Goldman

Carrot Facts

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History

-- Carrots originated in Afghanistan and possibly northern Iran and Pakistan.
-- Queen Anne's Lace is wild carrot which interpollinates readily with carrot and occurs in disturbed ecological areas (roadsides, vacant lots, etc.) all around the world in temperate regions with adequate moisture.
--Domestication of carrots took the following path:

900 - 1000 AD:	Purple and yellow carrots had been spread from Afghanistan to the eastern Mediterranean.
1300s:	Purple and yellow carrots in western Europe and China
1600s:	Yellow carrots in Japan
1700s:	In addition to purple and yellow, white carrots were reported in Europe with an orange type first reported in The Netherlands and adjoining regions
Today:	Orange carrots predominate world-wide although some white types persist in western and eastern Europe (for livestock), some red (not orange) in Japan, some yellow and purple in the Mideast, and some purple, yellow, and red from Turkey to India and China

-- The US collection of carrot and its wild relatives is at the USDA Plant Introduction Station in Ames, Iowa. The USDA Carrot Genetics and Breeding Project is at the University of Wisconsin.

Consumption

-- Outside the US and Canada which consume Imperator type (long, thin) carrots, the rest of the world consumes shorter, thicker-rooted conical (Danvers or Chantenay type) and cylindrical (Nantes) carrots.
-- Carrots are worth approximately $300 million per year to US growers, with over half the production in California.

Nutrition

-- Carrots provide 30% of the vitamin A in the US diet.
-- Vitamin A is synthesized in the human metabolism by the breakdown of carotenes, the orange pigments in carrot roots. Vitamin A itself occurs in meat, liver, eggs, milk, and other animal products.
-- Over-consumption of vitamin A can be toxic to humans but over-consumption of carotenes is never toxic since carotene breakdown is well-controlled. Over-consumption of carotenes or carrots can give the skin an orange tone but this is not harmful.
-- Vitamin A deficiency is a significant world problem, especially in the developing world. The magnitude of human suffering fromVitamin A deficiency is comparable to that of protein deficiency and second only to caloric deficiency.
-- One crop of high-carotene carrots (twice the US carotene content) on one square meter of land produces enough carotene to provide an adult with all the vitamin A needed in a year.

Some additional Notes

- 30% of Provitamin A in Human Diet
- 60% of carrot crop in CA
- $88 million for seed crop value
- Not sensitive to photoperiod
  - Temperate + tropical crops
    ⇓
    Kuroda, Nantes

  Main diff is vernal. Requirement not photoperiod

- Energy production
- Public programs
  - USDA, UW, Texas A&M

- Wild carrot is actually a winter annual; will flower in spring; Native to Europe; came over as a weed; could have gone feral from cultivated material

Commercial Value of the World Carrot Seed Crop

P.W. Simon, Department of Horticulture, 1575 Linden Drive, Madison, WI 53706

The commercial value of the world carrot seed crop is not well-documented. To obtain an estimate of this value, a survey was taken of 24 vegetable seed companies in North America, South America, Europe, and Asia. Thirteen of these companies completed and returned the survey.

Surveys were sent to carrot breeders or research directors (one per company) in 1995, with instruction to complete the accompanying table with the U.S. dollar value of the seed crop (what growers pay) and hectarage planted for each of the root classes listed. Responses requested were not for their individual company's market share but rather for the estimate of the entire world carrot market. They were invited to seek input from sales, production, and other personnel in their company.

Estimates of commercial sales markets were included. Therefore, state-run seed production operations outside the normal commercial markets (as may exist in some former U.S.S.R. states or parts of Asia) would not be included in these estimates. Similarly, local productions for regional dissemination would not be included in these estimates. The former source of carrot seed (state-run operations) could be sizeable but the latter (local production) probably is not.

The 1995 worldwide commercial value of the carrot seed crop was estimated to be $88 million (U.S.). About half of the seed value and area was in Nantes types for Europe and Asia. About 25% of the value but only 10% to 15% of the area was in Imperator types for North America and Australia. Value estimates generally had a two-to-three fold range among respondents. World production area estimates made by respondents were slightly lower than FAO values. Survey estimates for Africa were especially low whereas those for Asia, South America, and Australia were high.

