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Inheritance of Non-Wrapper Leaf Number, Efficiency Index, and Non-Wrapper Leaf Size in Cabbage[1]

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Abstract. **A comparison of inheritance patterns and heritability estimates from a NCII crossing model which included green and red cabbage, *Brassica oleracea* L. Capitata group, indicated differences between green x green and red x green crosses. Green x green crosses exhibited dominance for few non-wrapper leaves, greater efficiency index, and smaller leaf size while red x green crosses showed the opposite dominance pattern.**

Although cabbage is widely grown and consumed throughout the world, genetic investigations of plant parts have been limited primarily to studies of head maturity, head weight, non-wrapper leaf number, dry matter, and various head dimensions of smooth leaf types of green cabbage. Both Pearson (11) and Yarnell (20) found low numbers of non-wrapper leaves were dominant. In addition, Pearson (11) noted that increased temperature promoted larger numbers of non-wrapper leaves at the expense of early head maturity. Chiang's (2) work suggested that significant environmental components contributed to produce a non-wrapper leaf number heritability estimate of 35%. Changes in the environment or cultural practices may lead to reduced leaf number. In contrast, Swarup and Sharma (18) found heritability estimates for non-wrapper leaf number and non-wrapper leaf size (area) were 52% and 74% respectively. Detjen and McCue (4) found that non-wrapper leaf size was directly related to head and stalk size and suggested that selection for one of these traits might lead to improvement in the other two.

Present genetic information for both red and savoy cabbage consists of models for red leaf color inheritance proposed by Sutton (17), Kristofferson (8), and Pease (12) and models for savoy leaf inheritance by Kwan (9), Rasmusson (14), and Tschermak (19). Currently, genetic improvement in red or savoy cabbage lines are based on research data from green cabbage with smooth leaves.

The purpose of this paper is to present the results of inbreeding tests, inheritance patterns, and heritability estimates for 3 traits in half-sib populations derived by crossing green or red cabbage with green cabbage.

Materials and Methods

Parental selection. During the summer of 1973 five commercially available open-pollinated cabbage cultivars were selected as previously described (16) using an efficiency index, EI = [total non-wrapper leaf weight + stalk size (weight)]/head weight. Single plant selections of the 2 most efficient and 3 least efficient cultivars were vernalized for 13 weeks at 4.4°C to induce flowering.

Crossing scheme. The North Carolina "Factorial" Design II (NCII) proposed by Comstock and Robinson (3) was chosen for this study because it yields the maximum amount of genetic information per family group evaluated (6, 13). Crosses and their reciprocals were made as previously described (16). Four F_1 seedlings of each cross were randomly selected, grown, vernalized and selfed to provide the F_2 population. Since a large amount of seed was required for this 2-year experiment each of the parent and F_1 plants were vegetatively propagated to increase flower and pollen production.

Original seedlots of each parental cultivar were grown in each planting and were designated the P_1 population. Each parent plant was selfed. The resulting seed produced the S_1 population which was grown in each planting. The parental populations P_1 and S_1 were analyzed to determine the effect of one generation of inbreeding. Using the NCII analysis, F_1 data provided estimates of genetic variance components and trait heritability for each field planting. Frequency distributions of the 12 F_2 populations were compared with the P_1 and F_1 distributions. Due to incompatibility, only a limited number of backcrosses (BC) were obtained.

Plantings. Three randomized complete block plantings were made: July 23, 1974 [P_1, S_1, F_1], June 3, 1975 [P_1, S_1, F_1, F_2, BC], and July 2, 1975 [P_1, S_1, F_1, F_2]. Each replication of each P_1 and S_1 population was represented by 20 plants per plot, each F_1 population was represented by 30 plants per plot. Within each plot, plants were spaced 0.46 m apart in rows spaced 0.92 m apart. In 1974, the harvest began October 26 and ended November 20. Plants were harvested at the ground line when the heads were judged firm by hand pressure. Individual plant parts, head, non-wrapper leaves, and stalk were separated and their fresh weights recorded. In addition, days to maturity, non-wrapper leaf number, cabbage plant efficiency, and mean leaf size (weight) were calculated. After harvest, other measures of maturity were used to obtain an objective measure of firmness at harvest time. These included: 1) pressure testing each cabbage head 4 times with a Magness-Taylor Penetrometer (10) and recording the pounds of force required for a 0.48-cm diameter probe to penetrate 1.3 cm into the head, and 2) use of the water displacement method to determine head volume and density. Penetrometer measurements increased to a peak and remained constant prior to overmaturity or bursting. In 1975, harvesting began on August 9 for the early planting and October 20 for the late planting. Aboveground plant parts were harvested when the mean of 2 penetrometer punches was equal to, or greater than, the appropriate parent or mid-parent penetrometer reading determined in 1974.

