Red Harvest Yield and Fruit Characteristics of *Phytophthora capsici*-resistant Bell Pepper Inbred Lines in New York

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Summary. ***Phytophthora capsici* is an oomycete pathogen that causes disease on bell pepper (*Capsicum annuum*) and many other vegetable crops globally. Newly developed bell pepper inbred lines have been shown to be resistant to *P. capsici* and have been previously evaluated for green harvest yield. Nine *P. capsici*-resistant inbred lines and three commercial cultivars were evaluated for red harvest yield and fruit characteristics at three sites and disease resistance was evaluated through field inoculation studies. Three of the *P. capsici*-resistant lines were further evaluated as hybrid parents by measuring hybrid yield and disease resistance. *P. capsici*-resistant lines had excellent disease resistance and provided high levels of resistance to F_1 hybrids. Inbred lines had comparable yields to the commercial cultivars, but fruit were smaller in size and weight. These lines are suitable for use as inbred lines for markets where small fruit size is acceptable and have potential for use as hybrid parents.**

Bell peppers are an important vegetable crop in the United States. More than 1.8 billion pounds of bell peppers were grown in 2012 at a value of $628 million (U.S. Department of Agriculture, 2013). Although most bell peppers are harvested and sold at the immature green stage, bell peppers at the mature ripe stage are also produced. Red bell peppers have excellent nutritional properties, with carotenoids, flavonoids, and vitamin C (Greenleaf, 1986).

Phytophthora blight is a disease of pepper (*Capsicum* sp.) that was first discovered in New Mexico in 1918 (Leonian, 1922). It causes severe losses in many bell pepper-producing areas around the United States and the world (Bosland and Lindsey, 1991; García-Rodríguez et al., 2010; Hwang and Kim, 1995; Oelke et al., 2003). Phytophthora blight is caused by the oomycete pathogen *Phytophthora capsici,* which can infect a wide range of vegetable crops (Crossan et al., 1954; Polach and Webster, 1972).

Management of phytophthora blight is difficult because it can spread quickly throughout a field from an initial inoculation source. *P. capsici* reproduces asexually through the formation of sporangia and zoospores (Ristaino, 1991) which are dispersed by water (Granke et al., 2009). Because the sporangia and zoospores move in water, rainfall and irrigation events have a significant impact on disease development and can spread inoculum throughout a field (Bowers and Mitchell, 1990; Café-Filho and Duniway, 1995; Ristaino, 1991). *P. capsici* reproduces sexually by forming oospores, which are capable of overwintering in the field and acting as a persistent inoculum source (Lamour and Hausbeck, 2003). In New York, phytophthora blight is a growing issue for bell pepper production (Dunn et al., 2010), with zoospore-containing irrigation water infesting previously unaffected farms and recent flooding spreading inoculum between farms. Fungicide-insensitive populations of *P. capsici* are increasingly common and there are no fully resistant bell pepper cultivars that are commercially available; field infestations can lead to total yield loss for multiple years.

Current control strategies for phytophthora blight include the application of fungicides, cultural practices aimed at reducing the spread of inoculum, and the use of resistant bell pepper cultivars (Hausbeck and Lamour, 2004; Ristaino and Johnston, 1999). Unfortunately, control strategies are

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
102.7902	acre-inch(es)	m^3	0.0097
29.5735	fl oz	mL	0.0338
0.0970	fl oz/ft	$L \cdot m^{-1}$	10.3065
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
3.7854	gal	L	0.2642
12.4193	gal/ft	$L \cdot m^{-1}$	0.0805
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.4516	$inch^2$	cm^2	0.1550
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922
0.1198	lb/gal	$kg \cdot L^{-1}$	8.3454
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
2.2417	ton/acre	$Mg \cdot ha^{-1}$	0.4461

not always fully effective. Due to the prolonged use of a limited number of chemistries, fungicide-insensitive *P. capsici* isolates have been reported. Insensitivity to the fungicide mefenoxam is common and resistance to other fungicides has also been reported (Lamour and Hausbeck, 2001; Lu et al., 2010). In addition, once a field is infected, inoculum can remain for years (Lamour and Hausbeck, 2003). The most grower- and environment-friendly control strategy is the use of bell pepper cultivars that are resistant to *P. capsici*, combined with cultural practices. Unfortunately, there has been significant difficulty with breeding bell peppers resistant to *P. capsici*, with no commercially available bell peppers with full resistance as well as the desired horticultural type (Oelke et al., 2003; Ristaino and Johnston, 1999; Thabuis et al., 2004). This difficulty is due to the multigenic nature of the resistance, as well as linkage drag of negative horticultural traits linked to resistance genes (Thabuis et al., 2004). Partial resistance of some commercially available bell peppers varies in effectiveness depending on the *P. capsici* isolate used for testing (Foster and Hausbeck, 2010). These resistant bell pepper cultivars also tend to have a problem with silvering, where the bell pepper cuticle separates from the epidermis causing a silver coloration (Kline et al., 2011).

