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Pepper Host Plant Resistance to Tomato Spotted Wilt Virus (Bunyaviridae: Tospovirus) in Georgia and North Carolina

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ABSTRACT

Commercially available lines of pepper were field tested for resistance to tomato spotted wilt (TSW) virus, a Tospovirus (Bunyaviridae), for 5 years (2006 to 2010) at the Coastal Plain Experiment Station at Tifton, GA USA and 2 years (2009 to 2010) in North Carolina. Selected cultivars were transplanted each year into four randomized complete block plots which consisted of black plastic mulch beds with drip irrigation. These tests were conducted in the spring of each year when the incidence of TSW tended to be highest. Also, presence of thrips vectors was monitored using beat cup sampling of foliage and flower samples. Yield was quantified according to USDA pepper grades and the percent TSW symptomatic fruit was assessed. Pepper cultivars with the 'Tsw' resistance gene provided significant levels of control of disease expression whenever TSW occurred at >4% symptomatic plants in the susceptible check. Due to a lack of thrips pressure, differences in resistance to TSW were not observable in any of the cultivars tested. Overall, the top 5 commercial TSW-resistant pepper cultivars for production in decreasing order were 'Declaration', 'Monarch', 'Vanguard', 'Magico', and 'Heritage', but the TSW-susceptible cultivars of 'Patriot', 'Allegiance', 'Aristotle', 'Regiment' and 'Excursion II' yielded as well under the disease pressure experienced from 2006 to 2010.

Additional index words: Capsicum annuum, Thripidae, *Frankliniella fusca*, cultivars.

Thrips-transmitted *Tomato spotted wilt virus* (*Bunyaviridae*: *Tospovirus*) can have serious detrimental economic impact on pepper, *Capsicum annuum* L. in the southeastern U.S. and elsewhere (Gitaitis et al., 1998; Momol et al., 2000; Lima et al., 2000; Persley et al., 2006). Average annual losses due to TSW virus 1996-2006 in tomato and pepper were estimated to total $326 million in Georgia alone. As in other Solanaceous crops, the symptoms of this disease in pepper include reddish-brown ring spots on leaves, interveinal speckling of the leaves that coalesce and give the appearance of areas of necrosis (Gitaitis, 2009). If the infection is early, plants can be severely stunted or show severe wilt. On young pepper fruit, symptoms include necrotic spots or streaks with mosaics or rings, and later on ripened fruits, concentric rings or streaks appear around yellow spots (Adkins et al., 2009).

In the southeastern U.S., western flower thrips, *Frankliniella occidentalis* (Pergande), and tobacco thrips, *Frankliniella fusca* (Hinds) are two main vectors of TSW virus (Riley and Pappu, 2000; 2004). Normally, immature thrips feed on TSW virus infected -weed plants surrounding vegetable fields, acquire TSW virus infection then migrate to a pepper field when planted (Groves et al., 2001; 2002). Studies showed that thrips population dynamic and dispersal has been determined by fluctuating temperature and precipitation patterns (Morsello et al., 2010; Stumpf and Kennedy, 2007). As thrips mature, the acquired virus replicates within the thrips and is readily transmitted, making control measures more difficult (Ullman et al., 1997). This unique epidemiology and wide host ranges of both thrips and TSW virus makes TSW virus disease control difficult (Edwardson and Christie, 1986; Yudin et al., 1986), indicating a need for preventative management such as host-plant resistance (Maris et al., 2003; Beaudoin et al., 2009). Development of TSW-resistant pepper is likely to provide the most stable solution to this disease (Genda et al., 2008). Black et al. (1991) identified a TSW-resistant gene from various accessions of *Capsicum* species that functioned through a hypersensitive response. Subsequently, a TSW-resistant gene, Tsw was identified (Boiteux and de Avila, 1994; Boiteux et al., 1993; Boiteux 1995; Costa et al., 1995; Moury et al., 1997) that has since been introgressed into commercial lines to create TSW-resistant pepper cultivars (Black et al., 1996; Roggero et al., 2002; Persley et al., 2006).

There have been several reports of resistance breaking TSW virus isolates world-wide (Boiteux and Nagata, 1992; Roggero et al., 2002; Margaria et al., 2004; Sharman and Persley, 2006), including Louisiana in the U.S. (Hobbs et al., 1994). Most resistant cultivars of *Capsicum annuum* L. that are available for commercial pepper production have the Tsw gene (Roggero et al., 2002; Persley et al., 2006). Variation in the TSW virus isolate and plant phenotypes may affect the yield and quality of resistant pepper cultivars with Tsw gene (Sharman and Persley, 2006). In addition, temperature, plant age and gene dosage may influence hypersensitive response of the Tsw gene (Roggero et al., 1996; Moury et al., 1998; Soler et al., 1998). Moreover, in the southeastern U.S., information related to marketable pepper yield among TSW-resistant cultivars under varying TSW field incidence is still lacking. Therefore, the present study assessed the relative yields among TSW-resistant and susceptible pepper cultivars under natural incidence of TSW over five years. We also evaluated pepper cultivars for their ability to influence thrips populations under field conditions.

