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Performance of Three Selection Cycles from Four Slicing Cucumber Populations Hybridized with a Tester

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ABSTRACT. **Recurrent selection has been used as a breeding method to improve traits having low heritability such as fruit yield, earliness, and fruit shape. The objective of this study was to measure the progress of recurrent selection in four slicing cucumber populations in terms of hybrid performance when crossed with a common tester. The four populations, North Carolina wide-base slicer (NCWBS), medium-base slicer (NCMBS), elite slicer 1 (NCES1), and Beit Alpha 1 (NCBA1) populations, which differed in their genetic diversity and mean performance, were developed using modified intrapopulation half-sib recurrent selection to improve fruit yield and quality. Eleven S_0 families were taken randomly from each of three selection cycles (early, intermediate, and advanced) from each population. Those families were self-pollinated to form S_1 families, and the S_1 families were crossed to 'Poinsett 76', a popular slicing cucumber cultivar. The experiment was a split-plot treatment arrangement in a randomized complete-block design with 22 replications per population, with the four populations as whole plots and the three cycles as subplots. When 10% of fruit were oversized (>60 mm in diameter), plants were sprayed with paraquat to defoliate them for once-over harvest. Plots were evaluated for total, early, and marketable yield and fruit shape. Recurrent selection for improved fruit yield and shape per se resulted in improved hybrid performance of the NCWBS and NCBA1 populations for fruit yield and shape rating when tested in the selected or nonselected environment. The NCWBS population had the largest gain (21%) in hybrid performance averaged over all traits. In addition, early yield was improved an average of 18% from early to late cycles for each population. Even though the fruit yield and shape rating of 'Dasher II' was greater than the hybrid performance of each population mean for the same traits, several F_1 families within each population exceeded the fruit yield of 'Dasher II'.**

North Carolina is the sixth leading state in the production of slicing cucumber (*Cucumis sativus* L.) based on production area and dollar value, and cucumber is the second most important vegetable crop in North Carolina based on production area and dollar value (U.S. Dept. of Agriculture, 1996). Breeding efforts have focused on improving yield, earliness, fruit quality, disease resistance, and gynoecy. Although progress has been made for all of those traits, improvements in yield have been more difficult to achieve since it is quantitatively inherited and has low heritability.

Recurrent selection has been used to improve quantitatively inherited traits with low heritability through the accumulation of small gains in each selection cycle. In cucumber, recurrent selection methods such as half-sib and full-sib family and S_1 line selection have been effective for improving yield (Lertrat and Lower, 1983; 1984; Nienhuis and Lower, 1988; Wehner, 1989; Wehner and Cramer, 1996a; 1996b), improving herbicide resistance (Staub et al., 1991), improving disease resistance (Sloane et al., 1985), and increasing low-temperature germination ability (Nienhuis et al., 1983; Staub et al., 1988). Wehner and Cramer (1996b) reported a 37% gain in yield for a medium-based slicing cucumber population after 10 cycles of recurrent selection. In addition, early yield increased an average of 63% for three slicing cucumber populations after 10 cycles of recurrent selection.

Hybrid performance, resulting from crosses with a specific tester, has been used in cucumber in studies of recurrent selection for improved fruit yield (Nienhuis and Lower, 1988). In cucumber, hybrid performance in terms of fruit yield in the early stages of inbred development was correlated with late stages (Rubino and Wehner, 1986). The objective of this study was to measure the hybrid performance (using 'Poinsett 76' as a tester) for fruit yield, earliness, and shape in four slicing cucumber populations improved using modified half-sib recurrent selection.

Materials and Methods

POPULATION FORMATION AND SELECTION. Four slicing cucumber populations were begun at North Carolina State Univ., Raleigh, from 1981 to 1984. The North Carolina wide-base slicer (NCWBS) population consisted of 1165 cultigens (cultivars, breeding lines, and other accessions) intercrossed and selected for slicer types (Wehner, 1998a). A group of 143 slicer cultigens representing diverse but elite germplasm were intercrossed to form the North Carolina medium-base slicer (NCMBS) population (Wehner, 1998a). The North Carolina elite slicer 1 (NCES1) population consisted of eight elite slicer cultigens intercrossed from 1981 to 1982 (Wehner, 1998a). Eight middle-eastern ('Beit Alpha' or Mediterranean-type) cultigens were intercrossed to form the North Carolina Beit Alpha 1 (NCBA1) population (Wehner, 1998b). The NCES1 population had the highest mean performance for fruit yield and quality, the NCWBS population had the lowest mean performance, and the two other populations were intermediate in performance (Wehner, 1998a, 1998b). The populations were developed using modified intrapopulation half-sib recurrent selection to improve fruit yield, earliness, and fruit shape of the population (Wehner and Cramer, 1996b). Half-sib families were selected in the spring based on a simple weighted index (SWI), which was weighted (70%) toward yield traits (Wehner and Cramer, 1996b).