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Variance component analysis (ANOVA). Initial analysis of the F_1 data suggests significant differences exist between planting times, reciprocal crosses, and female parents for most traits. Appropriate ANOVA tests were made to find whether these mean differences were significant. Based on the results of these tests, the data were separated by planting time (3), reciprocal cross (2), and female parent (2) to provide 12 unique data groups. Each group represented data from 3 F_1 populations replicated 3 times. Within each data group, F_1 plants were related as paternal half-sibs. Variance component analysis was completed for each of the 12 data groups using one ANOVA based on unbalanced plot means to provide estimates of male and between-plot variance, and a second ANOVA based on individual data, to provide a single, combined estimate of ¾ additive genetic variance and environmental variance between full-sib related individuals in the same plot (1, 7). Use of the male variance (σ^2_s)and the variance from the second analysis (σ^2_w)provide estimates of heritability based on paternal half-sib data $h^2_s = 4\sigma^2_s/(\sigma^2_s + \sigma^2_w)$.In this study, heritability estimates greater than 1 and less than 0 were produced. Estimates of this type may arise due to sampling error inherent in estimates of a parameter whose real value is close to 1 or 0 (5). For each trait, 2 mean heritability estimates were calculated. The first estimate, $\bar{h}^2$,was calculated by pooling only heritability estimates between 0 and 1 using a weighting process described below. The second heritability estimate, $\bar{h}^2_x$, was calculated by pooling every heritability estimate, where estimates greater than 1 were set equal to 1 and estimates less than 0 were set equal to 0. Mean heritability estimates were pooled across years for both green x green and red x green cabbage crosses. The estimates were weighted and pooled using the following equation:

$$\Sigma[h^2/\text{SE estimate})^2]/\Sigma[1/(\text{SE estimate})^2], (15).$$

Results

Inbreeding. In this study, cultivar x inbreeding interactions were significant for the traits non-wrapper leaf number and efficiency index. These traits appear to be fixed in certain parental lines but not others. When inbreeding was imposed and non-wrapper leaf number was considered, cabbage cultivars responded in 1 of 3 ways. Both PI 215514 and 'Chieftain Savoy' showed no significant change in leaf number, while 'Badger Ballhead' and 'Red Danish' both produced significantly more leaves after inbreeding. In contrast, 'Baby Head' produced significantly fewer leaves after inbreeding. Efficiency index was also affected. One generation of inbreeding produced significantly poorer efficiency index readings in PI 215514, 'Red Danish', and 'Chieftain Savoy'. The remaining cultivars showed no significant change in efficiency index. Cabbage cultivars inbred 1 generation also responded differently when grown under different environments. Inbreeding produced no significant change in non-wrapper leaf size (weight). This result suggests that this trait was fixed in the population, assuming a mixture of additive and dominant gene control found in previous studies (18, 20). However, in the ab-

Table 1. Leaf number performance means for cabbage populations grown 3 times in a 2-year period.

