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Efficiency of Single-harvest Methods for Measurement of Yield in Fresh-market Cucumbers

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Abstract. **Three rapid methods of measuring yield (small plots harvested at the green stage, and single plants harvested at the green or at the mature stage) were tested for correlation with yield from a replicated multiple-harvest yield trial to determine how well they predicted performance of 10 hybrids in 1981, and 18 lines and cultivars tested in 1982. Only 2 methods of measuring yield were evaluated in 1981, small plots harvested once-over at the green stage and the standard replicated multiple-harvest trial. In that year, the most efficient method for measuring yield, based on capacity of the method to handle lines and to predict multiple-harvest trial performance, was 2 or 3 replications of 3 m plots harvested once-over. Those methods had a calculated advantage (relative capacity × correlation coefficient) of 43% to 80% over the replicated multiple-harvest trial. The most efficient method for measuring yield, of the 4 tested in 1982, was single plots with 1, 2, or 3 replications harvested once-over at the green stage. The tests had a calculated advantage of 102 to 107% over the replicated multiple-harvest trial, respectively. It was concluded that 2 or 3 replications in the test would provide the best results by controlling environmental variability without using an excessive number of seeds per family. In addition, the best correlation with yield in the multiple-harvest test was obtained when all fruit from the plot were counted, rather than just those of marketable size (38 to 60 mm diameter).**

Cucumber breeders usually test advanced hybrids for yield using a replicated multiple-harvest yield trial. Due to the large number of lines that must be handled each year, early evaluation of germplasm for yield usually is performed using an easier, more rapid method than multiple-harvest trials. Due to the similarity of flowering habit and selection methods, breeding procedures for maize (*Zea mays* L.) easily are adopted for use with cucumber. Thus, in the development of an efficient cucumber breeding program, it is useful to study the evolution of maize selection methods.

Maize breeding has developed from single-plant selection to selection based on one progeny row, and finally, to selection with control of environmental variability (12). Single-plant selection (mass selection) has been used with success in maize breeding when environmental variability was controlled. Gardner (2) divided his selection field into 40-plant blocks and selected the best 10% of the plants in each block, achieving a yield gain of 3.9% per year. Further control of environmental variability was obtained by replication of the genotypes over locations. Lonnquist (6) proposed a method of family selection in which maize populations were subjected to selection with testing of progeny rows at 3 locations that permitted one cycle of selection per year.

Methods for yield evaluation in cucumber populations involve either the evaluation of single plants, or of progeny rows, and involve either a single harvest, or multiple harvests. Selection for cucumber lines with high multiple-harvest yield capacity could be handled with the least effort for the plant breeder by measuring single plants at the mature fruit stage (seeds ready to harvest). By that time, the foliage has died back, and fruit counts can be made easily to estimate the yield of each plant. Seed of the selections also can be harvested then. With some additional effort, yield could be measured by counting fruit on single plants at the green stage. In this study, green stage was defined as 10% of the fruit > 60 mm diameter. The optimum stage for once-over harvest of pickling cucumbers is when 10% of the fruit are oversize (7); therefore, we used that as the harvest index for fresh-market cucumbers. Use of the method where fruit were counted at the green stage would require moving the vines to

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expose the fruit for data collection, flagging the best plants with a marker, and then harvesting seeds from the flagged plants at the mature stage.

The most accurate method for selecting plants for high multiple-harvest yield would be to evaluate the progeny in the same type of trial used for final evaluation of advanced hybrids, involving a large effort. A reasonable compromise between single-plant, single-harvest evaluation, and large plot, multiple-harvest trials would be the use of small plots harvested once at the green stage.

The single-harvest methods mentioned above permit more genotypes to be evaluated than in multiple-harvest trials (as estimated by the capacity of the North Carolina breeding program to handle lines in each type of test), but they may not predict yield accurately. Previous studies indicate some correlation between the yield variables of interest. For example, mature stage fruit number has been shown to be slightly correlated ($r = 0.36$) with processing stage fruit number (10), but it may not be high enough to be useful in selection of lines for yield. On the other hand, fruit number was highly correlated with fruit value in once-over harvested pickling cucumbers. Smith et al. (11) measured a genetic correlation of 1.01 and a phenotypic correlation of 0.78 between the 2 traits using a North Carolina Design I analysis. In another study, correlation of fruit number with fruit value ranged from 0.64 to 0.85 for the 3 harvests of a multiple-harvest trial, all of which were highly significant (10). In that study, fruit number from once-over harvest was not correlated with fruit value from a simulated multiple-harvest trial.