MATERIALS AND METHODS

Plant materials, field design and management. The field studies were conducted each spring in 2006, 2007, 2008, 2009, and 2010 at the Coastal Plain Expt. Sta., Tifton, GA to simultaneously evaluate different TSW-resistant pepper cultivars unprotected from thrips vectors (Table 1). A randomized complete block design with four replicates was used each year except in 2006 and 2008 where there were three replications. The pepper production system used was raised, black plastic covered beds fumigated with methyl bromide (277 kg a.i./ha, Albemarle Corp., Magnolia, AK). A 0.3 m between row spacing on the bed was used and there were two 8 m length rows per plot. Peppers were transplanted on 23 March, 18 April, 9 April, 21 April, and 6 April for 2006, 2007, 2008, 2009, and 2010, respectively. A minimum of 560 kg/ha of 10-10-10 was applied to Tift pebbly clay loam field plots each year and liquid fertilizer, 8 kg/ha (7-0-7), was applied every two weeks using drip irrigation. In these tests, peppers were treated weekly in April and May with a fungicide (Ridomil Gold-Bravo® WP 2.2 kg product/ha, Syngenta, Greensboro, NC) and *Bacillus thuringiensis* (DiPel® 2.2 kg product/ha, Valent U.S.A. Corporation, Walnut Creek, CA) to prevent disease and reduce Lepidoptera damage without affecting thrips populations. Paraquat (Gramoxone Inteon® 2SL 2.3 l/ha, Syngenta, Greensboro, NC) was applied to the edges of plastic mulch for weed control.

A similar method was followed in the North Carolina studies conducted at the Horticultural Crops Research Station in Mills River, NC. The row-to-row and plant-to-plant spacing was 0.3 m and 0.46 m, respectively. Row length was 8 m in each year of this study. Seedlings were transplanted on 15 May 2009 and 26 May 2010. Six weeks prior to planting, black plastic covered beds were fumigated with PicChlor® 60 (Soil chemicals corporation, Hollister, CA). Fertility and disease management followed conventional recommendations for pepper production as outlined in the Southeast U.S. Vegetable Crop Handbook (Kemble, et al., 2010).

Disease ratings and Enzyme-linked immunosorbent assay. Pepper plants were monitored for TSW symptoms on foliage and fruits (Gitaitis 2009). In Georgia, disease ratings were done on: 22 May in 2006; 4, 11, 18 and 29 May; 7, and 12 June in 2007; 6, 14, 20 and 28 May; and 4, 10, and 18 June in 2008; 28 April; 4, 11, 19, 29 May; and 4, and 10 June in 2009; and 14, 23, and 27 April, and 5, 11, and 25 May in 2010. The disease rating was not reported for North Carolina due to the low incidence of TSW. The number of plants with foliar TSW disease symptoms per plot was recorded throughout the season and percent TSW incidence was calculated.

Thrips samples and evaluation. In Georgia for all five years, the total number of thrips by species was determined using a sample beat cup, direct counting following manual shaking into a Styrofoam cup, (Joost and Riley, 2004) and blossom samples. Beat cup samples were collected on: 2 May in 2006; 3 and 18 May 2007; and 29 April, and 7, 15, 22 May in 2009, while blossom samples were collected on: 5 June in 2008; and 29 May in 2009. In NC, blossom samples were collected by removing 10 flowers per plot and placing them in vials containing 50% ethanol. Samples were returned to the laboratory where thrips were removed from the flowers and examined under a stereomicroscope to determine the number of the thrips and the

Table 1. Pepper cultivars, their seed source, resistance designation, TSW-resistance confirmation and average plot yield for the years evaluated from 2006 to 2010.

Cultivar[z]	Plant source	TSW-resistant gene[y]	TSW-resistant expression[x]	Marketable fruit yield (Kg)
Magico	Harris Moran	+	****(7)	13.9 ± 2.3
Heritage	Harris Moran	+	**(7)	12.5 ± 2.1
Plato	Seminis	+	****(7)	11.7 ± 2.0
Stiletto	Syngenta	+	****(7)	10.2 ± 1.9
Declaration	Harris Moran	+	**(4)	17.6 ± 3.2
Monarch	Hazera	+	*(2)	16.7 ± 4.7
Vanguard	Johnny's Selected Seeds	+	(2)	15.4 ± 4.9
Sargon	Hazera	+	(1)	8.7 ± 0.9
HMX 7633	Harris Moran	+	*(1)	6.8 ± 0.4
Aristotle	Seminis	–	*(7)	13.5 ± 2.4
Excursion II	Abbott & Cobb	–	(5)	11.2 ± 2.0
Revolution	Harris Moran	–	(5)	11.1 ± 2.4
PS 5776	Seminis	–	(4)	13.5 ± 3.5
Allegiance	Harris Moran	–	(3)	13.8 ± 2.9
Patriot	Harris Moran	–	(2)	15.3 ± 5.1
HM 2641	Harris Moran	–	*(2)	14.8 ± 5.4
HM 8302	Harris Moran	–	*(2)	13.7 ± 4.7
Regiment	Harris Moran	–	(2)	11.9 ± 3.9
El Jafe	Harris Moran	–	(2)	8.4 ± 1.1
Excel	Sakata	–	(1)	7.1 ± 0.2
Bandido	Harris Moran	–	(1)	2.4 ± 0.6

[z] Cultivars ranked (from highest to lowest) based on the marketable fruit yield (Kg) within number of years they were tested.

[y] = Tsw absent.

[x] Number of year(s) when significant TSW-resistance was detected ('*') on a selected cultivar compared with susceptible-cultivars per total years evaluated (in parenthesis). Cultivars are arranged from highest to lowest yield with the group with the resistance gene and without.

species composition. Collection dates for each year in NC were 16 June and 23 June in 2009 and 30 June and 13 July in 2010. Adult thrips in the blossom samples were identified using identification keys (Oetting et al., 1993, Stannard, 1968) under 70-140X magnification using a SZH10 Olympus® (Olympus America, Lake Success, NY) stereomicroscope. Only *F. occidentalis* and *F. fusca* were individually counted and all other thrips, including *F. tritici*, *F. bispinosa*, and others were placed into an "other" category. Key characters were used to verify species including the anteromarginal and anteroangular setae, postocular setae, the pedicel of the third antennal segment, comb on abdominal tergite VIII, and other features (Stannard, 1968).

