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Leaf and stem seedling rust resistance in wheat cultivars grown in Croatia

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Abstract Diseases caused by *Puccinia* species can have devastating effects on wheat and other crops, causing severe economic losses by reducing grain yield and quality. Generally, three strategies are used to control leaf and stem rust wheat diseases: (i) incorporating genetic resistance into new cultivars (ii) the use of fungicides (iii) crop management. The first approach is the most environmentally and economically efficient. Combined with traditional selection techniques, marker-assisted selection (MAS) has become a valuable tool in selection of individuals carrying genes that control traits of interest, such as disease resistance. The objective of this study is to postulate leaf and stem rust resistance genes in 50 mostly Croatian wheat cultivars. Most of the cultivars were screened for the first time for rust diseases. The studies detected six leaf rust resistance genes (*Lr2a*, *Lr3*, *Lr10*, *Lr14a*, *Lr17* and *Lr26*) and four stem leaf resistance genes (*Sr8a*, *Sr31*, *Sr36* and *Sr38*). Nine wheat cultivars had one or more unidentified *Lr* genes that were not included in the set of 24 isolines, and six wheat cultivars had one or more unidentifed *Sr* genes. Knowledge on the identity of the seedling rust resistance genes in released cultivars and germplasm is essential for the incorporation of effective resistance genes into breeding programs to maintain a diversity of resistance genes in commonly grown cultivars.

Keywords Wheat · Gene postulation · Leaf rust · Stem rust

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Introduction

Diseases caused by *Puccinia* species have reached epidemic proportions in many parts of the world, and sometimes cause severe economic losses by reducing grain yield and quality of wheat and other crops. Leaf rust, caused by *Puccinia triticina* formerly *Puccinia recondita* Roberge ex Desmaz.f.sp. *tritici* Eriks and Henn., *Pt*, is a common disease of wheat (*Triticum aestivum* L.) in Croatia and worldwide (Roelfs et al. 1992). *P. triticina* is now recognized as an important pathogen in wheat production world-wide, causing significant yield losses over large geographical areas (Bolton et al. 2008). In Croatia, wheat production is approximately 4.6 t ha^{-1} in average with harvested area of 169,583 ha from 2000 to 2012 (Croatian bureau of statistics in Republic of Croatia 2013)., where in the last 20 years, leaf rust mostly occured with average disease severity around 5–15 % but fungicides are regularly applied to control the disease. In 2014 severe epidemics of wheat stripe rust in combination with leaf rust occured and there was a significant yield loss in susceptible wheat genotypes, when rusts were responsible for 40–50 % yield loss. In the spring, with temperatures of 20–25 °C with free water on the leaf surface for 8 h, new leaf rust infections can rapidly develop. Leaf rust in wheat appears as brown to orange dusty pustules (circular to oval in shape) on the upper surface of leaves. Leaf rust reduces yields and test weights because infected leaves die prematurely and can also reduce grain quality.

In Europe, epidemics of stem rust (caused by *P. graminis* Pers. f. sp. *tritici*, *Pgt*) began in Bulgaria, but spread through eastern and northern Europe (Zadoks 2008). Stem rust can be a highly destructive disease of wheat and is capable of destroying entire wheat fields over a large area within a short time period. It has the potential to cause losses up to 100 %, whereas up to 40 % losses due to leaf rust have been reported. Infections of stem rust have not been noted in wheat fields in Croatia. In some countries the recent outbreak of a new wheat stem rust pathogen race that is virulent to the majority of commercial wheat cultivars highlights the need for durable disease resistance in crop plants (Ayliffe et al. 2008). Stem rust can be found on plant stems, leaves, sheaths, glumes and awns. Usually pustules of stem rust are elongated, reddish-brown in color. They could become black, due to the production of non-infectious teliospores. Heavy rusting causes early loss of these leaves, which reduces the grain filling period and results in smaller kernel size. Grain from stem rust infected wheat is often shriveled, which may reduce yield and quality.

Wanyera et al. (2009) suggest that fungicides can be used effectively in reducing stem and leaf rust severity and increasing yield of susceptible wheat cultivars. However, this can be an expensive method of disease control. The best approach to control diseases such as rusts is genetic resistance based on effective resistance genes. Selection for a leaf and stem rust resistance in wheat cultivars can be facilitated by extensive genetic analyses using molecular markers that are linked or are specific to the resistance genes (Kolmer et al. 2013). Over 70 leaf rust resistance genes have been described in wheat (McIntosh et al. 2009) and a number of genes have been used in the wheat breeding programs, such as *Lr12* (McIntosh and Baker 1996), *Lr13* (Dyck et al. 1966), *Lr22a* and *Lr22b* (Dyck 1979), *Lr34* (Dyck 1987), *Lr35* (Kerber and Dyck 1990), *Lr37* (Bariana and McIntosh 1993), *Lr46* (Singh et al. 1998), *Lr67* (Herrera-Foessel et al. 2011), *Lr68* (Herrera-Foessel et al. 2012) and more recently trp-1 and trp-2 (Da-Silva et al. 2012). To date, molecular markers have been identified for several stem rust resistance genes including *Sr2* (Spielmeyer et al. 2003), *Sr6* (Tsilo et al. 2009), *Sr9a* (Tsilo et al. 2007), *Sr22* (Pretorius et al. 2000; Singh et al. 2011), *Sr24* and *Sr26* (Mago et al. 2005), *Sr25* and *Sr26* (Liu et al. 2009), *Sr28* (Rouse et al. 2012), *Sr31* (Mago et al. 2002), *Sr32* and *Sr35* (Pretorius et al. 2000; Singh et al. 2011), *Sr36* (Tsilo et al. 2008), *Sr38* (Seah et al. 2001), *Sr39* (Mago et al. 2009), *Sr40* (Wu et al. 2009), *Sr44* (Liu et al. 2013), *Sr45* (Sambasivam et al. 2008), *Sr50* (synonym SrR, Anugrahwati et al. 2008), *Sr51* (Liu et al. 2011a, b), *Sr52* (Qi et al. 2011), *SrCad* (Hiebert et al. 2010a) and and *SrWeb* (Hiebert et al. 2010b).