A set of nine *P. capsici*-resistant bell pepper inbred lines (hereafter referred to as "PR lines") has been developed that provides a new option to growers with phytophthora blight in the northeastern United States. These PR lines displayed excellent resistance when challenged in a greenhouse assay using four Michigan *P. capsici* isolates (Foster and Hausbeck, 2010). They have also been evaluated in inoculated field studies and were found to be resistant to the crown rot phase of phytophthora blight caused by *P. capsici* (Dunn et al., 2013). In that study, the number and weight of fruit per plot of green (immature) harvested fruit of the PR lines were comparable to commercial cultivars, especially under disease pressure, and they had a low incidence of silvering (Dunn et al., 2013). In this study, we evaluated the ripe red harvest yield and fruit characteristics of the PR lines and several commercial cultivars, compared their performances in organic, conventional, and conventional drought environments, and tested their potential to provide disease resistance as hybrid parents.

Materials and methods

Germplasm evaluated. All of the cultivars and lines evaluated in this study are described in Table 1. Nine PR lines bred at Cornell University were evaluated in this experiment. Three commercial cultivars, two of which were described by the supplier as having "intermediate resistance" to phytophthora blight, were grown as controls. 'Aristotle' could not be obtained as untreated seed, so it was omitted from the organic trial site. In 2012 only, six F_1 hybrids created by manual cross-pollinations between a PR line and a commercial cultivar were also tested. The two commercial cultivars used as hybrid parents, Keystone Giant and King of the North, were also grown in 2012 as controls.

Field sites. These experiments were conducted at three field sites: yield trials were conducted at the East Ithaca Research Farm of Cornell University in Ithaca, NY, in 2011 and 2012 (hereafter referred to as "East Ithaca") and the Freeville Organic Research Farm of Cornell University in Freeville, NY (hereafter referred to as "Freeville Organic") in 2012, while disease resistance trials were conducted at the Phytophthora Blight Farm at the New York State Agricultural Experiment Station in Geneva, NY, in 2011 and 2012. The Phytophthora Blight Farm is used annually for field-based inoculation studies because it is quarantined from nearby farms, but does not have an overwintering population of *P. capsici*. The East Ithaca Research Farm has an Arkport sandy loam soil type, the Freeville Organic Research Farm has a Rhinebeck clay soil type, and the Phytophthora Blight Farm has Odessa silt loam soil. At all sites, raised beds were constructed, which were 4 inches high, 30 inches wide, and 7 ft between centers. Beds were covered with 1.25-mil black embossed plastic mulch (Belle Terre Irrigation, Sodus, NY) and drip tape [emitter spacing of 12 inches and flow rate of 0.45 gal/min per 100 ft (Aqua-Traxx; Toro, Bloomington, MN)] was used.

At the East Ithaca site, 10N–8.7P–16.6K fertilizer was applied before planting at a rate of 300 lb/acre (Arrow; Royster-Clark, Princeton, NC). At the Freeville Organic site, compost (2.4N–1.25P–0.9K) was applied to the field at a rate of 10 t/acre before planting. At the Phytophthora Blight Farm, 300 lb/acre 10N–4.4P–8.3K fertilizer (Phelps Supply, Phelps, NY) was applied under the mulch at the time beds were built.

In 2011, total monthly rainfall at the East Ithaca site was 2.59, 1.99, and 4.63 inches for June, July, and August, respectively; and at the Phytophthora Blight Farm, monthly rainfall was 2.34, 0.72, and 2.62 inches for June, July, and August, respectively. In 2012 at the East Ithaca and Freeville Organic sites, total monthly rainfall was 1.84, 1.59, and 3.58 inches for June, July, and August, respectively; and monthly rainfall was 2.59, 2.80, and 2.26 inches for June, July, and August, respectively at the Phytophthora Blight Farm. At East Ithaca in 2012, a low rate of supplementary irrigation (0.44 acre-inch) was provided using drip tape every other week to create significant drought stress for the plants, simulating conditions for growers with no supplemental irrigation. Drought stress was confirmed through visual observation of the plants. At the Freeville Organic site, the Phytophthora Blight Farm and the East Ithaca in 2011, irrigation was provided to prevent drought stress.

Plant culture. Bell pepper seedlings were grown in a greenhouse using natural and supplemental light. Six weeks after seeding, transplant seedlings were transferred to a coldframe for hardening off and 8 weeks after planting, seedlings were transplanted to the field. Transplanting dates were 3 June 2011 and 31 May 2012 at the East Ithaca site, 10 June 2011 and 15 June 2012 at the Phytophthora Blight Farm, and 30 May 2012 at the Freeville Organic site.

At the East Ithaca site, water-soluble fertilizer (Peters 10N–13.1P–16.6K; JR Peters, Allentown, PA) was applied at transplant, at an approximate rate of 0.083 gal/ft of row (7.8 g/gal of water). At the Freeville Organic site, fish emulsion (Hydrolyzed Fish 2N–4P–1K; Neptune's Harvest, Gloucester, MA) was applied immediately after transplanting at an approximate rate of 0.055 fl oz/ft of row. At the Phytophthora Blight Farm, water-soluble fertilizer (Peters Excel 21N–2.2P–16.6K, JR Peters) was applied at transplant at an approximate rate of

Table 1. Bell pepper cultivars, lines, and F_1 hybrids used in yield and phytophthora blight-resistance trials.

