Predicting Overwintering of Wheat Stripe Rust in Central and Northwestern China

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Abstract

Stripe rust, caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks. (*Pst*), is an important disease of wheat. In China, stripe rust management has been focusing on the Gansu region where the pathogen can complete its annual cycle including oversummering and overwintering. From this region, *Pst* inoculum is dispersed to the southern Yangtze River region in the late autumn to early winter, and then to the main wheat production regions in the following spring. We used historical weather data (1995-2016) and field stripe rust assessment data (eight years) in the spring to evaluate performance of a published model for predicting the potential of *Pst* overwintering in the Gansu region. Both predicted and observed values of *Pst* overwintering in the Gansu region varied greatly between years and between sites within a single year, indicating the value of predicting *Pst* overwintering for stripe rust management. The model predictions fitted with observed values satisfactorily. All high incidences of stripe rust in the spring were observed in the fields of the monitoring sites where the high potential of overwintering were predicted. Conversely, in the fields where stripe rust in the spring was not observed, the predicted *Pst* overwintering potential were also close to zero. There were some false positive predictions, which might be due to the absence of *Pst* in autumn seedlings. This model can be used to manage stripe rust in the spring, and its effectiveness can be further improved if autumn rust assessment is carried out.

Stripe rust, caused by *Puccinia striiformis* Westend. f. sp. *tritici* Erikss. (*Pst*), is an important disease of wheat worldwide (Chen 2005). It is a polycyclic disease and *Pst* can produce urediniospores in multiple cycles in a crop season when the climatic conditions favour for the disease development. Its annual cycle on winter wheat in China can be divided into four stages: oversummering, infection of seedlings in autumn, overwintering, and spring epidemic. It has to overcome the two bottlenecks of overwintering and oversummering in living green wheat plants to complete its life cycle (Li and Zeng 2002; Sharp and Hehn 1963). Temperature is the most important factor determining both *Pst* overwintering and oversummering potential on wheat. In most wheat-growing areas in China, the pathogen usually cannot survive the summer and/or winter because the temperatures limit its overwintering and oversummering.

In China, *Pst* oversummers primarily in the mountainous regions of southern and eastern Gansu Province and northwestern Sichuan Province due to three major reasons: relative low temperature, variable harvest time at different altitudes, and volunteer wheat seedlings following harvest in the summer. Thus, *Pst* can survive and re-infect volunteer wheat seedlings in the summer. Furthermore, winter wheat is sown early in the regions, allowing *Pst* from volunteer plants to infect autumn seedlings. Urediniospores produced in the oversummering region are dispersed (usually via air currents) eastward to cause infections on winter wheat seedlings in the late autumn in more east regions. Similarly, *Pst* urediniospores from the volunteering wheat plants and autumn seedlings are dispersed to cause infections on the winter wheat in the south Yangtze River region. Because of relatively warm winter temperatures in the Yangtze River region, *Pst* can infect, colonize leaves, and sporulate during the winter. In the coming spring, spores from this region are dispersed with air currents towards the northeast direction into the main wheat production in central China, resulting in crop losses. Thus, managing stripe rust in the oversummering region in the spring is critically important in China in order to reduce disease pressure in the main wheat production areas the following year.

The spring epidemic level of stripe rust in the oversummering area is primarily dependent on following factors: cultivar susceptibility, severity of autumn infections, the extent of *Pst* overwintering, and spring weather conditions. The ability being able to predict pathogen survival potential may enable timely implementation of integrated disease management to reduce inoculum and prevent stripe rust development in the spring. Mild winters favour *Pst* survival in infected leaves whereas severe winters do not allow the pathogen survival (Grabow et al. 2016). Potential *Pst* overwintering areas in China have been identified (Chen et al. 2013; Ma et al. 2005; Shen and Wang 1962), based on the data from field observations. However, recent field observations suggest that the overwintering boundary may have been gradually pushed towards the northwest (Pan et al. 2011; Yao et al. 2014), which may partially result from climate changes in recent times (Fang et al. 2012). In addition to low temperatures, wind chill may also result in reduced *Pst* overwintering potential (Ma et al. 2016). In cold high-altitude regions, *Pst* is likely to overwinter in young green leaves as latent infection established in late autumn (Ma et al. 2016). *Pst* mycelia inside green leaves may be killed by low temperatures rather than through death of green leaves (Ma et al. 2015).

Many models have been developed to describe the relationship of winter temperature with stripe rust epidemics based on field observations (Coakley et al. 1982; Coakley and Line 1981; Coakley et al. 1988) and were further revised (Sharma-Poudyal and Chen 2011). Recently, we used filed stripe rust data in northwestern China to develop a quantitative model that predicts the overwintering potential of *Pst* on winter wheat (Xu et al. 2019). Overwintering potential is predicted based on the number of days with daily average temperature < -2°C and -4°C for cultivars with weak and strong winter-hardiness, respectively. In the present study, we used this model to predict the overwintering potential of *Pst* in wheat in four provinces located in central and northwestern China, including Gansu, a key region of stripe rust epidemics in China. Weather data recorded at 340 stations in the four provinces from 1995 to 2017 were used to predict rust overwintering potential. Furthermore, the predicted overwintering potential is compared to the observed rust occurrence in the spring at the monitoring sites in Gansu Province. As the rust survey in the spring was only for disease management, the number and exact locations of sites surveyed varied greatly among years. Nevertheless, this is the best long-term data set we current have on the extent of spring rust development in Gansu.

Material and methods

Temperature data. Daily average temperatures from 1st January 1995 to 31st October 2017 were obtained from 340 weather stations located in four provinces (Fig. 1) including Gansu where *Pst* overwintering and early spring epidemic development are of great importance for stripe rust management in China. These data passed the quality control procedure as implemented by Chinese Meteorological Office. The density of these weather stations varied greatly with regions (Fig. 1), much denser in the eastern part than in the western because of differences in the terrain and local populations. There were 116, 95, 80, and 49 weather stations in Henan, Shaanxi, Gansu, and Qinghai provinces, respectively. The highest and lowest locations were 4,612.0 m and 32.5 m above the sea level, respectively.

