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Evaluation of a Core of the U.S. *Capsicum* Germplasm Collection for Reaction to the Northern Root-knot Nematode

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Abstract. **Several species of root-knot nematodes [*Meloidogyne incognita* (Kofoid & White) Chitwood, *M. arenaria* (Neal) Chitwood, *M. javanica* (Treub) Chitwood, and *M. hapla* Chitwood] are major pests of peppers (*Capsicum* spp.) in the United States and worldwide. Resistance to *M. incognita*, *M. arenaria*, and *M. javanica* has been identified in several *Capsicum* accessions, but there are few reports of resistance to *M. hapla*. Therefore, we selected a 10% core (440 accessions) of the 14 available *Capsicum* spp. in the *Capsicum* germplasm collection (3,731 accessions) maintained by the U.S. Dept. of Agriculture (USDA), and evaluated this core for resistance to *M. hapla* in unreplicated greenhouse tests. The 11 best (most resistant) and the 3 worst (most susceptible) accessions identified in these unreplicated tests were re-evaluated in a replicated greenhouse test. Seven of these 11 "best" accessions (PI 357613, PI 357503, PI 439381, PI 297493, PI 430490, PI 267729, and PI 441676) exhibited root gall severity indices <5.0 (1 = no galls; 9 = more than 80% of the root system covered with galls) in the replicated test, and each of these indices was significantly lower than the indices of the "worst" accessions and susceptible controls. Although a gall index <5.0 indicates a moderate level of resistance, more than 3000 *M. hapla* eggs were extracted per gram of fresh root tissue and the reproductive index was >1.0 for each of these accessions. These observations suggest that the most resistant accessions tested are somewhat susceptible to *M. hapla*. The results of our evaluation of a core of the USDA *Capsicum* germplasm collection demonstrates clearly that there is significant genetic variability within the overall collection for *M. hapla* resistance. Additionally, these results identify portions of the collection where future evaluations for *M. hapla* resistance should be focused. For example, the origin of the two most promising *C. annuum* accessions (PI 357613 and PI 357503) in the core was Yugoslavia. Thus, additional accessions from this temperate region of the world should receive priority attention in any effort to identify better sources of resistance in *C. annuum* to *M. hapla*.**

Root-knot nematodes (*Meloidogyne incognita*, *M. arenaria*, *M. javanica*, and *M. hapla*) are major pests of both bell and hot peppers (*Capsicum* spp.) in the United States and worldwide (Di Vito et al., 1992; Thies et al., 1997; Thomas et al., 1995). Fumigation with methyl bromide is the primary control method for root-knot nematodes in bell pepper, and accounts for 12% of all methyl bromide used for pre-plant soil treatment in the United States. The pending loss of methyl bromide from the U.S. market in 2005 has focused significant interest in host resistance as an alternative management tool for root-knot nematodes.

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Resistance to *M. incognita, M. arenaria,* and *M. javanica* has been identified in several *Capsicum* germplasm sources, including *C. annuum* L., *C. chacoense* L., *C. chinense* Jacq., and *C. frutescens* L. (Di Vito, 1986; Di Vito et al., 1992; Di Vito and Saccardo, 1986; Fery et al., 1986, 1998; Fery and Thies, 1998; Hare, 1956; Hendy et al., 1985; Thies and Fery, 2000, 2001). However, there are only two reports of resistance to *M. hapla* in *Capsicum* germplasm. Di Vito et al. (1989) observed resistance to *M. hapla* in germplasm line "589-20" of *C. frutescens* and one line, "201", of *C. chinense*. Djian-Caporalino et al. (1999) reported resistance of five pepper lines to a population of *M. hapla* from England, but variable reactions to a population of *M. hapla* from Canada and another population of *M. hapla* from La Mole, France.

The U.S. Vegetable Laboratory pepper breeding program [U.S. Dept. of Agriculture (USDA), Agricultural Research Service (ARS), Charleston, S.C.] has developed and released several pepper cultivars and germplasm lines with resistance to root-knot nematodes. 'Carolina Cayenne' is a cayenne-type pepper with exceptionally high resistance to *M. incognita* (Fery et al., 1986; Thies et al., 1997). Recently, Fery and co-workers developed and released 'Charleston Belle' and 'Carolina Wonder', the first two bell-type pepper cultivars with resistance to *M. incognita* (Fery et al., 1998). Both of these open-pollinated, bell-type cultivars are homozygous for the *N* gene, which confers resistance to *M. incognita*, *M. arenaria* races 1 and 2, and *M. javanica*, but not to *M. hapla* (Thies and Fery, 2000). Fery and Thies (1997, 1998) also recently identified high levels of resistance to *M. incognita* in three Scotch Bonnet-type (*C. chinense*) cultigens obtained from heirloom collections, and subsequently released the resistant Scotch Bonnet-type germplasm lines PA-353, PA-398, and PA-426 (Fery and Thies, 1998). However, these three Scotch Bonnet-type germplasm lines are also susceptible to *M. hapla* (Thies and Fery, 2001).