Population	N	1974	DD[z]	N	1975E	DD	N	1975L	DD
1. Baby Head (P)[y]	105	8.25 ± 3.23		42	14.19 ± 2.52		53	3.08 ± 2.28	
Baby Head (S)[y]	90	6.10 ± 2.74		10	11.60 ± 6.75		37	1.89 ± 0.94	
2. Badger Ballhead (P)	94	18.28 ± 4.02		39	15.85 ± 3.99		49	10.14 ± 4.18	
Badger Ballhead (S)	89	18.75 ± 4.22		34	18.15 ± 5.06		43	13.05 ± 4.80	
3. P.I. 215514 (P)	3	24.00 ± 0.00		18	23.77 ± 3.86		13	19.23 ± 3.30	
P.I. 215514 (S)	61	23.41 ± 6.33		36	23.36 ± 6.68		20	21.50 ± 2.26	
4. Red Danish (P)	7	14.80 ± 2.49		35	16.43 ± 3.29		32	11.12 ± 2.20	
Red Danish (S)	8	21.71 ± 3.44		24	15.54 ± 2.80		26	18.38 ± 3.51	
5. Chieftain Savoy (P)	66	20.30 ± 4.85		34	16.94 ± 6.91		43	15.14 ± 5.34	
Chieftain Savoy (S)	34	20.20 ± 3.77		50	15.68 ± 4.57		23	12.65 ± 5.83	
F_1									
1 x 2	96	11.96 ± 3.10	1.30	83	16.57 ± 3.89	−1.55	38	9.55 ± 4.95	−2.94
2 x 1	101	11.81 ± 2.39	1.45	89	16.08 ± 2.83	−1.06	77	3.87 ± 2.45	2.74
1 x 3	101	13.57 ± 3.16	2.55	86	14.12 ± 3.69	4.87	73	7.88 ± 3.43	3.28
3 x 1	107	13.45 ± 3.27	2.68	70	13.88 ± 3.41	5.10	81	8.48 ± 3.02	2.67
1 x 5	99	18.18 ± 3.96	−3.91	52	12.52 ± 5.98	3.05	20	9.80 ± 3.22	−0.69
5 x 1	106	18.20 ± 4.55	−3.93	83	11.52 ± 4.65	4.05	59	7.24 ± 4.29	1.87
4 x 2	40	20.72 ± 3.05	−4.19	96	17.20 ± 3.05	−1.06	23	12.74 ± 2.51	−2.10
2 x 4	98	20.28 ± 3.01	−3.74	90	18.29 ± 2.84	−2.15	19	13.42 ± 2.67	−2.79
4 x 3	83	20.72 ± 3.41	−1.32	89	19.65 ± 3.63	0.45	14	15.00 ± 7.33	0.18
3 x 4	97	21.16 ± 3.49	−1.76	85	21.06 ± 3.25	−0.96	44	20.25 ± 3.51	−5.07
4 x 5	35	20.46 ± 3.74	−2.90	33	19.09 ± 2.71	−2.41	28	9.32 ± 2.16	3.81
5 x 4	28	21.39 ± 4.02	−3.84	80	19.68 ± 3.84	−2.99	30	8.57 ± 2.14	4.57
F_2									
1 x 2				252	13.73 ± 5.70	1.28	130	5.82 ± 3.78	0.79
2 x 1				248	12.84 ± 4.70	2.18	211	5.94 ± 3.82	0.67
1 x 3				259	13.38 ± 5.92	5.60	168	9.98 ± 6.23	1.18
3 x 1				451	13.26 ± 5.33	5.72	244	8.68 ± 4.85	2.47
1 x 5				192	11.39 ± 5.62	4.18	215	7.40 ± 4.63	1.70
5 x 1				197	14.57 ± 6.28	0.99	178	8.70 ± 6.34	0.40
4 x 2				209	19.24 ± 4.61	−3.10	291	14.43 ± 4.25	−3.79
2 x 4				154	19.03 ± 4.60	−2.89	30	13.60 ± 8.13	−2.79
4 x 3				---	--- ± ---	---	---	--- ± ---	---
3 x 4				311	21.49 ± 5.94	−1.38	---	--- ± ---	---
4 x 5				107	20.13 ± 5.13	−3.44	199	17.54 ± 5.64	−4.40
5 x 4				102	21.46 ± 5.58	−4.78	224	18.19 ± 5.91	−5.06

[z]Direction of dominance: positive values suggest that populations produced fewer leaves than were expected when compared to mid-parent means.
[y]P = sib-pollinated, S = inbred one generation.

sence of dominant gene control, additive genetic variation may be present even though population means do not change significantly with added inbreeding (7).