Predicting rust overwintering. A recently published model was used to predict *Pst* overwintering potential of strong winter-hardy cultivars. This model was derived from field data collected in 2012-2014 in northwestern China (Qinghai and Gansu provinces, Fig. 1) (Xu et al. 2019). The model is

$$ln\left(\frac{p}{1-p}\right) = -1.411 - 0.039 \bullet \mathrm{DLT4}$$

where p is the probability of *Pst* being able to overwinter and DLT4 is the number of days with daily average temperatures < -4°C during the 30 days from 30th December to 28th January the following year. This model did not include low temperatures outside this period during the winter because there were only few extra days with average temperatures < -4°C for one season at few sites during the study period for model development (Xu et al. 2019). This model has maximum and minimum predictions of overwintering potential of respective 0.20 (DLT4 = 0) and 0.07 (DLT4 = 30). In the present study, all the estimated overwintering values were normalized to the range of 0 to 1.

Temporal trends in winter temperatures. For each winter, the average temperature from 16th December to 15th March the following year was calculated for each location to represent the overall winter temperature. Similarly, the number days with average temperature < -4°C was calculated over the same period for each location. Then, for every location, a simple linear regression model was fitted to determine whether there was a linear trend in average temperature or the number of days with temperatures < -4°C during the 22-year period. Similarly, a linear model was fitted to the predicted annual *Pst* overwintering potential over time for each location.

Spring rust assessment in Gansu. In Gansu Province where *Pst* is able to oversummer, a number of sites were assessed for the incidence of stripe rust in April to measure overwintering potential and early spring epidemics for disease management. The survey results were then used by the local government to finalize and implement stripe rust management across a number of provinces in China. In total, 425 sites were assessed for stripe rust in the spring of eight years in Gansu. There were 69, 97, 37, 81, 46, 43, 21 and 31 sites assessed in 2005, 2007, 2008, 2009, 2011, 2012, 2014 and 2015, respectively. Within each site (usually an individual local village), a number of fields were selected for stripe rust assessment, with the size of individual fields usually in the range of 70 to 700 m^2. In total, 2,117 (ca. 5 fields per site) fields were assessed in the eight years. Spring assessment was carried out in 2013 but failed to find any stripe rust lesions.

Depending on the field size and the overall level of stripe rust and the field, rust was assessed through one of the two following methods. (1) For fields with a very low incidence of rust, five areas (each of ca. 70 m^2) were selected to check for the presence of stripe rust within a field with the size > 667 m^2. For a field with the size < 667 m^2, the whole field was assessed for stripe rust. Within each selected area or whole field, an assessor walked slowly and regularly squatted down to check for the presence of stripe rust. (2) For fields with a moderate or high incidence of rust, five areas (each of ca. 2 m^2) were randomly selected; 200 leaves within each area were examined for the presence of stripe rust.

Incidences of leaves, areas and fields with *Pst* pustules were estimated for each location. Plants in 1,154 out of the 2,117 fields were examined just prior to or at the elongation stage, 605 fields at the pre-anthesis stage, and the remaining fields at the period from anthesis to the milk stage.

Results

Temperatures over time. Figure 2 shows the average annual winter temperatures for the 22 years at each location where a weather station was located in the four provinces. As expected, Qinghai and Henan were the coldest and warmest provinces in winter, respectively (Fig. 2). For instance, the average annual winter temperatures ranged from -9.5°C to -6.5°C and from 0.5°C to 5.2°C for Qinghai and Henan provinces, respectively. Similarly, Qinghai had more days of DLT4 than other three provinces (Fig. 3). Among the four provinces, Gansu had the greatest variation of DLT4 in the winter (25 to 51 days), while Henan had the least variation of DLT4 (0 to 9 days) from 1995 to 2017.

For most locations, average annual winter temperatures did not show an apparent increasing trend over the 22-year period (Fig. 4). However, at fifteen sites the annual winter temperature increased significantly during the 22-year period, with an average increase of 0.1°C per year. Fourteen of the 15 sites were in Qinghai and the other one in Gansu (Fig. 1, Fig. 4). These 15 sites are all located in high elevations (> 3,000 m).

Rust overwintering predictions. Winter temperature is not a limiting factor for rust overwintering in Henan and southern Shaanxi (Fig. 5) because DLT4 was all within the range of 0 to 10 days (Fig. 3). Average predicted overwintering potential is 0.91, 0.66, 0.30, and 0.04 for Henan, Shanxi, Gansu, and Qinghai, respectively. For most sites in Qinghai and northwestern Gansu, the predicted *Pst* overwintering potential is close to zero. In addition to the large variation in the predicted overwintering potential among locations, there were large fluctuations in the average overwintering potential among years particularly in Gansu and Shaanxi (Fig. 5, Fig. 6). However, despite the large variability among sites in Shaanxi and Gansu, *Pst* overwintering was possible for most sites, particularly so in warm years, such as 2002 and 2010 (Fig. 5).

Observed rust overwintering in Gansu. Of the 425 sites, there were 258 sites with no rust detected in the early spring, 83 sites with the stripe rust incidence ≤ 1%, 12 sites with the incidence from >1% to 3%, and 72 sites with the incidence > 3%. Stripe rust incidence varied greatly among individual fields in spring, and the incidence can be over 50% in some fields.