Gene postulations are possible because of gene-for-gene specificity, where the infection types produced by pathogen isolates on wheat cultivars under study are compared to infection types produced by the same isolates on the so-called differentials, often near-isogenic lines, each carrying a single known resistance gene (Pathan and Park 2007). Seedling *Lr* and *Sr* resistance genes can provide protection at all stages of plant growth, but are usually race-specific, in contrast to adult plant resistance (APR) genes, which may not be race-specific. Surveillance of wheat rust pathogens, including assessments of rust incidence and virulence characterization through either trap plots or race (pathotype) surveys, has provided information fundamental in formulating and adopting appropriate national and international policies, investments and strategies in plant protection, plant breeding, seed systems, and in rust pathogen research (Park et al. 2011).

For breeding for leaf or stem rust resistance in Croatia, it is important to make uredinial collections of leaf and stem rust from wheat plots and fields in Croatia. After that the identification of virulence phenotypes should be done (Kolmer et al. 2011). Virulence surveys have been done in different countries in Europe, in the former Czechoslovakia

(Hanzalova et al. 2008), France (Goyeau et al. 2006), Spain (Martinez et al. 2005), Hungary (Manninger 1994), Germany (Lind and Gultyaeva 2007) and the UK (Bayles and Borrows 2011). As new virulent races can appear, it is important for breeders to know of the genetic background of the leaf and stem rust resistance in their cultivars (Purnhauser et al. 2011). Little information about the leaf and stem rust resistance genes present in Croatian wheat cultivars and lines is available. In this study we characterized the leaf and stem rust reaction of 50 wheat cultivars and postulated the presence of known genes based on infection type in response to well-characterized races of these pathogens.

Materials and methods

Plant materials

Fifty winter wheat cultivars (Table 1), mostly from Croatia, were tested for infection types (ITs) to postulate seedling leaf and stem rust resistance genes. At least six seedlings of each cultivar were grown in 10 by 10 cm square pots in Metro-Mix 200 vermiculite peat-perlite medium in a greenhouse with supplementary lighting to provide a 16 h photoperiod.

Inoculum and inoculation

All isolates were derived from single pustules, increased in isolation, and stored at −80 °C. Inoculation of *P. graminis* and *P. triticina* isolates was performed in an inoculation booth at the United States Department of Agriculture Research Service (USDA-ARS) Cereal Disease Laboratory during November 2012 through February 2013. Inoculum of 10 different races was used for leaf rust inoculation and 12 different races for stem rust inoculation. Isolates of *Pgt* races are described in Rouse et al. (2011). In addition, isolate 06YEM34-1 was used for race TRTTF. Inoculation and incubation were performed as described previously (Jin et al. 2007). *P. graminis* and *P. triticina* urediniospores were retrieved from storage at −80 °C and heat shocked at 45 °C for 15 min. Spores were rehydrated by placing the capsules in an air-tight container at 80 % humidity maintained by a KOH solution for 2–4 h. Urediniospores were then suspended in a light-weight mineral oil (Soltrol 70) and sprayed onto seedlings. Seedlings were inoculated when the first leaf was fully expanded with a suspension of urediniospores of single *P. triticina* and *P. graminis* races. The inoculation booth was washed with water between inoculations of plants with different *P. graminis* and *P. triticina* isolates in order to prevent contamination. For approximately 30 min plants were under a fume hood for oil evaporating. Plants were kept in a 100 % humidity chamber overnight and maintained in the greenhouse at 15–25 °C with supplemental lighting after inoculation.