Umbelliferae Improvement Newsletter 1995

World carrot seed value (M = US$ 1 million, r = range of value in responses) and root production area (H = hectare) by geographic region and root class.

Root Class	World	Africa	North America	South America	Asia	Europe	Australia	Former USSR
Imperator-Cello	$\bar{x}$ = 14M 50,000H		$\bar{x}$ = 11M r = 6-14 40,000H				$\bar{x}$ = 3M r = 1-4 10,000H	
Imperator-Cut & Peel	$\bar{x}$ = 10M 20,000H		$\bar{x}$ = 10M r = 5-12 20,000H					
Processing-Slicer	$\bar{x}$ = 1M 4,000H		$\bar{x}$ = 1M r = 0.5-1.5 4,000H					
Processing-Dicer	$\bar{x}$ = 1.5M 4,000H		$\bar{x}$ = 1.5M r = 1-2 4,000H					
Nantes	$\bar{x}$ = 46.5M 366,000H		$\bar{x}$ = ½M r = 0-1M 2,000H	$\bar{x}$ = 2M r = 1-3 80,000H	$\bar{x}$ = 14 r = 7-17 200,000H	$\bar{x}$ = 29M r = 15-42 80,000H	$\bar{x}$ = 1M r = ½-2 4,000H	
Berlicum/ Amsterdam/ Flakee	$\bar{x}$ = 6M 20,000H					$\bar{x}$ = 6M r = 2-14 20,000H		
Kuroda	$\bar{x}$ = 9M 32,000H	$\bar{x}$ = 1M r = 0-2 2,000H		$\bar{x}$ = 4M r = 3-5 10,000H	$\bar{x}$ = 4M r = 3-4 20,000H			
Value	88M	1M	24M	6M	18M	35M	4M	
Total Area in hectares/1000 (this survey)	496	2	70	90	220	100	14	
Total Area in hectares/1000 (FAO Yearbook)	632	66	61	36	160	140	6	160

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Table 1. World carrot production 1961-1993. Area = 1,000 hectares harvested, Prod. = 1,000 MT produced.

	World		Africa		N & Cen. America		South America		Asia		Europe		Oceania		USSR		Developed		Developing	
Year Avg 3 yr	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.	Area	Prod.
1963	189	4226	15	165	39	922	13	167	16	447	103	2443	3	82	40	738	116	3109	34	379
1970	415	7908	19	214	41	1099	19	281	116	1776	118	3049	4	117	97	1371	286	6169	129	1739
1975	459	8747	25	291	42	1241	21	322	125	2078	120	2906	4	126	121	1782	310	6585	149	2162
1980	515	10499	31	383	46	1328	27	465	142	2677	129	3591	5	141	136	1914	338	7616	178	2884
1985	558	12156	35	416	53	1480	30	545	163	3369	134	4043	5	158	139	2443	351	8764	208	3692
1990	617	13696	43	558	56	1773	34	630	181	4003	143	4304	6	193	154	2233	379	9183	239	4512
1994	666	14176	66	739	64	1958	40	685	179	4075	143	4535	6	229	---	---	---	---	---	---

Source: FAO Yearbook Production Statistics; China and Asian USSR not included in 1963 estimate; Nigeria not included before 1985; former USSR included in Asia and Europe for 1994.

U.S. Seed Production of Umbelliferous Crops, 1940-1980

Year\Crop	Carrot	Celery	Parsley	Parsnip	Dill
1940	3900/1290	66/34	250/220	260/180	48/23
1945	7280/2630	102/44	335/230	260/190	81/36
1950	2550/1220	58/37	147/121	88/75	34/20
1955	1560/840	28/23	130/110	57/55	23/14
1960	1600/810	50/32	140/70	70/50	20/19
1965	1840/830	20/14	110/90	50/40	----
1970	1570/1130	40/35	140/100	50/40	----
1975	2350/1440	70/40	100/85	50/35	----
1980	1900/1100	35/15	210/120	45/25	----

Source: USDA Agricultural Statistics. Values in acres harvested/1000 pounds produced. These values were not included in USDA Agricultural Statistics after 1980.