Except 2013, a varying degree of stripe rust pustules was observed in all years. In the 2013 spring, there was a severe drought event, causing wheat not growing well and the autumn infections in 2012 were not severe. In addition to 2013, stripe rust was low in the springs of other years except 2005, 2014 and 2015 (Fig. 7). In six years, *Pst* uredinial pustules were not seen in more than 50% of the locations assessed in the spring. The incidence of locations with spring *Pst* lesions ranged from 25% (2009) to 77% (2005). The incidence of leaves with stripe rust pustules in the spring was > 3% for nearly half and one third of the locations in 2005 and 2014, respectively (Fig. 7). Within individual years, the level of spring rust also varied greatly among sites; many sites had the rust leaf incidence at a very low level (< 1%) (Fig. 7).

Stripe rust incidence was generally higher on plants at late developmental stages than at early stages. For instance, only 11 out of the 245 sites where plants were either prior to or at the elongation stage at the time of assessment had the rust leaf incidence > 3%, compared to 61 out of 180 sites with plants passed the elongation stage. This difference was highly significant ($P < 0.001$).

Comparison of the predicted with the observed rust in Gansu. Fig. 8 shows the observed rust in the spring and predicted probability of overwintering. Over the eight years, predicted overwintering potential was higher in the 2014 and 2015 winters than in other winters (Fig. 6C, Fig. 8). The predicted rust overwintering varied greatly among locations within each year, as did the observed spring rust. Despite the large variation in the number of sites assessed, their geographical locations, and the levels of rust observed, Fig. 8 shows the following trends or results. 1) High level of spring rust occurred only in southern locations. 2) The high level of stripe rust in spring was observed only for those sites in the regions with high-predicted overwinter potential, usually > 0.50, as shown, for instance, for 2005, 2014, and 2015. 3) Stripe rust in spring was not observed for those sites in the regions with very low-predicted overwinter potential, usually < 0.25. This was best illustrated by the data from 2007, 2009, 2011, and 2012 in which locations were more spread geographically. 4) Stripe rust in spring was not observed for many sites in the regions with moderate to high values of predicted overwinter potential in all years, indicating a high level of false positive predictions.

Discussion

Wheat stripe rust overwintering is important in the northwest China regions, particularly Gansu province that is the major region where the rust can complete its annual disease cycle (Chen et al. 2013). Despite wheat being a relative minor crop in Gansu, stripe rust development in the region may have a disproportionate effect on crop losses in the main wheat production in China. This is due to the factor that the Gansu region provides the initial rust inoculum during autumn to early winter to winter wheat areas in the Yangtze River region, which in turn provide inoculum to the main wheat production areas in the north in the following spring. Thus, accurate prediction of overwintering hot spots in Gansu should allow timely implementation of control measures in the early spring to control stripe rust and hence reduce the over-summering inoculum, which should lead to low autumn epidemics in the region. In the present study, we evaluated a recently developed model (Xu et al. 2019) for predicting *Pst*overwintering in Gansu.

Both model-predicted rust overwinter potential and observed rust in the spring in the Gansu region showed large variations between years and between locations within a single year. These variations indicated the need for predicting rust overwintering in order to apply more targeted disease management in the spring. Furthermore, the present results are encouraging, showing that the model is able to predict overwintering potential of *Pst* in Gansu. Thus, all the high incidences of rust in the spring occurred only in the regions where high overwinter potential was predicted. Conversely, rust in the spring was not observed in the regions where the predicted overwinter potential was close to zero.

There were some false positive predictions, i.e. high overwinter potential was predicted but no rust was observed in the spring. This false positive prediction was expected since the present model is only based on winter temperatures. In addition to weather conditions, two other important factors affecting spring rust severity are cultivar resistance and the severity of autumn rust on seedlings. We argue that autumn rust severity is primarily responsible for these false positive predictions. First, wheat in the study region is usually grown by smallholders who select cultivars based on yield potential rather than stripe rust resistance. Second, there are many *Pst* races present in the study region, regarded as the *Pst* diversity centre in China (Hu et al. 2017). Thus, it is unlikely that most cultivars grown in the region are resistant to the all races.

In the present study, we did not assess the severity of stripe rust in autumn seedlings in each field. Ideally, to validate the model, it would be better to assess both autumn and spring rust severities at the same locations in order to estimate rust overwinter accurately. Indeed, it would be even better to tag plants with stripe rust pustules in the autumn and then assess rust development on these tagged plants in the spring. This is the approach we used to obtain experimental data to develop the overwinter model evaluated in the present study (Ma et al. 2016; Xu et al. 2019). Unfortunately, to obtain sufficient amount of stripe rust data for model validation using this approach would be prohibitive in cost given the number of sites needed and geographical distances among sites. Thus, we used historical data for the purpose of model validation. When implementing the model in practical disease management, we may use remote sensing technology to assess rust severity in late autumn. For instance, we recently demonstrated that it is possible to estimate wheat stripe rust development with the UAV (unmanned aerial vehicle) based imaging technology (Su et al. 2018). By combining the model prediction with autumn rust assessment, spring rust management can be further prioritised with confidence. This kind of disease management can be implemented in the Gansu region since the local government is responsible for providing small-scale growers with information and advice.

There was no overall trend in the predicted *Pst* overwinter potential in the four provinces over the period of 22 years, although there were large variations among years. However, there was a clear indication of increasing winter temperature over time in the Tibetan Plateau at an approximate annual rate of 0.1°C. Indeed, such an increase in temperature has already been reflected in the cropping system in the regions (Liu et al. 2017). Nevertheless, this increase in temperature has not affected *Pst* overwintering yet since the overwintering model is based the number of days with daily average temperature below -4°C rather than the exact temperatures.

