Geographic Distribution of Stem Rust Resistance in Wheat Landraces

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ABSTRACT

Wheat stem rust, caused by *Puccinia graminis* Pers.:Pers f. sp. *tritici* Eriks.& Henn., is of renewed concern due to the emergence of a new virulent race in East Africa. Landrace accessions of common wheat (*Triticum aestivum* L. subsp. *Aestivum*) and durum wheat (*T. turgidum* L. subsp. *Durum*) from the National Small Grains Collection (NSGC) could be sources of new stem rust resistance genes. In an effort to better target the screening of NSGC landrace accessions against the new race, data from the NSGC were analyzed for the geographic distribution of resistance. We used data for 5700 landrace accessions of common wheat and 2719 of durum wheat. Areas with a high incidence of stem rust resistance were found in Ethiopia, Chile, Turkey, Bosnia and Herzegovina, and adjacent areas of the former Yugoslavia. Resistance to multiple races at the seedling stage was most frequent in accessions from Ethiopia and Turkey. Resistance in durum wheat was more frequent than resistance in common wheat. The distribution of the areas with high incidence of resistant durum landraces was similar to that for common wheat landraces. A logistic regression model predicting resistance in common wheat accessions (n = 3607) from 10 traits identified 192 previously untested accessions with a greater than 50% chance of being resistant. Based on this model and on the identification of geographic centers for resistance, accessions will be prioritized for future screening against new stem rust races.

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For the past 50 years in North America, the use of host resistance to the wheat stem rust pathogen (*Puccinia graminis* Pers.: Pers f. sp. *tritici* Eriks.& Henn.), in concert with barberry eradication and earlier maturing cultivars, has been a primary means of control of this potentially devastating disease (Kolmer, 2001; Leonard, 2001). Recently, however, uniquely virulent races have arisen within the *P. graminis* f. sp. *tritici* population in eastern Africa. These races include TTKS, which overcomes the widely used resistance gene *Sr31* (Wanyera et al., 2006; Jin and Singh, 2006), and a new variant of TTKS which overcomes *Sr24* (Y. Jin, personal communication, 2007). Because many U.S. wheat cultivars are susceptible to the new races (Jin and Singh, 2006) there is a renewed interest in the discovery, characterization, and deployment of stem rust resistance genes.

Accessions of common wheat (*Triticum aestivum* L. subsp. *aestivum*) and durum wheat (*T. turgidum* subsp. *durum*) from the USDA-ARS National Small Grains Collection (NSGC) were tested for stem rust resistance from 1988 to 1994 by D. McVey of the ARS Cereal Disease Laboratory in St. Paul, MN. Among the accessions tested were more than 8000 landraces, representing common and durum wheats selected by farmers and still cultivated in some parts of the world. Such landrace accessions could possess

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disease resistance genes that have not yet been deployed in modern wheat cultivars and which could be of great utility for plant breeding.

The USDA-ARS is cooperating with CIMMYT (International Maize and Wheat Research Center, Mexico) and the Kenya Agricultural Research Institute to screen U.S. wheat cultivars and breeding lines, as well as accessions from the NSGC, against the new virulent races of *P. graminis* f. sp. *tritici* in eastern Africa. The second year of testing is currently underway and this cooperative work is likely to continue as long as these races represent a threat to global wheat production. The screening is focused primarily on cultivars and breeding lines, since these represent the most immediately useful germplasm for resistance breeding. There is limited capacity to test NSGC accessions against the new race and it is thus impractical to quickly test all of the more than 25,000 landraces of cultivated wheat in the collection, particularly since more than 7500 of these accessions have winter growth habit, and thus require artificial vernalization treatment to enable tests of adult plants in Kenya.

There is presently no means to choose NSGC accessions more likely to show resistance to TTKS and its derivatives because the existing stem rust data for the NSGC has not been systematically analyzed. The purpose of the present study was to analyze the NSGC data for stem rust resistance in common and durum wheat with respect to the geographic origin of resistance. We also examined the association of resistance with various agronomic traits using a statistical model. Results will be used to guide the selection of landrace accessions for further testing against the stem rust pathogen in eastern Africa and elsewhere.

