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Maize inbreds for multiple resistance breeding against major foliar, ear and stalk rot diseases

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Abstract

Resistance breeding is considered the most effective and eco-friendly method to manage most of the crop diseases, but it can be challenging to find sources of resistance in maize for short growing season regions. In this study, 218 maize inbreds were evaluated in order to select those, which possess resistance to one or more of the following diseases: Northern Corn Leaf Blight (NCLB), common rust, eyespot, grey leaf spot (GLS), goss's bacterial wilt and leaf blight (goss's wilt), Gibberella (fusarium) ear and stalk rot, and common smut. Significant variation in disease resistance was detected in the inbreds evaluated. Twenty six inbreds, most of them of Canadian origin, were found to possess excellent resistance to multiple diseases. Three inbreds (CO428, CO470 and CO471) exhibited resistance to five foliar diseases (NCLB, common rust, eyespot, GLS, and goss's wilt), while another seven inbreds had a resistant reaction to four diseases (CO452, CO466 and CO468 to common rust, eyespot, GLS and goss's wilt; C0473 to NCLB, common rust, GLS and goss's wilt; CO464 to NCLB, eyespot, GLS, and goss's wilt, and PHZ51 to eyespot, ERSC, common smut, and goss's wilt). Five of these inbreds also had intermediate resistance against stalk and ear rot. Forty five inbreds were found to have resistance against two to three diseases. Inbreds CO457, CO458, CO459 and CO460 released as highly resistance to common rust were also found to have good resistance against eyespot, and GLS or goss's wilt. CO450 released for eyespot resistance had good resistance against common rust and GLS, and moderate resistance against goss's wilt. Three inbreds CO387, CO441 and CO449 were found to have resistance for gibberella ear rot both by silk and kernel inoculation methods and common smut. Most of these inbreds found resistant in this study were from the Stiff Stalk (BSSS), Lancaster and Iodent maize heterotic groups. Many of the resistant inbreds identified in this study are excellent sources of resistance to leaf, ear and stalk rot diseases, and could be utilized in maize breeding programs for developing new hybrids with multiple disease resistance

Introduction

Maize or corn (*Zea mays* L.), the second largest cereal crop in Canada after wheat, is primarily grown in the eastern parts of the country in the provinces of Ontario and Quebec, although maize production is expanding in western Canada, especially in the province of Manitoba. In 2016, the crop was planted on ~1.4 million hectares with 13.2 million tonnes production, accounting for 9.3% and 23.3% of the total area and production, respectively, of cereal crops (Stat Canada, 2017). In the last two decades, improved hybrids and agronomic practices resulted in a substantial jump in maize acreage, yield and production (increased by 44.1%, 46.6% and 110.1%, respectively) but this also led to an increase in leaf diseases, as well as ear and stalk rots. These diseases, if not taken care of, may cause severe economic losses and can become one of the foremost limiting factors to sustain the current production in future. Globally, about 9% yield losses in maize have already been estimated due to diseases (Oerke 2005).

Among leaf diseases, Northern corn leaf blight (NCLB) caused by *Exserohilum turcicum* (Pass.) Leonard & Suggs, is the most common and economically important disease affecting Canadian maize. Epidemics of this disease have appeared repeatedly in various parts of the world causing huge losses until the discovery and incorporation of a single dominant resistance gene (*Ht1*) in maize hybrids in the 1960s. Unfortunately, the resistance conferred by *Ht1* did not last long, and world-wide, this disease is on the rise again in the last two decades as a result of emergence of new races of the fungus (Welz and Geiger, 2000; Yang and Wang, 2002; Dong et al, 2008). In the past seven years (2010-2016), NCLB was detected in more than 85% of maize fields surveyed in Ontario and Quebec (Jindal et al, 2017). NCLB infection prior to flowering (at silking and pollen-shed) can cause grain yield losses of over 50% (Perkins and Pedersen, 1987). Another key leaf disease, common rust (*Puccinia sorghi* Schwein), usually appears after tasseling and causes significantly less yield loss than NCLB; however, early infection (at V3 to V7 growth stage) can cause significant economic losses (Shah and Dillard, 2006; Jackson-Ziems, 2014). In Canada, common rust can be severe in Southern Ontario, but there are no reports of significant economic losses. Still, a continuous change in the common rust's pathogen population and climate poses a potential threat to existing commercial hybrids which are predominantly susceptible to this disease. In 2017, common rust was found in 98% of the fields visited in Ontario (Jindal et al., 2018). Another leaf disease, eyespot [*Aureobasidium zeae* (Narita & Hirats.) Dingley], recently has become significant due to changes in hybrid susceptibility, cultivation practices (minimum tillage resulting in higher maize residues), and climate (Boosalis et al, 1986; Wise and Mueller, 2011; Mallowa et al, 2015). In 2015, eyespot was found in 87% of the fields surveyed in Ontario (Jindal et al, 2016). Grey leaf spot (GLS) (*Cercospora zeae-maydis* Tehon & Daniels) and Goss's bacterial wilt and leaf blight, hereafter referred as goss's wilt [*Clavibacter michiganensis* subsp. *nebraskensis* (Vidaver & Mandel) Davis et al.] are two other emerging diseases of maize in Canada. GLS predominantly is an issue in Southern Ontario (Jindal et al, 2016) and goss's wilt in Manitoba and Alberta (Harding et al, 2018).

Ear and stalk rots are the other most economically destructive maize diseases which occur wherever the maize crop is grown. There are three main ear rots: one, the most common one, Gibberella ear rot [*Fusarium graminearum* Schwabe (teleomorph = *Gibberella zeae* (Schwein.) Petch]; two, Fusarium ear rots [*Fusarium verticillioides* (Sacc.) Nirenberg (teleomorph = *Gibberella fujikuroi* (Sawada) Ito in Ito & Kimura mating population A), [*F. proliferatum* (Matsushima) Nirenberg (teleomorph = G. fujikuroi mating population D), and [*F. subglutinans* (Wollenweb. & Reinking) Nelson *et al* (teleomorph = G. *fujikuroi* Mating population E)]; and three, Aspergillus ear rot (Aspergillus flavus (Link: Fr)]. All the three rots can potentially cause substantial economic losses by reducing grain yield and producing mycotoxins which render the grains unsafe for human and livestock consumption (Bello et al, 2012). Among stalk rots, Gibberella stalk rot (*F. graminearum*), Fusarium stalk rot (*F. verticillioides*), Charcoal stalk rot [*Macrophomina phaseolina* (Tassi) Goidanich], Diplodia stalk rot [*Stenocarpella maydis* (Berk.) Sutton] and Anthracnose stalk rot [*Colletotrichum graminicola* (Ces.)Wils.] are the most important in reducing grain yield. Another ear disease, Common smut [*Ustilago maydis* (DC.) Corda] occurs worldwide wherever maize is grown, and is often found in Canada. Annual yield reduction due to common smut is usually estimated in the range of 1-5% but under epidemic conditions it may exceed 10% (Shurtleff, 1980).

Most of the above mentioned diseases can be managed by growing resistant hybrids, if available. In the last few years, severe yield losses due to diseases have been reported due to changes in pathogen populations (new races), improper cultivation practices, increased susceptibility of hybrids, and weather conditions becoming more suitable for disease development (Wise and Mueller, 2011). Currently, only a few commercial hybrids are available, which have resistance to some of these diseases and probably not have multiple resistance. Therefore, improvement of genetic resistance to leaf, ear and stalk diseases remains an important objective in maize breeding programs. Resistance breeding is considered the most effective and eco-friendly method to manage maize diseases, but it is not an easy task to find resistance sources, especially in genotypes which are adapted to the short growing season of Canada. In this study, 218 inbreds of maize were evaluated for resistance to eight diseases [NCLB, common rust, eyespot, GLS, goss's bacterial wilt and leaf blight, Gibberella ear rot, Fusarium (Gibberella) stalk rot, and common smut] to select inbreds with multiple disease resistance for use in breeding programs for the development of maize hybrids for the short-season growing regions of Canada.

Materials and Methods

Plant material

A total of 218 inbred of maize were evaluated for resistance to eight maize diseases [NCLB, common rust, eyespot, Gibberella (Fusarium) ear (both silk and kernel infection) and stalk rot and common smut] under artificial epiphytotic conditions. Some inbreds which exhibited susceptibility to a given disease for two years were not re-evaluated in next year. In 2016, eight of these inbreds were also evaluated against GLS under natural infection conditions in a trial planted in the Chatham Kent area of Ontario (42.30837N, 82.42481W), a hot spot for this disease. In 2017, these 8 inbreds and an additional 15 inbreds were evaluated for GLS as in 2016. Sixty seven inbreds were evaluated for goss's bacterial wilt and leaf blight in Carman, Manitoba from 2014-16 in a screening trial performed by our collaborators at E.I. du Pont Canada. In addition, in 2017, we evaluated 29 inbreds for goss's wilt in our nursery in Carberry, Manitoba. The 218 inbreds consisted of 150 released by AAFC and 68 obtained from USDA-ARS GRIN. Genetic background and heterotic grouping of these inbreds were determined by tracing the genotype pedigree, simple sequence repeat markers (SSR), and/or as obtained from the gene bank. Inbreds were divided into 8 heterotic groups: 1=BSSS (Iowa Stiff Stalk Synthetic); 2=European Flint; 3=Lancaster; 4=Minnesota 13; 5=Early Butler; 6=Iodent; 7=Pioneer 3990 and 8=Pioneer 3994 (Reid et al, 2011). Seeds of all the inbreds were multiplied in the AAFC Ottawa maize breeding nursery, Ottawa Research and Development Centre (ORDC), to have sufficient seed of the same quality for these studies

Table 1 Rating scale for evaluation of maize inbreds for resistance to multiple diseases

Rating scale	Diseases						
				Ear rot			
	NCLB	Common rust and eyespot	Grey leaf spot	ERK	ERSC	Common Smut	Stalk rot
1	No symptoms	No symptoms.	No symptoms.	No Symptoms.	No symptoms.	No symptoms.	No visible spread of the pathogen from point of inoculation.
2	<1% leaf area with symptoms.	A few pustules. (<1% of the leaf area with symptoms).	A few lesions. (<1% of the leaf area with symptoms).	1-3 % kernals with visible symptoms on ear tip.	Infection does not spread from wounded kernals to unwounded kernels. 1-3 % kernals with visible symptoms.	1-3% kernels have galls.	1-25% of inoculated internode symptomatic.
3	1-10% leaf area with symptoms.	Several pustules not linked together (1- 5% infected leaf area).	Several lesions not linked together. (1-5% leaf area with symptoms).	4-10% of the kernels with visible symptoms on ear tip.	4-10% of the kernels with visible symptoms. Infection spread beyond point of inoculation.	4-10% kernels have galls.	26-50% of inoculated internode symptomatic.
4	11-25% of leaves with symptoms.	Many pustules, some linked together to form a necrotic dead area. (6-20% infected leaf area).	Many lesions, some linked together to form a bigger lesion and necrotic dead areas on lower leaves (6-20% leaf area with symptoms).	11-25% of the kernels with visible symptoms. Infection spread across the ear.	11-25% of the kernels with visible symptoms.	11-25% kernels have galls.	51-75% of inoculated internode symptomatic.
5	> 50% of the lower leaves with symptoms, < 25% of center and upper leaves with symptoms.	Necrotic areas linked together with a few dead leaf tips (21-50% infected leaf area).	21-50% leaf area with symptoms (many lesions linked together to form bigger lesions and necrotic dead tissue on the lower and middle leaves).	26-50% of the kernels with visible symptoms. Infection spread across the ear.	26-50% of the kernels with visible symptoms.	26-50% kernels have galls.	>75% of inoculated internode symptomatic.
6	Lower leaves are dead, > 50% of the center leaves, < 25% of upper leaves with symptoms.	50% of the leaf tips dead (> 50% of leaf area with symptoms).	>50% leaf area with symptoms (many lesions linked together to form bigger lesions and necrotic dead tissues all over the plant).	51-75% of the kernels with visible symptoms. Infection spread across the ear.	51-75% of the kernels with visible symptoms.	51-75% kernels have galls.	Symptoms spread to one adjacent internode.
7	Most of the leaves dead.	Most of the leaves dead.	Most of the leaves dead.	>75 % kernels with visible symptoms.	>75 % kernels with visible symptoms.	>75% kernels have galls.	Symptoms spread to two or more adjacent internodes.