Cultivar or line	Source	
'Aristotle'	Seminis Vegetable Seeds	St. Louis, MO
'Paladin'	Syngenta	Greensboro, NC
'Revolution'	Harris Moran Seed Co.	Modesto, CA
Pcap-NY8001–1	Cornell University	Ithaca, NY
Pcap-NY8002–3	Cornell University	Ithaca, NY
Pcap-NY8003–2	Cornell University	Ithaca, NY
Pcap-NY8006–1	Cornell University	Ithaca, NY
Pcap-NY8006–4	Cornell University	Ithaca, NY
Pcap-NY8007–1	Cornell University	Ithaca, NY
Pcap-NY8007–2	Cornell University	Ithaca, NY
Pcap-NY8007–3	Cornell University	Ithaca, NY
Pcap-NY8007–4	Cornell University	Ithaca, NY
F_1 #1 – 'Keystone Giant' × Pcap-NY8002–3	F_1 hybrid (this study)	—
F_1 #2 – 'Keystone Giant' × Pcap-NY8003–2	F_1 hybrid (this study)	—
F_1 #3 – 'Keystone Giant' × Pcap-NY8007–3	F_1 hybrid (this study)	—
F_1 #4 – 'King of the North' × Pcap-NY8002–3	F_1 hybrid (this study)	—
F_1 #5 – 'King of the North' × Pcap-NY8003–2	F_1 hybrid (this study)	—
F_1 #6 – 'King of the North' × Pcap-NY8007–3	F_1 hybrid (this study)	—
'Keystone Giant'	Gourmet Seed	Tatum, NM
'King of the North'	High Mowing Organic Seeds	Wolcott, VT

0.07 gal/ft of row (0.04 lb fertilizer per gallon of water). At the Freeville Organic site, plants were fertilized once during the season by applying diluted Neptune's Harvest fish emulsion at the base of each plant at the approximate rate of 0.055 fl oz/ft of row.

Yield trial harvest. Yield was measured in three environments: the conventional, irrigated field at the East Ithaca site in 2011 (hereafter referred to as "2011 Conventional"), the conventional, drought-stressed field at the East Ithaca site in 2012 (hereafter referred to as "2012 Drought-stressed"), and the organic, irrigated field in 2012 at the Freeville Organic site (hereafter referred to as "2012 Organic"). For the yield trial, plants were arranged in a three-replicate randomized complete block design. Each plot consisted of 12 plants with the middle 10 plants being harvested. Plants were spaced 18 inches apart in an offset double row. Beginning the week of 15 Aug. 2011 and the week of 6 Aug. 2012, plots were harvested weekly for 8 weeks. Mature fruit (at least 80% red or yellow) were harvested and graded into marketable and unmarketable classes. Marketable fruit had a diameter of greater than 2.5 inches and were blemish-free. Yield of both classes was measured both by number of fruit and by total weight of fruit. Yield data were recorded on a 10-plant plot basis and were added across the eight harvest dates to calculate cumulative yield, which was used for subsequent statistical analyses. In 2012, the numbers of fruit in the unmarketable class with silvering and blossom-end rot were also counted to confirm between-line differences initially observed in 2011.

Ten marketable fruit (if available) were arbitrarily selected from each plot and the following measurements were made on each fruit: fruit length (centimeters), fruit width at the widest point (centimeters), fruit wall thickness (millimeters), fruit weight [grams (in 2012 only)], number of lobes, and percent soluble solids, measured using a refractometer. In 2011, fruit weight was calculated as the mean weight of the 10 fruit selected for analysis. The number of lobes per fruit was used to calculate the percent of marketable fruit with four lobes. Lines with less than seven marketable fruit for individual fruit measurements were excluded from analyses due to inadequate sample size.

Disease-resistance testing. At the Phytophthora Blight Farm, all trial entries were evaluated for susceptibility to *P. capsici*. The PR lines and the commercial cultivars were evaluated in 2011 and the F_1 hybrids and hybrid parents were evaluated in 2012. Plants were arranged in a randomized complete block design with four replicates in 2011 and three replicates in 2012. Each plot consisted of 10 plants and plants were spaced 18 inches apart in a single row. Inoculation and data collection procedures were as described in Dunn et al. (2013). Briefly, a New York isolate of *P. capsici* (NY 066–4, collected from a bell pepper on a commercial vegetable farm in central New York in 2006; Dunn et al., 2010) was used to inoculate bell peppers 2, 4, and 6 weeks after transplanting in 2011. About 5 mL of a 4×10^4-zoospores/mL suspension were applied at the crown of each plant using a 1.5-gal hand-pump sprayer for the first inoculation and 5 mL of a 1×10^5-zoospores/mL suspension were applied higher up the stem of the plants for the later inoculations. In 2012, bell peppers were inoculated 5 d and 3 weeks after transplanting. About 5 mL of a 1×10^5-zoospores/mL suspension were applied at the crown of each plant using a 1.5-gal hand-pump sprayer for the first inoculation and 5 mL of a 1×10^5-zoospores/mL suspension were applied higher up the stem of the plants for the later inoculation. Inoculation procedure was adapted each year based on weather conditions to achieve high levels of disease pressure. In both years, starting ≈5 d after the first inoculation, the proportion of plants showing symptoms of phytophthora blight (either wilting of at least one branch or plant death) was recorded on a per-plot basis. These ratings continued about twice weekly for 3 months. Disease resistance was quantified by calculating the area under the disease progress curve (AUDPC). Isolations were taken from a representative sample of diseased plants to

confirm that the causal organism was *P. capsici*.