MATERIALS AND METHODS

From 1988 to 1989 and 1991 to 1994, 8433 accessions from the NSGC were evaluated for resistance in field tests at St. Paul, Minnesota against a composite of races chosen to represent a diversity of virulence to specific resistance genes (Don McVey, personal communication, 2006). Accessions were rated at soft dough stage by scoring on a 0 to 9 scale based on the diseased area of stem tissue, with 0 representing no disease and 9 representing the highest possible area affected. Accessions with scores of 1 or less in the field studies constituted less than 10% of the total sample tested and were considered resistant in our analysis. In each year both common and durum wheat accessions were tested and a broad range of disease severity occurred. In addition, accessions were tested as seedlings in the greenhouse in 1988 and 1991 against the specific races of the pathogen that were used for the field inoculations. Approximately 3000 common wheat accessions and 1000 durum accessions were tested against races QFCS, RTQQ, and TPMK designated following Roelfs and Martens (1988) and Roelfs et al. (1993). Greenhouse tests were rated based on the 0 to 4 infection type scale described by Stakman et al. (1962) and scores of 2 or less were considered resistant.

In the tests for adult plant resistance, 5700 common accessions and 2733 durum accessions were included. In the seedling resistance tests, 2719 common wheat accessions and 764 durum accessions were tested that were also evaluated in the field. The accessions tested in the field represent about three quarters of the landrace accessions classified as either spring or facultative growth habit that were available in the NSGC at the time the tests were conducted. Because of the vernalization requirement of winter wheats, it was not feasible to include a large number of winter habit accessions in the field screening trials; however, 89 accessions classified as winter habit were tested and flowered normally.

Agronomic Descriptor Data

Nearly all of the landrace accessions in the NSGC have been scored for growth habit based on spring-sown trials at Aberdeen, ID (43°2′ N, 112°49′ W, 1331 masl). Accessions flowering normally were designated as having spring habit, those that did not flower as having winter habit, and those that flowered very late as facultative.

Landrace classification was determined by the NSGC curator (H.E. Bockelman) based on information available in the passport data and is somewhat subjective. The NSGC also generates data on various 'descriptors', such as morphological characteristics and resistance to other pests and diseases. Among the landrace *T. aestivum* accessions in the NSGC, 3607 had data for adult plant stem rust reaction from the St. Paul field trials plus complete descriptor data for the following characters: region of origin (derived from country of origin), growth habit, seedling reaction to leaf rust based on tests with a composite of races, seedling reaction to Hessian fly biotypes C and E, plant height, days to flower, reaction to common bunt, and stripe rust infection type and severity scores.

Data Analysis

Country of origin was known for nearly all accessions and these were classified into regions based on the United Nations designations for World Macroregions (United Nations, 2000). Non-overlap of the 95% binomial confidence intervals was used as a basis for determining significant differences between accessions from various geographic groupings.

Sites of collection for individual wheat accessions were georeferenced as described previously (Bonman et al., 2006). We obtained coordinates for a total of 3763 common accessions and 1448 durum accessions that had been tested for stem rust resistance in the field trials and, using DIVA-GIS 5.2 (Hijmans et al., 2005), mapped the location of these accessions and determined the number of resistant and susceptible accessions in 150 × 150 km grid cells. We used a binomial test to determine which grid cells had significantly higher numbers of resistant accessions than expected, using the fraction resistant accessions as the expected probability.

Logistic regression analysis was conducted using data from the 3607 common wheat accessions for which a complete data set was available for stem rust field reaction plus 10 other descriptors. To facilitate the analysis, certain geographic regions were combined. A model was fitted to the response variable y = field reaction of an accession to stem rust, with two values: y = resistant, coded as 1, for scores ≤ 1, and y = susceptible, coded as 0, for scores > 1. The explanatory variables were: x_1 = region of origin is eastern Asia or South-central Asia with values: here and below, yes was coded as 1, and no was coded as 0; x_2 = region of origin is eastern Europe or western Europe with values: yes and no; x_3 = region of origin is northern Africa or eastern Africa with values: yes and no; x_4 = region of origin is South America, with values: yes and no; x_5 = region of origin is southern Europe, with values: yes, and no (note: if x_1 to x_5 are all 0, region of origin is western Asia); x_6 = habit is facultative with values: yes and no; x_7 = habit is spring, with values: yes and no (note if x_6 and x_7 are both 0, habit is winter); x_8 = reaction to leaf rust, with values: resistant, coded as 1 if score ≤ 2; and susceptible, coded as 0, if score > 2; x_9 = reaction to Hessian fly (*Mayetiola destructor* Say) biotype C, with values: resistant, coded as 1 if score ≤ 2; and susceptible, coded as 0, if score > 2; x_{10} = reaction to Hessian fly biotype E, with values: resistant, coded as 1, if score ≤ 2; susceptible, coded as 0, if score > 2; x_{11} = plant height; x_{12} = days to flower; x_{13} = reaction to common bunt with values: resistant, coded as 1, if score ≤ 5 (Bonman et al., 2006); and susceptible, coded as 0, if score > 5; x_{14} = severity of stripe rust tested in Mt. Vernon with values: resistant, coded as 1, if score ≤ 5; and susceptible, coded as 0, if score > 5; and x_{15} = infection type to stripe rust tested in Mt. Vernon with values: low, coded as 1, if score ≤ 2; and high, coded as 0, if score > 2. Detailed descriptions of how each trait was scored are available online via the USDA-ARS Germplasm Resources Information Network (http://www.ars-grin.gov/npgs/searchgrin.html/ verified 24 July 2007).