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1950	2550/1220	58/37	147/121	88/75	34/20
1955	1560/840	28/23	130/110	57/55	23/14
1960	1600/810	50/32	140/70	70/50	20/19
1965	1840/830	20/14	110/90	50/40	----
1970	1570/1130	40/35	140/100	50/40	----
1975	2350/1440	70/40	100/85	50/35	----
1980	1900/1100	35/15	210/120	45/25	----

Source: USDA Agricultural Statistics. Values in acres harvested/1000 pounds produced. These values were not included in USDA Agricultural Statistics after 1980.

U.S. carrot and celery production, consumption, and value 1925 - 1993

	Carrot							Celery			
Year Avg 3 yr	Area (1000 ha)	Production (1000 MT)	Value ($$10^6$)	Consumption (Kg/yr/capita) Fresh	Canned	Frozen	Total	Area (1000 ha)	Production (1000 MT)	Value ($$10^6$)	Consumption Fresh (Kg/yr/capita)
1925	6	100	3	2.0	---	---	2.0	10	258	13	3.1
1930	14	258	7	3.1	---	---	3.1	14	421	18	4.0
1935	17	299	8	3.5	0.1	---	3.6	15	390	16	3.8
1940	25	439	14	3.2	0.1	---	3.3	17	476	23	3.6
1945	38	738	40	4.7	0.2	---	4.9	18	530	52	3.7
1950	35	675	43	3.8	0.2	(+)	4.0	15	607	50	3.9
1955	32	698	57	3.5	0.2	0.1	3.8	14	702	53	3.9
1960	32	747	57	3.2	0.2	0.2	3.6	14	689	49	3.6
1965	33	770	63	3.0	0.3	0.2	3.5	13	639	66	3.1
1970	31	834	80	2.7	0.3	0.3	3.3	13	711	86	3.3
1975	30	924	121	3.0	0.3	0.4	3.7	13	743	115	3.3
1980	34	978	177	3.1	0.2	0.5	3.8	15	838	177	3.4
1985	36	1060	229	3.5	0.4	1.1	5.0	14	824	210	3.3
1990	40	1332	301	3.5	0.4	1.2	5.1	14	899	229	3.3
1993 (prelim)	42	1436	296	3.8	0.5	1.3	5.6	12	797	261	2.8

Source: USDA Agricultural Statistics; canned and frozen per capita values given on processing weight basis before 1985, on farm weight basis after 1980.

FAXED 2/18/97

FAX

February 18, 1997

TO: **BRYAN RENK and PAULANNE CHELF, WARF**

FROM: **IRWIN GOLDMAN**

This Fax Contains ___8___ Pages, including cover

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College of Agricultural and Life Sciences

February 18, 1997

Dear Bryan and Paulanne:

The world carrot seed market is estimated at $88 Million and the United States carrot crop itself is valued at $300 Million, according to figures put together by Phil Simon of the USDA-ARS (see attached documents).

The cut-and-peel baby carrot market seems to be expanding all the time and there is great interest in new products. A new trade magazine called *Carrot Country* lists a number of the newest trends in carrot production in the US, and if you are interested I have many of the issues here in my office.

Thanks again for all of your help.

Look forward to seeing you again soon,

Irwin Goldman

Goldman

Carrots

Acreage: 95-108,000

Farm Value: $250-330 million annually

Crop: 75% fresh market, 25% processed; cultivars are hybrids, often adapted for use in many U.S. production areas

Export Value: 5%

Breeding Effort: 3 public programs (ARS, Wisconsin, Texas), 10-13 private seed companies. This ARS program contains 0.9 out of 1.5 total public FTE's U.S.Per Capita Consumption: 4.0-4.5 kilos (increasing slightly)

A. Production Efficiency

1) Newly available carrot germplasm from the Far East and Mideast will contribute genetic characteristics which reduce root color defects (yellow core or cambium, green shoulder), impart early maturity and allow carrot production into warmer spring weather of California, Florida, and Texas. Genetic variation is available to impart stronger tops, thereby improving the efficiency of mechanical harvesting (since carrots are mechanically harvested by lifting the top). Improved production efficiency with lower producer costs will result as the carrot germplasm base is broadened.