PLANT MATERIALS. Hybridizations between 'Poinsett 76' and each family of each population cycle combination were conducted in the greenhouses at North Carolina State Univ. In 1995, seven families from each population–cycle combination of NCWBS and NCMBS

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were self-pollinated to generate S_1 progeny. Those S_1 progeny were then crossed to 'Poinsett 76' (female parent). Four families from each population–cycle combination of NCWBS and NCMBS were derived from S_0 progeny. S_0 progeny were used because not enough families were selfed in time to conduct the designed experiment in 1995. There was no difference in hybrid performance using S_0 or S_1 progeny. For the NCES1 and NCBA1 populations, all 11 families from each cycle were derived from S_1 progeny and then hybridized to 'Poinsett 76'. In 1996, all 11 families of each population were derived from S_1 progeny before hybridization with 'Poinsett 76'. The three cycles chosen from each population were 0, 3, and 6 for NCWBS; 2, 6, and 10 for NCMBS; 1, 5, and 10 for NCES1; and 0, 4, and 8 for NCBA1. Those cycles were chosen because they were the earliest and latest cycles available in each population along with an intermediate cycle.

Experimental design. The experiment was a split-plot treatment arrangement in a randomized complete-block design with 22 replications in each of two seasons (spring and summer) in each of 2 years (1995, 1996). In North Carolina trials, seasons provide more information than locations and are just as effective as years (Swallow and Wehner, 1989). Whole plots were the four slicer populations, and subplots were three cycles (early, intermediate, late) along with a check ['Dasher II' (gynoecious hybrid) or 'Poinsett 76' (monoecious inbred)].

Plots were planted with 23 seeds on 17 May 1995 and 29 Apr. 1996 for the spring season and 13 July 1995 and 8 July 1996 for the summer season at the Horticultural Crops Research Station, Clinton, N.C. Plots were 1.2 m long with 1.2-m alleys separating the ends. Each field was surrounded by guard rows on the sides and plots on the row ends to provide competition for plants in the outside plots (Wehner, 1989). The plot size used in this study was based on plot size recommendations by Swallow and Wehner (1986) for the once-over harvest of pickling cucumber using paraquat. Large, multiple-row plots were not used because they are not as efficient as small, single-row plots (Wehner and Miller, 1990). Plot end borders were not used since they were found unnecessary for yield trials (Wehner, 1988) and it is easier to distinguish plots when they are separated by alleys. The soil type was a mixture (through the fields used) of Norfolk, Orangeburg, and Rains (fine-loamy, siliceous, thermic, Typic Kandiudults) with some Goldsboro (fine-loamy, siliceous, thermic, Aquic Paleudults). Recommended cultural practices were used throughout the experiment (Schultheis, 1990).

Plots were thinned to 16 plants (10 in Spring 1995 due to cool, wet conditions). The test plots were harvested 13 July 1995 and 27 June 1996 for the spring season and harvested 14 Sept. 1995 and 26 Aug. 1996 for the summer season. Once-over harvest was simulated by spraying the foliage with paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) at 0.6 $kg\cdot ha^{-1}$ when the checks had reached the 10% oversized (>60 mm in diameter) fruit stage (Strefeler and Wehner, 1986; Wehner, 1989; Wehner et al., 1984).

Data collection. Hybrids of 'Poinsett 76' by S_1 families were evaluated for total yield (number of fruit per plot), early yield (number of oversized fruit per plot), percentage marketable yield (total minus crooked-shaped and nubbined-shaped fruit as percentage of total), fruit shape rating, and a simple weighted index (SWI) (Wehner, 1982). Fruit shape rating reflected how straight, uniform, and cylindrical the fruit in a plot were, using a scale of 1 to 9, where 1 to 3 = poor, 4 to 6 = intermediate, and 7 to 9 = excellent (Strefeler and Wehner, 1986). The SWI was weighted 70% yield and 30% quality traits and was calculated as SWI = 0.1(total yield) + 0.3(early yield) + 0.02(% marketable) + 0.3(shape rating).