Evaluation for disease reaction

Separate sets of inbreds were planted for evaluation/screening against each disease at ORDC, Ottawa, Canada from 1999 to 2017. Gibberella ear rot, Fusarium stalk rot, and common smut screening plots were separated from each other by at least 5 m, common rust and eyespot by 30 m, and NCLB by 500 m to prevent any secondary infection of the disease. Each inbred was evaluated for resistance for a number of years depending on the confirmed results. Standard field management practices, including fertilization and herbicide application were followed to raise the crop.

Inbreds were planted in 3.8 m long rows of 15-20 plants per row; several resistant and susceptible inbred checks were also planted. As the severity of natural infection was not consistent from year to year, artificial inoculation methods were used to inoculate the plants with fungal spores for all diseases except GLS. For leaf diseases, inoculations were done twice, one at the 6-8 leaf and afterwards at the 8-11 leaf stage; for ear rot-silk channel (ERSC), common smut, and fusarium stalk rot, plants were inoculated at 4-7 days post silking; and for ear rot-kernel (ERK), inoculations were done 10-15 days post silking. Silking dates were determined as the time when 50% or more of the plants in a row had silk protruding from their ears. After inoculation, disease nurseries were irrigated 5 mm daily on days without any rainfall to maintain higher moisture levels for disease development. Response of the inbreds to different diseases were recorded using a 1-7 rating scale given in Table 1. Plants were rated individually for disease severity and then the mean of 10 plants was taken.

Northern corn leaf blight

Plants were inoculated by placing approximately 0.2 g of ground diseased leaf powder into the whorl of each plant using a Bazooka (Sistrunk Inoculators, Starkville, MS 39759, USA). Diseased leaf tissue was collected from the previous field season crop following the procedure described by Zhu et al (2011a). Disease severity was recorded at the soft dough stage following a 1-7 rating scale given in Table 1.

Common rust

The common rust pathogen, *Puccinia sorghi*, was kept alive on maize plants grown in a greenhouse and a suspension of urediniospores for inoculation was prepared following the protocol developed and described by Zhu et al (2011b). Urediniospores were also collected from the diseased plants grown in the field in the previous season and stored at -80 °C. Plants were inoculated by injecting two ml of urediniospore suspension (2.5×10^5 urediniospores ml^{-1}) into the whorl of each plant with a graduated, 10 ml, self-refilling, and automatic vaccinator attached to a 2.5 L backpack container (Nasco Co., Fort Akinson, WI). Plants were injected twice, at the 6-8 leaf and 10-12 leaf stages to achieve good infection. At the soft dough stage of kernel development, about 3 weeks after silk emergence, plants were rated for general resistance on a 1-7 rating scale given in Table 1.

Eyespot

Inoculum of *Aureobasidium zeae* was produced in a liquid culture with modified carboxyl methyl cellulose (CMC)-maltose-yeast medium as described by Reid and Zhu (2005). Two ml of conidial suspension (2.5 x 105 conidia ml-1) was dispensed into the whorl of each plant by using a graduated, 10 ml, self-refilling, automatic vaccinator attached to a 2.5 L backpack container (Nasco Co., Fort Akinson, WI). For inoculum dispensing, 18 cm long, 0.5 cm diameter stainless steel drenching nozzle was used. Plants were not injured during the inoculation process. In years with higher than normal temperatures and/or dry conditions at time of inoculation, a third inoculation with ground diseased leaf powder (collected from the previous season's inoculated plants) was also done one week after the second inoculation using the Bazooka method as described above. Plants were rated for general resistance at the soft dough stage about 3 weeks after silk emergence on a 1-7 rating scale given in Table 1.

Grey leaf spot

Due to the high degree of natural GLS infection in a field in Chatham Kent county, Ontario, plants were not artificially inoculated. Disease severity was recorded at the soft dough stage using a 1-7 rating scale given in Table 1.

Common smut

Inoculum of *Ustilago maydis* was prepared following the procedure described by Reid and Zhu (2005). About 36 hours before inoculation, dried, matured smut galls were slightly tapped to discharge teliospores onto maize meal agar (CMA) or potato-dextrose agar (PDA) medium in Petri dishes. The plates were then incubated at 24-28 °C with 12 h light/darkness for 30 h to allow sporidia formation. Each plate was washed twice with sterilized distilled water, filtered, and diluted with sterile water to a concentration of 5×10^5 sporidia/ml. One ml of 0.5% Tween 20 was added to every 500 ml of suspension to improve the ability of the spore suspension to adhere to the ears after inoculation. Sporidia suspensions were stored at 4-6 °C

Table 2 Summary table for inbreds having multiple resistance to major leaf, ear and stalk diseases, Ottawa, Canada

Inbreds[a]	Pedigree	Genetic background	Northern corn leaf blight	Disease rating on 1-7 scale								Resistance to # of diseases
				Common rust	Eyespot	Grey leaf spot (GLS)	Goss's Wilt	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut	
CO428	Oh43 x H99	Oh43/H99	2.6	3.1	3.8	2.0	3.0	4.4	5.8	5.3	3.7	5
CO470	[CO388xH102Htm]xCO388	H102 Htm x CO388^4	3.3	4.0	3.8	2.8	3.5	3.6	4.7	4.3	4.5	5
CO471	[CO428xA619Ht2]xCO428	A619 Ht2 x CO428^4	3.5	3.0	3.5	3.0	3.8	6.1	4.8	4.8	4.2	5
CO452	(CO388xCO328)xCO388(4)	B73/BSTE/Early Butler/ Pride 5/BSSS	7.0	2.8	3.3	2.5	3.5	5.8	5.7	4.3	4.8	4
CO464	(N192 x CO388) x CO388	BSSS	3.5	5.0	2.5	3.0	4.0	6.1	5.7	5.0	5.3	4
CO466	C6 (99ESR)	BSSS	4.5	3.8	3.0	2.5	3.5	6.6	6.0	4.7	5.3	4
CO468	[CO388xA553Htn2]xCO388	A553N Htn2 x CO388^4	4.5	4.0	3.8	3.0	3.3	6.4	5.3	4.6	4.7	4
CO472	A632 Htn x CO428^4	Oh43/H99	3.0	3.5	4.2	2.5	3.0	6.2	5.0	4.7	4.3	4
CO473	H102 Htm x CO428^4	Oh43/H99	2.7	3.0	4.7	2.0	3.8	5.9	4.5	5.0	4.2	4
PHZ51	814 x 848	Mixed/iodent	4.5	5.2	4.0	-	3.0	3.0	3.3	5.0	2.7	4
A679	(A662 x B73)B73	BSSS/B73	4.0	4.5	4.0			4.4	6.7	5.0	3.0	3
CO353	Asgrow RX777	Asgrow RX777	3.9	3.8	3.2	-	-	4.3	5.4	5.7	6.0	3
CO388	(B73 x CO272) CO272	B73/BSTE/Early Butler	4.8	4.5	4.0	-	4.0	2.9	5.3	5.0	4.3	3
CO444	S1381xCO382	S1381/INRA 258/Mo17	6.1	4.0	4.0		5.0	3.5	4.8	5.3	2.9	3
CO450	Eyespot Resistant Synthetic (99ESR)	BSSS	5.0	2.9	2.3	3.5	4.3	5.1	6.4	5.7	4.2	3
CO451	CO309xCO328	Pride 5/BSSS	5.5	3.0	5.8		4.0	6.5	6.1	4.3	2.3	3
CO457	H95(Rp-G6J1) x CO325	H95/Early Butler/BSSS	7.0	1.3	3.7	4.0	7.0	5.6	5.0	5.4	4.4	3
CO458	H95(Rp-G15c) x CO388^4	H95/B73/BSTE/Early Butler	4.8	1.3	3.5		3.3	6.4	5.6	4.5	5.0	3
CO459	H95(Rp-G5) x CO388^4	H95/B73/BSTE/Early Butler	5.3	1.3	4.0	5.0	3.7	5.9	5.7	5.3	4.7	3
CO460	H95(Rp1-K) x CO388^4	H95/B73/BSTE/Early Butler	5.9	1.3	3.0	4.0	7.5	6.2	6.0	4.8	4.8	3
CO461	(CM174 x CO388) x CO388	B14/B73/BSTE/Early Butler	6.1	4.0	4.0	3.0	6.0	6.6	5.6	5.0	6.1	3
CO463	B73xBRC sync	BSSS/mix	4.0	5.2	5.0	2.5	8.0	6.6	5.6	3.8	4.9	3
CO469	[CO388xA632Htn1]xCO388	A632 Htn1 x CO388^4	4.0	3.5	4.5	4.0	5.0	6.5	5.6	4.9	4.4	3
LH176	P3704 x LH82	Mixed/Iodent	5.0	3.0	3.0	-	-	3.9	2.8	5.6	4.4	3
LH295	LH168xLH176	Iodent	6.0	4.0	3.0	-	-	3.7	4.7	3.3	5.5	3
PHK42	270 x 806	Iodent/NS	6.0	5.0	4.0	-	-	3.0	5.8	4.3	3.0	3
PHK76	AD18 x B102	Mixed/NS	4.5	3.3	3.8	-	-	4.7	5.0	4.0	6.0	3
11430	Nine inbreds population	Oh43/H99/Mo17	6.0	3.0	4.0	-	-	5.8	5.0	5.3	4.0	2
A681	(A662 x B73)B73	BSSS/B73	5.1	4.0	4.5	-	-	6.1	6.1	5.0	3.0	2
B113	BS11(FR)C9	BS11	7.0	2.5	3.0	-	-	5.5	4.3	5.0	5.9	2
CO352	Asgrow RX777	Asgrow RX777	3.9	5.0	3.7	-	-	4.7	6.2	4.9	5.1	2
CO373	Limagrain Syn. PRC-BRS	Unknown	7.0	5.5	4.5	-	-	3.8	3.0	6.9	2.2	2
CO387	CO272 x CO266	Pioneer 3990/BSTE/Early Butler	5.8	6.0	5.9	-	-	2.4	2.2	6.5	2.7	2

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Inbreds[a]	Pedigree	Genetic background		Disease rating on 1-7 scale								
			Northern corn leaf blight	Common rust	Eyespot	Grey leaf spot (GLS)	Goss's Wilt	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut	Resistance to # of diseases
CO390	(Oh43 x H99) H99	H99/Oh43	4.0	3.8	4.5	-	5.0	6.2	5.7	5.3	5.1	2
CO410	(B87 x CB8) CB8	BSSS/Pioneer 3994	7.0	4.8	4.5	-	-	2.2	4.9	5.7	3.0	2
CO441	Jacques 7700 x CO298	Unknown	7.0	6.5	4.5	-	7.0	2.4	2.5	6.5	3.0	2
CO442	Iodent/NSS	Iodent	5.7	4.8	3.9	3.0	8.0	6.5	6.3	5.5	4.2	2
CO445	CO386xW64AHt	Mo17/MAG/W64AHt	6.5	2.9	4.5	-	-	4.5	3.7	4.0	4.7	2
CO449	CO432xCO433	Pride K127/Unknown	6.0	4.6	4.9	-	5.0	2.3	3.0	6.3	3.0	2
CO454	Corn Belt Dent Population	BSSS	6.0	3.1	4.5	3.0	8.0	7.0	6.7	4.7	3.6	2
CO456	(N190 x CO388) x CO388	N190/B73/BSTE/Early Butler	6.7	4.5	3.0	-	4.0	6.1	6.4	4.8	4.9	2
CO465	B73 x BRCsyn	BSS/mix	4.3	5.0	4.5	3.0	4.0	6.7	5.8	4.7	6.0	2
CO467	Exotic x (CL29 x CO255	Unknown	6.0	6.0	4.0	4.0	7.0	6.7	6.5	5.8	4.6	2
FR19	A635 x W438	B14	6.5	4.0	5.0	-	-	6.3	6.1	3.8	3.3	2
HB8229	A634 x 8200	Pioneer309A	5.0	3.5	3.5	-	-	6.0	7.0	5.4	5.2	2
IBC2	J6 x Mo17Ht	NS/Mo17	6.0	4.0	4.0	-	-	5.7	7.0	6.8	3.8	2
LH145	A632 x CM105	BSSS/B14	6.0	4.0	4.0	-	-	5.5	6.6	7.0	6.8	2
LH195	LH117 x LH132	BSSS/B73	6.0	3.0	4.0	-	-	7.0	6.2	4.9	5.6	2
LH54	(Mo17)3X610	Mo17	4.4	3.2	4.0	-	-	7.0	6.2	4.5	5.4	2
OQ603	PH3713	BSSS/B14	7.0	4.0	4.0	-	-	4.0	5.9	5.2	5.7	2
PHG50	848 x 207	Iodent/NS	6.5	5.0	4.0	-	-	2.5	4.8	4.5	3.5	2
PHH93	806 x 207	Iodent/NS	4.5	3.5	3.5	-	-	5.2	4.0	4.5	4.3	2
PHJ40	B09 x B36	Mixed	4.0	5.5	4.5	-	4.0	5.3	3.8	5.1	3.7	2
PHN11	207 x (207x806)	Iodent/NS	5.0	3.5	5.0	-	-	2.2	5.0	4.3	3.6	2
PHR47	G39 x PHB49	SS/Iodent	4.0	6.0	4.0	-	-	4.4	4.9	4.4	4.7	2