2) Improved germplasm capable of higher seed yields in cold spring and hot summer production conditions will assure steady seed supplies with the development of more stable cytoplasmic male sterility.

B. Disease Resistance - It is estimated that 8% of the carrot crop is lost to disease.

1) Continued selection for resistance to Alternaria leaf blight and motley dwarf plus an opportunity to improve resistance to nematodes, cavity spot and root dieback pests will reduce disease losses and the threat to consumer health and the environment due to pesticides.

2) Resistance to nematode resistance (especially southern nematodes) occurs in unadapted and foreign carrot germplasm. Incorporation for resistance in U.S. cultivars will permit continued carrot farming in major production areas where nematicides are or soon will be banned.

3) Newly developed method for selection to postharvest soft rot resistance will yield germplasm capable of longer storage to extend carrot availability for domestic use and to improve export quality.

C. Quality

1) Carrots provide 30% of the U.S. vitamin A supply and have the highest level of carotene (a potent cancer protectant) of any U.S. natural food. New germplasm including domestic and foreign breeding stocks could easily triple carrot carotene content from 90 to 270 ppm. ARS experimental stocks with over 900 ppm carotene are available. Human nutrition could be improved by incorporating high carotene content into new broadly based germplasm. Carrots with 300 ppm carotene costing $.30 per pound could provide 100% of the adult RDA of vitamin A for 1.8 per day.

2) Fresh carrot flavor can be genetically improved by increasing sweetness and reducing harsh, chemical flavor. Carrot consumption can be increased and their nutritional benefits realized as a consequence of flavor improvement. Increased sweetness in raw carrots is also conferred to the processed product. Several new raw carrot snack products with high carotene content and excellent flavor are being commercially tested.

3) Knowledge of the genetics of carrot sugar storage and availability of unique germplasm has generated interest in expanded uses for carrot. Marketing trials are underway to evaluate carrot deep-fried chips, dehydrated carrots, and carrots as a biomass or sugar crop.

D. Related Basic Research

1) Development of a carrot RFLP linkage map
2) Relationship of gene expression in whole plants and tissue culture for selecting high carotene in culture.
3) Evaluation of Daucus germplasm for genetic markers
4) Biochemistry of sugar, carotene, and volatile terpenoid biosynthesis

J. ASoc. Hort. Sci. 111(6):965–968. 1986.

Atomy of Fertile and Male-sterile Carrot Flvers from Different Genetic Sources

B. ler Struckmeyer[1] and Philipp Simon[2]
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Addil index words. *Daucus carota*, partially fertile, petaloidy, brown anther sterility

Absr. An anatomical comparison of florets from fertile, brown anther partially fertile, petaloid male-sterile, and 3 bra anther male-sterile carrot (*Daucus carota* L.) lines indicated that most pollen was well-developed and deeply stain in fertile lines. Partially fertile plants contained fertile and sterile anthers in which meiosis had occurred. The 3 linof brown anther steriles examined failed to enter meiosis. In early development of the fine foliage brown anther steril all cells of the anther, including sporogenous cells, hypertrophied. Later, sporogenous tissue collapsed. The anatonical structure of the stamens in petaloid florets was leaf-like and similar to petals.

Study of genetic and anatomical characterization of brown anther and petaloid types of genic–cytoplasmic male sterility in carrot indicates that brown anther cytoplasm conditions anther degeneration before anthesis and consequently results in male sterility (17). Anatomical analysis disclosed enlargement of tapetal cells at the tetrad stage in genic sterile plants and subsequent breakdown of tapetal cells to form a plasmodium. Meiosis was normal in sterile plants, but anthers subsequently collapsed (18).