The outcome y_i of accession i was assumed to have a Bernoulli distribution with resistant and susceptible probabilities $P(y_i = 1) = \pi(x_{1i}, x_{2i},..., x_{15i}) = \pi(\underline{x}_i)$ and $P(y_i = 0) = 1-\pi(\underline{x}_i)$, respectively for i = 1, 2,..., 3607 accessions. The logistic regression model assumed was

$$P(y_i = 1) = \pi(x_{1i}, x_{2i}, \cdots, x_{15i}) = \frac{\exp(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_{15} x_{15i})}{1 + \exp(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_{15} x_{15i})}$$

or

$$\ln \frac{\pi(\underline{x}_i)}{1 - \pi(\underline{x}_i)} = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_{15} x_{15i} .$$

In the model β_j represents the change in the log odds ratio as x_j changes one unit when all the other explanatory variables are held fixed, j = 1, 2,..., 15. That is, $\exp(\beta_j)$ = odds ratio of resistance to stem rust as x_j is increased one unit when all the other explanatory variables are held fixed.

Estimates of the model were obtained using the maximum likelihood method and the likelihood ratio test was used to test whether resistance to stem rust depends on the explanatory variables (H_o: $\beta_1 = \beta_2 = ... = \beta_{15} = 0$). The Hosmer and Lemeshow chi square statistic was used to assess the goodness of fit of the model.

The logistic regression procedure of SAS (Statistical Analysis System v.9.1, SAS Institute, Cary, NC) was used for these analyses.

RESULTS AND DISCUSSION

Geographic Origin

Common Wheat

Common wheat accessions evaluated for resistance were mostly from Portugal, and a band from Switzerland through Turkey to Nepal, and in Ethiopia, northeast China, and Chile (Fig. 1). On a broad geographic scale, a higher proportion of resistance in common wheat occurred in eastern Africa, South America, southern Europe, and western Asia, with the highest frequency of resistance occurring in South America (Table 1).

In the seedling greenhouse tests, resistance to races QFCS and RTQQ was more frequent in the total sample and among the various regions compared to resistance to race TPMK (Table 2). For example, resistance to QFCS and RTQQ occurred in about 40% of the accessions tested, whereas only about 17% of these accessions showed resistance to race TPMK. This result is expected because race TPMK possesses a broader virulence spectrum than the other two races. TPMK can overcome all the resistance used in the North American stem rust differential series except *Sr*6, 9a, 9b, and 30. Compared to the other two races, the greenhouse results with race TPMK were

Table 1. Numbers of common and durum wheat landrace accessions tested, resistant[†], and percentage resistant to stem rust disease from nine geographic regions[‡§].

Geographic region	*Triticum aestivum* subsp. *aestivum*			*Triticum turgidum* subsp. *durum*		
	Resistant (n)	Total (n)	Resistant (%)	Resistant (n)	Total (n)	Resistant (%)
Eastern Africa	74	787	9.4b	169	1213	13.9a
Eastern Asia	1	554	0.2c	–[¶]	–	–
Eastern Europe	0	132	0.0c	0	127	0.0c
Northern Africa	0	133	0.0c	35	338	10.4ab
South America	33	155	21.3a	–	–	–
South-central Asia	22	2034	1.1c	2	151	1.3c
Southern Europe	26	324	8.0b	37	392	9.4ab
Western Asia	87	1272	6.8b	41	486	8.4b
Western Europe	7	279	2.5c	–	–	–
Total sample	251	5700	4.4	290	2733	10.6

[†]Accessions were classified as resistant if scored either 0 or 1 on a 0 to 9 scale in field tests at St. Paul MN from 1988 to 1994.

[‡]Macroregions with fewer than six accessions omitted, but data included in total sample.

[§]Percentages for regions in a column followed by the same letter are not significantly different by overlap of binomial confidence intervals at $P < 0.05$.

[¶]Data omitted because fewer than 10 accessions were tested.