[a]CO inbreds were released from AAFC research station at Ottawa ON.
For leaf diseases and stalk rot, inbreds with disease severity rating of ≤2.0 were classified as highly resistant (HR); 2.1-4.0 as resistant (R); 4.1-5.0 as intermediate resistant (IR), and >5 as susceptible (S). For Gibberella ear rot and common smut, inbreds with disease severity of ≤2 were classified as HR; 2.1-3.0 as R, 3.1-4.0 as IR, and >4.0 as S.

for a maximum of 4 hours before use. The inoculation method and disease rating are similar as that described above for ear rot silk inoculation (ERSC), Table 1.

Inbreds evaluated were grouped into four categories as highly resistant (HR), resistant (R), moderately/intermediate resistant (IR) and susceptible (S) on the basis of the disease severity ratings of the eight diseases i.e. NCLB, common rust, eyespot, GLS, goss's wilt, gibberella ear rot, fusarium stalk rot, and common smut. For leaf diseases and stalk rot, inbreds with disease severity ratings of ≤2.0 were classified as HR, 2.1-4.0 as R, 4.1-5.0 as IR, and >5 as S. For gibberella ear rot and common smut, inbreds with disease ratings of ≤2.0 were classified as HR, 2.1-3.0 as R whereas those with ratings of 3.1-4.0 were classified as IR, and >4.0 as S.

Results

All the maize inbreds tested in this study showed variable responses to all the eight diseases. Some of the inbreds exhibited resistant reactions to two or more of the diseases while others exhibited susceptible reactions to all or several diseases (S_table 1 and 2, Figs. 1 and 2).

Leaf diseases

The proportion of inbreds that exhibited HR, R, IR and S reactions to NCLB, common rust, and eyespot

S_table 1 Genetic background and reaction of 218 maize inbreds to major leaf, ear and stalk diseases at Ottawa, Canada

Inbreds[a]	Pedigree	Genetic background	Pedigree/ heterotic group[b]	Evaluation year	rating on 1-7 scale						
					Northern corn leaf blight	Common smut	Eyespot	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut
CO473	H102 Htm x CO428^4	Oh43/H99	3	2015-17	2.7	3.0	4.7	5.9	4.5	5.0	4.2
CO472	A632 Htn x CO428^4	Oh43/H99	3	2015-17	3.0	3.5	4.2	6.2	5.0	4.7	4.3
CO471	(CO428 x A619Ht2) CO428	A619 Ht2 x CO428^4	3	2015-17	3.5	3.0	3.5	6.1	4.8	4.8	4.2
CO470	(CO388 x H102Htm) CO388	H102 Htm x CO388^4	1	2015-17	3.3	4.0	3.8	3.6	4.7	4.3	4.5
CO469	(CO388 x A632Htn1) CO388	A632 Htn1 x CO388^4	1	2015-17	4.0	3.5	4.5	6.5	5.6	4.9	4.4
CO468	(CO388 x A553Htn2) CO388	A553N Htn2 x CO388^4	1	2015-16	4.5	4.0	3.8	6.4	5.3	4.6	4.7
CO467	Exotic x (CL29 x CO255)	Unknown	1	2015-17	6.0	6.0	4.0	6.7	6.5	5.8	4.6
CO466	C6 (99ESR)	BSSS	1	2015-17	4.5	3.8	3.0	6.6	6.0	4.7	5.3
CO465	B73 x BRCsyn	BSS/mix	1	2015-16	4.3	5.0	4.5	6.7	5.8	4.7	6.0
CO464	(N192 x CO388) x CO388	BSSS	1	2015-17	3.5	5.0	2.5	6.1	5.7	5.0	5.3
CO463	B73 x BRC sync	BSSS/mix	1	2015-17	4.0	5.2	5.0	6.6	5.6	3.8	4.9
CO462	CO388 x W153R	B73/BSTE/Early Butler/ W153	1/5	2012-17	6.1	5.3	5.0	6.7	5.0	5.1	5.3
CO461	(CM174 x CO388) CO388	B14/B73/BSTE/Early Butler	1	2011-15	6.1	4.0	4.0	6.6	5.6	5.0	6.1
CO460	H95(Rp1-K) CO388^4	H95/B73/BSTE/Early Butler	1	2012-17	5.9	1.3	3.0	6.2	6.0	4.8	4.8
CO459	H95(Rp-G5) CO388^4	H95/B73/BSTE/Early Butler	1	2012-17	5.3	1.3	4.0	5.9	5.7	5.3	4.7
CO458	H95(Rp-G15c) CO388^4	H95/B73/BSTE/Early Butler	1	2012-17	4.8	1.3	3.5	6.4	5.6	4.5	5.0
CO457	H95(Rp-G6J1) CO325	H95/Early Butler/BSSS	3	2012-17	7.0	1.3	3.7	5.6	5.0	5.4	4.4
CO456	(N190 x CO388) CO388	N190/B73/BSTE/Early Butler	1	2011-13	6.7	4.5	3.0	6.1	6.4	4.8	4.9
CO455	A82-8 x CO388	A82-8/B73/BSTE/Early Butler	1	2012-17	5.7	5.4	4.5	6.8	6.3	5.9	5.8
CO454	Corn Belt Dent Population	BSSS	1	2009-10	6.0	3.1	4.5	7.0	6.7	4.7	3.6
CO453	NZS3 x A82-8	NZS3 x A82-8	1	2007-09	6.1	4.9	4.8	5.4	6.6	5.1	4.2
CO452	(CO388 x CO328) CO388(4)	B73/BSTE/Early Butler/ Pride 5/BSSS	1	2012-17	7.0	2.8	3.3	5.8	5.7	4.3	4.8
CO451	CO309xCO328	Pride 5/BSSS	1/4	2010	5.5	3.0	5.8	6.5	6.1	4.3	2.3
CO450	Eyespot Resistant Synthetic (99ESR)	BSSS	1	2010-17	5.0	2.9	2.3	5.1	6.4	5.7	4.2
CO449	CO432 x CO433	Pride K127/Unknown	4	2010-17	6.0	4.6	4.9	2.3	3.0	6.3	3.0
CO448	CO273 x CO431	Pioneer 3990/Unknown	7/6	2008-11	6.0	5.0	5.3	3.6	4.2	5.7	3.4
CO447	CO352 x CO328	Asghgrow Rx777/Pride 5/BSSS	1/4	2008-11	6.3	4.7	4.3	5.0	6.1	5.7	3.5
CO446	CO341 x CO328	BSSS/Pioneer 3994/ Pride 5	1	2005-08	6.6	6.0	6.3	5.6	5.8	4.6	4.9
CO445	CO386 x W64AHt	Mo17/MAG/W64AHt	3	2006-08	6.5	2.9	4.5	4.5	3.7	4.0	4.7
CO444	S1381 x CO382	S1381/INRA 258/Mo17	2	2005-06	6.1	4.0	4.0	3.5	4.8	5.3	2.9
CO443	B104 x CO272	BSSS/Early Butler	5	2003-04	7.0	5.5	5.5	4.1	4.6	6.3	4.1

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S_table 1 Genetic background and reaction of 218 maize inbreds to major leaf, ear and stalk diseases at Ottawa, Canada

Inbreds[a]	Pedigree	Genetic background	Pedigree/ heterotic group[b]	Evaluation year	rating on 1-7 scale						
					Northern corn leaf blight	Common smut	Eyespot	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut
CO442	Iodent/NSS	Iodent	6	2001-17	5.7	4.8	3.9	6.5	6.3	5.5	4.2
CO441	Jacques 7700 x CO298	Unknown	3	2002-06	7.0	6.5	4.5	2.4	2.5	6.5	3.0
CO440	Pride 5 x CO258	Pride 5/BSSS	4	1999-03	5.5	4.1	5.0	5.1	6.0	5.7	4.7
CO439	Nebraska BSSS	BSSS	1	1999-03	6.4	4.6	4.5	4.4	4.2	5.3	3.5
CO438	CB3 x CL29	Pioneer 3994/ Unknown	8	1999-03	6.7	6.7	6.0	5.6	3.7	6.0	4.2
CO437	European Synthetic	European hybrids	2	1999-03	7.0	6.8	6.5	6.3	5.7	5.9	4.9
CO436	CO275 x CO300	Pioneer 3994/Minnesota 13	8	1999-03	6.2	6.3	5.6	3.5	4.0	6.0	3.7
CO435	A632 x A634	B14	1	1999-03	6.1	6.3	4.4	4.2	4.5	5.2	3.8
CO434	CM105 x A632	B14	1	1999-03	6.7	6.2	4.7	6.9	5.0	5.5	4.0
CO433	Pride K127	Pride K127	4	2003-08	6.8	5.5	4.5	2.7	2.9	5.6	3.6
CO432	Fusarium Resistant Synthetic	Unknown	4	2003-07	6.7	6.3	5.7	2.4	2.9	6.0	3.3
CO431	Fusarium Resistant Synthetic	Unknown	6	1999-16	6.0	6.0	4.8	4.2	4.1	4.0	4.0
CO430	Fusarium Resistant Synthetic	Pioneer 3990	7	2002-06	6.5	6.5	5.5	2.6	2.7	5.4	3.6
CO429	Pioneer 3707	W153R/LH82	3	2002-03	5.5	5.8	5.3	5.8	6.3	6.0	2.9
CO428	Oh43 x H99	Oh43/H99	3	2002-17	2.6	3.1	3.8	4.4	5.8	5.3	3.7
CO427	(Oh43 x H99) Oh43	Oh43/H99	3	2002-03	7.0	5.0	5.3	4.7	5.6	5.4	3.3
CO426	LG22 x Pioneer 3707 x Pioneer 3732 x Pride 4464	Unknown	3	1998-03	6.3	4.7	5.2	4.0	5.5	5.5	3.1
CO425	(B87 x CB8) CB8	BSSS/Pioneer 3994	8	1998-03	5.8	5.2	4.7	4.3	5.1	5.7	4.0
CO424	CO257 x CO290	BSSS/Early Butler	5	1998-03	6.3	4.3	3.8	5.0	5.1	6.2	3.5
CO423	Unknown Corn Hybrid	Unknown	5	1998-03	6.2	5.5	5.2	3.6	5.5	6.0	2.0
CO422	(391134 x CO255) CO255 x (A619L x A632)	INRA 258/B14	2	1998-03	6.7	6.2	6.2	5.3	3.9	5.6	4.0
CO421	Dea = Pioneer165 x F2	Iodent/F2	6	1998-03	7.0	5.8	6.0	4.2	3.6	6.4	2.8
CO420	CM423 (DOR X A)"	Unknown	6	2002-03	6.8	4.0	4.5	6.5	6.4	6.4	4.2
CO419	24-44-1	Unknown	4	1998-03	7.0	6.5	6.0	5.7	6.0	6.1	3.2
CO418	Ottawa Cold Tolerant Syn. CO	European hybrids	2	2002-03	7.0	5.0	5.8	4.2	6.2	5.9	4.8
CO417	CB3 x CM383	Pioneer 3994/Minnesota 13	8	2002-03	7.0	5.0	5.8	5.0	4.0	6.1	2.7
CO416	(A632 x CO125) CO125 (2)	Pfister 44/B14	2	2002-03	7.0	6.0	6.0	5.9	6.3	5.9	3.4
CO415	CO223 x Pioneer 3968	Pride 5/Pioneer 3968	4	2002-03	7.0	6.3	5.8	4.0	6.0	5.6	4.9
CO414	A632 x CO255	INRA 258/B14	2	2002-03	7.0	6.3	5.5	5.1	4.3	5.4	3.9
CO413	CO150 x Pioneer 3968	Pioneer 6124Pioneer 3968	7	2002-03	6.8	5.3	5.3	3.6	4.8	6.4	3.0
CO412	(391134 x CO255) CO255 x (A619L x A632)	INRA 258/Oh43/B14	2	1998-03	7.0	6.0	6.5	4.1	4.8	5.6	4.9
CO411	Pioneer 3995	Pioneer 3995	2	2002-03	7.0	7.0	6.3	4.2	4.6	4.9	4.3
CO410	(B87 x CB8) CB8	BSSS/Pioneer 3994	8	2002-03	7.0	4.8	4.5	2.2	4.9	5.7	3.0