Disease assessment and data analysis

After dew chamber incubation, plants were kept in a greenhouse at the USDA-ARS Cereal Disease Laboratory maintained at 18 ± 2 °C for 14 days. Infection types (ITs) were classified on a 0–4 scale 12–14 days after inoculation on seedlings as described by Stakman et al. (1962): IT 0 = immune response, with no uredinia or necrosis; IT fleck (;) = necrotic flecks; IT 1 = small uredinia surrounded by necrosis; IT 2 = small uredinia surrounded by chlorosis; IT 3 = moderate uredinia; IT 4 = large uredinia. Designations of + and − were added to indicate larger and smaller size of uredinia; X = a mesothetic response of flecks, small and large uredinia. Stem rust evaluations for *Pgt* races QTHJC, RKQQC, RCRSC, TPMKC and TTTTF were replicated so that a total of at least 20 seedlings from each cultivar were evaluated. The presence of resistance genes was postulated by comparing the IT pattern of tested cultivars with IT pattern of leaf (*Lr1*, *Lr2a*, *Lr2c*, *Lr3*, *Lr9*, *Lr16*, *Lr24*, *Lr26*, *Lr3 ka*, *Lr11*, *Lr17*, *Lr30*, *LrB*, *Lr10*, *Lr14a*, *Lr18*, *Lr3bg*, *Lr14b*, *Lr20*, *Lr28*, *Lr reselect*, *Lr21*, *Lr23* and *Thatcher*) and stem (*Isr5-Ra*, *Triticum monoccocum*, *Verstein 9e*, *Isr 7b-Ra*, *Isr11-Ra*, *Isr6-Ra*, *Isr8a-Ra*, *CnSSr 9 g*, *W269/SrTt-1*, *W2691Sr 9b*, *BtSr30Wst*, *Combination VII*, *Isr9a-Ra*, *Isr9d-Ra*, *W2691 Sr10*, *Cn SSr Tmp*, *Lc Sr 24Ag*, *Sr31 (Benno)/6*LMPG*, *Trident* and *McNoir 701*) rust differentials.

Results

Infection types of 10 *P. triticina* isolates on 24 Thatcher lines with seedling leaf rust resistance genes

Table 1 Origin and pedigree of tested winter wheat genotypes

Nr	Genotype	Origin and year released	Pedigree
1	U1	HR, AIO, 1936	Marquis/Carlotta Strampelli
2	Dubrava	HR, AIO, 1968	Pilot/U1//Libero
3	Tena	HR, AIO, 1973	Libellula/Bezostaya 1
4	Osjecka crvenka	HR, AIO, 1976	Libellula/Bezostaya 1
5	Osjecka 20	HR, AIO, 1978	Osk6.9-1-64/B188 M
6	Osjecanka	HR, AIO, 1980	Tena (EMS 1.5 %)
7	Slavonija	HR, AIO, 1984	Osjecka 20/Osk.4.216-2-76
8	Zitarka	HR, AIO, 1985	Osk.6.30-20/Slavonka//Osk.6.78-1- 73/Kavkaz
9	Srpanjka	HR, AIO, 1989	Osk.4.50-1/ZG.2696
10	Demetra	HR, AIO, 1991	Osk.5.216-2-76/Zg.2877-74
11	Golubica	HR, AIO, 1998	Slavonija/Gemini
12	Super Zitarka	HR, AIO, 1997	GO3135/Zitarka
13	Lucija	HR, AIO, 2001	Srpanjka/Kutjevcanka
14	Alka	HR, AIO, 2003	Osk.5.140-22-91/Sana
15	Renata	HR, AIO, 2006	Zitarka/Osk.7.5-4-82/Kom.Bg.160-86//Srpanjka
16	Katarina	HR, AIO, 2006	Osk.5B.4-1-94/Osk.5.140-22-91
17	Felix	HR, AIO, 2007	Srpanjka/K.160-86
18	Kraljica	HR, AIO, 2010	Osk.5.698-4-99/Osk.4.21-7-99
19	Seka	HR, AIO, 2006	Srpanjka/Demetra
20	Ilinca	HR, AIO, 2009	Osk.8.37-10-91/Srpanjka
21	Ficko	HR, AIO, 2007	Srpanjka/Rialto
22	Anđelka	HR, AIO, 2008	Srpanjka/Demetra
23	Bandolero	HR, AIO, 2011	Osk.5.87-7-90/Osk.9.11-2-95
24	Olimpija	HR, AIO, 2009	Slavonija/K.H.-1-98
25	Jana	HR, AIO, 2009	Osk.6.A.20-3-94/Prointa Super
26	Vulkan	HR, AIO, 2009	Osk.3.343-1-97/FS-811-98//Kom.RH.-44-99
27	Nova Zitarka	HR, AIO, 2010	FS-800-98/Zitarka
28	Silvija	HR, AIO, 2010	Soissons/Osk.2-97
29	Rebeka	HR, AIO, 2011	Br 442/Kom.RH.79-98
30	Antonija	HR, AIO, 2011	Victo/Brea//Victo
31	Leuta	HR, AIO, 2011	Osk.5.495-21-97/Osk.4.502-3-98
32	Sirban Prolifik	HU, 1905	Unknown pedigree
33	San Pastore	IT, 1940	Balilla/Villa gloria
34	Libellula	IT, 1965	San Pastore//Tevere/Guiliani
35	Bezostaya 1	Former USSR, 1955	Skorospelka 2/Lutenscens 17
36	Zlatna Dolina	HR, Bc,1971	Leonardo/ZG 414-57
37	Sana	HR, Bc, 1983	Mura/CI 14123//Zg 2413-72
38	Apache	FRA, 1998	Axial/Nrpb-84-4233
39	Adriana	HR, Bc, 1988	Zg-1758-70/T.P.R.349
40	Divana	HR, Jost, 1996	Favorit/5/Cirpiz/4/Jang/Kwang/2/A + 66/Comanche/3/Velvet
41	Renan	FRA, 1991	Mironovskaya 808/Maris Huntsman//VPM1/Moisson/3/Courtot
42	Dropia	ROM, 2006	Colotana/F-2120-W-1
43	Flamura 85	ROM, 1989	Rannyaya-12/Nadadores-63//Lovrin-12
44	Element	AUT, 2009	Capo/Kontrast