The northern root-knot nematode, *M. hapla*, is a major pest of peppers (*Capsicum* spp.) in temperate areas of the United States and the world. *Meloidogyne hapla* is the most common root-knot nematode in the northern United States and eastern Canada; it also occurs in every southern state and along the Pacific Coast from California northward to British Columbia (Society of Nematologists, 1984). Although the northern root-knot nematode causes serious damage to *Capsicum* spp., there are no sweet or hot pepper cultivars with resistance to *M. hapla* available to pepper growers in the United States or worldwide. There is a critical need for resistant pepper cultivars because of the imminent loss of methyl bromide from the U.S. market. Additionally, other nematicides are also being lost from the market due to environmental concerns and prohibitive re-registration costs. The objectives of the study reported here are 2-fold: 1) to determine the extent of genetic variation within the USDA *Capsicum* germplasm collection for reaction to *M. hapla*; and 2) to identify the portions of the collection where future efforts should be focused when searching for high levels of *M. hapla* resistance within specific *Capsicum* species.

Materials and Methods

Inoculum preparation and greenhouse evaluation procedures. A North Carolina isolate of *M. hapla* obtained from K.R. Barker (N.C. State Univ.) was cultured on 'Rutgers' tomato (*Lycopersicon esculentum* Mill.) in isolated greenhouse benches. Egg inocula were extracted using 0.5% NaOCl (Hussey and Barker, 1973). Seeds of each accession and control entries were planted in flats containing MetroMix™ 360 (The Scotts Co., Marysville Ohio) planting medium. About 10 to 14 d later, the seedlings were transplanted in a 12 × 12-cm planting arrangement into 4.0 × 2.0 × 0.2-m benches containing a steam-pasteurized mixture of 2 fine washed river sand : 1 sandy loam soil (by volume). Each plot consisted of five seedlings per accession or control entry. After the seedlings were established and growing, the root system of each plant was inoculated with ≈3000 *M. hapla* eggs. The greenhouse air temperature was maintained at 28 ± 3 °C. Eight weeks (replicated evaluation of selected accessions) or 12 weeks (unreplicated evaluation of core collection) after inoculation, the roots of all plants were removed from the benches, and washed and evaluated for galling severity and egg mass production using a 1 to 9 scale (1 = 0%, 2 = 1% to 3%, 3 = 4% to 12%, 4 = 13% to 25%, 5 = 26% to 38%, 6 = 39% to 50%, 7 = 51% to 65%, 8 = 66% to 80%, and 9 = 81% to 100% of root system galled or covered with egg masses, respectively) (Thies et al., 1997).

Unreplicated evaluation of core collection. A core of 440 accessions was selected from the USDA *Capsicum* germplasm collection (3,731 total available accessions) and evaluated for reaction to the northern root-knot nematode in unreplicated greenhouse tests. The 440 accessions (Plant Introductions = PI) represented at least 10% of each geographic origin/*Capsicum* taxa combination in the collection. The 440 PIs were selected in the following manner. First, the entire USDA *Capsicum* collection database was sorted in ascending order by PI accession number within each taxa/geographic origin (country) group. Then, the first PI (lowest accession number) and every 10th PI thereafter was selected in each taxa/country group, so that ≈10% of each taxa/country group was represented. If there were <10 PIs per taxa/country group, then the last PI in the group was selected. Five pepper accessions ('Carolina Cayenne', 'Charleston Belle', 'California Wonder', PA-426, and PA-350) and 'Rutgers' tomato were randomly included with each subset of 31 PIs as reference controls. 'Carolina Cayenne' is a cayenne pepper (*C. annuum*) selected from a population of 'Carolina Hot' that was segregating for many traits, including resistance to *M.*

Table 1. Gall indices and egg mass indices for *Capsicum* spp. plant introduction (PI) accessions and controls inoculated with *M. hapla* in a greenhouse test.[z]