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S_table 1 Genetic background and reaction of 218 maize inbreds to major leaf, ear and stalk diseases at Ottawa, Canada

Inbreds[a]	Pedigree	Genetic background	Pedigree/ heterotic group[b]	Evaluation year	rating on 1-7 scale						
					Northern corn leaf blight	Common smut	Eyespot	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut
CO409	CO255 x Pioneer 3977	INRA 258/Pioneer 3977	2	2002-03	7.0	6.3	5.8	3.8	5.6	6.8	3.0
CO408	(B76 x CO251) CO251	B37/Pfister44	1	2002-03	7.0	5.8	5.0	3.3	3.3	5.4	3.1
CO407	(CO266 x KW6114) CO266	Pioneer 3990	7	1998-03	6.7	6.3	6.2	5.8	3.7	6.2	2.4
CO406	(CO266 x KW6114) CO266	Pioneer 3990	7	1998-03	7.0	6.0	5.3	5.5	6.2	6.1	2.8
CO405	CO275 x CO300	Pioneer 3994/Minnesota 13	8	2002-03	7.0	5.0	5.0	4.3	5.4	4.9	3.1
CO404	CO275 x CO300	Pioneer 3994/Minnesota 13	8	2002-03	7.0	5.3	4.0	4.1	5.3	4.9	3.3
CO403	CO275 x CO300	Pioneer 3994/Minnesota 13	8	2002-03	7.0	7.0	6.3	5.4	5.6	6.1	4.1
CO402	Limagrain Syn. PRC-BRS 1985	Unknown	8	2002-03	7.0	6.5	5.8	4.8	4.9	6.0	2.9
CO401	Limagrain Syn. PRC-BRS 1985	Unknown	8	1998-03	6.7	6.7	5.7	3.4	5.1	6.1	2.7
CO400	Pioneer 3925	Pioneer 3925	4	2002-03	6.3	5.3	4.0	3.8	5.3	6.5	3.8
CO399	Pioneer 3925	Pioneer 3925	4	2002-03	5.0	5.5	4.5	6.8	4.8	6.5	4.5
CO398	(CO305 x CO289) CO289	Pioneer 3990/INRA 258/ BSSS	7	1998-03	6.2	5.8	5.2	5.0	3.9	6.2	2.8
CO397	(CO305 x CO289) CO289	Pioneer 3990/INRA 258/ BSSS	7	2002-03	6.8	6.5	5.8	5.2	5.0	6.6	5.1
CO396	(CO305 x CO289) CO289	Pioneer 3990/INRA 258/ BSSS	7	2002-03	7.0	6.8	6.5	5.5	5.5	6.4	4.3
CO395	(Mo17 x CO266) CO266	Pioneer 3990/Mo17	3	1998-03	6.3	6.0	6.5	5.1	5.2	5.7	3.6
CO394	(Mo17 x CO266) CO266	Pioneer 3990/Mo17	3	1998-03	6.7	6.0	6.0	5.2	5.2	5.6	3.1
CO393	(Mo17 x CO266) CO266	Pioneer 3990/Mo17	3	1998-03	6.3	5.5	5.5	4.5	4.0	4.9	2.9
CO392	(CM7 x 84L768) CM7 x (A619L x A632L)	Ottawa flint/Minnesota 13/ OH43/B14	2	1998-03	6.3	5.0	4.5	4.6	4.3	4.5	5.1
CO391	Asgrow RX777	Asgrow RX777	1	2002-03	4.8	4.0	4.5	4.7	6.5	6.6	4.2
CO390	(Oh43 x H99) H99	H99/Oh43	3	2002-03; 14-17	4.0	3.8	4.5	6.2	5.7	5.3	5.1
CO389	(B73 x CO272) CO272	B73/BSTE/Early Butler	1	1997-08	5.4	4.5	4.2	2.6	6.1	5.2	5.0
CO388	(B73 x CO272) CO272	B73/BSTE/Early Butler	1	1997-17	4.8	4.5	4.0	2.9	5.3	5.0	4.3
CO387	CO272 x CO266	Pioneer 3990/BSTE/Early Butler	5	1997-04	5.8	6.0	5.9	2.4	2.2	6.5	2.7
CO386	Mo17 x MAG	Mo17/MAG	3	1998-03	5.3	5.0	4.2	6.1	5.2	5.6	4.9
CO385	Unknown Corn. Hybrid	Unknown	2	2002-03	7.0	6.5	5.8	3.5	5.1	6.5	3.9
CO384	A632 x CO255	INRA 258/B14	2	2002-03	7.0	6.0	5.0	5.0	5.0	6.1	3.1
CO383	(Mo17 x CO255) CO255	INRA 258/Mo17	2	2002-03	7.0	6.0	5.3	5.3	5.2	6.5	3.5
CO382	(Mo17 x CO255) CO255	INRA 258/Mo17	2	2002-03	6.3	6.3	5.0	6.9	5.8	6.5	4.1
CO381	CO289 x CO266	Pioneer 3990	7	2002-03	7.0	6.8	5.8	5.3	5.0	6.3	2.3
CO380	CO265 x CO266	Pioneer 3990	7	2002-03	7.0	5.8	5.8	4.1	5.3	5.7	3.0
CO379	Unknown Com. Hyb.	Unknown	6	2002-04	7.0	5.8	5.8	4.8	3.2	6.5	3.4
CO378	CO289 x CO273	Pioneer 3990	7	2002-03	7.0	6.5	5.5	5.4	4.9	6.7	3.7
CO377	CO266 x CO273	Pioneer 3990	7	2002-03	7.0	6.3	4.8	5.5	5.4	5.8	6.0

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Inbreds[a]	Pedigree	Genetic background	Pedigree/ heterotic group[b]	Evaluation year	rating on 1-7 scale						
					Northern corn leaf blight	Common smut	Eyespot	Gibberella ear rot (ERSC)	Gibberella ear rot (ERK)	Gibberella stalk rot	Common smut
CO376	CO275 x CO300	Pioneer 3994/Minnesota 13	8	2002-03	7.0	6.8	5.3	4.1	4.3	6.5	3.5
CO375	CB5 x CM385	Pioneer 3994/Minnesota 13	8	2002-03	7.0	6.0	4.3	4.0	3.2	6.2	1.9
CO374	Limagrain Syn. PRC-BRS	Unknown	2	2002-03	7.0	6.0	4.5	4.1	4.6	5.4	3.8
CO373	Limagrain Syn. PRC-BRS	Unknown	4	2002-03	7.0	5.5	4.5	3.8	3.0	6.9	2.2
CO372	Pioneer Syn. PRC-BRS	Unknown	2	2002-03	6.0	4.5	4.0	5.7	4.9	5.8	3.8
CO371	Pioneer Syn. PRC-BRS	Unknown	4	2002-04	7.0	6.0	5.3	4.9	3.7	5.8	4.9
CO370	BSTE	BSTE	1	2002-03	6.3	6.0	5.0	7.0	7.0	5.2	6.5
CO369	Pioneer 3707	W153R/LH82	3	2002-03	5.0	4.8	5.5	4.9	5.1	5.7	3.6
CO368	Pioneer 3707	W153R/LH82	3	2002-03	6.0	6.0	4.5	4.9	6.1	6.4	5.5
CO367	Pioneer 3707	W153R/LH82	3	2002-03	5.8	5.8	4.0	6.0	6.4	6.2	4.3
CO366	CO275 x CO300	Pioneer 3994/Minnesota 13	8	2002-03	7.0	6.5	5.8	5.7	4.4	6.4	4.0
CO365	(B87 x CO251) CO251	Pfister44/BSSS	2	2002-03	7.0	6.3	5.8	4.9	5.4	5.3	3.9
CO364	CM105 x A632	B14	1	2002-03	7.0	5.8	4.0	3.9	4.9	6.2	3.2
CO363	CM105 x A632	B14	1	1997-03	5.8	5.8	4.0	4.4	4.4	5.8	3.8
CO362	CM105 x A632	B14	1	2002-03	7.0	5.8	3.8	4.7	6.4	5.0	3.8
CO361	CO256 x CO272	BSSS/BSTE/Early Butler	5	2002-03	7.0	4.5	4.0	5.4	5.4	5.0	5.7
CO360	B37-14E x A641	B37/B14/Minnesota 13	1	2002-03	6.8	5.8	5.0	5.6	4.9	6.1	5.2
CO359	Pioneer 3707	W153R/LH82	3	1997, 05, 17	4.3	5.0	4.1	6.2	6.1	5.3	4.2
CO358	Pioneer 3389	Pioneer 3389	5	2002-03	5.8	5.5	5.3	4.6	4.8	5.4	5.6
CO357	Pioneer 3389	Pioneer 3389	3	1998-03	5.2	5.0	5.2	6.3	6.3	4.8	5.2
CO356	Pioneer 3389	Pioneer 3389	5	1998-03	5.2	5.3	5.0	6.3	6.6	5.2	5.3
CO355	Pioneer 3389	Pioneer 3389	3	2002-03	5.8	4.5	4.8	6.9	6.9	5.0	6.1
CO354	Asgrow RX777	Asgrow RX777	1	1999, 03, 17	4.1	4.3	3.3	6.4	6.4	4.9	5.5
CO353	Asgrow RX777	Asgrow RX777	1	1997, 17	3.9	3.8	3.2	4.3	5.4	5.7	6.0
CO352	Asgrow RX777	Asgrow RX777	1	1997-03	3.9	5.0	3.7	4.7	6.2	4.9	5.1
CO351	Cateto A x CM7	Unknown/Ottawa Flint/ Minnesota 13	5	1997-03	6.3	4.8	5.0	4.2	4.8	6.2	3.8
CO350	CO216 x Pioneer 3977	Pride 5/Pioneer 3977	4	2002-03	6.3	5.3	5.3	4.2	3.4	6.4	4.0
CO349	(CH591-23 x CO255) CO255 (2)	INRA 258/B14	2	2002-03	7.0	5.8	5.0	5.2	4.0	6.5	2.6
CO348	CIMMYT-NTR-2	Unknown	6	2002-17	5.8	5.0	5.8	6.0	6.6	3.8	3.2
CO347	CIMMYT-NTR-1	Unknown	3	2002-03	5.8	5.3	6.0	6.4	6.0	5.5	4.4
CO346	Early Butler	Early Butler	5	2002-03	7.0	6.0	4.8	5.7	3.8	6.6	6.0
CO345	(B86 x CO255) CO251	Pfister44/INRA 258/Oh43	2	2002-03	6.3	5.5	4.8	3.4	4.0	6.2	2.5
CO344	Mo17 x CO255	Mo17/INRA 258	2	2002-03	7.0	6.0	5.0	5.2	4.7	5.3	4.2
CO343	Mo17 x CO255	Mo17/INRA 258	2	2002-03	6.5	6.3	5.3	4.7	5.2	5.7	3.3
CO342	Cateto B x CM7	Unknown	3	2002-03	6.8	5.3	5.8	5.5	5.0	6.5	4.4
CO341	CO256 x CO271	BSSS/Pioneer 3994	8	200-03	7.0	5.5	4.3	5.2	6.5	6.2	4.3