In validating the model, we had to normalize the predicted values to the range of 0 to 1.0. This is necessary because the data used to develop the model were collected at the sites where the number of days with daily average temperatures < -4°C (i.e. DLT4) was all less than 30 days. Thus, the model predicted a minimum overwintering potential of ca. 0.2. However, in the present data set, there are many year-site combinations with DLT4 much greater than 30 days. Consequently using the model to predict overwinter potential without normalization would lead to overestimation of overwinter potential for those sites with DLT4 much greater than 30. Of course, normalizing the model predictions may lead to underestimation of overwintering for those sites with DLT4 just over 30 days; this occurred only for a limited number of cases. Another aspect the present model did not include is the winter snow cover, which could reduce the negative effect of cold temperature on rust survival (Sharma-Poudyal et al. 2014). We did not include this factor in the model for two reasons. First, we do not have sufficient data to predict the quantitative effects of snow cover (and its duration) on rust overwintering. Second, it would be even more challenging to obtain snow cover (and duration) for using the model in practice. The model may be further improved by incorporating other weather variables that may affect *Pst* overwintering, e.g. dew point temperature, snow cover, relative humidity and precipitation (Sharma-Poudyal et al. 2014).

In summary, the simple model satisfactorily predicted *Pst* overwintering potential in the Gansu region; all the locations with spring rust pustules observed were in those regions with high-predicted values of overwintering potential. The impact of false positive predictions in practical disease management can be minimized if model predictions are combined with autumn rust severities. Currently, we are developing strategies of using a UAV-based imaging system (Su et al. 2018) to assess autumn rust in winter wheat fields, and evaluating the combined use of autumn rust assessment and overwinter predictions for rust management in the spring.

Acknowledgements

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A

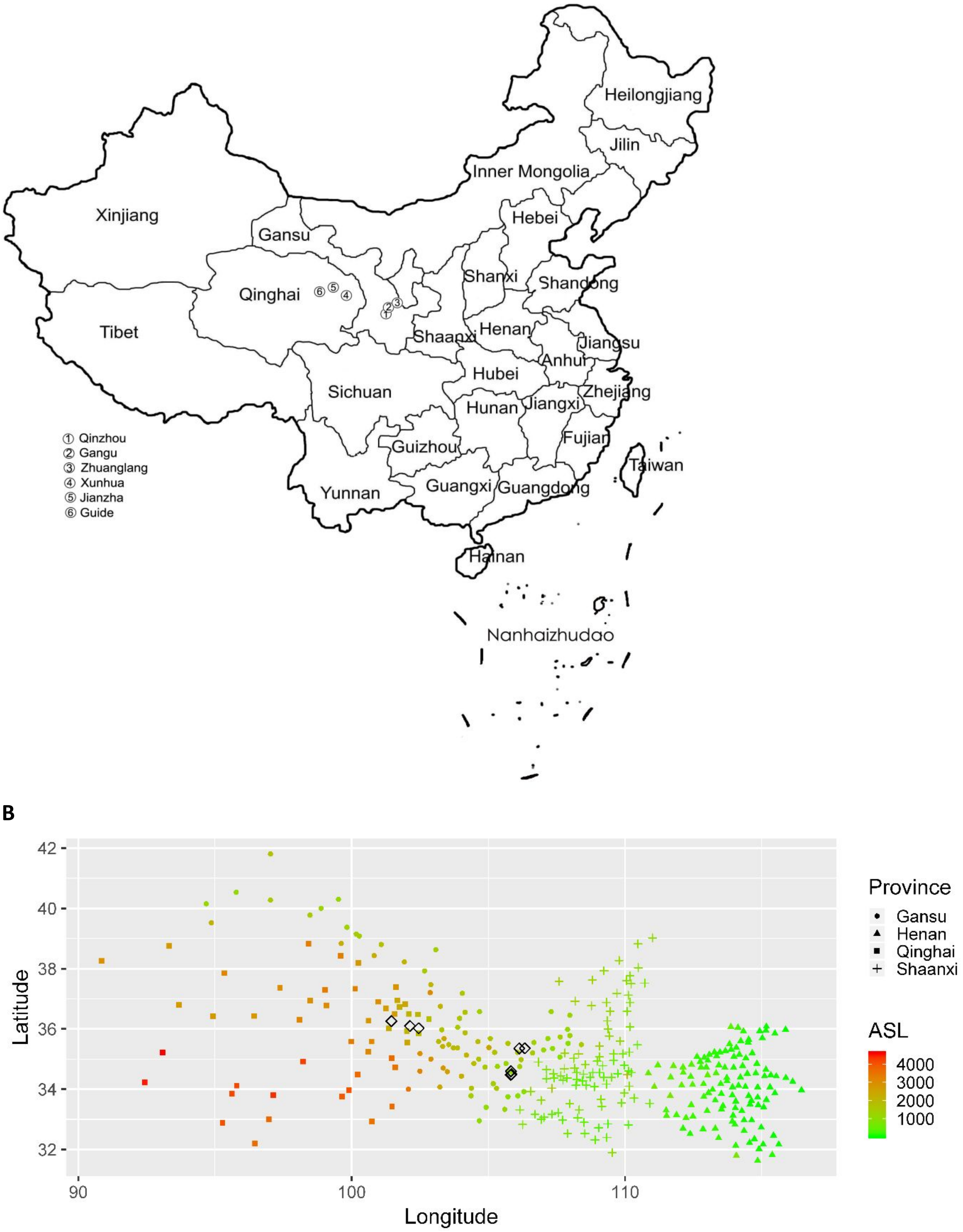

Fig. 1. The locations of the four provinces in China (**A**) and latitudes and longitudes of all weather loggers (**B**) in the four provinces from which daily average temperature data were used in the present study. The circles with numbers in (**A**) and open diamonds with black edge in (**B**) indicate the sites where the experimental data were collected to develop a model predicting the overwintering potential of *Puccinia striiformis* f. sp. *tritici* (Xu et al. 2019). ASL – above sea level in meters.