Table 1 continued

Nr	Genotype	Origin and year released	Pedigree
45	Lupus	AUT	Expert/Kormoran/Atom//Karat
46	Graindor	FRA, 2006	Petrus/Apache
47	MV Suba	HUN, 2002	Erythrospermum-1778-87-2/MV-Magdalena
48	Fiesta	HR, Bede, 1998	87-83/Osk.3.68-2-85
49	Gabi	HR, Bede, 1999	Srpanjka/GK 32-82
50	Capo	AUT, 2006	Pokal/Martin

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are not shown. These 10 isolates all had IT of 3 + to the Thatcher line with *Lr1*, *Lr14b*, *Lr20*, *Lr* reselect and Thatcher, but varied on the other Thatcher lines. IT of the 10 isloates on the 50 winter wheat cultivars are shown in Table 2. Cultivars 'Osjecka 20', 'Slavonija', 'Zitarka', 'Golubica', 'Super Zitarka', 'Nova Zitarka', 'Sirban Prolifik', 'Apache', 'Adriana', 'Element', 'Lupus', 'Graindor', 'Mv Suba' and 'Capo' had high ITs of 3+ to nearly every isolate, and were not postulated to have any of 24 seedling leaf rust resistance genes tested in this study. The one cultivar postulated to have *Lr2a* had low IT of 0; or; to isolates TCRKG, MHDS, Race 5 and MLDS. The 16 cultivars postulated to have *Lr3* all had low IT of 0; or; to isolate Race 9 or TCRKG that had low ITs on the Thatcher line with *Lr3*. Seven cultivars postulated to have *Lr10* all had 0; or; to isolate MCTNB. The four cultivars postulated to have *Lr14a* all had low IT of 0; or 0 to isolates TNRJ and TCRKG. The six cultivars postulated to have *Lr17* had low IT of 0; or; to isolates NBBR, TCRKG, TDBG and KFBJ. The seven cultivars postulated to have *Lr26* had low IT to isolates Race 9, Race 5 and MLDS, as did Thatcher line with *Lr26*. Nine wheat cultivars ('Tena', Osjecka crvenka', 'Srpanjka', 'Alka', 'Seka', 'Ilinca', 'Anđelka', 'Libellula' and 'Fiesta') had one or more unidentified *Lr* genes that were not included in the set of 24 isolines. The ITs of 14 cultivars did not allow the postulation of a seedling resistance gene. For cultivars 'U1', 'Vulkan', 'Leuta' and 'Renan' it was not possible to make a postulation because of too much variation in IT. The cultivars 'Tena', 'Osjecka crvenka', 'Srpanjka', 'Seka', 'Andjelka' had very low ITs to all isolates tested which also did not allow gene postulation.

Infection types of 12 *P. graminis* isolates to 20 differentials with seedling stem rust resistance genes are not shown. Seedling tests conducted on the 50 cultivars with 12 stem rust pathotypes allowed postulation of four seedling stem rust resistance genes present either singly or in combination. Four cultivars ('U1', 'Osjecka 20', 'Golubica' and 'Felix') postulated to have *Sr8a* had low ITs to MCCFC, QCCSM, QFCSC, TRTTF and RCRSC (Table 3). The 14 cultivars postulated to have *Sr36* all had low IT of 0; or 0 to isolates TTKSK, QTHJC, QFCSC, MCCFC and SCCSC. Gene *Sr36* was postulated in cvs 'Srpanjka', 'Demetra', 'Alka', 'Renata', 'Katarina', 'Felix', 'Kraljica', 'Seka', 'Ilinca', 'Ficko', 'Anđelka', 'Leuta', 'Sana' and 'Adriana'. The three cultivars postulated to have *Sr31* had lower IT of 0; or; or 1 or 2- to all isolates except for TTKSK. The four cultivars postulated to have *Sr38* all had low IT of 0; or 0 to all isolates except for TTTTF, TRTTF and TTKSK. The ITs of the other 27 cultivars did not allow the postulation of a seedling resistance gene.

Discussion

The objective of the present study was to identify sources of rust resistance in a selection of the Croatian-grown wheat cultivars and other international cultivars. Results of this study indicated that at least six named *Lr* genes and four *Sr* genes and several unidentified *Lr* and *Sr* genes are responsible for race-specific seedling resistance to leaf and stem rust among 50 winter wheat cultivars. A higher proportion (54 %) of the cultivars carried resistance effective against leaf rust, while 46 % of the cultivars carried seedling resistance genes against stem rust pathotypes employed in this study.