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S_table 1 Genetic background and reaction of 218 maize inbreds to major leaf, ear and stalk diseases at Ottawa, Canada

CO339A	BSSS x 70MP-1-1-0	BSSS	1	2002-03	6.5	6.5	5.0	4.9	6.7	6.0	4.1
CO328	(CO258 x CO216) CO216	Pride 5/BSSS	4	1998	4.0	4.5	4.5	3.6	3.7	6.2	4.8
CO325	(CO256 x CO264) CO264	Early Butler/BSSS	5	1997, 16-17	5.7	5.0	6.1	3.5	3.9	5.6	2.9
CO289	Pioneer 3990	Pioneer 3990	4	1998-03	6.3	5.7	5.8	5.7	3.8	5.9	4.3
CO272	BSTE x (CO109 x CO106) CO109 (2)	Early Butler	1	1997, 16-17	5.3	6.0	3.6	3.8	6.2	5.3	5.4
CO266	Pioneer 3990	Pioneer 3990	7	1997, 16-17	6.5	7.0	6.0	5.2	5.6	5.5	3.7
CO255	Inra 258 =(F115 x W33) x (F7 X EP1)	INRA 258	2	1997-03	6.3	7.0	5.7	5.4	4.3	6.1	3.1
CM174	(V3 x B14) B14 (2)	B14	1	1997-98	4.7	6.0	3.5	5.9	5.1	5.8	5.8
CM105	(V3 x B14) B14 (2)	B14	1	2002-03	7.0	6.0	3.8	6.2	4.0	6.0	4.9
CL30	Lethbridge Gene Pool	European flint	2	1998-17	7.0	6.4	5.9	6.7	5.3	6.3	3.8
CB25	(W182B x F2) W182B	Minnesota 13	4	1998-03	7.0	6.3	6.8	5.5	3.5	6.4	3.1
CB24	W182B x F2	Minn13/E.Flint	4/2	2002-03	7.0	6.8	5.8	3.9	3.4	6.3	3.9
CB21	CO125 x W401	Pfister44/Minnesota 13	4	2002-03	7.0	6.3	5.0	6.7	3.9	6.4	2.9
CB19	Pioneer 3990	Pioneer 3990	7	2003	7.0	6.0	4.5	6.4	4.5	7.0	6.2
CB18	Limagrain LG101	Limagrain LG101	4	2002-03	7.0	6.0	6.8	4.9	4.4	6.0	3.7
CB17	(CQ193 x F2) F2	European Flint	2	2002-03	7.0	6.3	5.8	5.8	5.4	6.4	4.8
CB16	Mo17 x MAG	Lancaster	3	2002-03	6.5	5.0	4.5	6.2	4.9	5.6	4.4
Public inbreds (GRIN, USDA)											
207	G3BD2 x G3RZ1	G3BD2/G3RZ1X154X1X	6	2009, 11	6.5	6.0	4.0	3.1	5.5	5.0	5.1
764	235 x B73	A635/B14/B73	1	2009, 11	6.0	4.5	4.5	4.4	6.9	5.0	5.5
4676A	1067-I x B-line composite	1067-1/B-line composite	1	2011	6.0	4.0	5.0	7.0	6.7	6.6	6.0
11430	Nine inbreds population	Oh43/H99/Mo17	3	2009	6.0	3.0	4.0	5.8	5.0	5.3	4.0
A509	A78 x A109	Minn13/E.Flint	4	2002	7.0	6.0	5.0	3.7	3.1	5.0	5.2
A654	A116 x Wf9	BSSS/Wf9	1	2001, 2017	7.0	6.0	5.0	3.4	4.0	5.3	5.8
A661	Minnesota Synthetic AS-A	Minn13/E.Flint	4	2001	6.0	5.0	3.0	5.8	5.4	6.9	3.8
A662	Minnesota Synthetic AS-A	Minn13/E.Flint	4	2001	6.0	7.0	6.0	3.4	3.5	5.3	3.2
A664	(ND302 x A636) A636	BSSS/Minn13/B14	4	2001	7.0	7.0	4.0	3.9	5.2	5.1	3.7
A665	(ND302 x A635) A635	BSSS/Minn13/B14	4	2001	7.0	7.0	4.0	6.0	6.1	5.5	5.5
A679	(A662 x B73) B73	BSSS/B73	1	2002, 17	4.0	4.5	4.0	4.4	6.7	5.0	3.0
A681	(A662 x B73) B73	BSSS/B73	1	2002, 17	5.1	4.0	4.5	6.1	6.1	5.0	3.0
B113	BS11(FR) C9	BS11	1	2002, 17	7.0	2.5	3.0	5.5	4.3	5.0	5.9
B47	A392 x R61	BSSS/B37	1	2009	6.0	6.0	4.0	6.6	6.0	5.0	5.3
B73	BSSS C5	BSSS/B73	1	2002-2003	5.5	4.5	5.3	5.5	5.2	5.7	5.0
CR1HT	W117Ht x Mo17Ht	Mo17/mixed	3	2009, 11, 17	5.1	4.2	5.0	6.7	7.0	5.9	6.0
F42	B73	B73	1	2009, 11	5.1	4.2	5.0	4.5	6.5	4.0	3.3
FBHJ	(FBAB x B84) FBAB	B14/LH23/B84	1	2009, 11	6.5	6.5	5.0	5.4	4.7	4.7	3.5
FR19	A635 x W438	B14	1	2009	6.5	4.0	5.0	6.3	6.1	3.8	3.3
H126W	Mo17 White Composite	Mo17	3	2002	6.0	5.0	4.0	6.1	6.6	5.0	4.5
HB8229	A634 x 8200	Pioneer309A	1	2011, 17	5.0	3.5	3.5	6.0	7.0	5.4	5.2
IBB14	Pioneer 3710 x Pioneer 3732	BSSS/B37	1	2011	7.0	5.0	5.0	7.0	6.3	6.1	5.3
IBC2	J6 x Mo17Ht	NS/Mo17	3	2011	6.0	4.0	4.0	5.7	7.0	6.8	3.8
L127	P3901 x W117	Mo17	3	2011, 17	7.0	4.0	6.0	5.3	5.4	6.4	4.5

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L139	Pioneer 3901 x Pioneer 3780	Oh43	3	2011, 17	6.7	3.5	6.0	5.7	6.3	5.5	3.9
LH38	A619 x L120	Mo17	3	2011	6.0	4.0	5.0	6.8	6.3	6.0	4.8
LH54	(Mo17) 3X610	Mo17	1	2009, 11, 17	4.4	3.2	4.0	7.0	6.2	4.5	5.4
LH61	(Mo17 x ASA) Mo17	Mo17	3	2009, 11, 17	5.5	6.0	5.0	5.0	5.4	4.8	4.6
LH132	B73 x H93	B73/B37	1	2009, 11, 15	6.0	5.5	4.0	4.8	6.0	4.7	5.0
LH145	A632 x CM105	BSSS/B14	1	2011	6.0	4.0	4.0	5.5	6.6	7.0	6.8
	(B73 x CM105) CM105^6	BSSS/B14	1	2009, 11, 17	4.5	4.5	4.5	6.0	6.7	4.3	4.1
LH160	ND246 x Mo17 Composite	Early Mo17	3	2003, 11	7.0	5.5	5.5	4.5	5.3	6.9	5.1
LH162	ND246 x Mo17 Composite	Early Mo17	3	2003, 11, 15	6.2	4.5	6.3	6.8	5.0	6.2	4.9
LH176	P3704 x LH82	Mixed/Iodent	3	2003	5.0	3.0	3.0	3.9	2.8	5.6	4.4
LH195	LH117 x LH132	BSSS/B73	1	2011	6.0	3.0	4.0	7.0	6.2	4.9	5.6
LH196	LH74 x LH119	B14/B73	1	2011	6.0	5.0	5.0	5.4	6.9	6.6	5.6
LH202	A662 x B73	A662/B73	1	2011	5.0	5.0	6.0	6.6	6.5	7.0	4.2
	LH74/LH145Ht	B14/B73	1	2011	6.0	5.0	4.0	4.5	3.7	6.8	5.0
LH290	LH85 x F2	Flint, Iodent	6	2003	7.0	6.0	5.0	6.2	6.8	3.0	5.7
LH295	LH168 x LH176	Iodent	6	2003	6.0	4.0	3.0	3.7	4.7	3.3	5.5
LH340	P3845	Unknown	6	2003	6.0	6.0	5.0	3.7	3.9	3.1	6.6
Mo17	C.I.187-2 x C103	Mo17	3	2002-03, 17	4.2	4.1	3.8	4.9	5.5	4.8	4.4
Oh43Ht	COF4OB x Wf	Oh73	1	1998, 17	5.0	5.6	4.5	4.4	5.7	4.2	4.7
OQ603	PH3713	BSSS/B14	1	2011	7.0	4.0	4.0	4.0	5.9	5.2	5.7
PB80	1067-1 x B73/ B73Ht1	B73	1	2009	6.0	5.5	5.0	4.3	5.0	5.0	3.5
PHG50	848 x 207	Iodent/NS	6	2009	6.5	5.0	4.0	2.5	4.8	4.5	3.5
PHH93	806 x 207	Iodent/NS	6	2009	4.5	3.5	3.5	5.2	4.0	4.5	4.3
PHJ40	B09 x B36	Mixed	3	2009, 2017	4.0	5.5	4.5	5.3	3.8	5.1	3.7
PHK42	270 x 806	Iodent/NS	6	2009	6.0	5.0	4.0	3.0	5.8	4.3	3.0
PHK76	AD18 x B102	Mixed/NS	6	2009, 11	4.5	3.3	3.8	4.7	5.0	4.0	6.0
PHM10	G39 x 207	Iodent/BSSS	6	2011	7.0	5.0	4.0	6.6	6.8	6.2	4.4
PHM49	PHB81 x PHR33	Iodent/NS	6	2011, 17	6.0	4.0	4.5	7.0	6.8	4.3	5.3
PHN11	207 x (207 x 806)	Iodent/NS	6	2009	5.0	3.5	5.0	2.2	5.0	4.3	3.6
PHN29	G69 x G40	B73	1	2011	7.0	6.0	4.0	6.3	7.0	6.4	4.6
PHN82	PHG29 x HD38	Iodent/NS	6	2011	6.0	3.0	6.0	6.3	7.0	6.4	5.5
PHP02	PHG44 x PHG 29	Iodent/NS	6	2011	6.0	4.0	4.5	5.1	6.5	7.0	2.7
PHP55	G44 x PHG 29	Iodent/BSSS	6	2011	6.0	3.0	5.0	7.0	7.0	6.7	4.6
PHP76	G50 x PHEJ68	Iodent/NS	6	2011	7.0	3.0	4.5	6.9	6.8	5.5	4.0
PHR47	G39 x PHB49	SS/Iodent	6	2009, 17	4.0	6.0	4.0	4.4	4.9	4.4	4.7
PHT60	PHW94 x PHV80	Iodent/NS	6	2011	7.0	5.0	5.0	7.0	7.0	4.5	4.4
PHW20	(1D11 x 1M12) B76	NS	3	2011	7.0	4.0	5.0	6.0	6.8	5.4	4.0
PHW52	B73 x G39	B 73	1	2011	7.0	5.0	5.0	7.0	7.0	5.2	5.3
PHZ51	814 x 848	Mixed/iodent	6	2009, 17	4.5	5.2	4.0	3.0	3.3	5.0	2.7
Q381	Pioneer 3369	PH207	1	2011	7.0	5.0	5.0	3.6	6.3	3.0	6.6
RS710	PAG1202 x 1250 (1250 = ND203 x B14)	BSSS	1	2011	7.0	4.0	5.0	3.4	5.3	4.7	4.0
SD65	A654*10(yellow dent)/SD316W	A654/SD316	4	2002	7.0	5.0	4.0	5.1	5.8	5.0	4.3
W64AHt	Wf9 x C.I. 187-2	BSSS/Wf9	1	1997-98	4.5	4.5	4.0	6.7	5.6	4.4	5.6
WIL903	82C43 population	Mo17	3	2011, 17	4.5	4.3	5.0	6.6	7.0	4.0	4.8

S_table 1 Genetic background and reaction of 218 maize inbreds to major leaf, ear and stalk diseases at Ottawa, Canada

[a]CO, CM, CL, CH and CB inbreds were released from AAFC research stations at Ottawa ON, Morden MB, Lethbridge AB, Harrow ON and Brandon MB, respectively.