Statistical analysis. JMP statistical software (version 9.0.0; SAS Institute, Cary, NC) was used for all analyses. Separate analyses of variance (ANOVA) were conducted for all yield, fruit characteristics, and disease-resistance data for each year and site to determine the effects of line on the assorted dependent variables. Following all significant ANOVAs ($P < 0.05$), Tukey's honestly significant difference (HSD) test (at $\alpha = 0.05$) was used to separate means, except when numbers of entries were unequal, in which case Tukey–Kramer's HSD test (at $\alpha = 0.05$) was used.

Results

Disease incidence. The Cornell University PR lines had excellent resistance to phytophthora blight. Seven of the breeding lines displayed no disease symptoms after being inoculated three times with a New York isolate of *P. capsici* on the Phytophthora Blight Farm in 2011 and the remaining two had minimal disease symptoms (Fig. 1). All of the PR lines were significantly more resistant to the crown rot phase of phytophthora blight than two commonly available commercial cultivars, Aristotle, which although not advertised as resistant to phytophthora blight, is generally regarded as moderately resistant (Keinath, 2012; Li, 2012; Louws et al., 2008), and 'Revolution', which is described as having intermediate resistance to phytophthora blight (Fig. 1). While the PR lines were not significantly more resistant than 'Paladin', a commonly available cultivar that is highly resistant to phytophthora blight, they all had a lower mean AUDPC than 'Paladin', showing that they had relatively less disease symptoms.

Yield and plant characteristics. Overall marketable yield, measured as number of red or yellow fruit per 10-plant plot, varied between sites (Fig. 2). Trial entries had significantly different fruit number per plot within each of the three sites. At the 2011 Conventional site, Pcap-NY8003–2, Pcap-NY8002–3 and Pcap-NY8006–1 had the highest yields, yielding significantly more than 'Revolution' (Fig. 2). Pcap-NY8006–1 also had the highest yield at the 2012 Drought-stressed site and yielded significantly more than 'Revolution' and 'Paladin' (Fig. 2). At the 2012

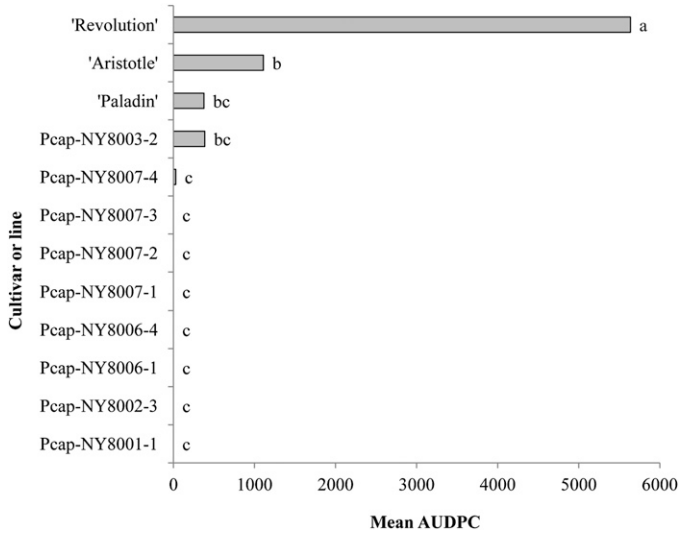

Fig. 1. Resistance of bell pepper lines to phytophthora blight. Resistance is measured as area under the disease progress curve, calculated by biweekly disease incidence ratings of inoculated plants on the Phytophthora Blight Farm in 2011. The Phytophthora Blight Farm is a research farm in Geneva, NY, used annually for field-based inoculation studies because it is quarantined from nearby farms, but does not have an overwintering population of *Phytophthora capsici*. Means followed by the same letter are not significantly different at $P < 0.05$ using Tukey's honestly significant difference test.