Non-wrapper leaf number. All interactions between the effects, cultivar, inbreeding, and plantings were significant at the 1 percent level. The large number of leaves produced by 'Baby Head' in the 1975E planting contributed to these interactions. Genetically, few non-wrapper leaves were dominant in crosses between 2 smooth green cabbage lines (Table 1). However, data from crosses between smooth green and red cabbage suggest many non-wrapper leaves were dominant. Crosses between smooth green and savoy green cabbage suggest non-wrapper leaf number was influenced by planting time. F_1 populations of 'Baby Head' x 'Chieftain Savoy' grown in 1974 produced 4 more leaves than the mid-parent mean. In contrast, the same populations grown in the 1975E planting produced 3–4 leaves less than the mid-parent mean. Thus, genetic models for non-wrapper leaf number (11, 20) should be modified to include dominance for many non-wrapper leaves if 'Red Danish' is used as a parent.

Efficiency index. The effects, cultivar, inbreeding, and planting combined to produce significant interactions. Poor efficiency index values for 'Baby Head' in the 1975E planting and 'Red Danish' in the 1975L planting contributed to these interactions (Table 2). Planting date also affects the interrelationship between plant parts. All 5 parents in the 1974 planting produced twice as much non-wrapper leaf and stalk weight per unit of cabbage head as they did in the 1975L planting (Table 2). A 30-day delay in planting, between 1975E and 1975L, resulted in a 25% decrease in efficiency index. Genetically, efficiency index was influenced by the use of 'Red Danish' as a parent. Crosses between 'Baby Head', 'Badger Ballhead', PI 215514, and 'Chieftain Savoy' indicate increased plant efficiency is controlled by dominant genes (Table 2). However, increased plant efficiency was recessive in crosses between 'Red Danish' and green cabbage cultivars. A comparison of the direction of dominance data for F_2 populations in Table 2 suggests that all populations produced fewer efficient plants in the late planting.

Non-wrapper leaf size (weight). While the leaf size of most cultivars decreased from 1974 to 1975L, the leaf size of 'Baby Head' remained unchanged (Table 3). Planting time also significantly effected the relationship between mid-parent means and F_1 or F_2 population means; 50% of the F_1 population grown in the 1974 planting produced population means heavier than the appropriate mid-parent mean (Table 3). In contrast, 83% were heavier in the 1975E planting and 25% were heavier in the 1975L planting. In 1975E and 1975L reversals of dominance occurred in F_1 populations of 'Baby Head' x PI 215514, 'Red Danish' x 'Bader Ballhead', and 'Red Danish' x PI 215514. In general, heavier non-wrapper leaves appear to be dominant, but this action may be masked by environmental effects.

Table 2. Efficiency index performance means for cabbage populations grown 3 times in a 2-year period.