Data analysis. Plots from 1996 and Summer 1995 were corrected to 16 plants for plots with 8 to 15 plants (plots with fewer than 8 plants were considered missing). Plots from Spring 1995 were corrected to 10 plants per plot for plots with 5 to 9 plants (plots with fewer than 5 plants were considered missing). Fruit yield and shape were corrected by dividing by plant stand and multiplying by 10 or 16 depending on the season. Plots with low stands were eliminated from analysis to prevent extreme biasing during stand correction. Plant stands were corrected to reduce mean differences in yield and shape resulting from differences in stand. Currently, a better correction method does not exist for cucumber or other vine crops. The stand correction increased coefficient of determination values and decreased coefficient of variability values for most analyses. Data were analyzed using regression and analysis of variance from SAS (SAS Inst., Cary, N.C.). The used model assumed seasons and years as random effects and populations and cycles as fixed effects. Regression analysis was used to measure the response to selection. Checks were excluded from regression analysis, but were included with cycle means to make comparisons for useful progress.

Results

When means were calculated for each season and year over populations, cycles, and replications, large seasonal and yearly differences existed for total yield, early yield, and SWI (Table 1). Hybrid performance for total yield, early yield, and SWI was larger in 1996 than in 1995. Hybrid performance for percentage marketable yield and fruit shape rating remained constant over years. Hybrid performance for all traits except fruit shape rating was larger in the nonselected (summer) than in the selected (spring) environment. When means were calculated over years, seasons, cycles, and replications for each population, differences in trait means between seasons and years were larger than the differences in trait means between populations (Table 1). The NCMBS and NCES1 populations had the largest hybrid performance for fruit shape rating. Hybrid performance for early yield was the largest for the NCWBS and NCBA1 populations. There was no difference in hybrid performance for total and percent marketable yield and SWI between populations when averaged over years, seasons, cycles, and replications.

Hybrid performance for all traits increased from the early to the late selection cycles when means were calculated over years, seasons, populations, and replications (Table 1). Differences in trait means between seasons and years also were larger than the differences in trait means among cycles. Each population and cycle had a larger hybrid performance for total yield, early yield, and SWI than the mean of the same traits for 'Poinsett 76' averaged over years and seasons (Table 1). Hybrid performance for early yield of the NCWBS population was larger than the early yield of 'Dasher II' (Table 1). 'Dasher II' had a higher total yield, SWI, and fruit shape rating than any population or cycle. Of the five traits measured for hybrid performance, early yield had the greatest gain (18%) from early to late cycles averaged over populations. Total yield and SWI averaged 8% to 12% gain over selection cycles. Fruit shape rating and percent marketable yield gained an average of 4% with selection.

Since there were large differences in means between seasons, and since populations were improved using recurrent selection in the spring, population–cycle means were calculated separately for each season (Table 2). The early and intermediate cycle of the NCES1 population tested in the summer had the largest hybrid performance for total yield, larger than the total yield of 'Dasher II' and 'Poinsett 76' (Table 2). In addition, the intermediate and late cycles of the NCWBS and NCBA1 populations in the summer had the largest hybrid performance for early yield, larger than the early yield of 'Dasher II' and 'Poinsett 76'. The hybrid performance for percentage marketable yield was the largest when tested in the summer for cycle

Table 1. Mean values[z] of hybrid performance for number of total (total), early (early) and percent marketable (marketable) fruit, fruit shape rating (shape), and simple weighted index (SWI[y]) of families crossed with 'Poinsett 76'.