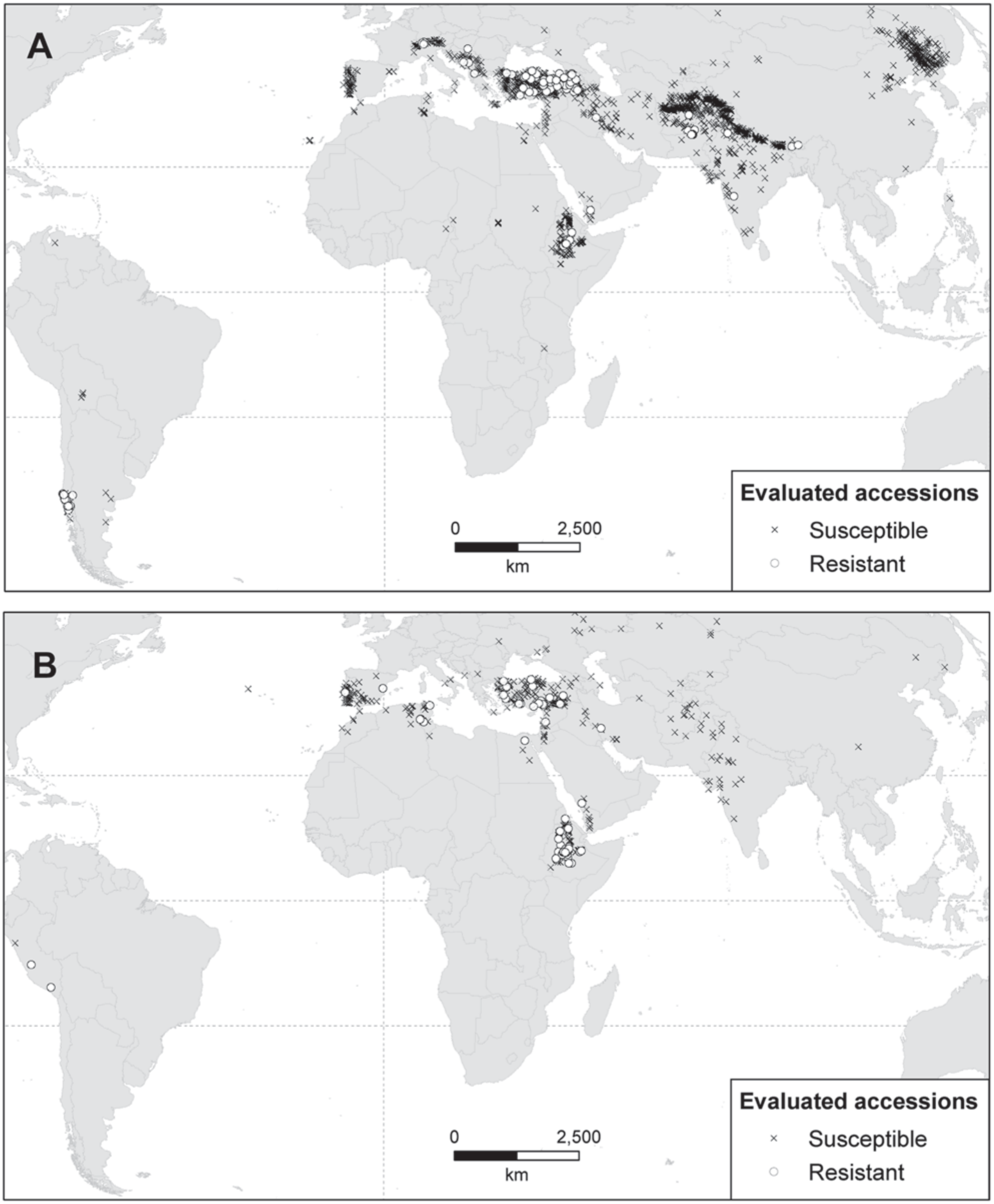

Figure 1. Distribution of accessions of (A) common wheat and (B) durum wheat for which coordinates were available and which had been scored as either resistant or susceptible based on adult plant data.

more similar to the field results in that accessions from eastern Africa, South American, and western Asia showed relatively higher frequency of resistance, suggesting that race TPMK was the most virulent race in the composite.

A high frequency of resistance occurred among the accessions from Chile. Most (71%) of the South American landrace accessions in the NSGC originated from Chile and 28.4% (33 of 116) of the Chilean accessions tested were resistant to stem rust as adult plants in the field tests. This high level of resistance was evident in the geographic distribution of resistance within the country, where all seven grid cells in Chile had at least 10% resistant accessions (Fig.