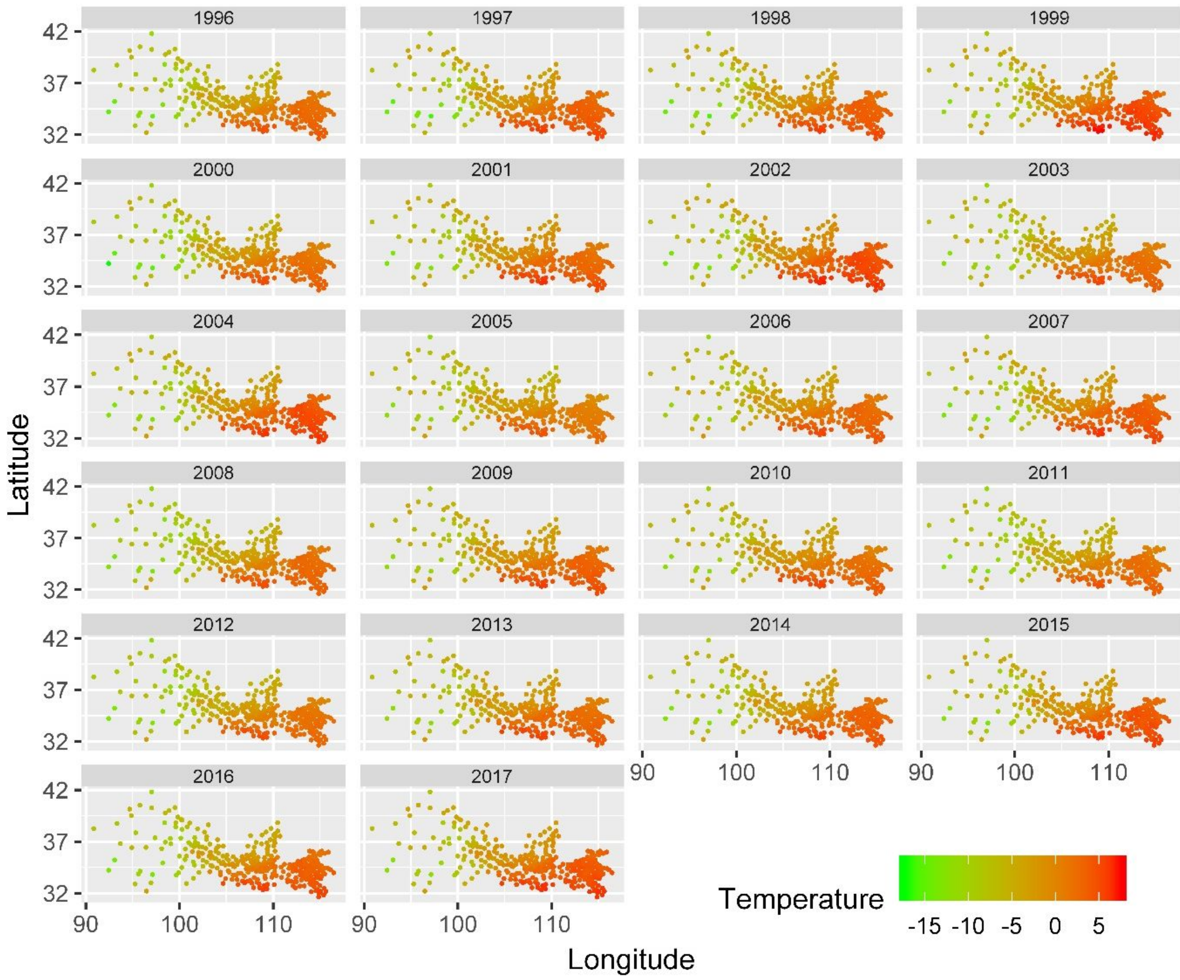

Fig. 2. Average winter temperatures for each logger site from 16th December to 15th March the following year in the four provinces in China from the 1995/96 winter to the 2016/17 winter.