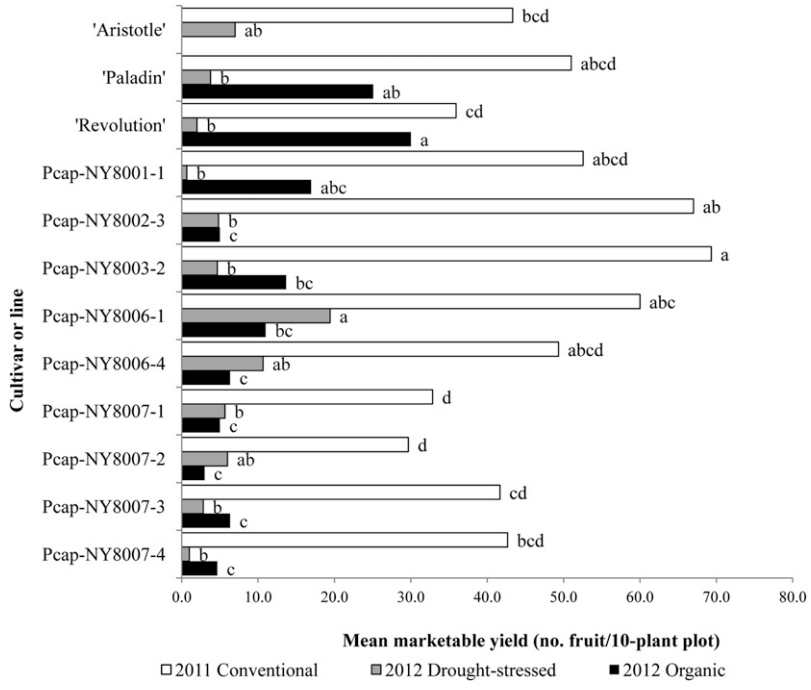

Fig. 2. Cumulative marketable yield of red or yellow bell peppers. Yield was measured as the total number of red or yellow marketable fruit per 10-plant plot [20.625 ft² (1.9161 m²)] summed across eight weekly harvests. The three treatments were "2011 Conventional," a conventional, irrigated field at the East Ithaca, NY site in 2011, "2012 Drought-stressed," a conventional, drought-stressed field at the East Ithaca, NY site in 2012, and "2012 Organic," an organic, irrigated field in 2012 at the Freeville, NY Organic site. 'Aristotle' was omitted from 2012 Organic because untreated seed could not be obtained. Means for a given site followed by the same letter are not significantly different at $P < 0.05$ using Tukey's honestly significant difference test; 1 fruit/10-plant plot = 0.0485 fruit/ft² = 0.5219 fruit/m².

Organic site, 'Revolution' and 'Paladin' had the highest yields of all of the trial entries, while Pcap-NY8003–2 had the highest yield of the nine PR lines (Fig. 2). Overall, three of the PR lines, Pcap-NY8001–1, Pcap-NY8003–2, and Pcap-NY8006–1, had numbers of marketable fruit comparable to the commercial cultivars across all sites.

The PR lines tended to have a high percentage of marketable fruit at the 2011 Conventional site, with Pcap-NY8003–2 and Pcap-NY8002–3 having a significantly higher percentage of marketable fruit than the three commercial cultivars (Table 2). A similar trend was observed at the 2012 Drought-stressed site, where Pcap-NY8006–1 and Pcap-NY8006–4 had a significantly higher percentage of marketable fruit than 'Paladin' or 'Revolution'. At the 2012 Organic site, 'Revolution' had the highest percentage of marketable fruit, but six of the PR lines were not significantly lower.

Based on observations of differences between lines in 2011, in 2012 the percent of fruit categorized as unmarketable because of either sunscald or blossom-end rot was also recorded at both sites (Table 2). At the 2012 Drought-stressed site, the three commercial cultivars had the highest percentage of fruit with sunscald, with 'Aristotle' having a significantly higher percentage of fruit with sunscald than any of the PR lines. At the 2012 Organic site, a similar trend was observed, but differences between lines were not significant. Pcap-NY8006–1 had the lowest occurrence of blossom-end rot at the 2012 Drought-stressed site, with a significantly lower percentage of fruit with blossom-end rot than 'Aristotle' or 'Revolution'.

Fruit characteristics. Fruit size varied significantly between lines at both the 2011 Conventional and the 2012 Organic sites (Table 3). The commercial cultivars had larger fruit than the PR lines. 'Revolution' had the largest fruit measured both as fruit weight and as fruit length × width and had a significantly larger length × width than all of the PR lines in both environments. Differences in fruit size were not significant at the 2012 Drought-stressed site because of low sample number, but the trends were similar across all sites (Table 3). However, all lines displayed an increased size at the 2012 Organic site compared with the other two sites. The differences between lines in fruit wall thickness were less pronounced (Table 3). The three commercial cultivars had relatively thick fruit walls, as did Pcap-NY8001–1, Pcap-NY-8002–3, and Pcap-NY8003–2.

The percent of fruit with four lobes did not differ significantly between lines in any of the environments (data not shown). In contrast, soluble solids were significantly different between lines in all three environments (Table 4). At the 2011 Conventional site, Pcap-NY8007–1, Pcap-NY8007–2, and Pcap-NY8007–4 had the highest percent soluble solids and were significantly higher than the three commercial cultivars. Similarly, Pcap-NY8007–1 had the highest percent soluble solids at the 2012 Organic site and had significantly higher percent soluble solids than 'Paladin' and 'Revolution'. In contrast, the 2012 Drought-stressed site displayed a different trend, with 'Aristotle' having the highest percent soluble solids, although it was only significantly higher than one of the PR lines.

Hybrid performance. F_1 hybrids were made using three PR lines (Pcap-NY8002–3, Pcap-NY8003–2, and Pcap-NY8007–3) as paternal parents and two commercial open-pollinated cultivars (Keystone Giant and King of the North) as maternal parents. In 2012, their resistance to phytophthora blight was evaluated at the Phytophthora Blight Farm. The F_1 hybrids were highly tolerant to phytophthora blight (Fig. 3), with five out of the six F_1 hybrids not significantly different from the Pcap-resistant parents. All of the hybrids were significantly more resistant than the commercial cultivar parents, which were extremely susceptible as displayed by their high AUDPCs.

Hybrid yields varied by hybrid combination (Fig. 4). One hybrid,

Table 2. Percent marketable bell pepper fruit, percent fruit with sunscald, and percent fruit with blossom-end rot, expressed as mean percent of total fruit number. Marketable fruit are those with no sunscald, blossom-end rot, or other blemishes. Bell peppers were evaluated in a conventional, irrigated environment, a conventional, drought-stressed environment (both in Ithaca, NY), and an organic, irrigated environment (in Freeville, NY).