[b]wPedigree group analysis based on pedigree of 209 inbreds, 1 = BSSS group; 2 = European Flint; 3 = Lancaster; 4 = Minnesota 13; 5 = Early Butler; 6 = Iodent; 7 = Pioneer 3990 and 8 = Pioneer 3994

For leaf diseases and stalk rot, inbreds with disease severity rating of ≤2.0 were classified as highly resistant (HR), 2.1-4.0 as resistant (R), 4.1-5.0 as intermediate resistant (IR), and >5 as susceptible (S). For gibberella ear rot and common smut, inbreds with disease severity of ≤2 were classified as HR, 2.1-3.0 as R, 3.1-4.0 as IR and >4.0 as S.

S_table 2 Reaction of 66 maize inbreds to grey leaf spot and Goss's bacterial wilt

Inbreds	Pedigree	Genetic background	Pedigree/ heterotic groupa	Evaluation year	Disease rating on[b]	
					Grey leaf spot	Goss's wilt
CO473	H102 Htm x CO428^4	Oh43/H99	3	2016, 17	2.0	3.8
CO472	A632 Htn x CO428^4	Oh43/H99	3	2016, 17	2.5	3.0
CO471	(CO428 x A619Ht) CO428	A619 Ht2 x CO428^4	3	2016, 17	3.0	3.8
CO470	(CO388 x H102Htm) CO388	H102 Htm x CO388^4	1	2016, 17	2.8	3.5
CO469	(CO388 x A632Htn1) CO388	A632 Htn1 x CO388^4	1	2017	4.0	5.0
CO468	(CO388 x A553Htn2) CO388	A553N Htn2 x CO388^4	1	2016	3.0	3.3
CO467	Exotic x (CL29 x CO255	Unknown	1	2015-17	4.0	7.0
CO466	C6 (99ESR)	BSSS	1	2017	2.5	3.5
CO465	B73 x BRCsyn	BSS/mix	1	2016	3.0	4.0
CO464	(N192 x CO388) CO388	BSSS	1	2014-16	3.0	4.0
CO463	B73 x BRC sync	BSSS/mix	1	2015, 17	2.5	8.0
CO462	B73/BSTE/Early Butler/ W153	Mixed	1/5	2014-17	3.0	8.0
CO461	(CM174 x CO388) CO388	B14/B73/BSTE/ Early Butler	1	2014, 17	3.0	6.0
CO460	H95(Rp1-K) x CO388^4	H95/B73/BSTE/ Early Butler	1	2016-17	4.0	7.5
CO459	H95(Rp-G5) x CO388^4	H95/B73/BSTE/ Early Butler	1	2016	5.0	3.7
CO458	H95(Rp-G15c) x CO388^4	H95/B73/BSTE/ Early Butler	1	2016	-	3.3
CO457	H95(Rp-G6J1) x CO325	H95/Early Butler/BSSS	3	2014, 17	4.0	7.0
CO456	(N190 x CO388) CO388	N190/B73/ BSTE/Early Butler	1	2014, 15	-	4.0
CO455	A82-8 x CO388	A82-8/B73/ BSTE/Early Butler	1	2014, 15	2.5	5.0
CO454	Corn Belt Dent Population	BSSS	1	2015, 17	3.0	8.0
CO453	NZS3 x A82-8	NZS3 x A82-8	1	2017	3.5	8.0
CO452	(CO388 x CO328) CO388(4)	B73/BSTE/Early Butler/Pride 5/ BSSS	1	2014, 15, 17	2.5	3.5
CO451	CO309 x CO328	Pride 5/BSSS	1	2014, 15	-	4.0
CO450	Eyespot Resistant Synthetic (99ESR)	BSSS	1	2014, 17	3.5	4.3
CO449	CO432 x CO433	Pride K127/ Unknown	4	2014	-	5.0
CO448	CO273 x CO431	Pioneer 3990/ Unknown	6/7	2015	-	4.0

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S_table 2 Reaction of 66 maize inbreds to grey leaf spot and Goss's bacterial wilt

CO447	CO352 x CO328	Asghgrow Rx777/Pride 5/ BSSS	1/ 4	2014	-	9.0
CO446	CO341 x CO328	BSSS/Pioneer 3994/Pride 5	1	2014, 15	-	4.0
CO445	CO386 x W64AHt	Mo17/MAG/ W64AHt	3	2014	-	5.0
CO444	S1381 x CO382	S1381/INRA 258/Mo17	2	2014	-	5.0
CO443	B104 x CO272	BSSS/Early Butler	5	2014	-	5.0
CO442	Iodent/NSS	Iodent	6	2014, 17	3.0	8.0
CO441	Jacques 7700 x CO298	Unknown	3	2014	-	7.0
CO440	Pride 5 x CO258	Pride 5/BSSS	4	2014	-	9.0
CO439	Nebraska BSSS	BSSS	1	2014	-	5.0
CO438	CB3 x CL29	Pioneer 3994/ Unknown	8	2014	-	7.0
CO437	European Synthetic	European hybrids	2	2014	-	7.0
CO436	CO275 x CO300	Pioneer 3994/ Minnesota 13	8	2014	-	5.0
CO435	A632 x A634	B14	1	2014	-	7.0
CO434	CM105 x A632	B14	1	2014	-	6.0
CO433	Pride K127	Pride K127	4	2014	-	7.0
CO430	Fusarium Resistant Synthetic	Pioneer 3990	7	2014	-	5.0
CO428	Oh43 x H99	Oh43/H99	3	2014, 15, 17	2.0	3.0
CO427	(Oh43 x H99) Oh43	Oh43/H99	3	2014	-	5.0
CO390	(Oh43 x H99) H99	H99/Oh43	3	2014	-	5.0
CO388	(B73 x CO272) CO272	B73/BSTE/Early Butler	1	2015	-	4.0
CO381	CO289 x CO266	Pioneer 3990	7	2015	-	6.0
CM105	(V3 x B14) B14 (2)	B14	1	2015	-	6.0
CM109	(V3 x B14) B14 (2)	BSSS	1	2015	-	5.0
CM145	(B14 x CMV3) B14	BSSS	1	2015	-	5.0
CM151	(Mt42 x Wf9) Wf9 (2)	Minn13	4	2015	-	5.0
CM155	Wf9 x Mt42	Minn13	4	2015	-	5.0
CM174	(V3 x B14) B14 (2)	B14	1	2015	-	5.0
CM385	ASB6 (synthetic of Minn 13)	Minn13	4	2015	-	5.0
CL30	Lethbridge Gene Pool	European flint	2	2014, 15, 17	-	8.0
CB21	CO125 x W401	Pfister44/Min-nesota 13	4	2014	-	6.0
A619Ht3	A171 x Oh43 (2)	Oh43/H99	3	2014	-	5.0
A632N	Mt42 x b14 (4)	B14	1	2014, 15	-	5.0
A638	V3 x Wf9 (2)	Wf9	1	2014	-	4.0
B73Ht	BSSS C5	BSSS/B73	1	2014	-	4.0
G80	495/331	BSSS/Mixed	1	2014	-	2.0
H99	Illinois Synthetic 60C	H99/Oh43	1	2014	-	4.0
PHJ40	B09 x B36	Mixed	3	2014	-	4.0

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S_table 2 Reaction of 66 maize inbreds to grey leaf spot and Goss's bacterial wilt

PHR55	PH005/PHG84	Iodent/NS	6/3	2014	-	3.0
PHR58	PH383/PHG16	Iodent/Ns	6/3	2014	-	3.0
PHW43	995/G35	Iodent/NS	6/3	2014	-	5.0
PHZ51	814 x 848	Mixed/iodent	6	2014	-	3.0

NOTE: - no data available as these inbreds were not evaluated.
a Pedigree group analysis based on pedigree of 223 inbreds, 1 = BSSS group; 2 = European Flint; 3 = Lancaster; 4 = Minnesota 13; 5 = Early Butler; 6 = Iodent; 7 = Pioneer 3990 and 8 = Pioneer 3994.
b Grey leaf spot rating on 1-7 scale and Goss's wilt rating on 1-9 scale.
For Grey leaf spot and goss's wilt, inbreds with disease severity rating of ≤2.0 were classified as highly resistant (HR), 2.1-4.0 as resistant (R), 4.1-5.0 as intermediate resistant (IR), and >5 as susceptible (S).

inoculations varied (Fig. 1). The proportion of inbreds resistant to NCLB was lowest followed by common rust and eyespot. None of the inbreds exhibited HR to NCLB or eyespot. Fifteen of the 218 inbreds (CO328, CO352, CO353, CO390, CO428, CO463, CO464, CO469, CO470, CO471, CO472, CO473, A679, PHJ40, and PHR47) exhibited a resistant reaction to NCLB (Table 2). Twenty five inbreds exhibited intermediate resistance. The remaining 178 inbreds were susceptible to NCLB including eight (FBHJ, IBC2, L139, LH132, LH145, PB80, PHM49, and PHT60) which were previously reported to have resistance against race 1 and race 2 of NCLB (S_table 1).

Four inbreds (CO457, CO458, CO459, and CO460) exhibited a highly resistant reaction to common rust with only yellowish pin-point fleck symptoms. Forty five inbreds (CO353, CO390, CO391, CO420, CO428, CO444, CO445, CO450, CO451, CO452, CO454, CO461, CO466, CO468, CO469, CO470, CO471, CO472, CO473, 11430, 4676A, A681, B113, FR19, HB8229, IBC2, L127, L139, LH38, LH54, LH145, LH176, LH195, LH295, OQ603, PHH93, PHK76, PHM49, PHN11, PHN82, PHP02, PHP55, PHP76, PHW20, and RS710) exhibited a resistant reaction characterized by very small pustules with light-green or yellowish or brown necrotic borders and still covered by the cuticle of the leaf. Fifty seven inbreds exhibited intermediate resistance (S_table 1). The remaining 112 inbreds were susceptible to common rust.