Effect	Total fruit (no.)	Early fruit (no.)	Marketable fruit (%)	Fruit shape rating	SWI
Grand	18.4	5.2	78.1	6.6	7.0
			Year		
1995	12.3	2.6	77.8	6.6	5.6
1996	24.2	7.8	78.4	6.5	8.3
F ratio	397.9***	297.5***	0.0	2.3	308.0***
			Season		
Spring	14.9	2.5	72.3	6.7	5.7
Summer	22.0	8.1	84.2	6.4	8.2
F ratio	103.5***	316.6***	146.9***	19.9***	230.2***
			Population		
NCWBS	18.2	6.1	76.0	6.3	7.1
NCMBS	18.5	4.5	81.1	6.8	6.8
NCES1	18.7	4.4	77.9	6.8	6.8
NCBA1	18.0	5.9	77.7	6.4	7.1
LSD 5%	1.2	0.6***	2.4	0.2***	0.3
			Cycle		
Early	17.2	4.8	76.3	6.4	6.6
Intermediate	18.7	5.5	78.1	6.6	7.1
Late	19.2	5.4	80.0	6.7	7.2
LSD 5%	1.0**	0.5*	2.1**	0.2*	0.3***
			Check		
'Dasher II'	21.8	5.4	80.9	7.4	7.6
'Poinsett 76'	16.5	3.6	79.7	6.6	6.4

[z]Data are means of 1056 (grand), 528 (year, season), 264 (population), 352 (cycle), or 176 (check) replications of 16 plants per plot.

[y]SWI = 0.1(total) + 0.3(early) + 0.02(% marketable) + 0.3(shape).

*,**,***Significant at $P = 0.05$, 0.01, or 0.001, respectively.

6 and cycle 10 of the NCMBS population and cycle 8 of the NCBA1 population. Cycle 1 of the NCES1 population tested in the summer had the largest hybrid performance for SWI. Several population–cycle combinations had comparable hybrid performance for fruit shape rating, but none were higher than the fruit shape rating of 'Dasher II'. In the spring and summer, most population–cycle combinations had a comparable or larger hybrid performance for total yield, early yield, and SWI than the total yield, early yield, and SWI of 'Poinsett 76'. In many instances, the total yield and fruit shape rating of 'Dasher II' was larger than hybrid performance for total yield and fruit shape of the population–cycle combinations.

Hybrid performance for early yield increased in the NCWBS and NCMBS populations when tested in either season (Table 2). Conversely, hybrid performance for early yield decreased in the NCES1 population from cycle 1 to cycle 10 in both seasons. Hybrid performance for SWI of the NCWBS population and for percentage marketable yield of the NCBA1 population increased from early to late cycles in both environments (Table 2). In addition, hybrid performance for percentage marketable yield in the spring and fruit shape rating in the summer increased with selection in the NCWBS population. In the NCBA1 population, hybrid performance for total yield in the spring and early yield in the summer increased from cycle 0 to cycle 8. Hybrid performance for SWI of the NCMBS population increased from cycle 2 to cycle 10 in the summer but remained constant in the spring (Table 2). When tested in either season, hybrid performance for total yield remained constant from early to late selection cycles in the NCWBS, NCMBS, and NCES1 populations. In the NCMBS and NCES1 populations, hybrid performance for percentage marketable yield and fruit shape rating remained constant over selection cycles when tested in either environment.

When the average gain over all traits was calculated for each population, the NCWBS population had the largest gain (21%) in hybrid performance from cycle 0 to cycle 6. The NCMBS and NCBA1 populations averaged 13% to 15% gain from early to late cycles in hybrid performance averaged over all traits. In contrast, the average hybrid performance over all traits decreased 11% from cycle 1 to cycle 10 for the NCES1 population.

Since most populations were superior to 'Poinsett 76' for fruit yield and shape rating, the two best F_1 families (based on SWI) were selected in 1995 and 1996 (11 different families were used each year) from each population–cycle combination and compared with the fruit yield and shape rating of 'Dasher II' and 'Poinsett 76'. Of the 48 families selected, 12 had a greater total yield and 18 had a greater early yield than 'Poinsett 76'. In addition, 10 families had a greater early yield than 'Dasher II'. Few families had a greater percent marketable yield or fruit shape rating than either 'Poinsett 76' or 'Dasher II'. Most families had fruit yield and shape rating comparable to 'Poinsett 76' or 'Dasher II'.