Species/ origin	Accession (P.I. No.)	Gall index[y]	Egg mass index[y]
C. annuum			
Afghanistan	127445	6.8	7.2
Afghanistan	256056	6.8	6.8
Argentina	260453	5.2	5.4
Argentina	439208	5.8	5.8
Australia	504809	6.6	6.6
Belize	438538	6.8	7.0
Brazil	439214	5.0	5.0
Brazil	593573	6.8	7.0
Bulgaria	466904	5.2	5.4
Bulgaria	495792	7.8	7.8
Canada	302987	7.8	7.8
Chile	439217	5.8	5.8
China	162607	7.4	7.6
China	432799	4.4	4.4
China	432809	5.6	5.4
China	432819	5.2	5.0
China	432829	6.2	6.2
China	432839	5.6	5.6
China	436645	5.0	5.0
China	478358	5.6	5.8
China	555600	4.8	4.8
Colombia	257055	6.6	6.6
Colombia	439218	5.4	5.4
Costa Rica	439219	5.4	5.4
Costa Rica	439229	7.2	8.0
Costa Rica	439239	6.6	6.8
Cuba	267731	5.0	5.0
Eastern Europe	224761	5.0	5.0
El Salvador	281341	5.0	5.0
Ethiopia	194723	6.6	6.6
Ethiopia	197409	5.2	5.2
Ethiopia	439241	6.2	6.2
Fiji	439242	6.4	6.4
Former Soviet Union	263110	8.4	8.4
Former Soviet Union	435945	5.4	5.6
France	195275	6.4	6.4
French Guiana	343929	5.0	5.0
Germany	264662	5.6	5.6
Greece	593479	8.0	8.0
Guatemala	194568	4.8	4.8
Guatemala	200724	5.0	5.0
Guatemala	224451	7.0	7.0
Guatemala	267739	5.2	5.2
Guatemala	439244	6.6	6.6
Guatemala	594134	5.6	5.6
Honduras	487622	6.2	6.6
Hungary	288941	5.8	5.8
Hungary	288951	5.8	5.8
Hungary	288962	7.6	8.0
Hungary	288972	5.8	6.0
Hungary	288982	5.6	6.0
Hungary	297470	7.6	8.0
Hungary	355721	4.8	4.8
Hungary	532983	7.4	7.6
Hungary	593477	6.2	6.2
Hungary	593601	6.2	6.2
India	124078	5.8	5.6
India	163186	6.2	6.4
India	163196	7.4	7.6
India	164287	5.6	5.6
India	164471	8.8	8.8
India	164771	5.4	5.4
India	165588	7.0	7.0
India	174809	5.8	6.4
India	179868	8.0	8.0
India	182925	5.4	5.4
India	183439	5.0	5.0
India	209653	5.0	5.0
India	244668	5.0	5.0
India	271462	5.8	5.8
India	297482	5.8	6.2
India	297493	4.2	4.2
India	322719	6.2	7.0
India	369997	5.6	5.6
India	439247	6.4	6.4
India	593597	5.2	5.2
Indonesia	470244	6.2	6.2
Iran	138566	5.4	5.4
Iran	142829	6.2	6.0
Iran	148628	6.0	6.0
Iran	222975	8.4	8.4
Iran	439250	6.0	6.0
Israel	390974	7.4	7.8
Italy	273415	5.8	6.0
Japan	593604	6.6	6.6
Kazakhstan	562692	7.6	7.6
Kenya	385961	5.8	5.6
Korea, South	508432	6.0	5.8
Korea, South	508440	6.6	5.6
Lebanon	181734	7.0	7.0
Madagascar	246331	7.8	7.8
Malaysia	368076	6.4	6.4
Malaysia	368091	6.8	6.8
Mexico	201224	5.0	5.0
Mexico	201235	6.6	6.6
Mexico	201247	7.2	7.2
Mexico	224410	6.6	6.6
Mexico	267734	7.8	7.8
Mexico	281363	8.2	8.2
Mexico	281379	7.2	7.2
Mexico	281390	6.2	6.2
Mexico	433547	8.6	8.6
Mexico	438620	5.6	5.6
Mexico	438646	7.2	7.2
Mexico	438657	6.4	6.4
Mexico	438667	6.8	6.8
Mexico	439269	5.6	5.6
Mexico	439279	6.4	6.6
Mexico	439289	5.6	5.4
Mexico	439299	7.0	7.0
Mexico	555619	8.0	8.0
Mexico	574547	5.4	5.6
Mexico	593490	7.0	7.0
Mexico	593500	5.0	5.0
Mexico	593510	7.8	7.8
Mexico	593520	9.0	9.0
Mexico	593530	5.6	5.8
Mexico	593540	6.2	6.2
Mexico	593563	7.6	7.6
Mexico	593578	8.2	8.2
Mexico	594116	8.0	7.8
Mexico	594127	5.0	5.0
Mexico	594133	9.0	9.0
Moldova	506437	6.2	6.2
Nepal	286419	5.0	5.0
Netherlands	439324	6.2	6.4
Nicaragua	311126	8.4	8.4
Nigeria	439327	6.4	6.8
Pakistan	593581	6.4	6.6
Panama	406987	5.8	5.8
Peru	241680	5.2	5.2
Peru	439329	7.2	7.2
Peru	593603	6.4	6.2
Philippines	439337	8.2	8.0
Portugal	249908	5.8	5.8
Puerto Rico	302665	5.2	5.2
Romania	439338	6.4	6.4
South Africa	409141	7.2	7.6
Spain	164565	5.6	5.6
Spain	223033	7.6	7.6
Spain	262905	6.8	6.8
Spain	297457	8.6	8.6
Sudan	555649	5.4	5.0
Syria	181934	6.2	6.2
Thailand	547069	7.2	6.4
Trinidad and Tobago	439342	6.8	5.8
Turkey	166998	6.0	6.0
Turkey	167244	6.2	6.2
Turkey	169115	8.8	8.8
Turkey	169126	6.2	6.4
Turkey	169136	5.8	5.6
Turkey	171563	6.8	6.8
Turkey	172773	5.0	5.0
Turkey	173776	7.0	7.0
Turkey	174121	5.0	5.0