Nine inbreds (CO450, CO456, CO460, C0464, CO466, A661, B113, LH176, and LH295) exhibited the best resistance against eyespot with disease rating of ≤3.0. Fifty four inbreds (CM105, CM174, CO272, CO352, CO353, CO354, CO361, CO362, CO363,

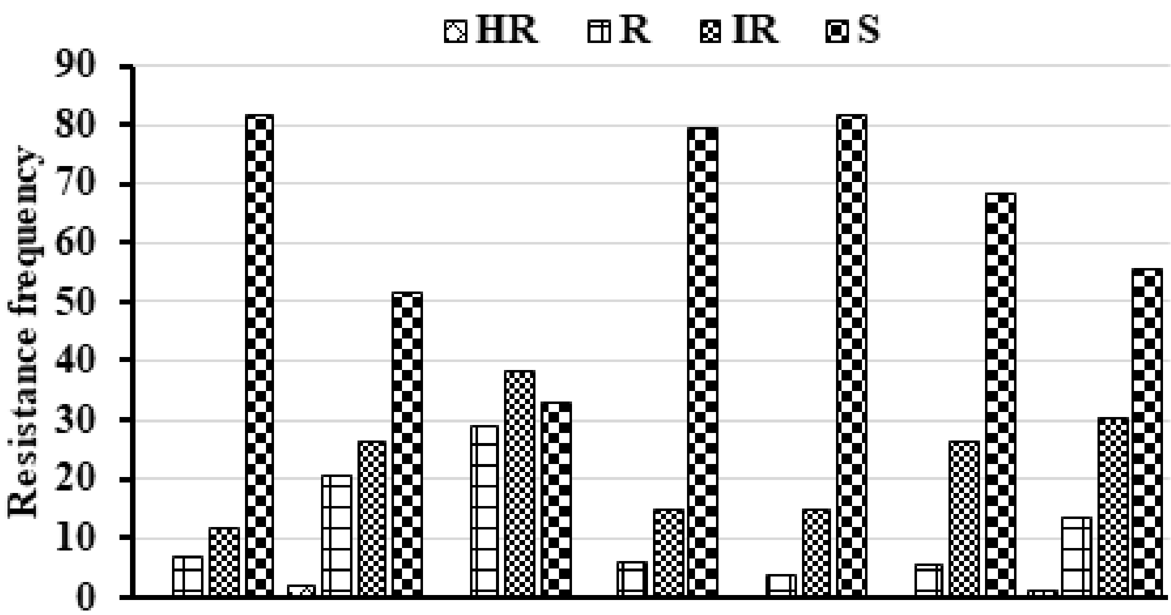

Fig. 1 - Frequencies of maize inbreds lines with highly resistant (HR), resistant (R), intermediate (IR), suscepl!ble (S) reactions to Northern Com Leaf Blight (NCLB), Common Rust (Rust), Eyespot, Ear Rot Silk Inoculation (ERSC), Ear Rot Kernel Inoculation (ERK), Stalle Rot, Common Smut (Smut)

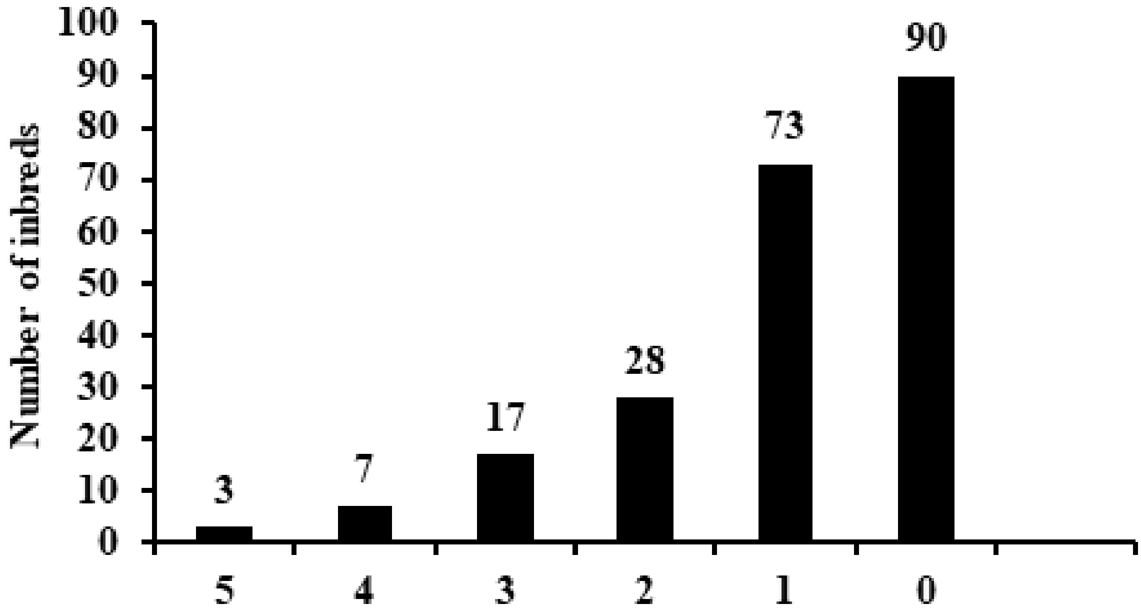

Fig. 2- Nwnber of maize inbreds out of 218 screened exlubited resistance to none or one or more diseases

CO364, CO367, CO372, CO388, CO400, CO404, CO424, CO428, CO442, CO444, CO452, CO457, CO458, CO459, CO461, CO467, CO468, CO470, CO471, 207, 11430, A664, A665, A679, B47, H126W, HB 8229, IBC2, LH54, LH132, LH145, LH195, LH220Ht, Mo17, OQ603, PHG50, PHH93, PHK42, PHK76, PHM10, PHN29, PHR47, PHZ51, SD65, and W64AHt) also exhibited a resistant reaction but with higher disease rating of 3.1- 4.0. Eighty three inbreds had intermediate resistance while the remaining 72 inbreds exhibiting susceptibility to eyespot (S_table 1).

Two inbreds (CO428 and CO473) exhibited a highly resistant reaction to GLS and/or goss's wilt. Twenty inbreds (CO442, CO450, CO452, CO453, CO454, CO455, CO457, CO460, CO461, CO462, CO463, CO464, CO465, CO466, CO467, CO468, CO469, CO470, CO471, and CO472) were resistant to GLS (S-table 2). Six inbreds (CO428, CO472, G80, PHR55, PHR58, and PHZ51) showed resistant reaction to goss's wilt with a limited spread of water soaking, chlorosis and necrosis towards the tip end of inoculated leaves. Another 19 inbreds (A638, B73Ht, CO388, CO446, CO448, C0451, CO452, CO456, CO458, CO459, CO464, CO465, CO466, CO468, CO470, CO471, CO473, H99, and PHJ40) also exhibited a resistant reaction to goss's wilt but with a higher disease rating (S_table 2).

Ear and stalk disease

The inbreds evaluated in this study also showed variability in their resistance to ear and stalk diseases but none was highly resistant (Fig. 1, S_table 1). Eight AAFC inbreds (CO387, CO389, CO410, CO430, CO432, CO433, CO441, and CO449) and four introductions (PHG50, PHK42, PHN11, and PHZ51) had excellent resistance to Gibberella ear rot silk channel infection with disease rating of ≤3.0. Five (CO387, CO430, CO432, CO433, and CO441) of these also exhibited good resistance to kernel infection whereas the other seven inbreds had intermediate resistance or susceptible to kernel infection.

Thirty three inbreds, 21 from AAFC (CB24, CO272, CO325, CO328, CO345, CO364, CO373, CO375, CO385, CO400, CO401, CO408, CO409, CO413, CO415, CO423, CO426, CO436, CO444, CO448, CO470) and 11 from introductions (207, A509, A654, A662, A664, LH176, LH295, LH340, OQ603, Q381, and RS710) exhibited an intermediate resistance to silk channel inoculation. Twelve of these (CB24, CO325, CO328, CO345, CO373, CO375, CO408, A509, A654, A662, LH176, and LHR340) also had intermediate resistance to kernel inoculation. The remaining 21 ERSC IR inbreds were found susceptible by ERK inoculation. Similarly, 20 of the 33 IR ERK inbreds (CB21, CB25, CM105, CO289, CO346, CO349, CO350, CO371, CO379, CO393, CO398, CO407, CO417, CO421, CO422, CO438, CO445, LH220Ht, PHH93, and PHJ40), were found susceptible to gibberella ear rot by silk channel inoculation. Five inbreds, CO387, CO430, CO432, CO433 and CO441, showed the highest resistance to both silk channel and kernel infection.

Seven (CO373, CO387, CO410, CO441, CO449, PHK42, and PHZ51) of the 14 inbreds having resistance to ERSC or ERK also exhibited an R reaction to common smut. Twenty six inbreds (CO345, CO349, CO375, CO380, CO381, CO393, CO398, CO401, CO402, CO406, CO407, CO408, CO409, CO413, CO417, CO421, CO423, CO429, CO436, CO444, CO451, A679, A681, PHK02, PHK42, and PHP02) which were susceptible to ear rot exhibited resistance to common smut. Thirty inbreds which had intermediate resistance to ERSC and/or ERK also displayed intermediate resistance to common smut. Only two inbreds (CO375 and CO423) had a highly resistant reaction to common smut. Twenty nine inbreds (CB21, CO325, CO345, CO349, CO373, CO380, CO381, CO387, CO393, CO398, CO401, CO402, CO406, CO407, CO409, CO410, CO413, CO417, CO421, CO429, CO441, CO444, CO449, CO451, A679, A681, PHK42, PHP02, and PHZ51) exhibited a resistant reaction to common smut.

For stalk rot, no inbreds showed a resistant reaction and 12 (CO348, CO431, CO445, CO463, F42, FR19, LH290, LH295, LH340, PHK76, Q381, and WIL903) showed resistant reaction to stalk rot. Of these, LH340 also had intermediate resistance to ERSC and ERK, and LH295 and Q381 to ERSC.

Multiple resistance to different diseases

Fifty five of the 218 inbreds evaluated had good resistance against two or more of the diseases. Three inbreds (CO428, CO470, and CO471) showed resistance to five diseases (NCLB, common rust, eyespot, GLS, and goss's wilt). These inbreds also had intermediate resistance to a few other diseases (CO428 to common smut, CO470 to ERSC and stalk rot, and CO471 to stalk rot). Seven inbreds had an R reaction to four diseases (CO452, CO466 and CO468 to common rust, eyespot, GLS and goss's wilt; C0473 to NCLB, common rust, GLS and goss's wilt; CO464 to NCLB, eyespot, GLS, and goss's wilt, and PHZ51 to eyespot, goss's wilt, ERSC, and common smut). Five of these inbreds also had intermediate resistance against two more diseases (CO452, CO466, CO468, and CO472 to stalk rot and PHZ51 to ERK). A good number of inbreds were also found to have resistance against three (17) and two diseases (28). Inbreds CO457, CO458, CO459 and CO460 which were released as highly resistant to common rust were also found to have good resistance against eyespot, GLS, and/or goss's wilt. CO450 released for eyespot resistance also had good resistance against common rust and GLS, and intermediate resistance to goss's wilt. Three inbreds (CO387, CO441 and CO449) were found to have resistance for ERSC, ERK and common smut. PHK76 and LH295 showed resistance to common rust, eyespot and stalk rot. LH295 also showed a resistant reaction to ERSC. Two other introductions showed resistant reactions against three diseases (LH176 to common rust, eyespot, and ERK; PHK42 to eyespot, ERSC and common smut). These inbreds also have intermediate resistance to stalk rot. CO461 and CO463 released in 2015 for early maturity exhibited resistance to three diseases (CO461 to common rust, eyespot, and GLS; CO463 to NCLB, GLS, and stalk rot. Nine inbreds (11430, B113, HB8229, IBC2, LH54, LH145, LH195, OQ603, and PHH93) exhibited resistant reaction to common rust and eyespot. Five inbreds (CO410, CO430, CO432, CO433 and CO449) exhibited resistance to ERSC and ERK as well as intermediate resistance to common smut. Two other inbreds (PHG50 and PHN11) had resistance to ERSC and eyespot or common rust. These inbreds also had intermediate resistance for common smut and stalk rot. CO352 and PHR47 showed resistance to NCLB and eyespot. CO465 showed resistance against GLS and goss's wilt (Table 2).

Discussion

Currently not many genotypes are known/ available which have multiple durable disease resistance for use in maize breeding programs, especially the public breeding programs. Many of the maize breeders rely on natural infection for selecting resistant inbreds; however, this is often unreliable except in heavily infected regions, as natural infection is not sufficiently uniform for effective selection of resistant inbreds. This is why an artificial inoculation method is often preferred using one disease at a time as was used in this study for evaluation of inbreds against all eight diseases except GLS where we relied on natural infection.

Significant variation in resistance was detected in the inbreds for the diseases evaluated but only a few of them exhibited a highly resistant reaction (disease ratings 1.0-2.0) for one or more diseases. The majority of the inbreds exhibited either a resistant (disease ratings 2.1 to 4.0 for leaf diseases and stalk rot; 2.1-3.0 for gibberella ear rot and common smut) or intermediate resistant reaction (disease ratings 4.1-5.0 for leaf diseases and stalk rot; 2.1-3.0 for gibberella ear rot and common smut) or susceptible reaction against one or more diseases. Eight inbreds, most of them of Canadian origin, showed highly resistant reaction to different diseases (CO457, CO458, CO459 and CO460 to common rust, CO450 to eyespot, CO428 and CO463 to GLS, and G80 to goss's wilt) in this study. None of the evaluated inbreds showed a highly resistant reaction to NCLB; however, 13 inbreds (CO328, CO352, CO353, CO390, CO428, CO463, CO464, CO470, CO471, CO472, CO473, PHJ40, and PHR47) displayed a resistant reaction. Similarly, none of the inbreds showed highly resistant reaction to gibberella ear rot; however, five inbreds (CO431, CO432, CO433, CO441 and CO449) exhibited a resistant reaction to both gibberella silk channel and kernel infections. Thus there is a need to look for the genotypes having highly resistance genes against these diseases.