Discussion

Many of the responses of hybrid performance for fruit yield and shape rating were similar to the responses observed for fruit yield and shape rating per se in the same populations reported by Wehner and Cramer (1996b) (unpublished results). For example, the NCBA1 population had increases from early to late selection cycles in fruit yield and shape rating per se and in hybrid performance for the same traits in the selected (spring) and nonselected (summer) environments. For the NCES1 population, hybrid performance for total yield and SWI and both traits per se remained constant with selection when

Table 2. Mean values[z] and F ratios (cycles linear) of hybrid performance for total (total), early (early), and percent marketable (marketable) fruit, fruit shape rating (shape), and simple weighted index (SWI[y]) of families crossed with 'Poinsett 76' (along with 'Dasher II' and 'Poinsett 76' checks) in each population, cycle, and season.

Effect	*Cycle or comparison*	Total fruit (no.)	Early fruit (no.)	Marketable fruit (%)	Fruit shape rating	SWI
			NCWBS			
Spring	0	12.1	1.9	67.6	6.2	5.0
	3	19.1	4.2	72.6	7.0	6.8
	6	15.2	3.6	75.0	6.7	6.2
	F ratio	3.7	6.6*	5.0*	2.6	10.4**
	Dasher II	19.2	3.2	78.4	8.2	6.9
	Poinsett 76	9.2	0.3	63.7	6.8	4.8
Summer	0	19.1	7.2	78.3	5.4	7.3
	3	21.7	10.1	81.3	6.1	8.7
	6	22.2	10.1	81.9	6.1	8.7
	F ratio	3.8	6.6*	2.8	13.5***	9.6**
	Dasher II	23.1	6.0	80.3	6.8	7.8
	Poinsett 76	18.3	4.5	77.3	6.2	6.6
			NCMBS			
Spring	2	13.8	1.8	74.0	7.0	5.5
	6	14.3	2.3	72.9	6.7	5.6
	10	16.2	2.7	76.2	7.1	6.1
	F ratio	1.3	4.0*	0.0	0.1	1.9
	Dasher II	15.6	2.4	80.0	7.7	6.2
	Poinsett 76	8.1	0.6	74.3	6.9	4.5
Summer	2	20.1	5.2	87.0	6.6	7.3
	6	22.9	7.4	88.4	6.6	8.3
	10	23.6	7.3	88.0	6.6	8.3
	F ratio	3.7	5.5*	0.2	0.0	5.7*
	Dasher II	25.3	5.9	85.0	7.4	8.2
	Poinsett 76	22.8	5.1	82.0	6.7	7.8
			NCES1			
Spring	1	13.7	2.4	74.3	7.0	5.7
	5	11.7	0.5	69.5	6.5	4.7
	10	13.9	0.8	69.0	6.8	5.1
	F ratio	0.0	11.1**	1.6	0.8	5.2*
	Dasher II	19.9	3.9	81.4	8.1	7.2
	Poinsett 76	6.9	0.5	82.8	7.5	4.7
Summer	1	24.9	9.6	85.2	6.5	9.0
	5	25.8	6.2	85.2	7.1	8.3
	10	22.4	6.7	84.4	6.8	8.0
	F ratio	3.2	6.9*	0.2	2.7	5.5*
	Dasher II	23.3	6.6	76.5	6.8	7.9
	Poinsett 76	20.3	3.9	84.4	6.5	6.9
			NCBA1			
Spring	0	14.8	3.2	66.6	6.5	5.7
	4	12.6	3.0	70.7	6.1	5.4
	8	19.6	3.1	78.1	7.0	6.5
	F ratio	7.0**	0.4	11.0**	3.0	2.3
	Dasher II	22.1	5.9	82.6	8.1	8.1
	Poinsett 76	12.4	2.1	78.2	7.0	5.5
Summer	0	19.4	7.2	79.2	6.2	7.7
	4	21.4	10.0	84.5	6.3	8.7
	8	20.4	9.8	88.4	6.4	8.7
	F ratio	0.0	4.2*	5.2*	0.6	2.0
	Dasher II	25.3	8.7	83.7	6.7	8.8
	Poinsett 76	22.8	7.3	88.6	6.3	8.1

[z]Data are means of 44 (population-cycle) or 22 ('Dasher II', 'Poinsett 76') replications of 16 plants per plot in each season.
[y]SWI = 0.1(total) + 0.3(early) + 0.02(% marketable) + 0.3(shape).
*,**,***Significant at $P = 0.05, 0.01, 0.001$, respectively.

tested in both environments (Wehner and Cramer, 1996b). The lack of gain for total yield in the NCES1 population may result from the large amount of environmental variance and low heritability observed for total yield at the inception of that population (Strefeler and Wehner, 1986). In addition, early yield and fruit shape rating had large environment × additive interaction variance ($\sigma^2_{E \times A}$) and environment × dominance interaction variance ($\sigma^2_{E \times D}$) (Strefeler and Wehner, 1986), which may explain the gain in hybrid performance for early yield and fruit shape rating of the NCES1 population when tested in either environment.