Plot size is an important consideration for efficient testing of many progeny rows or lines. Rectangular plots control field variability better than square plots of the same area (1). Optimum plot size can be calculated using the method of Smith (9), which has been shown to be a useful approximation for plot sizes commonly used in agricultural research (8). A modification of that method permits the use of yield trial data to calculate optimum plot size (4, 5). Using that method, the optimum plot size for pickling cucumbers harvested once-over was calculated to be 3.6 m^2 (1.5 × 2.4 m) for a trial in North Carolina (10). For that reason, we used a similar plot size (1.5 × 3 m) for the small-plot test.

The rapid methods for measurement of yield in cucumbers may be useful in the early stages of a selection program to eliminate families or lines with low yield potential. Those methods should not be used, however, unless they predict yield adequately in the replicated multiple-harvest trials used for final evaluation of lines. The objective of this study was to determine which method of measuring yield was the most efficient for rapid evaluation of breeding lines of fresh-market cucumbers.

Materials and Methods

The experiment was conducted for 2 years using small plots (1.5 × 3 m) in 1981, and using single plants harvested at 2 stages, in addition to small plots in 1982. The resources of the North Carolina breeding program were sufficient to handle 50 cultivars and breeding lines routinely in a replicated, multiple-harvest trial. Use of one of the 3 rapid tests for yield-evaluation (small plots harvested once-over, and single plants harvested at the green or at the mature stage) permitted a substantial increase in number of lines to be evaluated (Table 1). All plots were planted at the Horticultural Crops Research Station near Clinton, N.C.

1981 experiment. Two methods of measuring yield were evaluated the 1st year: small plots harvested once-over at the green stage, and large replicated plots harvested 7 times. Twenty diverse inbred lines of fresh-market cucumbers were paired at random to make 10 hybrids (Table 2). The hybrids were planted 10 June on raised, shaped beds 0.5 m wide and 1.5 m apart (center-to-center). Plots were overplanted and thinned to 40 plants in the small (3 m) plots and 100 plants in the large (7.5 m) plots for a population of 86,000 plants/ha.

The large plots were arranged in a randomized complete block design with 4 replications, and were harvested 7 times (twice weekly) from 23 July to 13 Aug. The small plots were planted in the same field with the large plots and then harvested once-over on 3 Aug. Fruit counts were made in the small plots to determine yield of total and marketable (total minus cull) fruit. Fruit from large plots were graded, weighed, and counted to determine yield of USDA grade Fancy, No. 1, No. 2, and cull

Table 1. Number of lines tested, selection differential, and relative capacity to handle lines for 4 methods of yield measurement.

Evaluation method	No. of replications	No. of genotypes tested[z]	Selection differential in standard units (k)[y]	Relative capacity[x]
Replicated, multiple-harvest yield trial	3	50	0.966	1.000
Small plots harvested at green stage	4	700	2.143	2.218
	3	850	2.353	2.436
	2	1150	2.466	2.552
	1	1700	2.602	2.693
Single plants harvested at green stage	1	4300	2.913	3.016
Single plants harvested at mature stage	1	14,300	2.357	3.475

[z]Estimated using the resources of the North Carolina State Univ. research project.
[y]Calculated under the assumption that 20 genotypes were selected out of the total number tested for each method.
[x]Capacity of each yield test relative to the replicated, multiple-harvest yield trial. Calculated by taking the ratio of the selection differentials.

Table 2. Yield of 10 hybrids tested in 1981 using a rapid method (small-plots harvested once-over) compared with the standard multiple-harvest method[z].