Population	N	1974	DD[z]	N	1975E	DD	N	1975L	DD
1. Baby Head (P)[y]	105	0.33 ± 0.30		42	0.71 ± 0.25		53	0.17 ± 0.10	
Baby Head (S)[y]	90	0.19 ± 0.13		10	0.66 ± 0.52		37	0.12 ± 0.05	
2. Badger Ballhead (P)	94	1.12 ± 0.69		39	0.59 ± 0.40		49	0.35 ± 0.19	
Badger Ballhead (S)	89	1.36 ± 0.98		34	0.73 ± 0.31		43	0.85 ± 1.05	
3. P.I. 215514 (P)	3	1.68 ± 0.22		18	0.96 ± 0.32		13	0.87 ± 0.34	
P.I. 215514 (S)	61	2.70 ± 2.23		36	0.94 ± 0.47		20	0.90 ± 0.26	
4. Red Danish (P)	7	2.01 ± 0.98		35	0.90 ± 0.43		32	0.90 ± 0.50	
Red Danish (S)	8	3.96 ± 1.78		24	0.68 ± 0.26		26	4.43 ± 2.97	
5. Chieftain Savoy (P)	66	2.20 ± 1.08		34	0.56 ± 0.38		43	0.84 ± 0.46	
Chieftain Savoy (S)	34	3.39 ± 1.37		50	0.60 ± 0.24		23	0.78 ± 0.47	
F_1									
1 x 2	96	0.35 ± 0.17	0.38	83	0.74 ± 0.26	–0.09	38	0.33 ± 0.23	–0.07
2 x 1	101	0.32 ± 0.14	0.40	89	0.65 ± 0.22	0.00	77	0.35 ± 1.48	–0.09
1 x 3	101	0.51 ± 0.16	0.49	86	0.46 ± 0.20	0.38	73	0.30 ± 0.12	0.22
3 x 1	107	0.56 ± 0.36	0.44	70	0.43 ± 0.16	0.40	81	0.32 ± 0.10	0.20
1 x 5	99	0.87 ± 0.78	0.39	52	0.48 ± 0.36	0.16	20	0.32 ± 0.21	0.18
5 x 1	106	0.76 ± 0.42	0.51	83	0.36 ± 0.21	0.28	59	0.24 ± 0.18	0.26
4 x 2	40	2.90 ± 1.79	–1.34	96	0.79 ± 0.32	–0.05	23	0.84 ± 0.60	–0.22
2 x 4	98	2.62 ± 1.78	–1.06	90	1.00 ± 0.45	–0.26	19	1.09 ± 0.63	–0.46
4 x 3	83	4.34 ± 2.33	–2.49	89	1.12 ± 0.56	–0.19	14	1.34 ± 0.94	–0.45
3 x 4	97	2.99 ± 1.66	–1.14	85	1.27 ± 0.49	–0.34	44	1.98 ± 1.00	–1.09
4 x 5	35	3.56 ± 1.81	–1.46	33	0.90 ± 0.48	–0.17	28	0.84 ± 0.55	0.02
5 x 4	28	2.96 ± 1.64	–0.85	80	0.91 ± 0.42	–0.18	30	0.70 ± 0.32	0.16
F_2									
1 x 2				252	0.51 ± 0.72	0.14	130	0.27 ± 0.19	–0.01
2 x 1				248	0.56 ± 0.36	0.09	211	0.29 ± 0.23	–0.03
1 x 3				259	0.49 ± 0.27	0.34	168	0.66 ± 0.74	–0.13
3 x 1				451	0.47 ± 0.24	0.36	244	0.44 ± 0.84	0.08
1 x 5				192	0.38 ± 0.18	0.26	215	0.30 ± 0.23	0.20
5 x 1				197	0.45 ± 0.24	0.19	178	0.41 ± 0.49	0.09
4 x 2				209	0.91 ± 0.56	–0.17	291	1.29 ± 1.04	–0.67
2 x 4				154	0.96 ± 0.56	–0.22	30	1.04 ± 0.84	–0.42
4 x 3				---	--- ± ---	---	---	--- ± ---	---
3 x 4				311	1.34 ± 0.83	–0.41	---	--- ± ---	---
4 x 5				107	1.08 ± 0.55	–0.35	199	1.54 ± 1.17	–0.67
5 x 4				102	1.47 ± 1.26	–0.74	224	1.73 ± 1.28	–0.86

[z]Direction of dominance; positive values suggest that observed population means were more efficient than expected when compared to mid-parent means.

[y]P = sib-pollinated, S = inbred one generation.

Table 3. Leaf size (gm) performance means for cabbage populations grown 3 times in a 2-year period.