Petaloid male sterility in several genetic stocks of carrot results in flowers with stamens transformed into petal- or leaf-like structures without sporogenous tissue (3, 10, 15). Genetic analysis of the maintenance of male sterility in both the brown anther and petaloid types suggested control by at least 2 genes (1, 5, 6, 13).

This study examined 2 new male-sterile carrot stocks found in the course of genetic studies. Meiosis, pollen, and tapetal development were evaluated in brown anther and petaloid male-sterile stocks and in stable fertile and brown anther partially fertile stocks to compare the manifestations of male sterility from different genetic sources.

Materials and Methods

Carrot plants were grown in 1982 and 1983 in Palmyra, Wis. Roots were vernalized at 3°C for 8 weeks, and plants then were grown in the greenhouse at Madison, Wis. with supplemental fluorescent lighting (12-hr days, 125 $\mu mol \cdot s^{-1} \cdot m^{-2}$). Genetic stocks included plants from partially fertile B9304 (maintainer cytoplasm), cytoplasmic petaloid male sterile B3615 (established by backcrossing into Cornell cytoplasm), and cytoplasmic brown anther male-sterile B9668 (established by backcrossing into Tendersweet cytoplasm), developed by C.E. Peterson, USDA, Univ. of Wisconsin–Madison. The male-fertile line, C60-1, and 2 new male-sterile stocks of the brown anther phenotype were examined. The F_1 hybrid, B493 x HC271, was completely male-sterile, even though both parents were tested fertile lines. One F_1 plant was pollinated with an unrelated inbred, and the resulting sterile and fertile progeny (5 sterile/4 partially fertile) were examined. Test crosses with these plants suggested that male sterility may be controlled by several nuclear genes without involvement of a brown anther cytopla[...] new male-sterile stock was a single plant found by [...] Univ. of Florida, Gainesville in an open-pollinat[...] derived from 'Hicolor 9'. It was selected because [...] finely-divided leaves and was later found to be [...] (probably unrelated to the foliage). This line is re[...] the fine-foliage male-sterile. This plant was propag[...] ally and multiplied by tissue culture, and the resu[...] were used as the female parents in crosses with B49[...] and B10138. The fine-foliage male-sterile plant, its [...] sterile progeny from the crosses with B493 and B930[...] uniformly fertile progeny with B10138 were examine[...]

Center and peripheral umbellets from primary and se[...] umbels, which provide the early and advanced stages [...] development, were fixed in formalin-aceto-alcohol (FA[...] umbellets were dehydrated through a n-butyl alcohol ser[...] embedded in paraplast. Sections were cut 10 µm and s[...] with safranin, crystal violet, and light green SF yellowis[...]

Results and Discussion

Examination of the staminal structure of the floret from fe[...] line C60-1 indicated a male-fertile floret with 5 petals, 5 [...] mens, and the ovary (Fig. 1A). After meiosis, nearly all of [...] pollen grains were plump and deeply stained. Tapetal cells h[...] disintegrated, and the endothecium was normal (Fig. 1B).

The partially fertile carrot line B9304 showed a high inc[...] dence of sterile pollen similar to partial fertiles described b[...] Hansche and Gabelman (6). Some locules had misshapen, shri[...] veled, and lightly stained pollen grains; others had a mixture of [...] fertile and sterile pollen. More locules had all sterile pollen than [...] a mix of fertile and sterile. Tapetal cells were disintegrating at [...] the periphery of the locule. Large endothecial cells had tangential and anticlinally thickened walls (Fig. 1C).

Partially fertile plants in the segregating population derived from B493 x HC271 had sterile and fertile anthers. In sterile anthers, meiosis had occurred, but pollen grains were shriveled and lightly stained. Tapetal cells were disintegrating, and endothecial cells were thin-walled (Fig. 1D). In the same umbellet were florets with anthers containing nearly all plump and darkly stained pollen grains. In these, the tapetum had disintegrated and the endothecial cells had anticlinal and inner tangetial wall thickenings (Fig. 1E). Sterile plants in this population (Fig. 1F) were at the same stage of development as the partially fertile plant from which samples were taken in Fig. 1D. Unlike the carrot population segregating for genic sterility examined by Zenkteler (18), meiosis had not occurred in sterile plants derived from B495 x HC271. The endothecium had thi[...]