Table 1 continues on following page.

incognita; it is highly resistant to *M. incognita* (Fery et al., 1986). 'Charleston Belle' is one of only two bell peppers (*C. annuum*) with resistance to *M. incognita* (Fery et al., 1998). 'California Wonder' is a bell pepper that is susceptible to *M. incognita* (Thies et al., 1997). PA-427 is a Scotch Bonnet-type *C. chinense* cultigen that is resistant to *M. incognita* and PA-350 is a habanero-type *C. chinense* cultigen that is highly susceptible to *M. incognita* (Thies and Fery, 2001). Each plant was rated for severity of root galling and egg mass production 12 weeks after inoculation with *M. hapla*. Means of all accessions were calculated using the PROC MEANS statement of SAS for Windows (SAS Institute, Cary, N.C.). The data from the controls were analyzed using the GLM procedures of SAS for Windows, v. 6.12 and the means were separated using least significant difference (LSD) procedures.

Replicated evaluation of selected accessions. Eleven accessions that exhibited the least amount of root galling [gall index (GI) = 4.0 to 6.0] in response to *M. hapla* (referred to hereafter as "best") and three of the accessions that exhibited the most root galling (GI = 8.0 to 9.0) (referred as to as "worst") were selected from various taxa/origin groups evaluated in the unreplicated test described above. These accessions were evaluated in a 5-replicate greenhouse test, and each plant was rated for severity of root galling and egg mass production eight weeks after inoculation with *M. hapla*. The fibrous roots were clipped from the tap roots of all plants in a plot, cut into 1- to 2-cm pieces, and root fresh weight recorded. *Meloidogyne hapla* eggs were extracted from a 10-g subsample of fibrous roots using 1.0% NaOCl (Hussey and Barker, 1973). Numbers of eggs were counted using a stereomicroscope. Nematode reproduction was assessed by calculating the reproduction factor (R) in

Table 1. Continued.