Population	N	1974	DD[z]	N	1975E	DD	N	1975L	DD
1. Baby Head (P)[y]	105	27.2 ± 11.2		42	26.5 ± 7.2		53	24.3 ± 17.6	
Baby Head (S)[y]	90	17.5 ± 8.1		10	30.9 ± 25.9		37	8.7 ± 4.6	
2. Badger Ballhead (P)	94	97.7 ± 28.3		39	79.2 ± 30.9		49	41.4 ± 13.2	
Badger Ballhead (S)	89	85.8 ± 19.2		34	66.5 ± 26.8		43	28.9 ± 9.0	
3. P.I. 215514 (P)	3	97.8 ± 14.6		18	94.2 ± 26.7		13	104.4 ± 31.1	
P.I. 215514 (S)	61	153.1 ± 43.3		36	99.1 ± 41.5		20	97.9 ± 42.2	
4. Red Danish (P)	7	124.6 ± 34.1		35	88.0 ± 34.6		32	56.9 ± 25.7	
Red Danish (S)	8	137.9 ± 26.2		24	79.0 ± 32.0		26	45.8 ± 8.8	
5. Chieftain Savoy (P)	66	127.4 ± 32.2		34	70.1 ± 27.7		43	43.6 ± 17.2	
Chieftain Savoy (S)	34	111.8 ± 26.1		50	82.9 ± 29.8		23	43.5 ± 17.9	
F_1									
1x2	96	55.1 ± 43.3	7.4	83	46.9 ± 15.6	6.0	38	31.4 ± 17.8	1.5
2x1	101	52.6 ± 10.8	9.9	89	44.9 ± 13.6	8.0	77	32.7 ± 12.8	0.2
1x3	101	97.3 ± 31.1	-34.8	86	72.3 ± 23.6	-12.0	73	37.6 ± 11.7	26.8
3x1	107	92.5 ± 21.6	-30.0	70	84.1 ± 27.2	-23.8	81	45.0 ± 15.0	19.4
1x5	99	85.6 ± 20.5	-8.3	52	67.7 ± 38.7	-19.4	20	37.4 ± 10.5	-3.5
5x1	106	77.3 ± 15.5	0.0	83	73.2 ± 25.9	-24.9	59	33.8 ± 10.9	0.1
4x2	40	109.1 ± 25.4	2.0	96	99.2 ± 26.0	-15.6	23	42.3 ± 12.5	6.9
2x4	98	106.2 ± 20.9	5.0	90	94.4 ± 29.6	-10.8	19	39.6 ± 8.7	9.6
4x3	83	130.1 ± 36.9	-18.9	89	112.7 ± 23.9	-21.6	14	54.2 ± 24.3	26.5
3x4	97	144.8 ± 38.0	-33.6	85	118.4 ± 29.9	-27.3	44	55.2 ± 22.9	25.5
4x5	35	133.8 ± 36.1	-7.8	33	120.2 ± 32.8	-41.2	28	96.4 ± 34.8	-46.2
5x4	28	139.6 ± 27.8	-13.6	80	110.5 ± 29.2	-31.5	30	101.0 ± 35.7	-50.8
F_2									
1x2				252	52.8 ± 26.8	0.1	130	26.8 ± 14.0	6.1
2x1				248	42.3 ± 23.0	10.6	211	26.6 ± 13.6	6.3
1x3				259	56.7 ± 24.4	3.7	168	35.0 ± 22.9	29.4
3x1				451	72.4 ± 28.2	-12.0	244	38.3 ± 61.6	26.1
1x5				192	63.4 ± 28.5	-15.1	215	33.5 ± 15.4	0.5
5x1				197	50.3 ± 21.0	-2.0	178	32.3 ± 44.2	1.7
4x2				209	76.4 ± 26.8	7.2	291	44.8 ± 16.1	4.4
2x4				154	77.2 ± 26.4	6.4	30	40.0 ± 23.5	9.2
4x3				---	--- ± ---	---	---	--- ± ---	---
3x4				311	99.5 ± 28.4	-8.4	---	-- ± --	---
4x5				107	99.2 ± 28.6	-20.1	199	49.7 ± 25.5	0.6
5x4				102	106.5 ± 37.2	-27.4	224	51.0 ± 19.1	-0.7

[z]Direction of dominance; positive values suggest that leaf size in grams was less than expected when compared to mid-parent means.
[y]P=sib-pollinated, S=inbred one generation.

Heritability estimates. Large additive genetic variances were estimated in green x green crosses while reduced additive genetic variances were estimated for red x green crosses (Table 4). For example, the heritability estimate for efficiency index in green crosses was 75%, while a similar estimate for red x green crosses was 35%. The large heritability estimates for green x green cabbage crosses imply that selection and sib-pollination might be applied with success. In contrast, the lower estimates of heritability for red x green cabbage crosses suggest hybrid production might be more efficient.