Three inbreds (CO428, CO470, and CO471) showed resistance to five diseases (NCLB, common rust, eyespot, GLS, and goss's wilt). CO428 also had intermediate resistance to common rust, CO470 for ERSC and stalk rot, and CO471 for stalk rot. Seven inbreds (CO452, CO464, CO466, CO468, CO472, CO473, and PHZ51) exhibited resistant reaction against four diseases. Sixteen inbreds displayed resistance against three diseases and 29 to two diseases. All these inbreds can be an important source for breeding programs for the development of maize hybrids with multiple disease resistance for the short-season growing regions of Canada and elsewhere also.

Northern Corn leaf blight, which is a common and increasingly important disease in maize producing regions of Canada and elsewhere was well managed by growing resistant hybrids with *Ht* resistance genes; however, in the past few years with the changing pathogen population, cultivation practices, and climatic conditions, most of the previously resistant hybrids have become susceptible. Recently, 17 races of the NCLB fungus were identified from maize growing regions of Ontario and one of these races (Race 123MN) overcame all five *Ht* resistance genes *Ht1, Ht2, Ht3, Htm1* and *Htn1* (Jindal et al, 2019). In this study, 13 of the inbreds had good resistance to NCLB, five (CO428, CO470, CO471, CO472 and CO473) of which, also had good resistance to common rust, GLS, and goss's wilt. CO428, CO470 and CO471 had good resistance for eyespot as well. Eight of the inbreds (FBHJ, IBC2, L139, LH132, LH145, PB80, PHM49, and PHT60) which were identified earlier as resistance to NCLB race 1 and race 2 were found susceptible in this study, may be due to use of different pathogen population for inoculation.

Common rust has been well managed with the use of current hybrids but in recent years its occurrence and incidence has increased, particularly in southern Ontario (Jindal et al, 2018). In this study, the resistance of four inbreds (CO457, CO458, CO459 and CO460) which were released in 2016 by Reid *et al* 2017 for common rust resistance is confirmed. These inbreds were also found to have resistance for GLS and goss's wilt. These four inbreds can very well be used in breeding programs to develop hybrids with a high degree of resistance for multiple diseases as the resistance genes (H95(Rp-G6J1), H95(Rp-G15c), H95(Rp-G5), and H95(Rp1-K) of these inbreds expressed very well in hybrids when they were combined with susceptible inbreds (Reid et al, 2017).

The increasing importance of eyespot and GLS, especially in south western Ontario and other maize growing regions of the world, also requires resistant inbreds for hybrid development. Nine inbreds (CO450, CO456, CO460, C0464, CO466, A661, B113, LH176, and LH295) including CO450 which was released in 2013 for eyespot resistance by Reid et al (2014), were found to have resistance to common rust, GLS and goss's wilt. These inbreds can be used in breeding programs for multiple disease resistance but still there is a need to look for higher levels of resistance to eyespot and GLS. However, it is not an easy to find a high level of resistance, given that resistance to these diseases is polygenic (Chiang et al, 1990; Lehmensiek et al, 2001), thus a broad range of germplasm from various sources should be evaluated to identify the inbreds that are highly resistant to either or both diseases.

Goss's bacterial wilt is another important disease of maize which can pose a serious threat to its cultivation in Canada as this disease is spreading from the mid-west USA to the western provinces Manitoba and Alberta (Harding et al, 2018). Already there are reports of significant yield losses due to goss's wilt in the United States (Carson and Wicks, 1991). In a recent study, Mueller and Wise (2012) estimated yield losses as high as 0.878 Tg from goss's wilt in Iowa, Illinois, Minnesota, and Nebraska states of North America. While the reasons for the rapid re-emergence of goss's wilt are not completely known, one possibility is an increase in susceptibility within the germplasm base which is used for breeding commercial maize hybrids. In this study, inbred G80 displayed HR reaction and five inbreds (CO428, CO472, PHR55, PHR58, and PHZ51) R reaction under artificial inoculation conditions. A few more genotypes having resistance genes against goss's wilt have been identified earlier (Calub et al, 1974; Gardner and Schuster, 1974; Martin et al, 1975; Schuster et al, 1972; Treat and Tracy, 1990; Treat et al, 1990), but a comprehensive evaluation of a large germplasm collection has not been conducted and there is a need to look for the resistance sources.

Ear rot caused by different species of *Fusarium* is another most threatening disease in maize production for food and feed safety due to the production of mycotoxins by these fungi. Agriculture and Agri-Food Canada (AAFC) in Ottawa has been doing breeding work on lowering gibberella susceptibility for the last

30 years and has released 11 inbreds (CO272, CO325, CO387, CO388, CO389, CO430, CO431, CO432, CO433, CO441 and CO449) with improved resistance to gibberella ear rot infection through silk channel and kernel infection (Reid et al, 2001, 2003). Resistance of all these inbreds except CO272, CO325, CO388, CO389, and CO431 through silk channel is confirmed in this study. As well, four of the inbreds (PHG50, PKH42, PHN11, and PHZ51) sourced from USDA displayed resistant reactions to gibberella ear rot infection on silk channel inoculation in this study. Inbreds CO387, CO430, CO432, CO433, CO441 and CO449 had high resistance both for ERSC and ERK. The inbreds CO430 and CO432 were derived from a population made up of five commercial hybrids with moderate levels of resistance, and CO432 have the best combining ability for yield of the two inbreds (Reid et al. 2001) while CO433, CO441 and CO449 released in 2000, 2002 and 2012, had very high resistance to ear rot and excellent combining ability for yield (Reid et al. 2003; 2013). These inbreds also have good resistance to common smut. These six inbreds can be used in breeding programs for ear rot and common smut resistance.

There are few contrasting reports available on the correlation of silk channel and kernel resistance to gibberella ear rot. Mesterházy (1983), Mesterházy and Kovács (1988), and Mesterházy et al (2000) found low correlations (r = 0.12), whereas Löffler et al (2010) reported a much closer relationship (*r*P = 0.66). In this study, we found five inbreds (CO387, CO430, CO432, CO433 and CO441), which have good resistance to both modes of fungal entry have a correlation of 0.52 between silk channel and kernel resistance.

Inbreds developed and selected for gibberella ear rot resistance also exhibited high levels of resistance to common smut (*U. zeae*) indicating that it may be possible to develop hybrids having resistance to both of these diseases (Reid et al, 2009). In this study, seven gibberella ear rot resistant inbreds (CO373, CO387, CO410, CO441, CO449, PHK42 and PHZ51) also had resistance for common smut.

None of the inbreds exhibited highly resistant reactions to fusarium stalk rot but two of them (LH290 and Q381) had a resistant reaction. There are reports that a substantial number of maize germplasm accessions have already been evaluated for stalk rot resistance and some have demonstrated high levels of resistance (Ledencan et al, 2003; Afolabi et al, 2008) but sources of resistance having adaptation to Canada are scarce.

Maize breeding programs for multiple disease resistance involves making multiple crosses depending upon the target diseases and the available resistance sources, and screening of the resulting populations for resistance against different diseases. Five inbreds, [CO449 (Minn 13 heterotic group), CO452, CO458, CO468 and CO470 BSSS (B73/Minn13 heterotic group)], identified in this study as possessing multiple disease resistance can be used as an example to demonstrate how these inbreds can be best used in a maize breeding program for developing hybrids with multiple disease resistance. CO449 can be used for both ear rot resistance and as a source of early maturity genes. One could make four single crosses (CO452, CO458, CO468, and CO470 crossed to CO449) and evaluate their resulting populations for the target leaf, ear and stalk rot diseases. The different resistant F_1 crosses could be used to make double crosses and again screen these populations against the target diseases. Genotypes for double crosses will depend on the final target. For improving resistance to leaf diseases, use 50% of CO452, CO458, CO468 and CO470, and for better resistance to ear diseases use 50% of CO449. Double crosses (CO452xCO449 with CO458xCO449 and CO468xCO449 with CO470xCO449) have 50% of inbreds with resistance to leaf diseases and 50% to ear diseases. Evaluate the resulting populations of double crosses for resistance to leaf, and ear diseases using multiple nurseries with artificial inoculations. Sometimes, it may be difficult to use all the selected double crosses in one population for all diseases. In this situation, use of molecular markers can be very helpful in selecting the plants with multiple disease resistance. This will not only reduce the field work to screen the populations but will also help to develop genotypes with multiple resistance in less time. The other alternative, in the non availability of molecular markers, which will reduce the inoculation load for target diseases is to use chain crosses [(CO452xCO449) (CO470xCO449); (CO458xCO449) (CO470xCO449); (CO468xCO449) (CO470xCO449); (CO458xC0449) (CO470xCO449)] for making resistant populations. On an average, chain crosses needs 3-5 generations to improve a single target. Multiple targets may require more inoculations and more generations to improve their resistances. Chain crosses have another advantage of having more inbred-like plants because a population in chain cross starts from 50% of same genotype. Inbred selection from such population is easier than selection from a single-cross. Similarly, the Lancaster heterotic group inbreds (CO457, CO471, LH176, PHZ51, and CO441) with resistance to multiple diseases can also be used to develop an inbred from this heterotic group. CO441 can be used as a source of ear rot resistance and early maturity genes to make five single crosses. PHZ51xCO441 would be the most important cross for double crosses. Thus multi-resistance inbreds from either BSSS (B73/Minn13) or Lancaster populations can be used to make hybrids with multi-resistance to ear rots and leaf diseases as both of these heterotic groups have an excellent combining ability with each other.

The background origin of the inbreds used in this study had an effect on resistance to some of the diseases. Most of the inbreds found to be resistant in this study were from the BSSS, Lancaster and Iodent a maize heterotic group (Group 1, 3 and 6 in Table 1) which confirms the findings of Sokolov et al (1996). In a breeding program, the Lancaster inbreds (Group 3), CO390, CO428, CO457, CO471, CO472, CO473, LH176, and the Iodent inbreds LH295, PHH93, PHK76 and PHR47 can be used to make a non-stiff stalk population for selecting inbreds with multi-resistance to leaf diseases. CO352, CO353, CO452, CO458, CO464, CO466, CO468, CO470, B113, HB8229, and LH54 can be used to make a stiff stalk population by selecting inbreds with multi-resistance to leaf diseases. For multi-resistance to ear diseases, PHN11 and PHZ51 had better leaf disease resistance than CO441, therefore, CO441×PHR11 or CO441× PHZ51 may be used to improve the leaf resistance of CO441.

The selection of parents for developing a resistant hybrid is more complicated than selection for developing a resistance population. Many factors such as adaptation to ecosystem (based on soil and weather conditions, maize heat units, irrigation, breeding targets), heterotic background of parents, complimentary traits between parents for important characteristics, and synchronization of male and female flowering times for hybrid seed production must be taken into consideration for selecting parents for developing resistant hybrid. These studies have generated a useful data that can assist with the selection of parents having resistance and development of new inbreds. For example, the multi-disease resistance inbreds, CO428, CO471, CO472 and CO473, Lancaster type genotypes (Pedigree/SSR Group 3), can be matched with inbred CO470, a pedigree Group BSSS and Iodent for resistance hybrids. In the AAFC breeding program, inbred CO388, a very good yielder, was used as one of the parents to develop inbreds for disease resistance and grain yield. CO388 crossed with CO428 yielded 10-14 Ton/ha and has an excellent multi-disease resistance to leaf diseases. Another inbred, CO441, with excellent ear rot resistance crossed with CO388 has good grain yield but not high resistance to leaf diseases. Rust resistance conferred by the Rp genes, was introgressed into CO388 that led to the development of four inbreds (CO457, CO458, CO459, CO460) having higher resistance to common rust. Similarly many of the other resistant inbreds identified here could be utilized in breeding programs as potential sources of resistance to leaf, ear and stalk rots for developing new hybrids with multiple disease resistances.

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