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[2]Associate Professor and Research Geneticist, ARS/USDA.

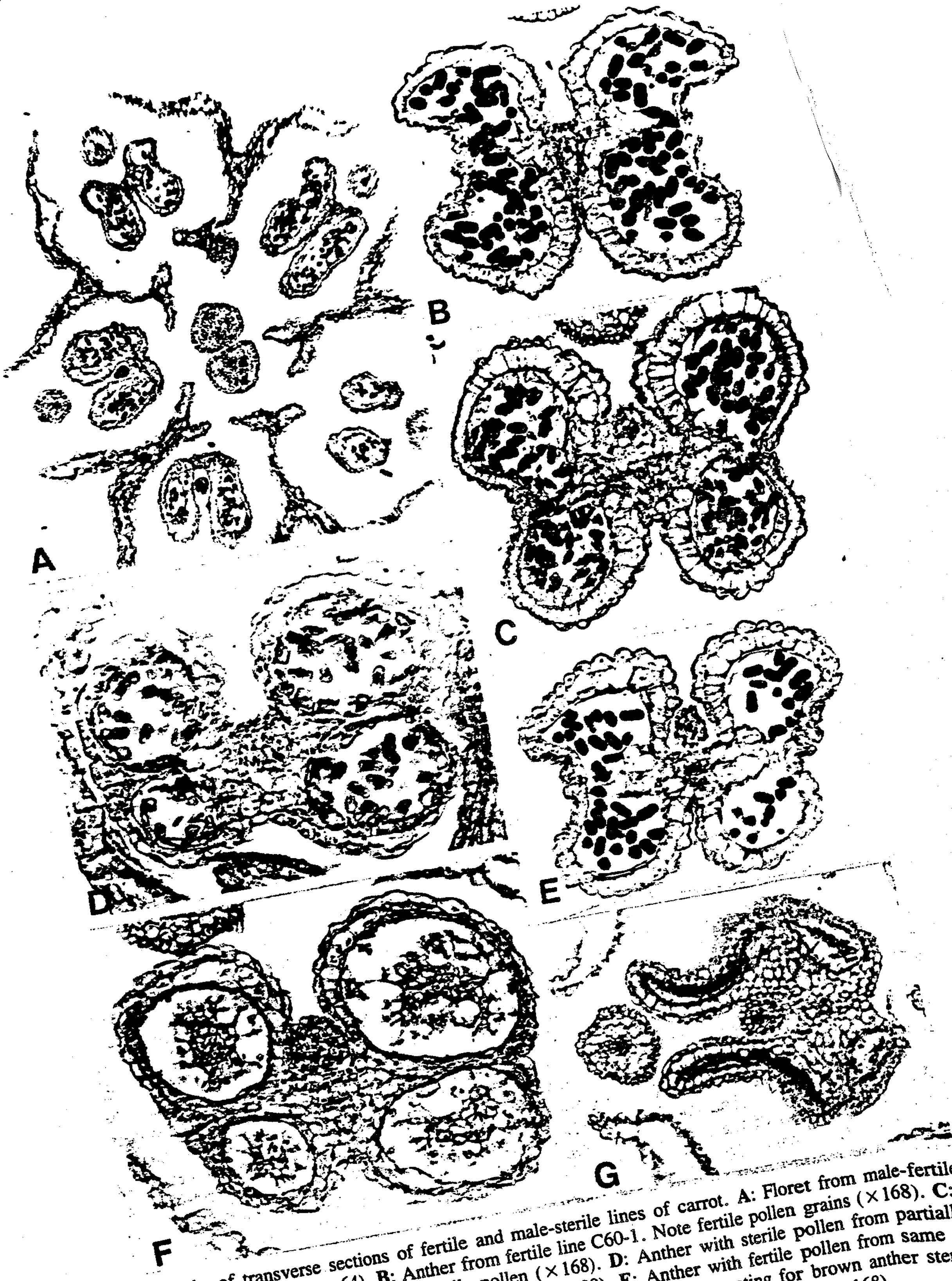

Fig. 1. Light micrographs of transverse sections of fertile and male-sterile lines of carrot. **A**: Floret from male-fertile line C60-1 showi upper part of the floret and split style (×64). **B**: Anther from fertile line C60-1. Note fertile pollen grains (×168). **C**: Anther from partia fertile line B9304. Note mixture of fertile and nonfertile pollen (×168). **D**: Anther with sterile pollen from partially fertile plant deri from B493×HC271 where sterility is the result of nuclear genes (×280). **E**: Anther with fertile pollen from same plant as **D** (×168) Young anther in floret from sterile plant derived from B493×HC271 population segregating for brown anther sterility. Meiosis faile occur (×280). **G**: Anther from same plant as **F** at a later stage showing collapse of locular contents (×168).

ing an early stage of differentiation. The tapetum and sporogenous cells had atrophied prior to the usual spore mother cell formation (Fig. 1F). At a later stage of development, the anthers collapsed and the tapetum and sporogenous cells were obliter- [illegible] f darkly staining material (Fig. 1G). Plump,

stainable pollen was not found in primary or secondary un of sterile plants.

The fine foliage brown anther sterile discovered in 'H 9' differed from the brown anther sterile derived from B HC271 in having an endothecium with thick and hypertr