Yield assessment. In Georgia, yield was assessed on: 1, 12 and 19 June in 2006; 12 and 18 June in 2007; 3, 10 and 19 June in 2008; 17, 29 June and 13 July in 2009; and 11 June in 2010. In North Carolina, yield was assessed on 16 July, 28 July, and 4 August 2009; and 2 and 23 August 2010. Fruit were harvested from the all plants in a subplot and quantified into various damage categories and marketable categories by size at the time of harvest using USDA standards for fresh market pepper (USDA, 2007). Thrips damage to the fruit called 'flecking' on the fruit surface (Funderburk et al., 2009), physiological fruit damage (i.e. misshaped), and blossom end rot resulted in fruit being counted as unmarketable. For marketable yield, the approximate value of the crop was estimated per acre using $7.50, $8.80, $8.10, and $8.80 (for 2006, 2007, 2008, and 2009, respectively) in GA, and $7.90 (for 2009) in NC per 11.3 kg carton of marketable fruit (USDA National Agricultural Statistical Service), and a pepper plant population of 14,520 plants per 0.4 ha. Analysis of variance was conducted using PROC GLM (SAS Institute, 2003). There was a significant year effect and year by cultivar interaction, therefore each year is reported separately. The separation of means at the cultivar level was performed using Fisher's LSD tests.

RESULTS AND DISCUSSION

In 2006, TSW disease pressure was relatively high (8-21%) and the TSW-symptoms were greater on susceptible cultivars such as 'Revolution', 'Excursion II', and 'Aristotle' than on those cultivars marketed as TSW resistant (Table 2). However, there was no yield benefit obtained with resistant rather the susceptible cultivar. Furthermore, there were no significant differences in the marketable pepper-fruit yield among cultivars. The lowest unmarketable fruit weight was observed for 'Heritage' and 'Aristotle' cultivars and was greatest for 'Excursion II'. Tomato spotted wilt damaged pepper fruits were significantly greater ($F_{6, 12} = 13.9$; $P < 0.001$) for 'Excursion II' in 2006 than for all other cultivars (Fig. 1a). Total thrips densities found in the beat cup samples were not significantly different among pepper cultivars (data not shown).

TSW-symptoms expressed in 2007 season ranged from 2 to 5% in susceptible cultivars, while resistant cultivars were less than 2% (Table 3). Greater TSW-symptoms were observed on 'Revolution', 'Aristotle', breeding line 'PS 9915776', 'El Jafe' and 'Excursion II' than most of the other cultivars tested. The TSW-symptom was apparent on a susceptible cultivar, 'El Jafe' sooner than all other cultivars and more plants were affected by 18 May 2007, when compared with all other cultivars (Fig. 2). In the following weeks, TSW-symptoms were observed in susceptible entries; and as of 12 June, TSW-symptoms were numerically highest on 'Excursion II', having significantly more prevalence of symptoms than the other cultivars. However, TSW-symptom expression did not translate into reduced marketable fruit yield for susceptible cultivars, 'Revolution', 'El Jafe', and 'Aristotle' (Table 3). The commonly planted resistant cultivar 'Heritage' had significantly less disease symptoms and produced significantly higher marketable fruits than the susceptible pepper, 'Bandido'. Unmarketable fruit yield was significantly greater for 'Revolution' than other cultivars studied in the 2007 season. Similarly, 'Revolution' had significantly more TSW-damaged fruits ($F_{9, 27} = 4.5$; $P = 0.001$) than other cultivars (Fig. 1b).

In 2008, although the impact of TSW disease was not different among cultivars, marketable fruit yield was generally higher for 'Excursion II', 'El Jafe', 'Heritage', and 'Magico' than other cultivars (Table 4). Symptoms expressed on the breeding line 'PS 5776' were greatest on 18 June (Fig. 3). The number of fruits was more abundant for 'Magico' and 'Excursion II' compared with other cultivars (Table 4). The weight and number of unmarketable fruits were significantly more for 'Stiletto' than for any other cultivars tested that season. The number of thrips captured in beat-cup samples was not significantly different among cultivars.

In 2009, TSW-symptoms were the most severe for 'Excursion II' and 'Aristotle' in Georgia (Table 5). Disease progression curves showed that TSW-symptoms were significantly greater in the susceptible cultivars, especially 'Excursion II' and 'Aristotle' by 10 and 18 June (Fig. 4). Highest marketable yield was observed on resistant cultivar, 'Magico' whereas 'Stiletto' had the lowest (Table 5). Weight and number of unmarketable fruits were significantly lower for 'Magico' than for other cultivars. No significant difference was observed in thrips density when the