Genes *Lr3*, *Lr10* and *Lr26* were identified in 48 % (32, 14 and 14 %, respectively) of the wheat cultivars in this study. Presence of *Lr3* gene was determined in cultivars 'Demetra', 'Lucija', 'Alka', 'Katarina', 'Jana', 'Silvija', 'Rebeka', 'Libellula', 'Bezostaja 1',

Table 2 Seedling infection types of 50 wheat (*T. aestivum*) cultivars to 10 races of *P. triticina* and the *Lr* genes postulated

Genotype	Race 9	NBBR	TCRKG	TDBG	MHDS	Race 5	TNRJ	MLDS	MCTNB	KFBJ	*Lr* gene
U1	;/3+	;1	3+/;12	1+	;1+2	;12−/3	;12−	1+2	;1−	;1−	?
Dubrava	3	3+	33+	0;	3+	32+	23	33+	32+	3+	*Lr14a*?
Tena	;/3+	12−	;12	0;	;22+	;2/3+	;1	;2	12	;2−	+
Osjecka crvenka	0	;	;1	1	;2	1;	;	;2−	;1	;2−	+
Osjecka 20	3	33+ ;	3+	33+	32+	3	;1/3;	3+/;1	3−	3+	none
Osjecanka	;	;1	;1−	;	22+ ;	;	;1−	;12+	1;/0	;	*Lr17*?
Slavonija	33+	3;	2+3	;2−	3+	3+	3;	3+	3+	3+	none
Zitarka	3+	3+	33+	3+	3+	3+	3+	3+	3+	3+	none
Srpanjka	;	;	;	;2−	;2−	;	;	;	;2−	;2−	+
Demetra	;	;	32+ ;	3/0	32+	2+3	;123	3+	3+	32+	*Lr3*
Golubica	33+	32+;	3+	32+; (x)	3+	3+	3;	3+	3+	32+	none
Super Zitarka	3+/3+;	33+	3+	32+;(x)	3+	3+	23+;	3+	3+	32+ ;	none
Lucija	;	;	;2	3;	33+	2	;1	32+;	;2-	;	*Lr3*, *Lr10*, *Lr17*
Alka	;	;	;2-	3+2;(x)	;2	;1	;1-	;12−	3+	;2	*Lr3*, +
Renata	;	;	;	;1	2	;	;	;12−	3+	;	*Lr17*, *Lr26*
Katarina	;	;	32+	;2	3+	3	;2+3	3+	3+	3+	*Lr3*
Felix	;	;	;	;	;2−	;	;	;	32+	;	*Lr17*, *Lr26*
Kraljica	;	;	;2−	;	32+	;12−	;12−	2+3;	2;	;	*Lr10*, *Lr17*
Seka	;	;	;2−	2	;2	;1−	;1	;1	;2−	;	+
Ilinca	;	;	;2	;	;1	;0	;1	;	3+;	;2−	*Lr17*, *Lr26*, +
Ficko	;	;	2+3;	;	3+	;	;2−	;	;1	3−	*Lr10*, *Lr26*
Anđelka	;	;	;	;2−	;	;2−	;	;	;12	;	+
Bandolero	;	;	32+	;2−	3+	;	3+;	;	;1−	3+	*Lr10*, *Lr26*
Olimpija	;123	32+;	32+	2;/0	3+	3+	3;	3+	2;	3+	*Lr14a*?
Jana	;	;	;/;2/2+	33+	;	;	3;	;	;/3+	3-	*Lr2a*, *Lr3*
Vulkan	;	0;	2;	;	;	;1	32+;	;12-	;1−	;1−	?
Nova Zitarka	3+	32+	2+3	32+; (x)	3+	33+	2+;	3+	3+	22+;	none
Silvija	;123	;2	3+	32+; (x)	3+	3+	3+;	3+	3+	3+	*Lr3*
Rebeka	;	;	2+	;2	32+;	23+	22+;	3+	0;	2+3	*Lr3*, *Lr10*
Antonija	;2=	;	3+	;2	;2	;	3;	;	3	2	*Lr26*
Leuta	;	;	;22+	32+; (x)	22+;	;2	;	2 + 3	33+	;1	?
Sirban Prolifik	3+	3+	3+	3+	3+	3+	22+	3+	3+	3+	none
San Pastore	0;	;	;22+	0;	;2	;	;	;	3	3+2+	*Lr26*
Libellula	0;	;	;2-	;2−	;2	;2-	;	;12-	32+;	;	*Lr3*, +
Bezostaya 1	;1−	;	3+2+;	;/2−	;22+	23;	23+;	3	32+;	3+2+	*Lr3*
Zlatna Dolina	;	;	3+2+;	32+; (x)	32+	33+	2+3;	3	3+	33+	*Lr3*
Sana	;	;	3+	32+; (x)	32+;	;12	3;	3	3+	3+	*Lr3*
Apache	2+ ;	;23	32+	3+	3+	23+	22+;	3+	3+	2+3+	none
Adriana	3	3+	3+	32+; (x)	3+	3+	3+	3+	3+	3+	none
Divana	0;	;	3+	32+; (x)	32+	3+	;23	3+	3+	3+	*Lr3*
Renan	2-;	32+	;22+	;2	3+	;	;12−	3+	3+	;2	?
Dropia	0;	0;	23+	;	32+	33+	32;	3	;	32;	*Lr3*, *Lr10*, *Lr14a*
Flamura 85	0;	;	3+2+	;	32+;	33+	32+;	3+	;1	;2/3+	*Lr3*, *Lr10*, *Lr14a*
Element	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	none
Lupus	0;/3+	;/3+	3+	;2	3+	3+	33+ ;	3+	3+	3+	none
Graindor	3+/3+;	;23	33+	3+	3+	23;	;12−	2	3+	3+2+	none
MV Suba	3+	3+	3+	;23	3+	3+	3;	3+	3+	3+2+	none
Fiesta	;	;	2;	2+	3+	0;	;12−	2	3+	3+2+	*Lr3*, +