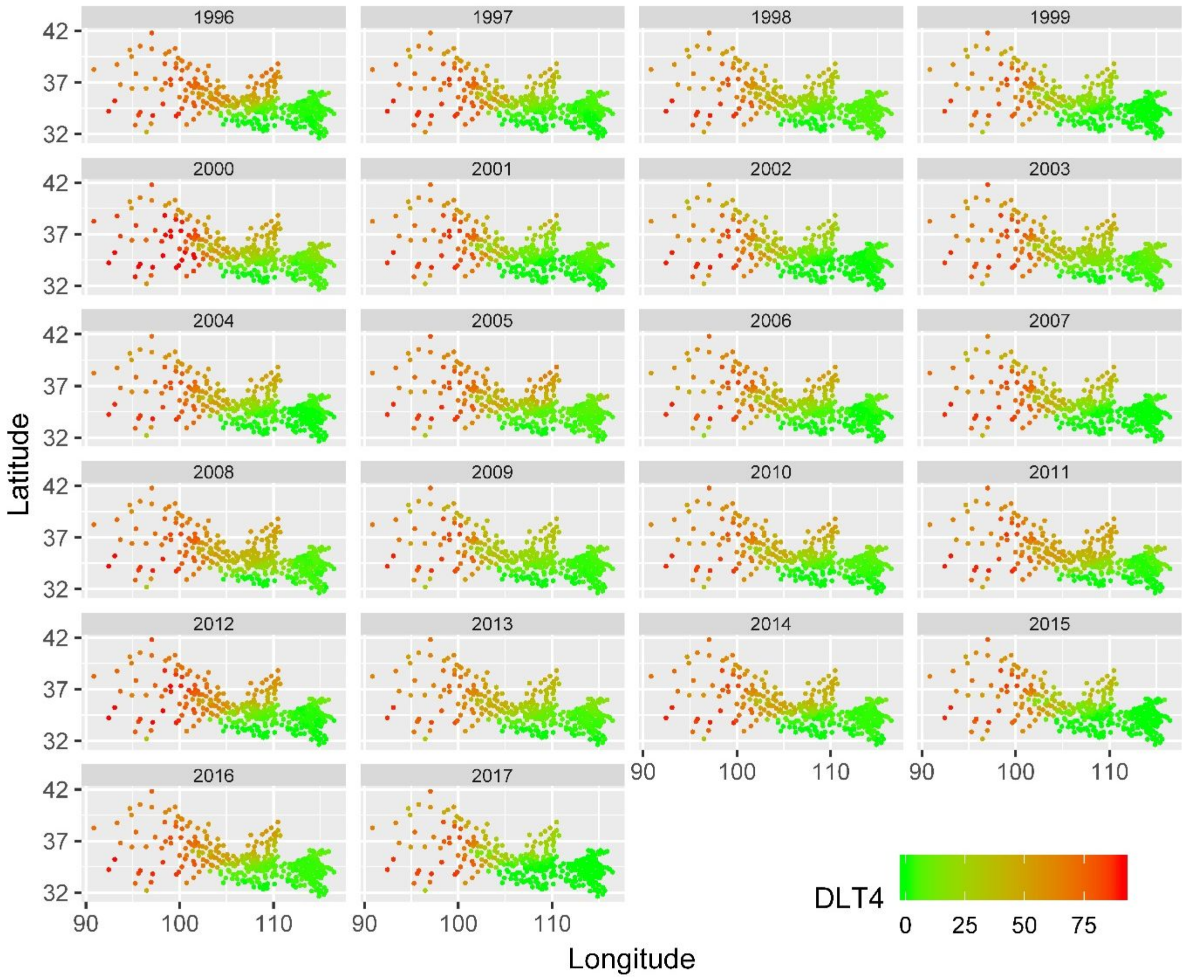

Fig. 3. Number of days with average daily temperature < -4°C during the entire winter period (16th December to 15th March the following year) for each logger site for all 22 winters; this specific variable was used to predict the overwintering potential of *Puccinia striiformis* f. sp. *tritici*.

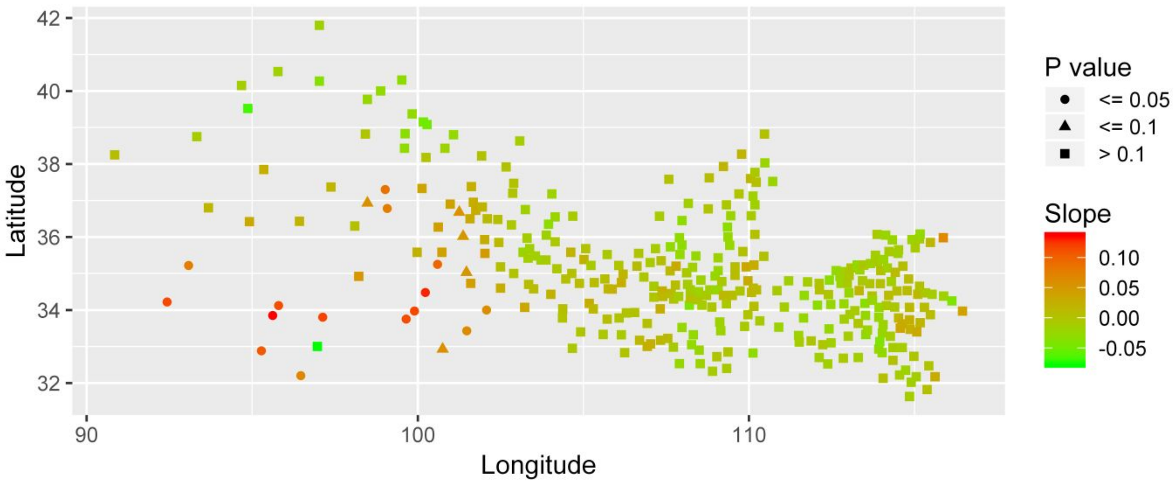

Fig. 4. The overall linear change rate (slope) in the average winter temperature from 16th December to 15th March the following year for each logger site during the period of from the 1995/96 winter to the 2016/17 winter. Color indicates the magnitude of this annual change rate whilst the symbol shape indicates its statistical significance.