	Mean sunscald (%)		Mean blossom-end rot (%)		Mean marketable fruit (%)		
Cultivar or line	2012 Drought-stressed[z]	2012 Organic[z]	2012 Drought-stressed	2012 Organic	2011 Conventional[z]	2012 Drought-stressed	2012 Organic
'Aristotle'[y]	10.6 a[x]	—	43.0 ab	—	46.4 cd	10.3 bc	—
'Paladin'	7.6 abc	5.3	28.9 abc	0.0	44.4 cd	4.8 c	44.5 abcd
'Revolution'	8.0 ab	2.4	45.4 ab	1.8	41.4 cd	3.2 c	69.0 a
Pcap-NY8001–1	0.0 d	0.0	48.0 a	1.3	59.3 abc	7.1 c	54.2 abc
Pcap-NY8002–3	2.8 bcd	0.0	29.4 abc	0.0	70.9 ab	18.1 abc	61.7 ab
Pcap-NY8003–2	0.0 d	0.0	48.8 a	0.0	74.4 a	23.8 abc	67.9 a
Pcap-NY8006–1	1.3 bcd	0.0	3.6 c	0.0	56.0 abcd	38.7 a	49.0 abcd
Pcap-NY8006–4	0.8 cd	0.0	12.8 bc	0.0	56.3 abcd	36.7 ab	25.2 cd
Pcap-NY8007–1	2.0 bcd	5.6	17.6 abc	2.8	40.8 cd	22.1 abc	36.8 abcd
Pcap-NY8007–2	1.0 cd	1.9	24.6 abc	0.0	35.8 d	20.5 abc	16.1 d
Pcap-NY8007–3	2.0 bcd	0.0	27.3 abc	0.0	47.5 cd	12.3 abc	26.1 bcd
Pcap-NY8007–4	1.4 bcd	0.0	14.4 abc	0.0	50.6 bcd	6.1 c	36.2 abcd
P value[w]	<0.0001	NS	0.0007	NS	<0.0001	0.0005	0.0002

[z]The three treatments were "2011 Conventional," a conventional, irrigated field at the East Ithaca, NY site in 2011, "2012 Drought-stressed," a conventional, drought-stressed field at the East Ithaca, NY site in 2012, and "2012 Organic," an organic, irrigated field in 2012 at the Freeville, NY Organic site.
[y]'Aristotle' was omitted from the 2012 Organic site because untreated seed could not be obtained.
[x]Within a column, means followed by the same letter are not significantly different at $P < 0.05$ using Tukey's honestly significant difference test.
[w]Probability value for analysis of variance testing for significant differences among lines. NS indicates lines were not significantly different at $P < 0.05$.

Table 3. Size of marketable red or yellow bell pepper fruit, measured as fruit weight, fruit length x width, and fruit wall thickness. Bell peppers were evaluated in a conventional, irrigated environment, a conventional, drought-stressed environment (both in Ithaca, NY), and an organic, irrigated environment (in Freeville, NY).

Cultivar or line	Mean fruit wt (g)[z]			Mean fruit length × width (cm^2)[y]			Mean fruit wall thickness (mm)[y]		
	2011 Conventional[x]	2012 Drought-stressed[w]	2012 Organic[x]	2011 Conventional	2012 Drought-stressed	2012 Organic	2011 Conventional	2012 Drought-stressed	2012 Organic
'Aristotle'[v]	196 ab[u]	166.9	—	77.0 ab	70.2	—	6.3 a	6.20 a	—
'Paladin'	148 bc	—	238.1 b	67.8 c	—	106.2 ab	5.7 b	—	6.09 abc
'Revolution'	211 a	—	318.5 a	82.3 a	—	112.8 a	5.9 ab	—	6.7 a
Pcap-NY8001–1	163 abc	—	236.7 b	66.0 c	—	89.8 c	5.9 ab	—	6.20 abc
Pcap-NY8002–3	164 abc	167.5	223.6 b	69.6 bc	65.3	90.7 bc	5.5 bc	5.90 ab	6.44 ab
Pcap-NY8003–2	155 bc	134.5	228.0 b	63.1 c	55.2	93.4 bc	6.0 ab	5.83 ab	6.20 abc
Pcap-NY8006–1	141 c	125.2	205.6 b	63.0 c	54.6	79.9 c	5.2 cd	6.04 a	5.92 bcd
Pcap-NY8006–4	147 bc	148.8	215.2 b	61.2 c	64.9	84.5 c	5.7 b	5.83 ab	6.11 abcd
Pcap-NY8007–1	146 bc	116.7	187.2 b	63.2 c	53.6	79.1 c	5.2 cd	4.84 b	5.35 cd
Pcap-NY8007–2	136 c	156.4	214.7 b	62.7 c	64.2	91.1 bc	5.0 d	5.38 ab	5.72 abcd
Pcap-NY8007–3	135 c	147.5	189.0 b	62.3 c	62.3	82.2 c	5.0 cd	5.59 ab	5.28 d
Pcap-NY8007–4	144 bc	—	194.5 b	61.7 c	—	80.1 c	5.1 cd	—	5.61 bcd
P value[t]	0.0003	NS	<0.0001	<0.0001	NS	<0.0001	<0.0001	0.0219	<0.0001

[z]2011 mean fruit weight was calculated from the average weight of 10 arbitrarily selected marketable bell peppers, while 2012 mean fruit weights were calculated from the individual weights of 10 arbitrarily selected marketable bell peppers; 1 g = 0.0353 oz.
[y]1 cm^2 = 0.1550 $inch^2$, 1 mm = 0.0394 inch.
[x]"2011 Conventional" treatment is a conventional, irrigated field at the East Ithaca, NY site in 2011 and "2012 Organic" treatment is an organic, irrigated field in 2012 at the Freeville, NY Organic site.
[w]"2012 Drought-stressed" treatment is a conventional, drought-stressed field at the East Ithaca, NY site in 2012. Lines from the 2012 Drought-stressed site with six or fewer analyzed fruit were omitted from the analysis.
[v]'Aristotle' was omitted from 2012 Organic because untreated seed could not be obtained.
[u]Within a column, means followed by the same letter are not significantly different at $P < 0.05$ using Tukey–Kramer's honestly significant difference test.
[t]Probability value for analysis of variance testing for significant differences among lines. NS indicates lines were not significantly different at $P < 0.05$.