Table 2 continued

Genotype	Race 9	NBBR	TCRKG	TDBG	MHDS	Race 5	TNRJ	MLDS	MCTNB	KFBJ	*Lr* gene
Gabi	;	;	3+	3	3+	3+	23	3+	23+	3+	*Lr3*
Capo	3+	3+ ;	3+	3+	3+	3+	3+	3+	3+	3+	none

"-" No *Sr* or *Lr* genes are detected; "+" Other genes could be present; "?" Unable to make postulation

'Zlatna Dolina', 'Sana', 'Divana', 'Dropia', 'Flamura 85', 'Fiesta and 'Gabi'. In a previous study of Morgounov et al. (2012) cultivar 'Bezostaya 1' had durable resistance to a few diseases. Previously 'Bezostaya 1' had a huge impact on agriculture and breeding because of its durable resistance, adaptability and good quality. *Lr10* was identified in cultivars 'Lucija', 'Kraljica', 'Ficko', 'Bandolero', 'Rebeka', 'Dropia' and 'Flamura 85'. This gene was not widely effective on its own or in gene combinations in Australasia (Singh et al. 2001). Gene *Lr26* has been associated with wheat lines that have the 1BL.1RS translocation from rye (Zeller 1973). In our research *Lr26* was present in seven cultivars ('Renata', 'Felix', 'Ilinca', 'Ficko', 'Bandolero', 'Antonija' and 'San Pastore'). Most European wheat genotypes carry the 1BL.1RS translocation which carries a cluster of stem, leaf and yellow rust and powdery mildew resistance genes transferred from rye (Singh et al. 2008; Molnár-Láng et al. 2010). The effectiveness of *Lr26* may be somewhat cyclical, depending on whether races with virulence to these genes are increasing or decreasing (Kolmer 2010). Genes *Lr17*, *Lr14a* and *Lr2a* were identified to be present in lower frequencies (12, 8 and 2 %, respectively). Gene *Lr14a* was postulated to be present only in 'Dubrava', 'Olimpija', 'Dropia' and 'Flamura 85'. This gene was reported to be difficult to detect due to its moderate reaction and hence epistatic effect of other genes with lower infection types and it has not has not been considered useful (McIntosh et al. 1995). It appeared that 'Dubrava', 'Olimpija', 'Dropia' and 'Flamura 85' had other seedling genes (*Lr3*, *Lr10* and unidentified *Lr* genes) that could be epistatic over *Lr14a*. Gene *Lr2a* was detected only in cultivar 'Jana'. If *Lr2a* used alone it has been considered as having limited value (McIntosh et al. 1995).

Cultivars 'U1', 'Osjecka 20', 'Golubica' and 'Felix' carried *Sr8a*. Gene *Sr36* was postulated in 14 cultivars. It was reported that *Sr36* was common in Hungarian wheat cultivars (Pathan and Park 2007). Kolmer et al. (2007) found that resistance genes *Sr2*, *Sr6*, *Sr17*, *Sr24*, *Sr31*, *Sr36*, and *SrTmp* are common in United States winter wheats, in comparison with genes *Sr6*, *Sr9b*, *Sr11*, and *Sr17* that are common in United States spring wheats. The ITs of the 27 cultivars did not allow the accurate postulation of a seedling resistance gene with the available *Pgt* races assessed. Almost all cultivars in our research had high ITs in response to race TTKSK. This is not surprising because stem rust is a disease of low importance in Croatia, and selection for stem rust resistance has not been practiced. Race TTKSK (Ug99) emerged in Africa (Wanyera et al. 2006) and was found to be virulent on stem rust resistance genes *Sr5*, *Sr6*, *Sr7b*, *Sr8a*, *Sr8b*, *Sr9b*, *Sr9e*, *Sr9 g*, *Sr11*, *Sr15*, *Sr17*, *Sr30*, *Sr31* and *Sr38*. Thus, Ug99 is an immediate threat to world wheat production and was the first stem rust race reported to be virulent on *Sr31*, a gene present on the short arm of chromosome 1R from 'Petkus' rye and introgressed into hexaploid wheat as a 1RS-1BL translocation (Zhang et al. 2010).

Yield loss studies in growing season 2013/2014 in field plots in Croatia with fungicide treatments in different stages of wheat development determined that combination of leaf and stripe rust was a major cause of yield loss in wheat, were susceptible wheat genotypes suffered losses that ranged from 20 % to over 65 % (unpublished data). Field rust tests are needed to verify if seedling susceptible entries carry adult plant resistance. The new races of wheat leaf rust challenge wheat breeders to develop cultivars with effective resistance genes to leaf rust, using marker-assisted selection. From a practical point of view, seedling resistance genes can be useful in future selection processes. The information presented can be useful for wheat breeders contributing to a more efficient exchange of information and use of germplasm, but this research needs to be complemented with additional studies on adult plant resistance because some leaf rust resistance genes express resistance optimally in adult plants.