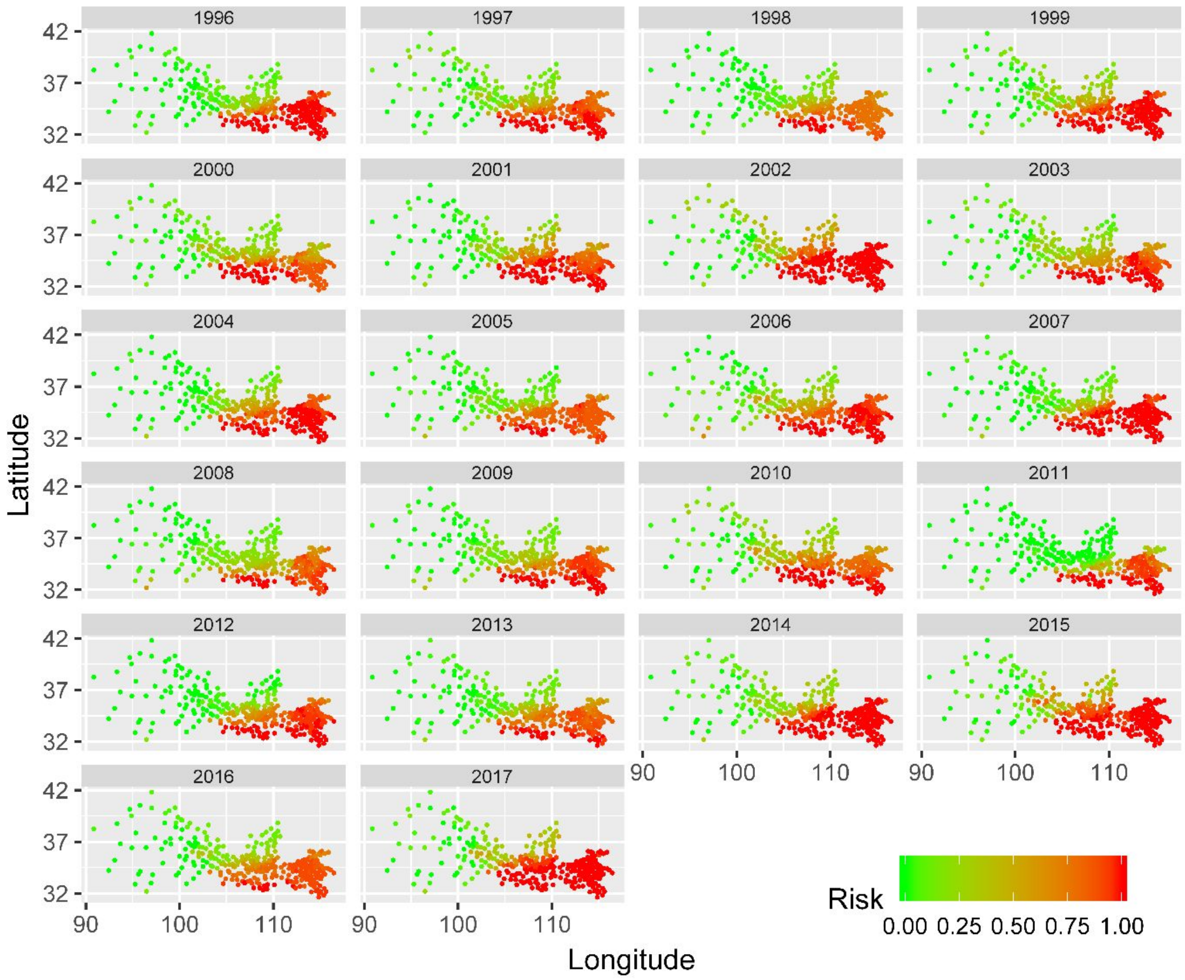

Fig. 5. Predicted overwintering potential of *Puccinia striiformis* f. sp. *tritici* on cultivars with strong winter hardiness based on a previously published model (Xu et al. 2019). The actual predictions were normalized taking into account the background information of the data from which the model was developed, as described in the main text.

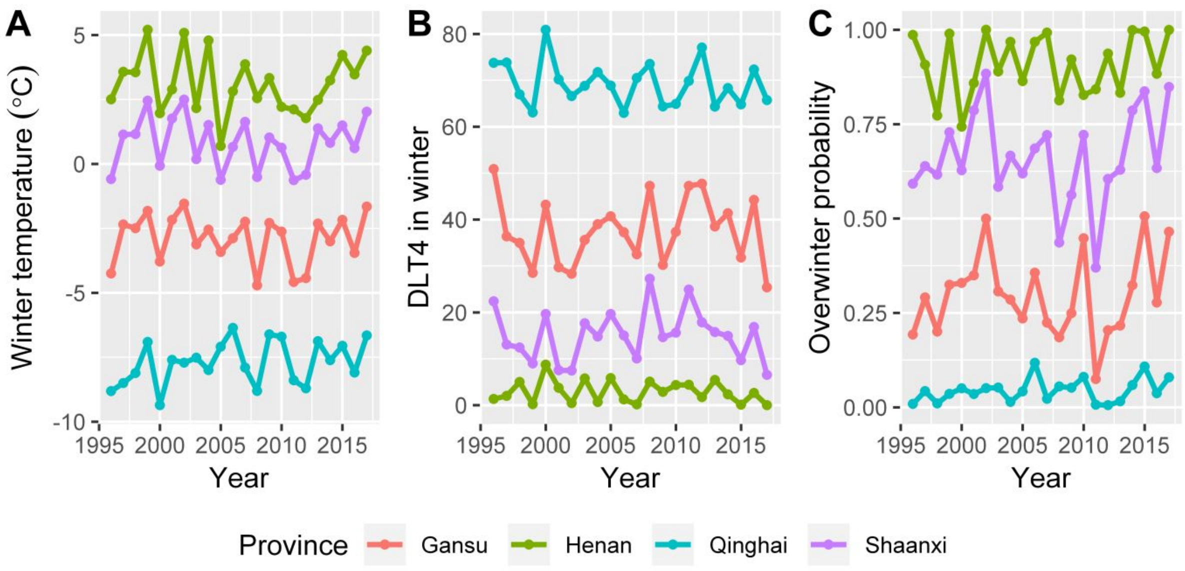

Fig. 6. Temporal plots of average winter temperature (**A**), average number of days with daily average temperature < -4°C in the winter (**B**), and average probability values of *Puccinia striiformis* f. sp. *Tritici* (*Pst*) overwintering (**C**) on cultivars with strong winter hardiness in each province. A winter period is defined from 16th December to 15th March the following year. *Pst* overwintering potential was estimated from a previously published model (Xu et al. 2019).