Discussion

The results of this investigation suggest that segregating generations produced by crossing red and green cabbage may not be compatible with genetic models proposed by previous researchers (4, 11, 20). Segregating generations produced by crossing smooth green cabbage cultivars exhibited dominance for few nonwrapper leaves and increased plant efficiency, whereas red x green crosses showed the opposite. For both sets of crosses, nonwrapper leaf size (weight) was shown to be larger in early plantings under warm conditions than when grown in cooler late plantings. At least 2 different genetic pathways were suggested to control the inheritance of economic traits in cabbage. The development of cabbage cultivars for specific seasons or planting conditions may be more useful commercially than attempting to develop a single cultivar for all seasons or conditions. The relatively large heritability estimates for green cabbage crosses suggest that inbreeding followed by hybrid production might produce cultivars with a better economic ideotype. Further investigation is needed to determine whether the observed changes in dominance are linked with red leaf color or savoy leaf texture.

Table 4. Mean heritability estimates.

	$\bar{h}^2$		$\bar{h}^2_x$	
Trait	Green	Red x Green	Green	Red x Green
Leaf number	0.67	0.50	0.90	0.51
Efficiency index	0.75	0.35	0.86	0.58
Mean leaf size	0.68	0.53	0.79	0.61

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Hydraulic Conductivity of Four Commercial Citrus Rootstocks[1,2]

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***Abstract*. The hydraulic conductivities of intact root systems of 4 commercial citrus rootstocks were estimated using a pressure chamber technique. The rootstocks used were rough lemon (*Citrus jambhiri* Lush.), sour orange (*C. aurantium* L.), Carrizo citrange [*Poncirus trifoliata* (L.) Raf. x *C. sinensis* (L.) Osb.], and Cleopatra mandarin (*C. reshni* Hort. ex TAN). Carrizo and rough lemon seedlings had the highest root conductivity, whereas Cleopatra and sour orange had the lowest root conductivity. Although these rootstocks as seedlings produce root systems in pots that differ from those in the field, some of the growth, yield, and drought resistance chartacteristics that have been previously assoicated with these rootstocks may be at least partially explained by the hydraulic conductivity of their roots.**

Citrus rootstocks can influence tree size (16, 18, 20), cold hardiness (21), relative wilting (10), leaf water potential (1, 6), transpiration rate (2, 16), fruit yield (11, 13), and juice quality (1, 9). Variations in citrus tree water relations that have been attributed to rootstocks are probably due to differences in root quantity, distrubtion (3) and/or apparent efficiencies in water uptake and transport (4).

Rough lemon (RL), a once-popular Florida citrus rootstock, is thought to be relatively drought-tolerant because of its extensive root system (3, 20). In addition, RL has higher stem conductivity (19) and transpiration rates (15), larger xylem vessels (14), and trees are larger on this rootstock than most other citrus rootstocks (3). Although Ramos and Kaufmann (17) described the effect of temperature on the hydraulic conductivity of RL roots, the hydraulic conductivity of RL roots has not been compared to that of other citrus rootstocks. Such comparisons should include the size and distribution of root systems as well as their water transport efficiency. Since many factors can influence root system development and hydraulic conductivity, any comparisons of different rootstocks must be made under uniform growth and measurement conditions.

The purpose of this study was to compare the growth characteristics and hydraulic conductivity of intact root systems of 4 citrus rootstocks commonly used in Florida. These data could then be used to determine whether potential differences in water transport capability could be used to interpret observed differences in the water relations of citrus rootstocks.

Materials and Methods

The plants used in this study were 6- and 12-month-old greenhouse-grown seedlings of RL, sour orange (SO), Carrizo citrange (Car), and Cleopatra mandarin (Cleo). All seedlings were raised in 4 x 21-cm plastic tubes filled with a commercial blend of peat, perlite, and vermiculite (3:1:1, v/v) with added nutrients (5). The seedlings received maximum irradiances of 700 $\mu E\ m^{-2}s^{-1}$ photosynthetically active radiation (400 to 700 nm) during natural photoperiods during the 12-month duration of the study. Temperature and relative humidity varied diurnally from 22 to 32°C and 40 to 100% respectively. The seedlings were kept well-watered and fertilized as needed.

After 6 months, a typical seedling had a stem diameter of 3 to 4 mm at the base and the root systemn had filled the small tubes. Root conductivity was measured on 3 replicates of each rootstock. In addition, 4 plants of each rootstock were transplanted into 12 x 20-cm plastic pots containing the same growth medium. After 6 additional months, these plants had a basal stem diameter

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