Parents of hybrid		Total yield		Marketable yield	
Female	Male	Multiple-harvest (MT/ha)	Once-over (No./plot)	Multiple-harvest (MT/ha)	Once-over (No./plot)
WIS 1397	Coolgreen	41	40	30	29
Gy 57u	Marketmore 76F	36	41	27	32
WIS 1321	WIS 1394	31	42	20	24
Tablegreen 72F	Poinsett 76	31	37	18	24
Marketer	Poinmarket	28	35	16	28
Ashley	Fletcher	26	40	15	16
Straight 8	Stono	25	29	15	24
Pacer	P-51	23	24	14	28
Palomar	Vaughn	21	21	14	14
WIS 1700	Aodai-Nazare	19	26	13	19
$\bar{x}$		28	34	18	24
LSD (5%)		8	11	8	10
CV (%)		20	21	30	28

[z]Data are means of 4 replications (summed over 7 harvests for the multiple-harvest trial). Plant population was 86,000 plants/ha.

fruit. Small plots were replicated 4 times in order to determine the effect of replication on the prediction value of the test.

1982 experiment. Four methods of evaluating yield were used in 1982, the same 2 as tested in 1981, plus single plants harvested at green stage (10% of the fruit > 60 mm diameter) and at mature stage (seeds ripe). Eighteen diverse lines and cultivars were evaluated using the 4 methods (Table 3).

Cultural practices were the same as for the 1981 experiments with the exception of the plot size used. The multi-harvest test used 60-plant plots 6 m long (62,000 plants/ha) arranged in a randomized complete block with 3 replications. The once-over harvest test used 30-plant plots 3 m long with 4 replications, and the single-plant tests used 30-plant plots 3 m long (to provide competition for the harvested plant) replicated 4 times. The tests were planted 19 Apr. in the same manner as described for the 1981 tests. The multi-harvest test was harvested 6 times (twice weekly) from 14 June to 1 July. The once-over plots were harvested 17 June, and the single-plant tests were harvested 17 June (green stage) and 12 July (mature stage).

Fresh-market cucumbers are harvested when they reach 38 mm in diameter, and are marketable up to 60 mm in diameter. Single plants and plots harvested once-over will produce a range of fruit sizes, however, from recently-pollinated ovaries to oversize fruit (> 60 mm diameter). In order to determine how to count fruit number to best predict yield in a multiple-harvest trial, fruit were separated into small (0 to 37 mm diameter) and large sizes (> 37 mm diameter) for all once-over harvested single plants and small plots. Total fruit number and number of large fruit from once-over harvest trials were analyzed for correlation with yield from the multiple-harvest trial to determine which was the better predictor.

Data analysis. A correlation analysis was run to compare fruit number from the 3 rapid test methods with the number and weight of total (Fancy, No. 1, No. 2 and cull grade), marketable (Fancy, No. 1 and No. 2) and quality (Fancy and No. 1) fruit from the replicated, multi-harvest trial. Yields from small-plot and single-plant tests were taken from each of the 4 replications and correlated with multi-harvest yield to determine the variability among replications. The above analyses also were run with replications combined to determine the effect of replication of small plots on the precision of yield estimation.

The advantage of the rapid tests (R) over the multiharvest test (M) was calculated using the formula for gain from selection (G) as follows:

$$\text{Advantage: } \frac{\text{Test}_R}{\text{Test}_M} = \frac{G_R}{G_M} = \frac{k_R\sigma^2_{A(R)}/\sigma_{P(R)}}{k_M\sigma^2_{A(M)}/\sigma_{P(M)}}$$

$$= \frac{k_R\sigma_{P(M)}b_{P(M)P(R)}2\sigma_{P(M)O}}{k_M\sigma_{P(R)}2\sigma_{P(M)O}}$$

$$= \frac{k_R\sigma_{P(M)P(R)}/\sigma^2_{P(M)}}{k_M\sigma_{P(R)}}$$

$$= \frac{k_R\sigma_{P(M)P(R)}}{k_M\sigma_{P(R)}\sigma_{P(M)}} = \frac{k_R}{k_M} \cdot r_{P(M)P(R)};$$

where k is the selection differential in SD; σ^2_A is the additive genetic variance; σ_P is the square root of the phenotypic variance; $b_{P(M)P(R)}$ is the regression of rapid test on multiharvest test phenotypes; σ_{PO} is the covariance of parent and offspring; $\sigma_{P(M)P(R)}$ is the covariance of rapid and multiharvest test phenotypes; and $r_{P(M)P(R)}$ is the correlation of rapid and multiharvest test phenotypes. See Hallauer and Miranda (3) for more detail on quantitative genetics and selection methods.