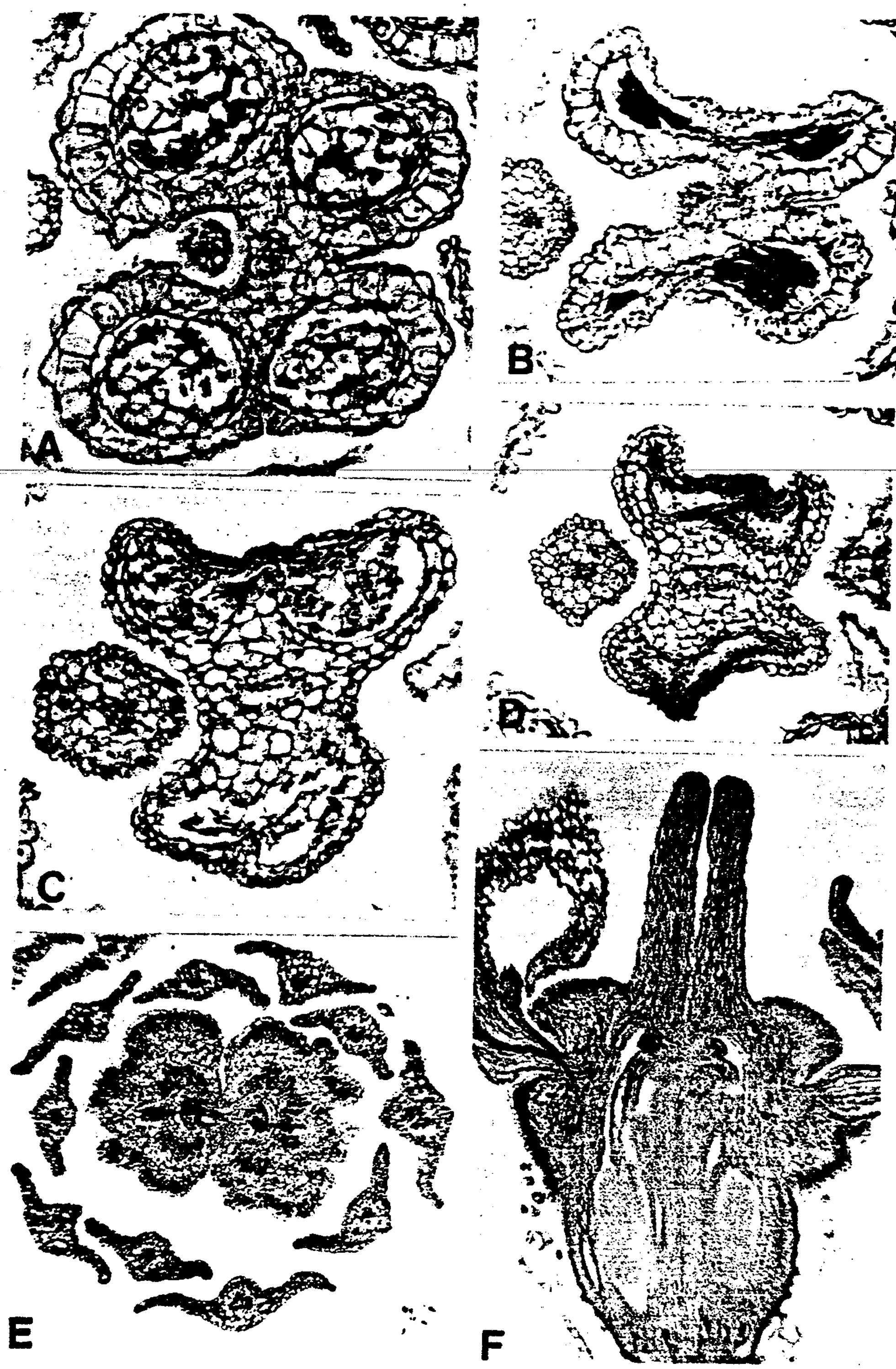

Fig. 2. Light micrographs of transverse sections of sterile anthers, petaloid floret, and longitudinal section of aborting ovules of carrot. **A**: Sterile brown anther from fine foliage plant derived from 'Hicolor 9.' Note hypertrophy of sporogenous tissue and anther walls (×280). **B**: Later stage of anther development. Same plant as A. Locular contents completely collapsed (×168). **C**: Brown anther from sterile plant in B9668. Sterility conditioned by cytoplasm from 'Tendersweet' (×280). **D**: Later stage of anther development from same plant as **C** with locular contents and anther walls collapsed (×168). **E**: Petaloid floret from sterile plant in line B3615. Note aborted ovules (arrows) (×64). **F**. Fertile floret from plant in line C60-1 showing 2 aborting and 2 functional ovules (×64).

walls with anticlinal thickenings. There was no evidence of meiosis, and the sporogenous tissue consisted of hypertrophied vacuolate cells. These cells filled the entire locule; only an outer thin layer of tapetum was apparent (Fig. 2A). At a later stage (Fig. 2B), anthers of this sterile showed collapse of the sporogenous tissue (compare with Fig. 1C). There were no plump or stainable pollen grains in primary or secondary umbels. Sterile progeny from crosses with B493 and B9304 had anthers structurally comparable to those of the fine foliage male-sterile parent, whereas progeny from the cross with B10138 were fully fertile with a normal endothecium and tapetum.