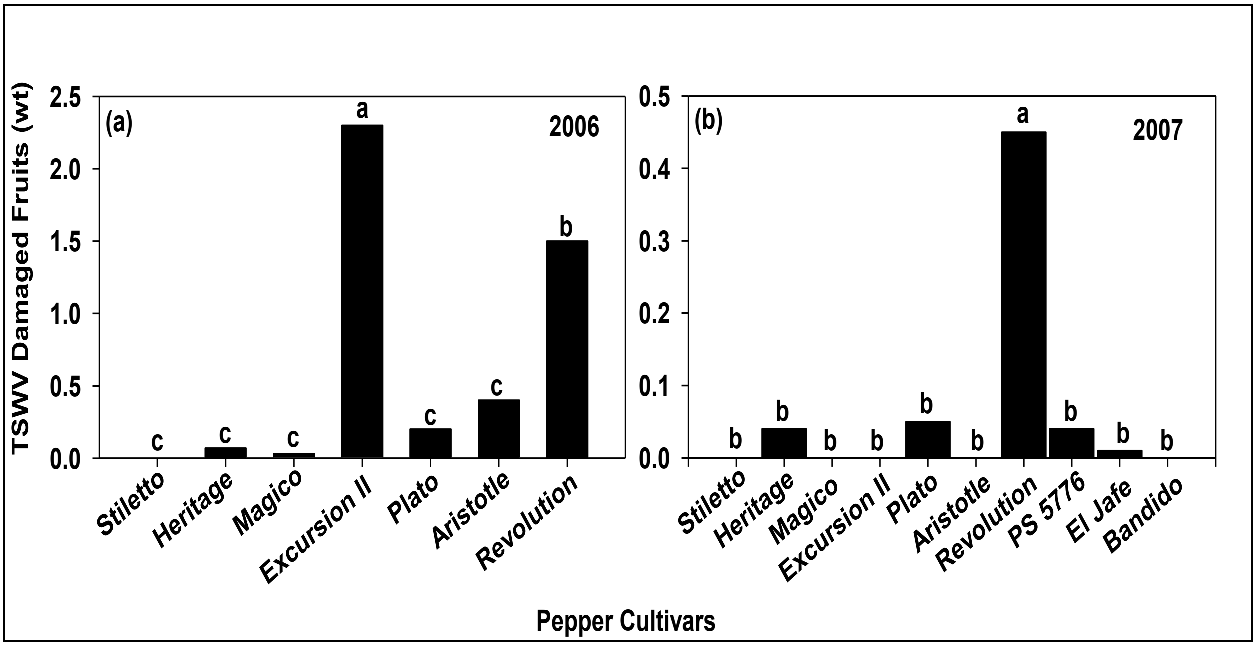

Fig. 1. TSW-damaged fruits by weight among the cultivars in Georgia in (a) 2006 and (b) 2007. Means followed by the same letter are not significantly different (LSD Test, $P < 0.05$).

Table 2. Marketable and unmarketable fruit yield per 9 m plot among pepper cultivars in Georgia in 2006.

Cultivar[z]	Marketable fruit yield			Unmarketable fruit yield		TSW[x]	Incidence[w]
	Wt (kg)	No. fruits	Price value ($)[y]	Wt (kg)	No. fruits	symptoms (%)	of thrips
Aristotle (S[v])	15.3 a	117.0 a	10.0	5.5 c	69.7 a	7.8 b	21.3 a
Magico (R)	13.4 a	127.3 a	8.8	9.9 ab	97.7 a	0.0 c	18.0 a
Heritage (R)	13.4 a	122.0 a	8.8	4.7 c	50.0 a	0.0 c	19.3 a
Revolution (R)	12.3 a	103.6 a	8.1	8.9 ab	100.7 a	21.0 a	14.3 a
Plato (R)	12.3 a	113.3 a	8.1	7.3 bc	67.3 a	0.0 c	15.0 a
Stiletto (R)	11.1 a	138.6 a	7.3	9.5 ab	88.7 a	0.0 c	25.0 c
Excursion (S)	10.3 a	110.0 a	6.7	11.3 a	101.7 a	13.3 b	25.0 a
$F_{(df1,\ df2)}$	$0.4_{(6,12)}$	$0.2_{(6,12)}$	-	$6.5_{(6,12)}$	$2.8_{(6,12)}$	$17.5_{(6,12)}$	$0.7_{(6,12)}$
P	NS	NS	-	**	NS	***	NS

The marketable and unmarketable yield data represent samples collected on 1, 12 and 19 June 2006.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.66/kg in Georgia (2006).
[x]Mean % TSW symptoms recorded per plant as per rating done on 22 May 2006.
[w]As per beat cup samples collected on 2 May.
[v]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.
NS, *, **, *** represent nonsignificant at $P < 0.05$ or $P \leq 0.05$, 0.01, and 0.001, respectively. Means followed by the same letter within the column (cultivars) are not significantly different (LSD Test, $P < 0.05$).