Species/ origin	Accession (P.I. No.)	Gall index[y]	Egg mass index[y]
Turkey	175617	5.4	5.4
Turkey	176458	5.5	5.5
Turkey	176468	5.0	5.0
Turkey	177294	7.0	7.0
Turkey	179193	6.6	6.6
Turkey	182155	5.4	5.4
Turkey	204565	5.4	5.4
Turkey	205171	5.4	5.4
Turkey	206421	5.2	5.2
Turkey	281432	6.0	5.0
Turkey	338993	7.4	7.4
Turkey	339003	9.0	9.0
Turkey	339013	5.8	5.8
Turkey	339023	5.80	5.80
Turkey	339033	8.33	8.33
Turkey	339043	8.60	8.60
Turkey	339053	8.80	8.80
Turkey	339064	8.60	8.60
Turkey	339074	8.20	8.20
Turkey	339084	8.00	8.00
Turkey	339094	9.00	9.00
Turkey	339104	5.00	5.00
Turkey	339115	8.00	8.20
Turkey	339126	4.00	4.40
Turkey	339137	9.00	9.00
Turkey	344283	5.60	5.60
Turkey	344293	7.80	7.80
Turkey	490994	8.20	8.20
United States	159232	5.40	5.40
United States	159257	7.60	7.40
United States	159271	8.20	8.20
United States	185475	7.80	7.80
United States	273418	5.60	5.40
United States	342948	6.60	6.40
United States	371874	7.80	7.60
United States	439349	8.60	8.60
United States	555597	6.00	5.80
United States	586666	7.40	7.60
United States	592804	6.60	6.60
United States	592814	5.40	5.40
United States	593474	7.80	7.80
United States	593584	6.40	6.40
United States	603810	5.40	5.60
Venezuela	439357	6.60	6.60
Virgin Island	294452	6.60	7.00
Yugoslavia	357413	5.40	5.40
Yugoslavia	357423	3.80	4.00
Yugoslavia	357433	4.60	4.60
Yugoslavia	357443	4.40	4.60
Yugoslavia	357453	5.20	5.20
Yugoslavia	357463	3.00	3.00
Yugoslavia	357473	6.20	6.20
Yugoslavia	357483	6.00	6.00
Yugoslavia	357493	5.33	5.33
Yugoslavia	357503	3.20	3.20
Yugoslavia	357513	4.20	4.20
Yugoslavia	357523	4.40	4.40
Yugoslavia	357533	6.00	6.00
Yugoslavia	357553	8.20	8.60
Yugoslavia	357563	6.60	7.00
Yugoslavia	357573	7.80	8.20
Yugoslavia	357583	4.60	4.60
Yugoslavia	357593	5.80	5.80
Yugoslavia	357603	8.80	8.80
Yugoslavia	357613	3.60	3.60
Yugoslavia	357623	4.20	3.60
Yugoslavia	357633	5.60	5.40
Yugoslavia	357643	5.20	5.20
Yugoslavia	368397	4.80	4.80
Yugoslavia	368407	5.00	5.00
Yugoslavia	368418	7.40	7.40
Yugoslavia	368430	6.40	6.40
Yugoslavia	368440	5.50	5.50
Yugoslavia	368450	5.40	5.20
Yugoslavia	368460	5.20	5.20
Yugoslavia	368470	9.00	9.00
Yugoslavia	368480	9.00	9.00
Yugoslavia	370368	5.00	5.20
Yugoslavia	370378	6.60	6.60
Yugoslavia	370388	4.40	4.40
Yugoslavia	370398	4.60	4.60
Yugoslavia	370408	5.00	5.20