Table 3 Seedling infection typesof 50 wheat *(T. aestivum)* cultivars to 12 races of *P. graminis* and the *Sr* genes postulated

Genotype	QTHJC rep 1	QTHJC rep 2	RKQQC rep 1	RKQQC rep 2	RCRSC rep 1	RCRSC rep2	MCC-FC	QCC-SM	SCC-SC	QFC-SC	BCC-BC	TPMKC rep 1	TPMKC rep 2	TTTTF rep1	TTTTF rep 2	TRTTF	TTKSK	*Sr* gene
U1	3+/0	3+ lif	3+	3+	2	3+	0/2−	0/2	3+/2	23+	0/2	3+	3+	3+	0/3 + lif	22+	3+	*Sr8a*
Dubrava	0/3 + Lif		3+	0/3 + Lif	3+	3	3+	3	3+/ 22+	3+	0	3+	3+	3+	3+	3+	3+/0	–
Tena	3+/0;	3+	3+	3+	3+	3+	3+	3+	0	3+	;2-	3+	33+	3+	3+	3+	3+	–
Osjecka crvenka	3+	3+	3+Lif	0/3 + Lif	3+	0	3+	3+	0/3+	3	;1/3-Lif		3	3+	3+	3+	3+	–
Osjecka 20	2/0	2	0;	0/3 + Lif	2−	0	0/1	0	0/2	2−	;	;/3Lif	3+	0/3 + Lif	3 + lif	2	3+	*Sr8a*
Osjecanka	0/3+	3+	3+	3+	3+	3+	3+	3+	0	3+	;2	3+	3+	3+	3+	3+	3+	–
Slavonija	2	2	33−;	0/23	2−	2−	2−	0/1	1	2−	;1	3+	3+	3+	3+		3+	–
Zitarka		23+	3+	0	3+	3+	3+	23	3+ ;/ 0;	2−	;1	3+	3 + ;	3+	3+	3+	3+	–
Srpanjka	0	0	0/3+	3	0/3	0	0	0	0	0	0	3+Lif	3+	3+	0/3+	3+	0/1+	*Sr36*
Demetra	0	0	3+2	3+	3+	3+	0;/ 3 + Lif	0	0	0	0	3+		3+	3+	3+	;1/0;	*Sr36*
Golubica	2/0	1		0/3+Lif	0;	0		0/1	0/2	0/2−	2−	3+	3+	3+	3+	12	3+	*Sr8a*
Super Zitarka	2	23		3+	3+	3+	3+	0		0/2−	;/2−Lif	3+	3+	3+	3+	33+ ;	3+	–
Lucija	1 + 3	0	3+	3		3	0/3+	3	3	3	3+	3+	3+	3+	3+	3+	3+	–
Alka	0;	0	3+	3+	0;2−	2	0	0	0	0	0	3+;	3+	3+	3+	22+	0;/;1	*Sr36*
Renata	0	0	33+	3+	3+	3+	0	0	0	0	0	3+	3+	3+	3+	3+	0/;1	*Sr36*
Katarina	0	0	3+	3+	3+/ ;2−		0	0/2− Lif	0	0	0/;1	3+	2−	3+/2−;	3+	3+/;2−	;1/31	*Sr36*, +
Felix	0	0	0/3+	3+	2;/0	0	0	0	0	0	0	3+	3+	3+	0/3+	22−	0/;1	*Sr36*, +, *Sr8a*
Kraljica	0	0	0/3+	3+	3	2−/ 3lif	0	0	0	0	0	0;/ 3Lif		3+	3+/2−/0	2−/3+	0;	*Sr36*
Seka	0	0	3+	3+	3+	3+	0	0	0	0	0	3+1;		3+	3+	3+	0;	*Sr36*
Ilinca	0	0	0	0	0;2-	1	0	0	0	0	0	2/0	2	3/0;	3	22-	0;1	*Sr36*, +
Ficko	0	0	0;	1-	0;	;	0	0	0	0	0	0;	0/2−	0;3+	0	;12-	0	*Sr36*, +
Anđelka	0	0	0/3+Lif	3+	33+Lif	3lif	0	0	0	0	0/;2− Lif	3+	0/3+	3+	0/3+lif	3+	0;1	*Sr36*
Bandolero	0/2	1	0;	0	0;	1	02−	12−	23	0/2−	0	2	2−	2−	2−	2−	3+	*Sr31*
Olimpija	3 +/0	3+	3+	3+	0;2−	0	0/2−	2−/0	2	3+	0	3+	3+		3+	22+	3+	–
Jana	2−/0;		0;	0	0;	0	0/1	0/;1	0	;	2−	12−	0/2−	0;		2−;	0;1	?
Vulkan	3+		3+	3+	3+	3+	3+	3+	3+/1;	3+	3+	3+	3+	3+	3+	3+	3+	–
Nova Zitarka	0/1	0	0	0		3lif	0	0	0	0	0;	0	0/2lif	3+ Lif/0	3+	3+	3+	*Sr38*
Silvija	22−	1	0;	0	0	0	0	0/;	0	0	0	0;	0	;	2−	33+	3+	*Sr38*, +