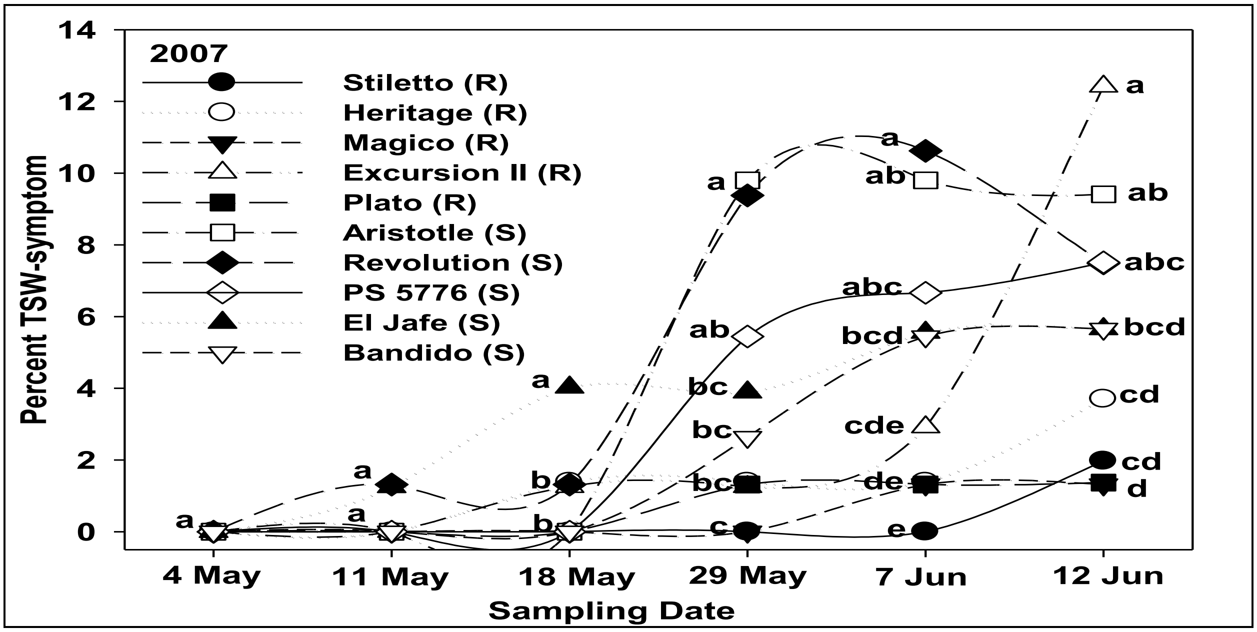

Fig. 2. Incidence of TSW-symptoms in Georgia in 2007. Means followed by same letter within a sample date are not significantly different (LSD test; P<0.05).

Table 3. Marketable and unmarketable fruit yield per 9 m plot among pepper cultivars in Georgia in 2007.

	Marketable fruit yield			Unmarketable fruit yield		TSW[x]	Incidence[w]
Cultivar[z]	Wt (kg)	No. fruits	Price value ($)[y]	Wt (kg)	No. fruits	symptoms (%)	of thrips
Revolution (S[v])	8.3 a	58.25 c	6.4	2.1 a	19.3 a	5.0 a	21.8 a
Heritage (R)	6.7 ab	46.50 c	5.2	0.3 b	3.5 b	1.3 bc	19.0 a
El Jafe (S)	6.3 ab	309.00 a	4.9	0.1 b	1.0 b	3.4 ab	24.0 a
Aristotle (S)	6.1 ab	45.50 c	4.7	0.3 b	2.0 b	4.8 a	16.8 a
PS 5776 (S)	5.9 b	43.75 c	4.6	0.2 b	1.5 b	3.3 ab	24.0 a
Magico (R)	5.1 b	36.50 c	3.9	0.5 b	2.3 b	0.4 c	15.5 a
Plato (R)	5.1 bc	36.25 c	3.9	0.3 b	2.3 b	0.7 c	19.0 a
Excursion II (S)	5.0 bc	40.50 c	3.9	0.1 b	1.0 b	2.9 ab	19.0 a
Stiletto (R)	2.9 cd	28.00 c	2.2	0.1 b	1.5 b	0.3 c	21.5 a
Bandido (S)	2.4 d	204.25 b	1.8	0.0 b	0.0 b	2.3 bc	21.5 a
$F_{(df1,df2)}$	$4.7_{(9,27)}$	$23.7_{(9,27)}$	-	$5.3_{(9,27)}$	$3.8_{(9,27)}$	$4.9_{(9,27)}$	$0.8_{(9,27)}$
P	**	***	-	***	**	***	NS

The marketable and unmarketable yield data represent samples collected on 12 and 18 June 2007.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.78/kg in Georgia (2007).
[x]Mean % TSW symptoms recorded per plant as per rating done on 4, 11, 18 and 29 May, 7, and 12 June 2007.
[w]As per beat cup samples collected on 3 and 18 May 2007.
[v]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.
NS, *, **, *** represent nonsignificant at P < 0.05 or P ≤ 0.05, 0.01, and 0.001, respectively. Means followed by the same letter within the column (cultivars) are not significantly different (LSD Test, P < 0.05).

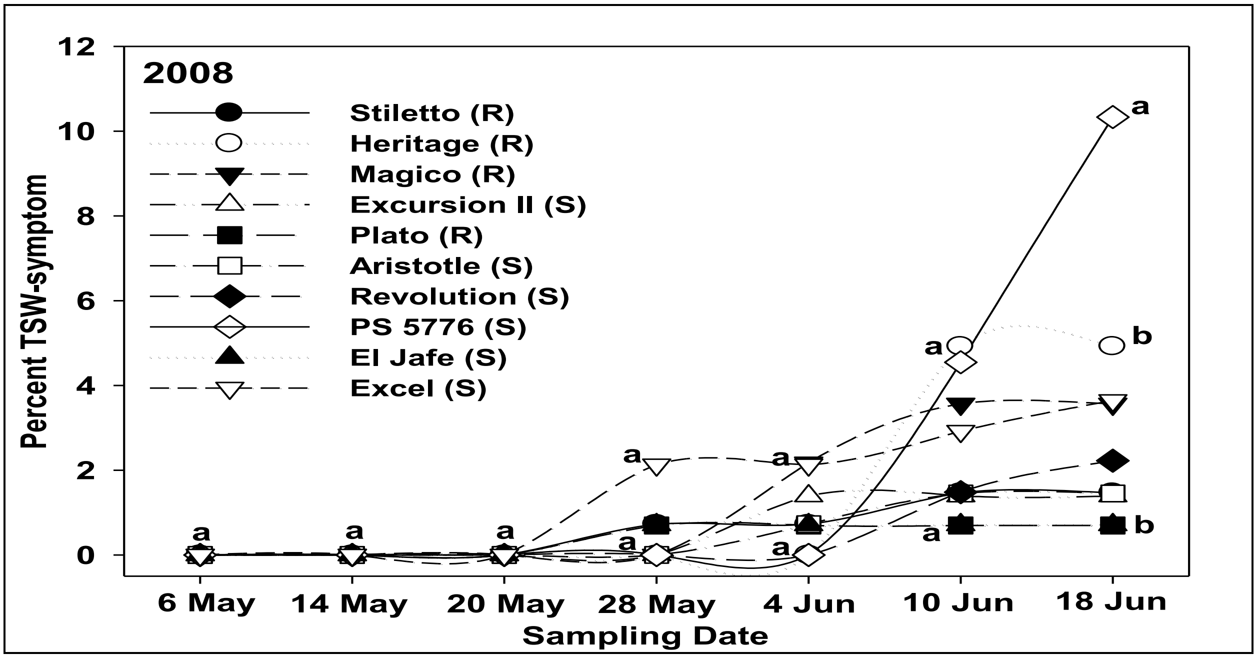

Fig. 3. Incidence of TSW-symptoms in Georgia in 2008. Means followed by the same letter within a sample date are not significantly different (LSD Test, $P < 0.05$).