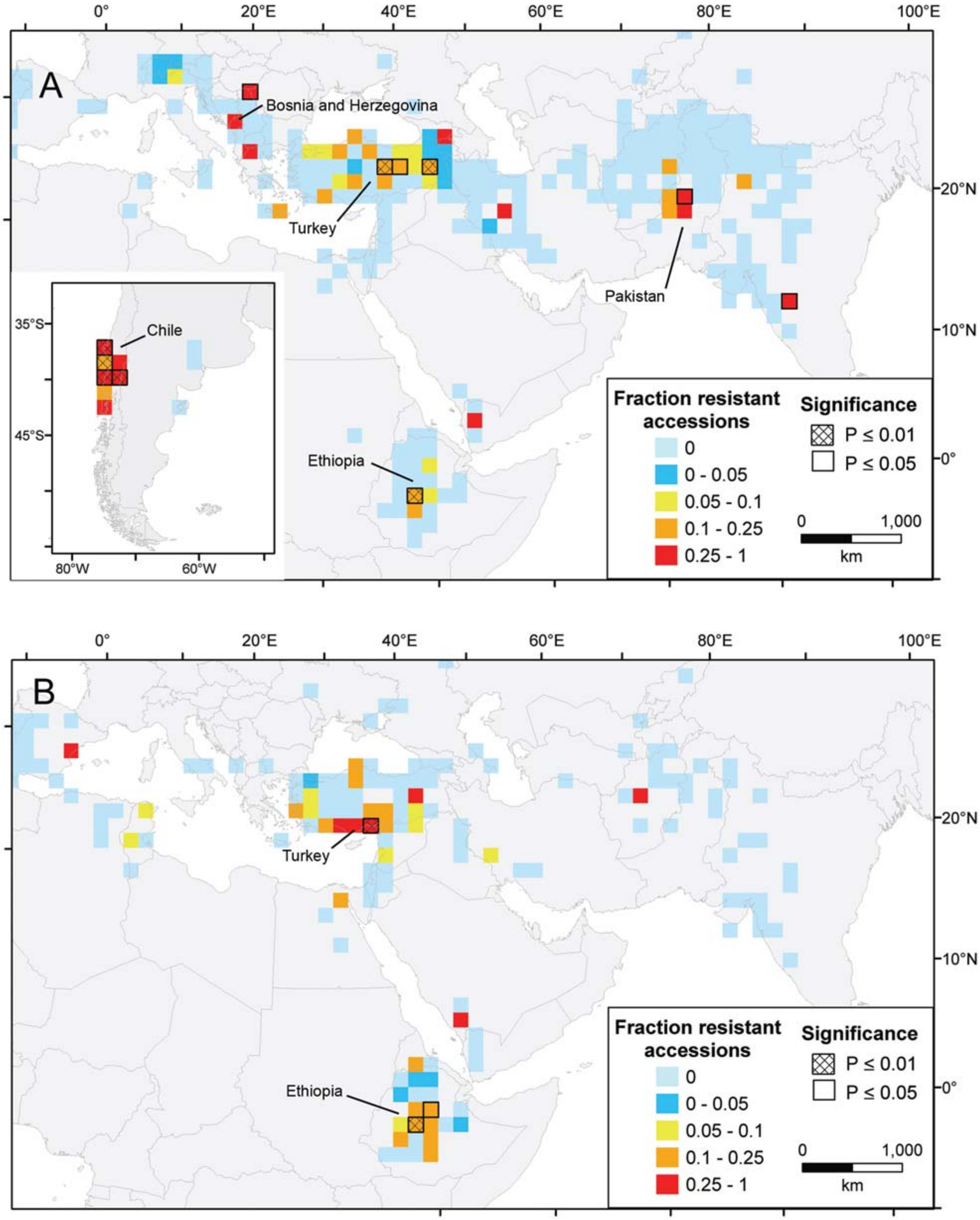

Figure 2. Fraction of stem rust resistant accessions in (A) common wheat and (B) durum wheat land races in 150- by 150-km grid cells. The presence of a statistically significant number of resistant accessions was determined with a binomial test.

2A). Out of a worldwide total of 11 grid cells, four grid cells in Chile had a significantly higher number of resistant accessions than expected. The Chilean accessions were also resistant as seedlings in the greenhouse tests. However, since wheat was introduced into South America within the past 500 yr, the high proportion of resistance in Chile could be caused by a founder effect and not necessarily to selection pressure by the stem rust pathogen.

Resistance to all three races among the common wheat accessions in the seedling tests was most frequent in the

Table 2. Percentage of common and durum wheat accessions from nine geographic regions resistant† to specific races of the stem rust pathogen.

