62	73.33	27.91	29.44	38.22
YrA (Funo)	90.32	99.18	100.00	100.00	98.48	98.67
YrVir1,2 (Virgilio)	74.60	71.31	85.33	83.72	83.25	92.00
YrJu1,2,3,4 (Jubilejina)	71.37	85.25	94.67	88.37	80.20	93.33
YrKy1,2 (Kangyin)	62.90	66.39	82.67	81.40	74.11	91.11
YrSu (Suwon11)	84.27	96.72	85.33	100.00	93.40	99.56
Unknown (Fulhard)	100.00	100.00	100.00	100.00	100.00	100.00
Unknown (Lutescenes 128)	89.96	97.54	97.33	100.00	95.43	98.67
Unknown (Mentana)	87.55	79.51	97.33	100.00	95.94	98.67
Unknown (Abbondanza)	94.78	97.54	97.33	100.00	96.95	98.67
Unknown (Early Piemium)	95.18	98.36	97.33	100.00	96.95	100.00
Unknown (Zhong 4)	0	0	0	0	0	0
Unknown (Guinong 22)	0	0	0	0	0	0

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