Table 4. Marketable and unmarketable fruit yield per 9 m plot among pepper cultivars in Georgia in 2008.

	Marketable fruit yield			Unmarketable fruit yield		TSW[x]	Incidence[w]
Cultivar[z]	Wt (kg)	No. fruits	Price value ($)[y]	Wt (kg)	No. fruits	symptoms (%)	of thrips
Excursion II(S[v])	35.5 a	306.0 ab	25.5	2.0 e	25.0 e	0.6 a	3.3 a
El Jafe (S)	33.8 ab	262.0 bc	24.3	3.1 de	28.3 de	0.4 a	3.3 a
Heritage (R)	32.1 a-c	236.3 c-e	23.1	4.9 cd	52.0 b-d	1.4 a	2.6 a
Magico (R)	31.2 a-d	308.7 a	22.4	2.9 de	34.7 c-e	1.3 a	2.3 a
Revolution (S)	29.5 b-e	258.0 cd	21.2	3.3 de	37.3 c-e	0.5 a	4.3 a
PS 5776 (S)	28.1 c-e	239.7 c-e	20.2	7.6 ab	72.7 b	2.1 a	3.6 a
Aristotle (S)	27.7 c-e	216.0 de	19.9	2.9 de	30.7 de	0.5 a	3.3 a
Plato (R)	26.7 de	236.0 c-e	19.2	6.1 bc	68.3 b	0.4 a	3.3 a
Stiletto (R)	25.5 ef	232.0 c-e	18.3	8.8 a	112.3 a	0.6 a	6.0 a
Excel (S)	21.3 f	205.7 e	15.3	4.8 cd	58.0 bc	1.5 a	5.6 a
$F_{(df1,df2)}$	$5.5_{(9,18)}$	$5.1_{(9,18)}$	-	$8.9_{(9,18)}$	$9.2_{(9,18)}$	$1.4_{(9,18)}$	$1.1_{(9,18)}$
P	**	**	-	***	***	NS	NS

The marketable and unmarketable yield data represent samples collected on 3, 10 and 19 June 2008.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.72/kg in Georgia (2008).
[x]Mean % TSW symptoms recorded per plant as per rating done on 6, 14, 20 and 28 May, and 4, 10, and 18 June 2008.
[w]As per blossom samples collected on 5 June 2008.
[v]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.

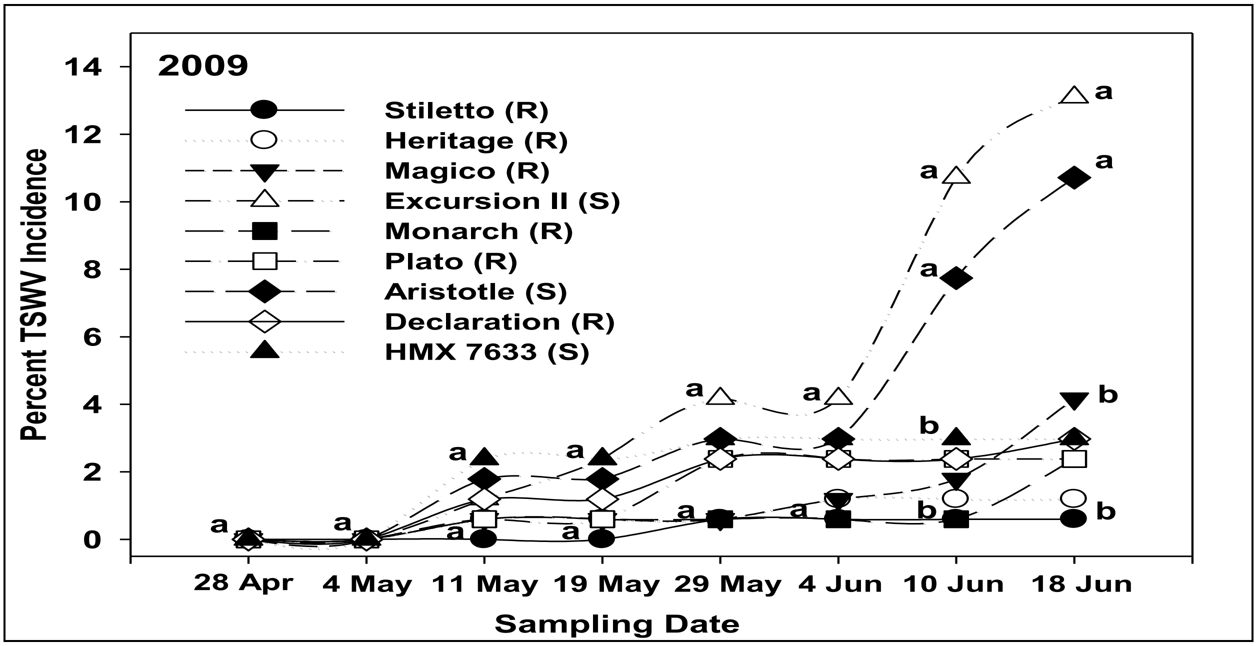

Fig. 4. Incidence of TSW-symptoms in Georgia in 2009. Means followed by the same letter within a sample date are not significantly different (LSD Test, P < 0.05).

Table 5. Marketable and unmarketable fruit yield per 9 m plot among pepper cultivars in Georgia in 2009.