Geographic region	*Triticum aestivum* subsp. *aestivum*				*Triticum turgidum* subsp. *durum*			
	QFCS	RTQQ	TPMK	Multiple‡	QFCS	RTQQ	TPMK	Multiple
Eastern Africa	51.6b§	51.4b	63.3a	25.4a	89.5a	86.3a	78.9a	74.6a
Eastern Asia	74.6a	75.0a	2.1d	0.6c	–¶	–	–	–
Eastern Europe	46.8b	44.6b	1.8cd	0.9c	61.3b	55.1b	7.5b	5.7b
Northern Africa	32.2bc	28.3bc	9.9c	6.7b	50.0b	32.0c	18.3b	11.0b
South America	33.9bc	34.2bc	28.3b	5.0bc	–	–	–	–
South-central Asia	24.6c	23.8c	4.0cd	1.1c	56.6b	47.2bc	17.8b	10.5b
Southern Europe	34.1b	29.6bc	19.4bc	9.6b	48.3bc	28.1bcd	16.1b	14.3b
Western Asia	49.3b	39.8b	36.2b	29.8a	25.9c	17.6d	9.1b	3.4b
Western Europe	50.9b	48.0b	24.7b	9.8b	–	–	–	–
Total sample	42.8(2919)#	39.7(3136)	16.8(3132)	8.6(2870)	61.3(962)	52.0(994)	36.4(992)	31.8(942)

†Accessions were classified as resistant if scored as infection type 2 or lower in greenhouse tests at St. Paul MN in 1988 and 1991.

‡Multiple resistant when scored as infection type 2 or lower against all three pathogen races.

§Percentages for regions in a column followed by the same letter are not significantly different by overlap of binomial confidence intervals at $P < 0.05$.

¶Data omitted because fewer than 10 accessions were tested.

#Numbers in parentheses are total samples tested across all geographic regions for each race or multiple races.

accessions from eastern Africa and western Asia (Table 2). The resistant accessions from eastern Africa all originated from Ethiopia and 94% of the resistant accessions from western Asia originated from Turkey. Coordinates were available for 381 of the 780 accessions from Ethiopia that were tested as adult plants. Resistant accessions occurred mostly in the central part of the country (Fig. 2A).

There is a high incidence of stem rust resistance in Bosnia and Herzegovina and adjacent areas of the former Yugoslavia (Fig. 2A) and in nearby Turkey. Resistance appears to be more common in landraces from central and eastern Turkey compared to the western part of the country. Turkey has a few areas with significantly higher proportion of resistant accessions than expected, but it stands out for having resistance in more than 5% of the accessions in about half of the grid cells. Turkey is also a center of concentration for common bunt resistance in spring habit accessions of *T. aestivum* (Bonman et al., 2006) and is part of the center of origin of cultivated wheats (Vavilov, 1992). Of the spring habit common wheat accessions from Turkey tested to date, 8.0% were resistant to stem rust.

Overall, accessions from eastern Asia showed little resistance in the field tests, but showed an exceptionally high frequency of resistance (75%) to races QFCS and RTQQ in the greenhouse seedling tests (Table 2). However, when tested as adult plants in the field, these accessions were susceptible (Table 1). This result indicates that accessions from this region may have resistance genes that are effective against QFCS and RTQQ, but ineffective against other races in the composite such as TPMK (Table 2).

Resistance was rare among landrace *T. aestivum* accessions from south-central Asia (Table 1). However, there was an unusual concentration of resistance within accessions from Baluchistan province in Pakistan (Fig. 2A). Ten of the 28 accessions tested from this province were resistant. The resistant accessions were collected in May–June of 1981 primarily from farm storage areas and the collection site elevations varied from 190 to 2200 masl, indicating environmental diversity in a relatively small geographic area. Such accessions, and other resistant accessions from centers of concentration, will be good materials for further experiments using molecular methods to determine the degree of genetic variation among resistant versus susceptible accessions from such areas. Previous work with common bunt resistance showed less variation in several agronomic characters for resistant versus susceptible landrace accessions from a single province in Iran (Bonman et al., 2006), perhaps indicating greater genetic uniformity among the resistant accessions.

The other grid cell in South-central Asia with significantly higher resistance occurred in Maharashtra state in India (Fig. 2A). Two of six accessions collected at this site were resistant and all six accessions were selections from the original collection PI 307167 made by P. Knowles in 1964. Thus, it is likely that the two resistant accessions have the same resistance gene or genes.