'King of the North' × Pcap-NY8003–2, had the highest yield, which was significantly more than three of the other hybrids. One of the three 'Keystone Giant' hybrids had a yield significantly greater than 'Keystone Giant' and its PR line parent. None of the 'King of the North' hybrids had a yield significantly greater than 'King of the North', but all were significantly greater than the PR line parents (Fig. 4).

Discussion

There is a growing need for northeastern-adapted *P. capsici*-resistant bell pepper cultivars as phytophthora blight becomes more widespread (Dunn et al., 2010). Nine new bell pepper inbred lines with excellent resistance to *P. capsici* have been developed. Four of these lines were previously evaluated for disease resistance and green bell pepper yield (Dunn et al., 2013). In this study, the disease screening data from the full set of PR lines is reported. The PR lines displayed excellent disease resistance to the New York isolate of the pathogen used for screening, which was consistent with results from a study conducted with four Michigan *P. capsici* isolates (Foster and Hausbeck, 2010). In all trials, the PR lines consistently displayed high resistance compared with 'Paladin', a commonly available *P. capsici*-resistant cultivar, indicating that the PR lines are a valuable addition to the available *P. capsici*-resistant material.

To fully characterize the PR lines, we conducted a three-site ripe harvest yield trial comparing the nine PR lines to three commercial cultivars. The yield data from this trial were consistent with the green harvest data previously reported (Dunn et al., 2013). A subset of the PR lines had numbers of fruit per plot and percentage of marketable fruit similar to the commercial cultivars, but tended to have smaller fruit, reducing yields on a weight basis.

Yields varied substantially between the three sites, which was expected based on the different environmental variables at each site. The yields were highest at the 2011 Conventional site, which is the environment for which the lines were developed. Yields were lower at the 2012 Organic site, which is likely due to differences between sites in weather, soil properties, and form of nutrition applied. It is common for

Table 4. Mean percent soluble solids of red and yellow marketable bell peppers. Bell peppers were evaluated in a conventional, irrigated environment, a conventional, drought-stressed environment (both in Ithaca, NY), and an organic, irrigated environment (in Freeville, NY).

	Mean soluble solids (%)		
Cultivar or line	2011 Conventional[z]	2012 Drought-stressed[y]	2012 Organic[z]
'Aristotle'[x]	6.7 bc[w]	9.4 a	—
'Paladin'	6.8 bc	—	7.3 bcd
'Revolution'	6.3 c	—	7.3 bcd
Pcap-NY8001–1	7.1 ab	—	7.5 bcd
Pcap-NY8002–3	6.2 c	7.6 b	6.9 d
Pcap-NY8003–2	6.8 bc	8.7 ab	7.1 cd
Pcap-NY8006–1	7.2 ab	8.3 ab	7.4 bcd
Pcap-NY8006–4	7.1 ab	8.4 ab	7.3 bcd
Pcap-NY8007–1	7.6 a	8.9 ab	8.4 a
Pcap-NY8007–2	7.7 a	8.2 ab	8.0 abc
Pcap-NY8007–3	7.3 ab	8.5 ab	7.6 abcd
Pcap-NY8007–4	7.4 a	—	7.9 ab
P value[v]	<0.0001	0.0165	<0.0001

[z]"2011 Conventional" treatment is a conventional, irrigated field at the East Ithaca, NY site in 2011 and "2012 Organic" treatment is an organic, irrigated field in 2012 at the Freeville, NY Organic site.
[y]"2012 Drought-stressed" treatment is a conventional, drought-stressed field at the East Ithaca, NY site in 2012. Lines from the 2012 Drought-stressed site with six or fewer analyzed fruit were omitted from the analysis.
[x]'Aristotle' was omitted from 2012 Organic because untreated seed could not be obtained.
[w]Within a column, means followed by the same letter are not significantly different at $P < 0.05$ using Tukey–Kramer's honestly significant difference test.
[v]Probability value for analysis of variance testing for significant differences among lines. NS indicates lines were not significantly different at $P < 0.05$.