Cultivar[z]	Marketable fruit yield Wt (kg)	Marketable fruit yield No. fruits	Marketable fruit yield Price value ($)[y]	Unmarketable fruit yield Wt (kg)	Unmarketable fruit yield No. fruits	TSW[x] symptoms (%)	Incidence[w] of thrips
Magico (R[v])	29.3 a	193.8 a	22.8	3.8 c	30.8 c	1.1 b	12.5 a
Declaration (R)	26.4 ab	147.6 bc	20.5	6.5 a	47.5 a-c	1.6 bc	10.0 a
Excursion II (S)	23.9 ab	154.2 b	18.6	3.9 bc	32.3 bc	4.5 a	10.3 a
Heritage(R)	21.7 a-c	146.5 bc	16.9	6.3 a	52.3 a	0.7 c	11.5 a
Aristotle (S)	21.2 bc	125.5 b-d	16.5	7.3 a	57.8 a	3.5 a	10.0 a
HMX 7633 (R)	20.5 bc	138.0 bc	15.9	6.6 a	55.8 a	2.1 b	12.3 a
Plato (R)	20.4 c	118.8 c-e	15.9	6.3 a	51.0 ab	1.3 bc	5.5 a
Monarch (R)	13.8 c	93.3 de	10.7	6.7 a	59.5 a	0.5 c	7.8 a
Stiletto (R)	9.9 d	88.5 e	7.7	5.9 ab	64.0 a	0.3 c	11.8 a
$F_{(df1,df2)}$	$9.5_{(8,24)}$	$7.4_{(8,24)}$	-	$3.2_{(8,24)}$	$3.2_{(8,24)}$	$7.9_{(8,276)}$	$0.8_{(8,24)}$
P	***	***	-	*	*	***	NS

The marketable and unmarketable yield data represent samples collected on 17, 29 June and 13 July 2009.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.78/kg in Georgia (2009).
[x]Mean % TSW symptoms recorded per plant as per rating done on 28 April; 4, 11, 19 and 29 May; and 4, and 10 June 2009.
[w]As per beat cup samples collected on 29 April, and 7, 15, 22 May, while blossom samples collected on 29 May in 2009.
[v]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.

Table 6. Marketable fruit yield per 3.7 m plot among pepper cultivars in North Carolina in 2009.

Cultivar[z]	Marketable fruit yield			Unmarketable fruit yield		Incidence
	Wt (kg)	No. fruits	Price value ($)[y]	Wt (kg)	No. fruits	of thrips
Aristotle (S[w])	30.4 a	190.5 ab	21.2	2.3 a	14.5 a	6.3 a
Excursion II (S)	30.1 ab	201.3 a	21.1	1.2 a	11.8 a	5.8 a
Monarch (R)	29.9 ab	180.3 ab	20.9	1.2 a	7.3 a	4.5 a
Allegiance (S)	29.4 ab	181.8 ab	20.5	1.3 a	10.5 a	3.8 a
Sargon (R)	28.9 ab	169.5 b	20.2	1.2 a	11.3 a	6.2 a
Declaration (R)	27.7 ab	188.0 ab	19.4	1.0 a	7.8 a	4.5 a
Plato (R)	27.4 ab	170.5 b	19.1	1.3 a	10.3 a	5.3 a
Magico (RV)	26.7 ab	195.0 ab	18.6	1.1 a	7.8 a	7.5 a
Heritage(R)	25.8 b	172.0 ab	18.0	0.7 a	7.5 a	6.0 a
Stiletto (R)	19.3 c	114.3 c	13.5	1.9 a	14.8 a	4.0 a
L.S.D.[v] $_{(\acute{\alpha}=0.05)}$	4.4	30.5	-	-	-	-
P	*	*	-	NS	NS	NS

The marketable and unmarketable yield data represent samples collected on 16 July, 28 July, and 4 August 2009.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.70/kg in North Carolina (2009).
[v]Least Significant Difference based on Fisher's Test.
[w]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.

beat-cup and blossom samples were combined (Table 5).

Incidence of TSW-symptoms was very low in North Carolina for the 2009 season (Table 6). Most cultivars evaluated had similar yields; only Stiletto was lower yielding. There was no significant difference among cultivars for unmarketable fruits by weight or number. Similarly, thrips densities collected were not different among cultivars.

In 2010, TSW pressure on pepper cultivars was lowest (~1%) compared with previous years in Georgia (Table 7). There were no differences in TSW-disease symptom time of incidence among cultivars (data not shown). Number of marketable fruits, and weight and number of unmarketable fruits were similar among cultivars (Table 7).

In North Carolina, TSW occurrence was extremely low in 2010 (<0.5%) (Table 8). Number and weight of marketable fruits were very similar among cultivars (Table 8). Unmarketable fruit weight or number did not differ significantly among cultivars. Number of thrips sampled was similarly dense among cultivars.

In this study, severity of TSW disease pressure varied through years and between states. Based on TSW-symptom expression on susceptible cultivars there was a moderately high TSW incidence in the most susceptible cultivars of 21% and 5% in 2006 and 2007, respectively. Overall, the top 5 commercial TSW-resistant pepper cultivars for production based on decreasing numerical order were 'Declaration', 'Monarch', 'Vanguard', 'Magico', and 'Heritage', but the TSW-susceptible cultivars of 'Patriot', 'Allegiance', 'Aristotle', 'Regiment' and 'Excursion II' yielded as well under the disease pressure experienced from 2006 to 2010. Resistance does reduce the risk of yield loss. For example, 'Magico' ranked within the top 5 cultivars based on higher marketable-fruit yield during the five years including those years when TSW incidence was greater. Although 'Plato' and 'Stiletto' resisted TSW disease expression, their marketable yields were relatively low. Previous studies on resistant-cultivars showed that 'Stiletto' had severe TSW symptoms in the foliage when exposed to both mild (GATb-1) and severe (GAL) TSW virus isolates in Georgia (Mandal et al. 2006), so resistance is not necessarily permanent. However, since the severity of TSW in pepper over the course of this study was relatively low, selection pressure for a resistance breaking strain should also be low.