Durum Wheat

Durum wheat accessions were mostly from Portugal, Spain, Turkey and Ethiopia. The frequency of resistance among durum wheat accessions was greater than that for common wheat accessions, both in the field tests at the adult plant stage (Table 1) and in the greenhouse seedling tests against specific races (Table 2). Similarly, based on postulation of resistance genes, Roelfs and McVey (A. Roelfs, personal communication, 2006) observed that several resistance genes produced lower infection types when in a durum background than when in a common wheat background. This finding could perhaps be due to the presence of one or more suppressors of resistance in the common wheat. A suppressor was identified on chromosome 7D in the cultivar Canthatch (Kerber and Aung, 1995) that suppresses stem rust resistance genes in the A and B genomes. Also, the A and B genomes of common wheat have genes that can suppress stem rust resistance transferred from tetraploid wheats (Knott, 2000; Knott et al., 2005).

On a broad scale the same regions that showed a high frequency of resistance in common wheat also showed high resistance among the durum accessions with the exception of (i) South America where few durum accessions were available for testing, although two out of the three accessions tested were resistant and (ii) northern Africa where a high frequency of resistance occurred among the durum accessions (Table 2), but no resistance occurred among the common wheat accessions (Table 1).

All of the resistant accessions from northern Africa originated in Egypt (19.6%, n = 112) and Tunisia (7.0%, n = 186). Coordinates for relatively few accessions from Egypt were available and thus mapping the frequency of resistance should be interpreted as preliminary (Fig. 2B).

Similar to the results with common wheat, most of the accessions that were resistant in the field tests mapped to the central part of Ethiopia, but there were more areas with resistance. Eight out of 23 cells had more than 10% resistant accessions, and two of these areas had a statistically significant higher fraction of resistant accessions than expected (Fig. 2B). Rust researchers have long recognized durums from Ethiopia as a source of stem rust resistance genes. Inheritance of resistance and pathology studies have been conducted with Ethiopian accessions and new sources of resistance have been identified (Ataullah, 1963; McVey, 1991; Kenaschuk et al., 1959). The present study, however, is the first to document the geographic pattern of resistance and to quantify the higher frequency of resistance relative to common wheat among durum accessions in general and among Ethiopian durum accessions in particular.

In western Asia the geographic distribution of resistant durum accessions differed from that of resistant common wheat accessions. Most of the resistant durum landraces from western Asia originated in Turkey (31 of 41) and most of the resistant durum accessions from Turkey were concentrated in the south central part of the country, in or near Adana province where nearly half of the resistant accessions from Turkey originated (Fig. 2B).

Table 3. Maximum likelihood estimates, their standard errors, Wald's chi-square statistic and p-values, from logistic regression analysis of data from 3607 landrace accessions of common wheat.

Variable	Parameter	Parameter estimate	Standard error	Wald's χ^2 statistic	Pr > χ^2
–	β_0	0.47	0.51	0.85	0.3556
Region				392.68	< 0.0001
x_1: Eastern and South-central Asia	β_1	–1.79	0.14	159.34	< 0.0001
x_2: Eastern and western Europe	β_2	–1.78	0.29	38.26	< 0.0001
x_3: Northern and eastern Africa	β_3	0.77	0.11	52.17	< 0.0001
x_4: South America	β_4	1.63	0.14	133.78	< 0.0001
x_5: Southern Europe	β_5	1.09	0.15	50.78	< 0.0001
Habit				31.94	< 0.0001
x_6: Facultative	β_6	–0.44	0.13	12.30	< 0.0005
x_7: Spring	β_7	–0.55	0.12	22.67	< 0.0001
x_8: Leafrust	β_8	0.39	0.11	11.93	0.0006
x_9: Hessian fly biotype C	β_9	0.46	0.14	11.51	0.0007
x_{10}:Hessian fly biotype E	β_{10}	0.42	0.20	4.65	0.0311
x_{11}:Height	β_{11}	–1.37	0.18	56.63	< 0.0001
x_{12}:Days to flower	β_{12}	0.92	0.26	12.66	0.0004
x_{13}:Common bunt	β_{13}	0.52	0.12	17.92	< 0.0001
x_{14}:Stripe rust severity	β_{14}	–0.30	0.08	14.52	0.0001
x_{15}:Stripe rust, infection type	β_{15}	0.22	0.07	9.74	0.0018

Multivariable Analysis

The likelihood ratio test indicated that at least one of the factors significantly affect reaction to stem rust in common wheat accessions for which complete data were available (χ^2_{15}= 763.91 with p value < 0.0001). All 15 variables had a significant effect on reaction to stem rust at the 5% level of significance (Table 3). The Hosmer and Lemeshow test indicated that the fit of the model is adequate (χ^2_8= 7.8435 with a p value = 0.4489).