In order to calculate the advantage of the rapid tests over the multiharvest test, the ratio of selection differentials (k_R/k_M) and the correlation between the tests ($r_{P(M)P(R)}$) was calculated or measured. Correlations were measured from field data. The ratio of the selection differentials was calculated assuming 20 genotypes selected out of the total number tested. The advantage was then calculated by multiplying the correlation coefficient by the ratio of the selection differentials as shown in the equation above.

Results and Discussion

The 10 hybrids tested in 1981 differed in yield in both the once-over and multiple-harvest trials (Table 2). Fruit number in

Table 3. Yield of 18 cultivars and lines tested in 1982 using 3 rapid methods (single-plants or small-plots harvested once-over) compared with the standard multiple-harvest method[z].

Cultivar or line	Seed source	Multiple harvest of large plots (MT/ha)[y]		Once-over harvest of small plots (fruit/plot)[x]	Single-plant harvest (fruit/plant)[w]	
		Fancy + no. 1 + no. 2	Fancy + no. 1		Green stage	Mature stage
Verino	Sluis & Groot	69	56	64	2.7	2.7
Guardian	Northrup-King	61	51	30	3.3	2.0
HYB 5505	Moran Seed	61	50	39	3.3	2.0
Sprint 440 S	Asgrow Seed	58	46	55	2.3	2.3
Slicemaster	Petoseed	58	45	53	2.0	2.3
Centurion	Northrup-King	56	42	44	1.7	2.0
Raider	Harris Seed	55	44	48	2.3	2.3
Castlehy 2506	Castle Seed	53	41	55	2.3	1.3
Lama	Asgrow Seed	53	43	43	3.3	2.0
Dasher	Petoseed	52	41	38	1.7	2.0
Medalist	Harris Seed	52	43	25	2.0	2.0
Early Triumph	Petoseed	50	45	17	2.3	3.0
GRP6	Harris Seed	50	42	43	1.3	1.7
Jet Set	Asgrow Seed	48	40	33	1.7	2.0
Ashley	Asgrow Seed	39	30	19	1.3	2.7
SC 22	Clemson Univ.	39	34	20	1.7	1.7
Poinsett 76	Harris Seed	33	29	11	1.0	2.7
Marketmore 76	Asgrow Seed	29	28	3	0.7	2.0
$\bar{x}$		50	39	36	2.1	2.1
LSD (5%)		14	13	16	2.0	1.8
CV (%)		16	20	28	58	51

[z]All plots thinned to a density of 62,000 plants/ha.
[y]Data are means over 3 replications summed over 6 harvests.
[x]Data are means over 4 replications.
[w]Data are means over 4 plants grown in a competitive density.

once-over harvested 3 m plots was a very close estimate of relative performances of the hybrids in multiple-harvested 7.5 m plots. The range, CV, and LSD values for the hybrids in the 2 tests were very similar as well.

The 18 lines and cultivars, evaluated using the 4 yield test methods in 1982, performed much differently in the single-plant tests than compared with the small- and large-plot tests (Table 3). Yields of the 18 cultivars and lines in the once-over harvested small plots had a wide range, similar to the range in multiple-harvested large plots. The SD and LSD/Range for the 2 yield tests were similar, and the highest and lowest yielding lines were the same in both tests. On the other hand, the single-plant test harvested at maturity had no predictive value for yield in the multiple-harvest test. For example, one of the highest yielding lines in that test was the 2nd lowest in the multiple-harvest trials.

Fruit were divided into small and large size, according to diameter, in order to determine the effect of counting small fruit in the once-over harvests of single plants and small plots in 1982. The best predictor of yield was provided by counting all fruit from a once-over harvested plant or plot, rather than just those with a marketable diameter of 38 mm or greater (Table 4). The gain in predictive value especially was notable for single-plant data where harvest was made at the green stage. At the mature stage, however, there was no predictive value in either

Table 4. Effect of fruit size from once-over harvested small-plots and multiple-harvest yield.

Multiple-harvest yield variable[y]	Fruit size harvested from once-over tests	Correlation (r) of once-over yield with multiple-harvest yield test[z]		
		Small-plot yield test	Single plant yield test	
			Green stage	Mature stage
Marketable yield	All sizes	0.83	0.77	0.00
	Only >37 mm dia	0.77	0.07	−0.03
Quality yield	All sizes	0.72	0.80	0.05
	Only >37 mm dia	0.65	0.11	0.03

[z]Correlations run on data from all 3 replications for all tests in 1982.
[y]Marketable yield is Fancy + No. 1 + No. 2; quality yield is Fancy + No. 1.