Yugoslavia	379116	6.40	6.60
Yugoslavia	379126	5.00	5.00
Yugoslavia	379136	5.20	5.20
Yugoslavia	379146	7.00	7.00
Yugoslavia	379156	5.40	5.60
Yugoslavia	379166	6.00	6.20
Yugoslavia	379177	7.80	8.20
Yugoslavia	379187	5.80	5.80
Yugoslavia	379198	7.60	7.80
Yugoslavia	379208	7.80	7.80
Yugoslavia	381321	8.20	8.20
C. annuum v. annuum			
United States	427291	7.80	7.80
C. baccatum			
Argentina	439359	8.20	8.20
Bolivia	260434	5.40	5.40
Brazil	497974	5.00	5.00
Bulgaria	439370	7.80	7.80
Chile	439372	4.40	4.40
Colombia	413669	5.60	5.60
Costa Rica	439375	5.60	5.60
Ecuador	585246	5.20	5.20
Ecuador	595905	4.60	4.60
Guatemala	200729	5.20	5.40
Hungary	594136	5.20	5.20
India	370005	6.20	6.20
Jamaica	439378	5.60	5.60
Mexico	439381	4.20	4.20
Paraguay	439382	5.00	5.00
Peru	439391	8.40	8.40
Peru	439401	4.80	4.80
Peru	593605	5.00	5.00
Russian Fed.	594138	5.80	5.80
United States	439407	8.20	8.20
Uruguay	439411	5.00	5.00
Venezuela	439412	6.20	5.80
C. baccatum v. baccatum			
Argentina	337523	5.80	5.80
Bolivia	260569	5.20	5.60
Bolivia	260581	8.40	8.40
Bolivia	281306	6.00	6.00
Bolivia	281308	6.20	5.20
Brazil	260533	9.00	9.00
Brazil	260593	5.80	5.80
Brazil	441521	6.00	6.00
Brazil	441531	5.00	5.20
Brazil	441541	5.00	5.00
Brazil	441551	5.60	5.60
Brazil	441561	7.20	7.20
Brazil	441571	5.20	5.20
Brazil	441581	5.40	5.40
Brazil	441591	5.60	5.60
Brazil	441597	5.00	5.00
Brazil	497985	5.40	5.40
Chile	281321	8.20	8.20
Colombia	257130	5.00	5.00
Costa Rica	224440	5.40	5.40
Ecuador	355814	5.00	6.00
Guatemala	267729	4.00	5.00
Guyana	199506	5.20	5.40
India	370010	5.00	6.00
Kenya	321078	7.00	7.00
Mexico	266042	8.00	8.00
Netherlands	273420	6.60	6.60
Peru	215699	7.20	7.40
Peru	241656	6.20	5.20
Peru	257153	5.00	5.00
Peru	257173	4.60	4.60
Peru	260506	7.00	7.00
Peru	281414	6.67	6.67
Peru	315025	5.60	5.60
Philippines	188803	5.00	5.00
United States	159279	6.40	6.00
United States	342947	6.80	6.80

Table 1 continues on following page.

which $R = P_f/P_i$, where P_i = the initial inoculum level and P_f = final egg recovery (Sasser et al., 1984). Eggs/g fresh root and nematode reproductive index data were $\log_{10}$ (x + 1) transformed before analysis. Data were analyzed using the GLM procedure of SAS for Windows, v. 6.12, and means were separated using Duncan's multiple range test.