The odds of an accession from eastern Asia and South-central Asia being resistant to stem rust is only 0.155 the odds of an accession from western Asia; that is, knowing that an accession comes from eastern Asia or South-central Asia reduces its odds of being resistant by 84.5% versus accessions from western Asia (Table 4). The same can be said of an accession from eastern and western Europe versus accessions from western Asia. However, the odds of an accession from northern or eastern Africa being resistant to stem rust is a little more than twice (2.006) the odds of being resistant from western Asia (Table 4).

The model can be used to estimate the probability of an accession being resistant to stem rust. Suppose the following information is known for an accession: region of origin is South America (x_4 = 1), habit is winter (x_6 = x_7 = 0), it is resistant to leaf rust (x_8 = 1), to Hessian fly-C (x_9 = 1), to Hessian fly-E (x_{10} = 1), height (x_{11} = 1.7), days to flower (x_{12} = 1.603), is resistant to common

Table 4. Odds ratio estimates and their 95% confidence intervals generated from logistic regression analysis of data from 3607 landrace accessions of common wheat.

Effect odds ratio		Wald's 95% confidence limits	
		Lower	Upper
Eastern and South-central Asia vs. western Asia	0.155	0.109	0.220
Eastern and western Europe vs. western Asia	0.156	0.078	0.312
Northern and eastern Africa vs. western Asia	2.006	1.529	2.631
South America vs. western Asia	4.720	3.381	6.591
Southern Europe vs. western Asia	2.739	1.892	3.965
Facultative vs. Winter	0.237	0.135	0.418
Spring vs. Winter	0.213	0.125	0.365
Leaf rust: resistant vs. susceptible	2.202	1.407	3.447
Hessian fly-C: resistant vs. susceptible	2.527	1.479	4.320
Hessian fly-E: resistant vs. susceptible	2.326	1.080	5.008
Height: short vs. tall	0.255	0.179	0.364
Days to flower: early vs. late	2.501	1.509	4.144
Common bunt: resistant vs. susceptible	2.717	1.710	4.317
Severity to stripe rust: resistant vs. susceptible	0.553	0.408	0.750
Stripe rust infection type: low vs. high	1.565	1.181	2.073

bunt ($x_{13} = 1$), has stripe rust severity score > 5 ($x_{14} = 0$), and has stripe rust infection type score of ≤ 2 ($x_{15} = 1$). Evaluating the expression

$$\hat{\beta}_0 + \hat{\beta}_1 x_{1i} + \hat{\beta}_2 x_{21} \ldots + \hat{\beta}_{15} x_{15i}$$

$$= 0.4727–1.7884(0)-1.7812(0)+...+0.2238(1) = 3.2533$$

gives the estimated probability as $\frac{\exp(3.2533)}{1+\exp(3.2533)} = 0.9628$. Hence, it is very likely that such an accession would be resistant to stem rust.

Among NSGC accessions there are currently 1864 landrace accessions of *T. aestivum* for which data are complete for the descriptors used in the logistic regression model, but for which there is no stem rust field data from the St. Paul tests. Using the model we were able to identify 140 winter accessions with a greater than 70% probability of being resistant and 52 spring and facultative accessions with a greater than 50% probability of being resistant. We anticipate improving the predictive value of this model in the future by incorporating additional descriptor data and, more importantly, including rust response generated in the field tests in Kenya.

Targets for Future Testing

Since the resistance reaction of adult plants is generally a better predictor of the agronomic value of the resistance, we will use the field test data as a primary criterion for selecting landrace accessions for future testing against race TTKS in Kenya. Also, accessions from outside the geographic areas of concentration will be included as a basis for comparison. Future testing of landraces from the NSGC will focus initially on spring habit *T. aestivum* accessions, since many spring common wheat cultivars from North America are vulnerable to race TTKS (Jin and Singh, 2006) and testing winter accessions at the site in Kenya requires much additional work to assure vernalization.

Continued screening of accessions against North American races of *P. graminis* f. sp. *tritici* will be useful, since resistance to current North American races in combination with resistance to TTKS from eastern Africa will be most valuable. In addition to the 251 resistant landrace accessions identified in the present study (Table 1), previously untested accessions will be targeted for further testing including (i) accessions from Bosnia and Herzegovina, the former Yugoslavia, Chile, Ethiopia, Baluchistan Province in Pakistan, and Turkey and (ii) other accessions identified based on the logistic model described in the present study. Accessions from Iran should also be included, because Iran is adjacent to regions where resistant accessions have originated (Fig. 2A), and more than 7000 Iranian landrace accessions were added to the collection since the St. Paul stem rust trials were completed, including nearly 3000 spring accessions (Bonman et al., 2006).

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