Table 3 continued

Genotype	QTHJC rep 1	QTHJC rep 2	RKQQC rep 1	RKQQC rep 2	RCRSC rep 1	RCRSC rep2	MCC-FC	QCC-SM	SCC-SC	QFC-SC	BCC-BC	TPMKC rep 1	TPMKC rep 2	TTTTF rep1	TTTTF rep 2	TRTTF	TTKSK	*Sr* gene
Rebeka	0;	0	0;	0	0;/3+	1	0/2;	0/;	0/2−/ 3+Lif	;1−	;	0;	2−	;/−	2	3+	3+	*Sr38*, +
Antonija	3+	3+	3+	3+	0;	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	–
Leuta	0	0	3+	0?	33+	3+	0	0	0	0	0	3+	0/2lif	3+		3+	;1/3+	*Sr36*
Sirban Prolifik	3+	3+	3+	3+	3+	3+	33+	3+	3+	3+	3+R	3+	0	3+	3+		3+	–
San Pastore	2−	1	0;	0;	0;	1	2/;0	0/1;	0	;	0	2-	2-	0;	2-	0;	3+	*Sr31*
Libellula	3+	3+	3+	3+	3+/;1	3+	3+	3+	23+	3+	3+	3+	3+	3+	3+	3+	3+	–
Bezostaya 1	3+/ 2−	3+	3+	23	;1/3+	2	3+	3+/2	3 +/2−/0	3+	0	3+/ 2-	3+	3+/ 11+	3+	3+	3+	–
Zlatna Dolina	23+	23	3+	3+	3+	23	3+	2+3	2+	2-	0/2	3+	3+	3	0	3+	3+	–
Sana	0/3+	0	0/3+Lif	0/2+lif	02−	2−	0/3+	0	0	0	0	3+	2−	33+	3+	3+/2−	0/3+	*Sr36*
Apache	;13+	2	;/3	23;	3+	3+	23;	0;	23+	;2	;1	3+	3+	;3+	3+	3+	3+	–
Adriana	0	0	3+/2−		3+	3+	0	0	12-	0	0/1-	3+	3+/ 2-	3+/2	3+	3+	3+/1	*Sr36*
Divana	3+	3+	;/3−	3+	3+	3+	3+	3+	3	3+	0	3+	33+	3	3+	3+	3+	–
Renan	0;	0;	0;	0;	3+/ ;13	23;	;2/0	0/;	0/1	;	;	3+	3+	3+	3+	3+	3+	–
Dropia	3+	3+	3+	3	3	3+	3+	3+	3+	3+	23	3+	3+	3+	2−/3	3+	3+	–
Flamura 85	3+	3+		3+	3+ Lif	3		3+	3+	3+	3+	3+	3+	3+	3 + ;	3+	3+	–
Element	3+	3+	3+	23	3+/ 2−	3+		3+	3+Lif	3+	3+	3+	3+	3+	3;	33+	3+	–
Lupus	3+	3	0/;1/3-	23	3+/0	3+	3+	3+	0/3	3+	1	3+	3	3+	3	3+	3+	–
Graindor	0/3Lif	0/2-	0	0;	3+	0	3+/0	0;	0/3+Lif	0/;	0	3+	3+	3+	3	3+	3+	–
MV Suba	3+	3	2−	2−		0		0	0	0/1−	0	3+	3	3+	3+		3+	–
Fiesta	2	0/2−	0/2−	1	2−	0	0/2−	0	0	1/0	2−	2−	0/2−	2;	0/2−		3+	*Sr31*, *Sr38*
Gabi	2+3-	0/2	3+	3+	3+	3+	3+	0/3	3+	0/2Lif	3+	3+	3+	3+	3+	3+	3+/0	–
Capo	3+	3	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	3+	–

"-" No *Sr* or *Lr* genes are detected; "+" Other genes could be present; "?" Unable to make postulation

Seedling leaf rust resistance genes need to be incorporated into wheat cultivars, although they confer mostly vertical (race-specific) resistance and susceptible to selection for new virulent races. Combinations of adult-plant *Lr* resistance genes with effective seedling genes can also provide good levels of durable resistance (Kolmer et al. 2010). *Lr34* and *Lr46* are two race non-specific adult plant resistance (APR) genes that can provide durable leaf rust resistance (Zhang et al. 2008). *Lr34* can often can interact with seedling resistance genes in seedling plants to produce lower than expected infection types. Genetic resistance to leaf and stem rust is the preferred method to control these diseases. Knowledge on the identity of the seedling rust resistance genes in released cultivars and germplasm is essential for the incorporation of effective resistance genes into breeding programs to maintain a diversity of resistance genes in commonly grown cultivars. The new races of wheat leaf and stem rust challenge wheat breeders to develop cultivars with effective resistance genes. These results can assist wheat breeders in Croatia for choosing parents for crossing in programs aimed at developing cultivars with desirable levels of leaf and stem rust resistance in Croatia and will also facilitate stacking of resistance genes into advanced breeding lines.

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