In addition to our observation for hybrid performance, Wehner and Cramer (1996b) also observed an increase in the early yield per se of the NCMBS populations when tested in the nonselected environment. Other similarities exist between the responses over selection cycles of fruit yield and shape rating per se and the responses of hybrid performance for fruit yield and shape rating. For the NCWBS population, an increase in hybrid performance for SWI over cycles correlated with a similar increase in SWI per se in both environments (unpublished data). In addition, hybrid performance for early yield and early yield per se increased in the nonselected environment from early to late selection cycles but failed to increase in the selected environment (unpublished data). Hybrid performance for percentage marketable yield and fruit shape rating and both traits per se had different responses to selection depending on the testing environment (unpublished data).

In general, gains in fruit yield and shape rating per se over cycles were larger than gains in hybrid performance for fruit yield and shape rating averaged over the NCMBS, NCES1, and NCBA1 populations (Wehner and Cramer, 1996b). However, Wehner and Cramer (1996b) did not examine the NCWBS population in their study. Hybrid performance for early yield and early yield per se had the greatest gain of a trait when averaged over all populations.

For several populations (particularly the NCWBS population), more gain in hybrid performance was observed from the early to intermediate selection cycles than from the intermediate to late cycles. For the NCWBS population, mean performance for fruit yield and quality was low (compared to more elite material) at the formation of the population (cycle 0) (Wehner, 1998a). In addition, the NCWBS population possessed more genetic variability for yield and quality than elite material such as the NCES1 population. With low mean performance and large variability, large gains in yield and quality would be expected for the early cycles of selection.

The large differences in yield between seasons and years suggested environmental variance was influencing total and early yield in each population. In a uniformity trial conducted by Wehner (1984), the yield of 'Calypso' in one test varied from 9 to 35 fruit per 1.5-long plot. In addition, Strefeler and Wehner (1986) reported a large amount of σ^2_e for fruit yield and shape rating of the NCWBS, NCMBS, and NCES1 populations. In cucumber, narrow-sense heritability of fruit yield has been reported to be only 0.17 to 0.25 (Smith et al., 1978; Strefeler and Wehner, 1986). Thus, little of the variation in fruit yield is due to additive genetic variance.

Since recurrent selection for fruit yield per se was conducted in the spring, progress would be expected only in the selected environment (spring season). However, Wehner and Cramer (1996b) observed progress for fruit yield and shape rating per se when populations were tested in the nonselected environment. In addition, progress for hybrid performance for fruit yield or shape rating was also observed in the nonselected environment (summer).

Some of the differences in hybrid performance for early yield and fruit shape rating observed among populations could be related directly to the germplasm used to form each population and to the mean performance of each population at the initial cycle. The wide-based population was formed with diverse germplasm, with considerable variation for total and early yield and fruit shape but low mean performance (Wehner, 1998a). The elite population was formed with few cultigens having little diversity in fruit yield and quality and high performance (Wehner, 1998a). Since 'Poinsett 76' and 'Dasher II' are genetically related to the NCES1 population, they were expected to have similar performance. In addition, the fruit quality of the NCWBS population has not reached the level of the NCES1 population. Thus, very few F_1 families that exceeded the fruit quality of 'Poinsett 76' or 'Dasher II' were observed. For early yield, many families exceeded 'Dasher II' or 'Poinsett 76'. Most of those families were from the NCWBS and NCMBS populations. There was apparently much genetic variance for early yield in the NCWBS and NCMBS populations, but not in the NCES1 population.

Several F_1 families isolated from certain population–cycle combinations produced total and early yield that exceeded that of 'Dasher II'. In addition, percentage of marketable fruit and fruit shape rating of those families was comparable to 'Dasher II'. It may be possible to produce cultivars from the best families in these populations that outperform 'Dasher II' for marketable and early yield and have comparable fruit quality.

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