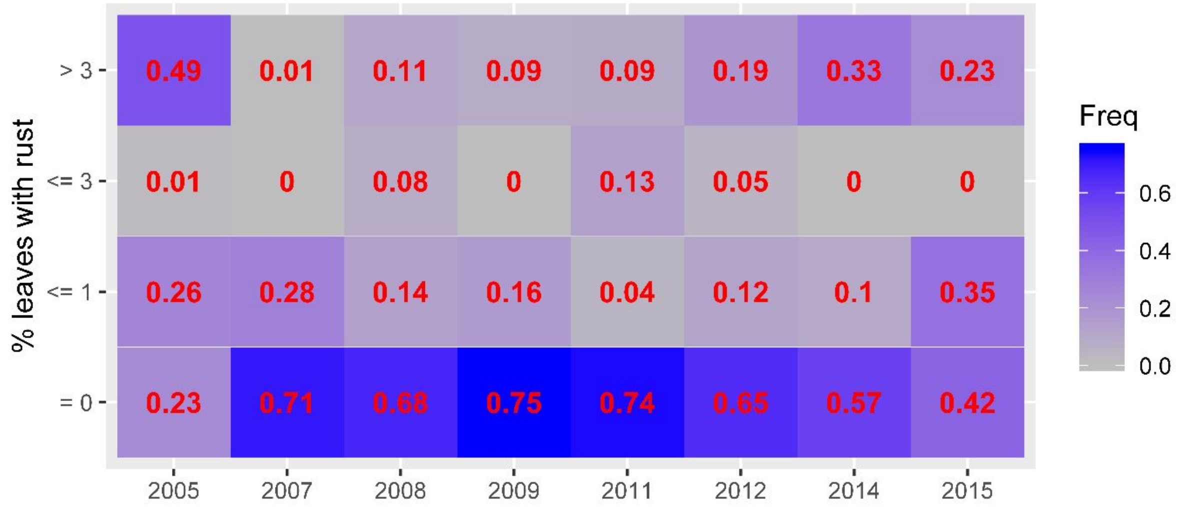

Fig. 7. Proportion of sampled sites with different levels of stripe rust incidences on leaves when assessed in the spring; rust were assessed in 425 sites [consisting of 2,117 individual fields] in the spring over the eight years.

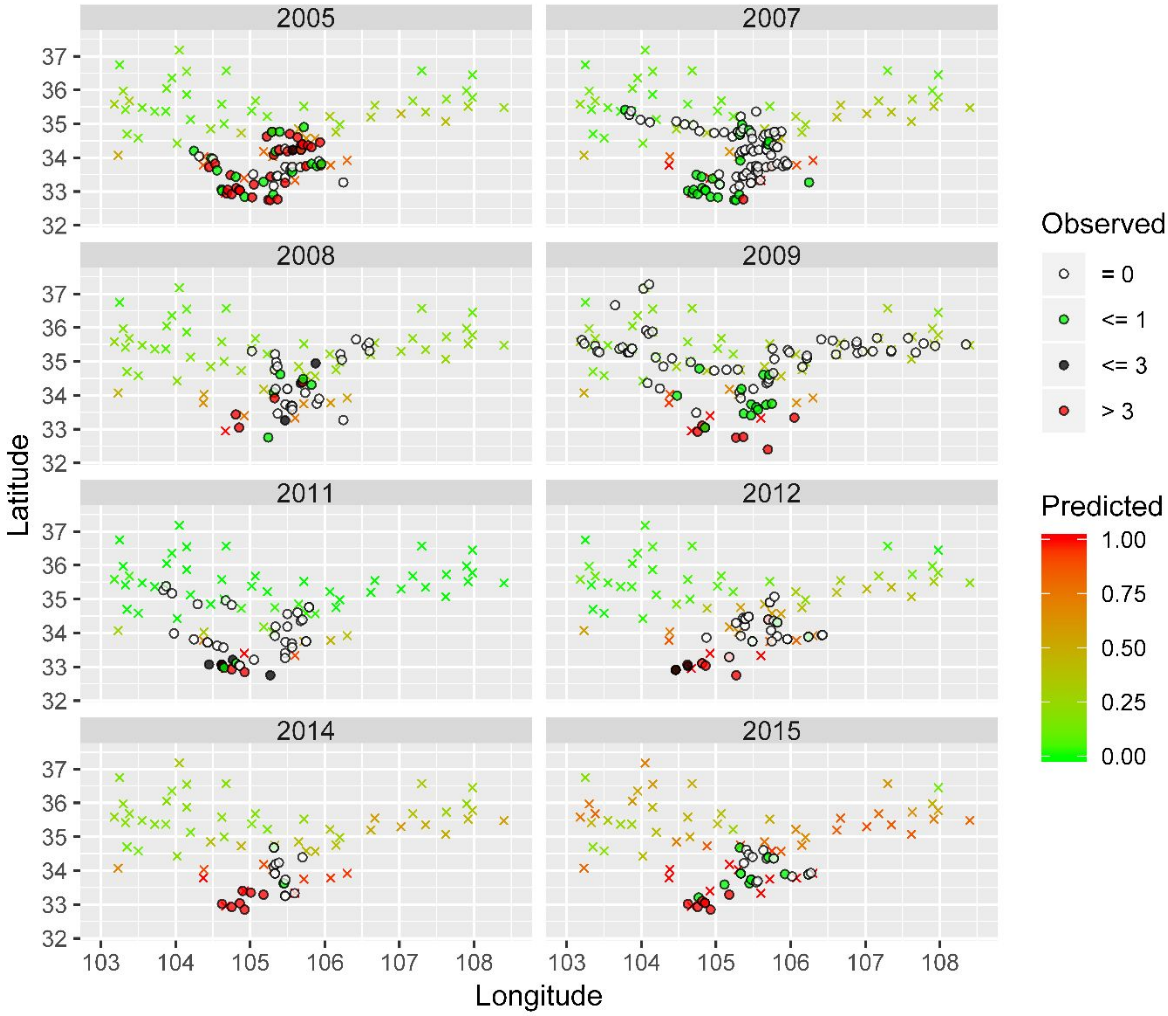

Fig. 8. Predicated overwintering potential of *Puccinia striiformis* f. sp. *tritici* (cross symbols) based on a previously published model (Xu et al. 2019) for Gansu Province, plotted together with those observed incidences of leaves with rust (circles) in the spring. Stripe rust was assessed in 425 sites [consisting of 2,117 individual fields] in the spring of eight years. No rust was observed in the spring 2013.