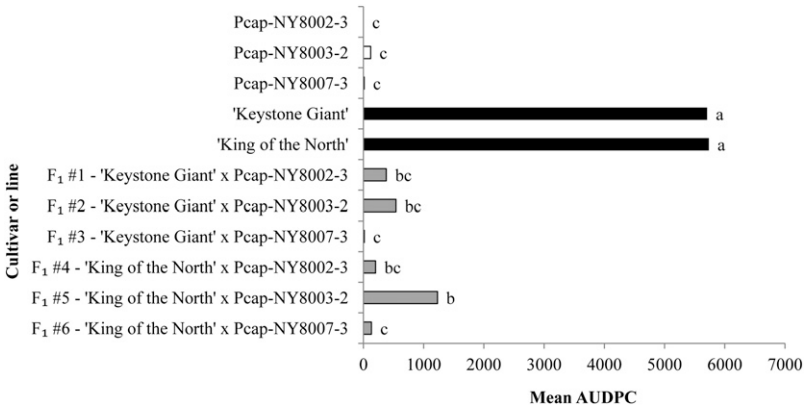

Fig. 3. Resistance of bell pepper test hybrids to phytophthora blight. Resistance is measured as area under the disease progress curve, calculated by biweekly disease incidence ratings of inoculated plants on the Phytophthora Blight Farm in 2012. The Phytophthora Blight Farm is a research farm in Geneva, NY, used annually for field-based inoculation studies because it is quarantined from nearby farms, but does not have an overwintering population of *Phytophthora capsici*. White bars indicate Cornell University inbred line parents, black bars indicate commercial parents, and gray bars indicate F_1 hybrids. Means followed by the same letter are not significantly different at $P < 0.05$ using Tukey's honestly significant difference test.

yields to be lower when lines bred for conventional conditions are grown in organic conditions (Murphy et al., 2007). This indicates a need for further breeding and selection to adapt the PR lines for organic systems. Yields were lowest at the 2012 Drought-stressed site, which was largely due to an increase in fruit loss through blossom-end rot and other fruit defects. Blossom-end rot is often an issue when bell peppers are grown under stress conditions, including water stress (Silber et al., 2005). Notably, Pcap-NY8006–1 had much less blossom-end rot than the commercial cultivars, suggesting that it could be a good option for areas in which drought stress is common.

The fruit size measurements reported in this study were consistent with those reported in the green harvest yield trial (Dunn et al., 2013), with the PR lines having smaller fruit than the commercial cultivars. The acceptability of these smaller fruit will vary by market and by the importance growers place on phytophthora blight resistance vs. fruit size. In general, fruit size was similar at the two conventional sites, demonstrating that the drought stress reduced the number of fruit per plant, but not the size of the fruit. In contrast, fruit tended to be much bigger at the 2012 Organic site, which was likely related to the lower number of fruit per plant at the site.

The test hybrids evaluated in 2012 demonstrated the potential of using the PR lines as hybrid parents. The majority of commercial bell pepper cultivars are F_1 hybrids. Hybrids provide uniformity and the opportunity to combine different disease-resistance traits possessed by each parent. The disease screening results indicated that F_1 hybrids with one of the PR lines as a parent had excellent resistance to phytophthora blight, even when combined with a highly susceptible commercial cultivar as the second parent. This confirmed previous observations that suggested resistance of the PR lines is predominantly dominant (M. Mazourek, unpublished data). The yield evaluation also demonstrated the potential of hybrid combinations to increase yield and improve adaptation, as yield was greater in the hybrids than in the PR lines and one of the commercial parents. For example, hybrids with the organic-adapted 'King of the North' as the commercial parent performed well in organic conditions.

In conclusion, this ripe harvest trial both confirmed previous green harvest results and further characterized the PR lines. The PR lines have excellent resistance to a New York isolate of *Phytophthora capsici* both as inbred lines and as F_1 progenitors. Some of the PR lines, such as Pcap-NY8003–2 and Pcap-NY8006–1, consistently yield numbers of fruit per plot similar to commercial cultivars with low incidence of sunscald and drought-related blossom-end rot. Areas to target in future breeding efforts include increasing fruit size, earliness of fruit set, and speed of green-to-red ripening. The PR lines meet a great need for new *P. capsici*-resistant bell peppers for northeast markets. They can be grown as inbreds for markets where smaller fruit size is acceptable and also

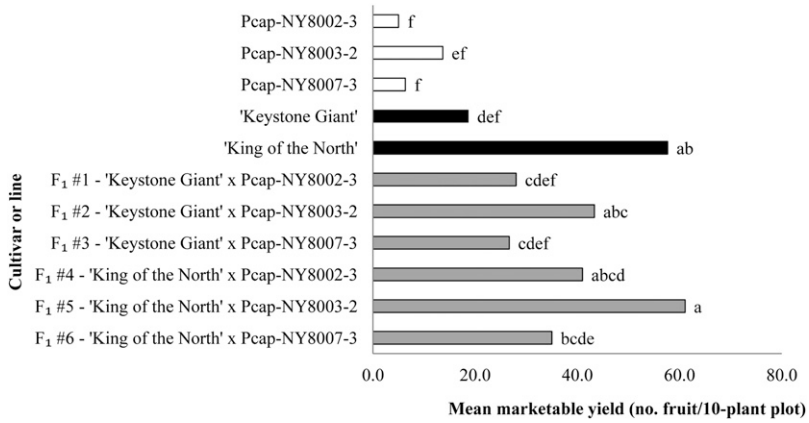

Fig. 4. Cumulative marketable yield of bell pepper test hybrids at the 2012 Organic site in Freeville, NY. Yield was measured as the total number of red or yellow marketable fruit per 10-plant plot [20.625 ft² (1.9161 m²)] summed across eight weekly harvests. White bars indicate Cornell University inbred line parents, black bars indicate commercial parents, and gray bars indicate F_1 hybrids. Means followed by the same letter are not significantly different at $P < 0.05$ using Tukey's honestly significant difference test; 1 fruit/10-plant plot = 0.0485 fruit/ft² = 0.5219 fruit/m².

have great potential to serve as hybrid parents to develop *P. capsici*-resistant hybrids for the northeast.

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