Results and Discussion

Unreplicated evaluation of core collection. Only 430 of the 440 *Capsicum* PI accessions were successfully evaluated for reaction to *M. hapla* because seeds of 10 accessions failed to germinate. None of the 430 *Capsicum* spp. accessions exhibited high levels of resistance to *M. hapla* (Table 1). Root gall severity indices ranged from 3.0 to 9.0 and egg mass indices ranged from 3.0 to 9.0 (1.0 to 2.9 = highly resistant, 3.0 to 4.9 = moderately resistant). However, the few accessions with root gall severity and egg mass indices <5.00 had poor fibrous root systems, suggesting that these accessions were not resistant. Eleven of the best (most resistant) accessions and three of the worst (most susceptible) accessions were selected for subsequent re-evaluation in a replicated greenhouse test.

Replicated evaluation of selected accessions. The 11 best accessions exhibited intermediate to susceptible reactions to *M. hapla* and the three worst accessions were susceptible (Table 2). Root gall severity and egg mass indices for the best accessions ranged from 3.96 to 5.80 and 4.00 to 5.80, respectively. Numbers of eggs/g fresh root ranged from 3,080 to 22,061 and reproductive indices ranged from 1.7 to 8.4 for the best accessions. Root gall severity and egg mass indices for the three worst accessions ranged from 6.25 to 8.08 and 6.21 to 8.08, respectively. Numbers of eggs/g fresh root ranged from 20,103 to 48,487 and the reproductive indices ranged from 14.1 to 28.8. The four *C. annuum* checks (PA-136, 'California Wonder', 'Charleston Belle', and 'Carolina Cayenne'), the two *C. chinense* checks (PA-426 and PA-350), and

Table 1. Continued.

Species/ origin	Accession (P.I. No.)	Gall index[y]	Egg mass index[y]
C. cardenasii			
Bolivia	590507	9.00	9.00
C. chacoense			
Argentina	560944	9.00	9.00
United States	555612	9.00	9.00
C. chinense			
Argentina	260465	6.20	6.40
Belize	594139	5.80	5.80
Bolivia	260490	8.00	8.00
Bolivia	543184	7.80	7.80
Brazil	441605	5.40	5.40
Brazil	441606	8.40	8.40
Brazil	441618	5.40	5.40
Brazil	441628	5.60	5.60
Brazil	441641	5.20	5.20
Brazil	497983	6.00	5.60
Colombia	257079	7.60	7.40
Colombia	257105	6.40	6.40
Colombia	257124	8.20	8.20
Colombia	439421	9.00	9.00
Costa Rica	439426	6.20	6.20
Cuba	209590	5.40	5.60
Ecuador	241668	9.00	9.00
Ecuador	281338	8.20	8.20
Ecuador	360725	6.80	6.00
Ecuador	585252	9.00	9.00
Ethiopia	197405	5.60	5.60
Fiji	439431	5.00	5.00
Guatemala	195301	6.40	6.40
Guyana	281315	8.40	8.60
India	322721	7.00	6.20
Jamaica	485593	5.40	5.40
Korea, South	439432	5.20	5.20
Mexico	438629	5.20	5.00
Mexico	438642	5.00	5.00
N. Mariana Islands	281353	5.60	6.20
Peru	224449	5.33	5.33
Peru	257156	9.00	9.00
Peru	260466	6.40	6.40
Peru	260498	8.20	8.40
Peru	260517	8.00	8.00
Peru	260557	8.40	8.40
Peru	315012	6.40	6.40
Peru	315022	5.80	5.80
Peru	439437	9.00	9.00
Peru	439447	6.20	6.20
Peru	439457	5.40	5.40
Peru	439467	8.80	8.80
Philippines	281421	5.00	5.00
Puerto Rico	281424	6.80	7.00
Spain	257284	6.60	7.20
Suriname	446902	8.00	8.40
Trinidad and Tobago	439475	5.80	5.60
United States	439477	5.60	5.60
United States	593612	7.60	7.60
Venezuela	439484	6.60	6.60
Virgin Island	294453	8.40	8.40
C. eximium			
Bolivia	594141	5.40	5.40
C. frutescens			
Afghanistan	255661	6.00	6.20
Brazil	441646	5.00	5.00
Brazil	497984	5.00	5.00
China	419039	7.00	6.80
Colombia	257071	7.00	7.20
Colombia	257121	6.00	6.00
Costa Rica	439499	5.60	5.60
Costa Rica	487623	4.60	4.60
Cuba	439506	5.00	5.00
Ecuador	585255	5.20	5.20
El Salvador	439508	5.20	5.20
Ethiopia	281342	6.00	5.00
Fiji	439509	5.20	5.20
Former Soviet Union	263109	5.40	5.40
Guatemala	594961	5.40	5.40
Guyana	194880	7.00	7.00
India	370009	4.80	4.80
Israel	451762	4.80	4.80
Malaysia	368085	5.20	5.00
Mexico	593615	5.60	5.60
Peru	439516	4.80	4.80
Philippines	446908	5.00	5.00
Portugal	239703	5.40	5.40
Puerto Rico	209109	8.00	7.00
Solomon Islands	439521	5.00	5.00
Suriname	439522	5.60	5.20
Thailand	321387	5.40	5.40
United Kingdom	439523	6.40	6.00
United States	593613	8.00	7.80
Vanuatu	188479	6.00	6.00
Venezuela	439525	8.00	8.00
C. pubescens			
Ecuador	355394	8.60	8.60
Ecuador	585264	7.00	7.00
Ecuador	585274	8.60	8.60
Guatemala	593625	7.00	7.00
Guatemala	593635	9.00	9.00
Guatemala	593644	9.00	9.00
Capsicum sp.			
Argentina	560934	4.80	4.80
Belize	438540	5.60	5.60
Bolivia	387832	5.40	5.60
Bolivia	543186	9.00	9.00
Bolivia	543201	4.60	4.60
Brazil	441666	5.60	5.60
Brazil	441676	4.00	4.00
Brazil	441692	4.60	4.60
Brazil	441703	6.20	6.20
Brazil	441714	6.60	6.60
China	430490	4.20	4.20
Colombia	257112	6.60	6.60
Former Soviet Union	555648	6.00	6.00
Guatemala	555634	4.60	4.60
Guatemala	555645	6.00	6.00
Honduras	487485	7.20	7.40
Indonesia	470245	8.80	8.80
Kenya	385962	4.80	4.80
Mexico	555626	8.25	8.25
Peru	257148	5.60	5.40
Spain	420379	6.20	6.20
Venezuela	487457	8.60	8.60
Controls			
PA-350[x]		4.38[w]	4.48[w]
PA-426[x]		5.81	5.71
California Wonder[v]		6.31	6.26
Charleston Belle[v]		6.53	6.64
Carolina Cayenne[v]		6.89	6.87
Rutgers tomato[u]		8.81	8.88
LSD (0.05)		0.54	0.54