Table 5. Relative capacity, correlation coefficient (r), and calculated advantage of handling lines with one rapid method of yield measurement compared with the standard method (replicated multiple-harvest trial with 7.5 m plots), 1981.

Evaluation method	No. of replications	Relative capacity to handle lines[z]	Correlation value (r)		Calculated advantage[y]	
			Total fruit	Marketable fruit	Total fruit	Marketable fruit
Replicated multiple-harvest trial	4	1.000	~1	~1	1.00	1.00
3 m plots harvested once-over at the green stage	4	2.218	0.77	0.62	1.71	1.38
	3	2.436	0.74	0.60	1.80	1.46
	2	2.552	0.70	0.56	1.79	1.43
	1	2.693	0.60	0.45	1.62	1.21

[z]See Table 1.
[y]Calculated advantage = (relative capacity) × (r).

measure of yield. Those results were fortuitous because the best method for measuring yield (total fruit count per plant or plot) also was the easiest.

The most efficient method of measuring yield of those evaluated in 1981 was 2 or 3 replications of small plots harvested once-over at the green stage (Table 5). The once-over harvested small plot tests with 2 or 3 replications offer a considerable advantage to cucumber breeders because of the additional capacity they provide for the evaluation of lines, estimated to be 79% to 80% better than the multiple-harvest trials in measuring total yield. The efficiency of the 2 or 3 replication test drops to 43% to 46% advantage over the multiple-harvest test in measuring marketable fruit, because of the lower correlation. The advantage of rapid methods of yield measurement led us to evaluate single-plant methods of measuring yield in 1982.

The method of using single plants harvested at the mature stage was not useful for yield evaluation. It was, by far, the method with the highest capacity to handle genetic material, but was not correlated with multiple-harvest yield (Table 6). Single plants harvested at the green stage, however, provided sufficiently good data to have a greater calculated advantage (48% better) than the multiple-harvest test. The major problem with using single-plant tests for yield is that it may not be possible to recover seed of the selected individuals. Cuttings can be taken of the plants, but the extra work required nullifies the advantage of this method. If the fruit are left on the plants during yield evaluation, however, the selected plants could be flagged and harvested at maturity for seed. That was the method on which we based our efficiency calculations.

The best method for efficient handling of test lines was 1, 2, or 3 replications of small plots harvested once-over. The 1, 2, or 3 replication small-plot test was twice as efficient as the multiple-harvest test. The calculated advantage ranged from 202% to 207%, depending on the number of replications used.

Based on the data collected, we suggest that initial selections be made in segregating material using 2 replications of small plots harvested once-over at the green stage (10% of the fruits oversize). After the initial evaluation, selections could be based on a similar test with 2 to 4 replications planted at slightly different times, or at different locations to sample more environments. Yield should be measured by counting all fruit in the plot in order to achieve the best correlation with marketable fruit yield in multiple-harvest trials.

The final evaluations of the breeding material should be within replicated, multiple-harvest trials conducted at several locations over several years to ensure that yield, earliness, quality, and stress resistance in the lines are enough to warrant release as cultivars. Yield in the once-over harvest tests is not sufficiently

Table 6. Relative capacity, correlation value (r), and calculated advantage of handling lines with 3 rapid methods of yield measurement compared with yield (weight of marketable fruit) from the standard method (replicated multiple-harvest trial with 6 m plots), 1982.

Evaluation method	No. of replications	Relative capacity to handle lines[z]	Correlation value (r)	Calculated advantage[y]
Replicated multiple-harvest trial	3	1.000	~1	1.00
3 m plots harvested once-over at green stage	3	2.436	0.83	2.02
	2	2.552	0.81	2.07
	1	2.693	0.75	2.02
Single plants harvested once-over at green stage	1	3.016	0.49	1.48
Single plants harvested once-over at mature stage	1	3.475	0	0

[z]See Table 1.
[y]Calculated advantage = (relative capacity) × (r).

correlated with the multiple-harvest test to be substituted completely. Also, the rapid tests do not necessarily provide adequate measure of earliness, quality, and stress resistance. The small-plot, once-over harvest test provides an excellent method for evaluation of families from recurrent selection, and for development of lines for use as hybrid cultivars.

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