Based on these studies, the horticultural characteristics of the commercial pepper cultivars appeared to be as important as resistance to TSW relative to yield

Table 7. Marketable and unmarketable fruit yield per 9 m plot among pepper cultivars in Georgia in 2010.

Cultivar[z]	Marketable fruit yield Wt (kg)	Marketable fruit yield No. fruits	Marketable fruit yield Price value ($)[y]	Unmarketable fruit yield Wt (kg)	Unmarketable fruit yield No. fruits	Incidence of thrips
Magico (R[w])	3.2 a	26.5 a	2.3	0.8 a	33.5 a	0.0 c
PS 5776 (S)	2.8 ab	24.3 a	2.0	0.5 a	26.3 a	0.1 bc
Aristotle (S)	2.7 a-c	23.0 a	1.9	0.6 a	37.5 a	0.0 c
Vanguard (S)	2.6 a-c	21.5 a	1.8	0.6 a	34.0 a	0.5 bc
Declaration (R)	2.5 a-d	19.0 a	1.8	0.7 a	30.8 a	0.0 c
Heritage (R)	2.4 a-d	19.3 a	1.7	0.6 a	35.7 a	0.6 ab
Patriot (S)	2.3 a-d	20.8 a	1.6	0.3 a	27.3 a	0.1 bc
Plato (R)	2.1 a-d	16.8 a	1.5	0.6 a	23.0 a	0.0 c
Revolution (S)	2.1 a-d	17.5 a	1.5	0.4 a	27.2 a	0.3 bc
Stiletto (R)	1.9 a-e	19.3 a	1.3	0.7 a	25.3 a	0.0 c
Regiment (S)	1.8 b-e	17.3 a	1.2	0.4 a	26.5 a	1.1 a
8302 (S)	1.4 c-e	12.5 a	1.0	0.9 a	35.5 a	0.0 c
HM 2611 (S)	1.2 de	11.5 a	0.8	0.3 a	14.5 a	0.0 c
Allegiance (S)	0.7 e	5.3 a	0.5	0.5 a	23.3 a	0.3 bc
$F_{(df1,df2)}$	$2.0_{(13,39)}$	$1.8_{(13,39)}$	-	$0.6_{(13,39)}$	$1.6_{(13,39)}$	$2.7_{(13,39)}$
P	*	NS	-	NS	NS	**

The marketable and unmarketable yield data represent samples collected on 11 June 2010.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.78/kg in Georgia (2010).
[w]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.

Table 8. Marketable fruit yield per 3.7 m plot among pepper cultivars in North Carolina in 2010.

Cultivar[z]	Marketable fruit yield Wt (kg)	Marketable fruit yield No. fruits	Marketable fruit yield Price value ($)[y]	Unmarketable fruit yield Wt (kg)	Unmarketable fruit yield No. fruits	Incidence of thrips
Declaration (R[w])	34.9 a-c	144.0 a-c	24.4	0.0 a	0.0 a	4.3 a
Patriot (S)	32.5 a-c	121.3 c-e	22.7	0.2 a	3.0 a	3.5 a
Aristotle (S)	30.9 a-c	108.5 e	21.6	0.1 a	1.0 a	2.8 a
Plato (R)	29.2 a-d	132.0 b-e	20.4	0.1 a	1.0 a	4.3 a
Vanguard (S)	29.0 b-d	160.3 a	20.3	0.1 a	1.0 a	2.3 a
Allegiance (S)	28.4 b-d	134.3 b-d	19.8	0.4 a	4.0 a	5.0 a
HM 2611 (S)	28.3 b-d	162.5 a	19.8	0.1 a	2.5 a	1.8 a
HM 8302 (S)	28.2 b-e	144.0 a-c	19.7	0. 2a	3.5 a	2.8 a
Stiletto (R)	25.9 b-f	145.5 a-c	18.1	0.2 a	4.5 a	2.8 a
PS 5776 (S)	25.9 c-f	109.5 de	18.1	0.0 a	0.8 a	2.3 a
Heritage (R)	24.7 d-f	146.0 a-c	17.2	0.1 a	2.5 a	3.5 a
Magico (R)	22.5 ef	131.8 b-e	15.7	0.1 a	3.0 a	1.0 a
Regiment (S)	22.0 f	115.5 de	15.4	0.1 a	3.3 a	3.5 a
Revolution (S)	21.3 f	150.8 a-c	14.9	0.0 a	0.3 a	2.8 a
L.S.D.(α=0.05)[v]	5.7	25.3	-	-	-	-
P	*	*	-	NS	NS	NS

The marketable and unmarketable yield data represent samples collected on 2 August and 23 August 2010.
[z]Cultivars sorted upon marketable fruit wt (from heaviest to lightest).
[y]Price value set by USDA National Agricultural Statistical Service as $0.70/kg in North Carolina (2009).
[v]Least Significant Difference based on Fisher's Test.
[w]Previously classified resistant or susceptible cultivars, R = Resistant; S = Susceptible.

in the southeastern USA when disease pressure ranges from 0 to 21% symptomatic plants (e.g., compare TSW susceptible 'Aristotle' to TSW resistant 'Magico' in Table 1). We also demonstrated that TSW resistance in pepper seems to have no discernable effect on thrips populations. Resistance to TSW in pepper reduces the risk of yield loss from this disease.

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