[z]Means of five plants.
[y]Scale of 1 to 9, where 1 = no galling or visible egg masses present, 2 = 1% to 3%, 3 = 4% to 10%, 4 = 11% to 25%, 5 = 26% to 35%, 6 = 36% to 50%, 7 = 51% to 65%, 8 = 66% to 80%, and 9 = 81% to 100% of root system galled or covered with egg masses, respectively.
[x]*Capsicum chinense* cultigens susceptible to *M. hapla*.
[w]Means of 14 replicates planted in a randomized complete-block design within each greenhouse bench (n=70).
[v]*Capsicum annuum* cultivars susceptible to *M. hapla*.
[u]*Lycopersicon esculentum* cultivar susceptible to *M. hapla*.

Table 2. Gall indices, egg mass indices, numbers of *Meloidogyne hapla* eggs per gram fresh root, and reproductive indices of *M. hapla* for 14 selected *Capsicum* sp. plant introduction (PI) accessions and controls inoculated with *M. hapla*, in a replicated greenhouse test.[z]

Pepper entry	Taxon	Origin	Gall index[y]	Egg mass index[y]	Eggs/g fresh root	Reproductive index[x]
Best[w]						
PI 357613	*C. annuum*	Yugoslavia	3.96 a[v]	4.00 a	4765 a–c[u]	2.2 bc[u]
PI 357503	*C. annuum*	Yugoslavia	4.20 ab	4.20 a	6004 a–c	2.7 b
PI 439381	*C. baccatum*	Mexico	4.32 ab	4.24 a	3080 a	1.7 b
PI 297493	*C. annuum*	India	4.52 a–c	4.56 ab	7926 a–d	5.6 de
PI 430490	*Capsicum sp.*	China	4.60 a–c	4.56 ab	10308 a–d	4.0 b–d
PI 267729	*C. baccatum*	Guatemala	4.74 a–c	4.66 ab	3557 ab	2.4 bc
PI 441676	*Capsicum sp.*	Brazil	4.79 a–c	4.79 a–c	7288 a–c	5.8 de
PI 357423	*C. annuum*	Yugoslavia	5.00 a–c	5.04 a–d	22061 c–f	8.4 ef
PI 441641	*C. chinense*	Brazil	5.08 a–d	5.04 a–d	7153 a–d	4.1 c–e
PI 432799	*C. annuum*	China	5.32 b–e	5.24 a–e	11056 b–d	6.4 de
PI 487623	*C. frutescens*	Costa Rica	5.80 a–e	5.80 a–e	8311 a–c	2.9 b–d
Worst[t]						
PI 263110	*C. annuum*	Former Soviet Union	6.25 d–f	6.21 d–f	37660 e–g	28.8 gh
PI 241668	*C. chinense*	Ecuador	8.08 g	7.96 g	20103 d–f	14.1 fg
PI 439407	*C. baccatum*	United States	8.08 g	8.08 g	48487 fg	26.9 gh
Controls[s]						
PA-136	*C. annuum*	United States	6.28 d–f	6.00 c–f	10015 b–d	6.5 d–f
California Wonder	*C. annuum*	United States	6.52 ef	6.40 ef	12908 cd	7.7 d–f
Charleston Belle	*C. annuum*	United States	6.52 ef	6.40 ef	13166 b–d	8.2 d–f
PA-426	*C. chinense*	United States	6.60 f	6.40 ef	13294 cd	3.6 b–e
Carolina Cayenne	*C. annuum*	United States	6.68 f	6.60 f	18234 c–e	8.1 d–f
PA-350	*C. chinense*	United States	6.88 f	6.84 f	8978 a–c	0.7 a
Rutgers	*L. esculentum*	United States	8.76 g	8.92 g	84843 g	41.5 h

[z]Means of 5 replicates of 5 plants each (n = 25).
[y]Root gall severity and egg mass production rated using a scale of 1 to 9, where 1 = 0, 2 = 1% to 3%, 3 = 4% to 12%, 4 = 13% to 25%, 5 = 26% to 38%, 6 = 39% to 50%, 7 = 51% to 65%, 8 = 66% to 80%, and 9 = 81% to 100% of root system galled or covered with egg masses, respectively.
[x]Reproductive index = P_f/P_i, where P_i = initial inoculum level and P_f = final egg recovery.
[w]Best PI = intermediate reaction to *M. hapla* in a preliminary greenhouse screening test of 430 PI.
[v]Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.
[u]Data were $\log_{10}(x + 1)$ transformed before analysis. Untransformed data are shown.
[t]Worst PI = highly susceptible reaction to *M. hapla* in a preliminary greenhouse screening test of 430 PI .
[s]*C. annuum, C. chinense,* and *Lycopersicon esculentum* entries with known reactions to *M. hapla*.

'Rutgers' tomato were all susceptible. Numbers of *M. hapla* eggs/g fresh root and reproductive indices for 'California Wonder', 'Charleston Belle', 'Carolina Cayenne', and PA-426 were similar to results from previous growth chamber and greenhouse tests (Thies and Fery, 2001). However, PA-350 supported much lower nematode reproduction in the present study (8,978 eggs/g fresh root) than in the previous growth chamber (118,422 eggs/g fresh root) and greenhouse tests (51,839 eggs/g fresh root) (Thies and Fery, 2001) because most of the fibrous roots of PA-350 plants in the present test were deteriorated and no longer contained egg masses. We often observe this phenomenon with PA-350 because it is highly susceptible to *M. hapla* and other *Meloidogyne* spp.

Seven of the 11 "best" accessions (PI 357613, PI 357503, PI 439381, PI 297493, PI 430490, PI 267729, and PI 441676) exhibited root gall severity indices <5.0, and each of these indices was significantly lower than the indices of the "worst" accessions and susceptible controls. Although a gall index <5.0 indicates a moderate level of resistance, >3000 eggs were extracted per g of fresh root tissue and the reproductive index was >1.0 for each of these accessions. This suggests that even the most resistant *Capsicum* accessions evaluated in this test are somewhat susceptible to *M. hapla*.

Conclusions

The results of our evaluation of a core of the USDA *Capsicum* germplasm collection clearly demonstrate that there is significant genetic variability in *M. hapla* resistance within the overall collection. However, none of the accessions in this core exhibited even moderately resistant reactions to *M. hapla* when evaluated using both root galling severity and nematode reproduction criteria. It is important that efforts be continued to evaluate additional accessions in the collection for better levels of resistance. The results of the present study can be used to identify portions of the collection where future evaluation emphasis should be focused. For example, the origin of the two most promising *C. annuum* accessions (PI 357613 and PI 357503) in the core was Yugoslavia. Thus, additional accessions from this temperate region of the world should receive priority attention in any effort to identify better sources of resistance in *C. annuum* to *M. hapla*.

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