The young anther from brown anther sterile B9668 (conditioned by 'Tendersweet' cytoplasm) was similar to brown anther sterile derived from B493 x HC271. Endothecial cells were small and thin-walled, and the tapetum was inconspicuous. Meiosis did not occur and the small cells in the locule remained sporogenous (Fig. 2C). Cells remained small throughout anther development. Collapse of sporogenous tissue was similar to that shown in Fig. 1C, except that cells external to the locule also were collapsed near the stomium (Fig. 2D). There were no plump or stainable pollen grains in any umbels of B9668 plants.

Petaloid florets from line B3615 sterile had stamens structurally similar to petals, as described in petaloid sterility (3, 10, 15). Thus, no sporogenous cells were observed in petaloid plants.

In spite of differences in anther development among the various carrot lines, ovule development was the same in all. Study of ovule morphology indicated aborted ovules at the upper level of the floret in sections made through the nectary (Fig. 2E), as first described by Borthwick (2). A longitudinal section of the fertile floret from C60-1 and of both petaloid and brown anther male steriles showed the pistil with a split stigma, style, and 2 aborted ovules subtended by the 2 large normal functional ones (Fig. 2F).

Brown anther partial male sterile lines had aborting pollen. No meiosis occurred in completely sterile lines. In partially fertile plants derived from the B493 x HC271 brown anther male sterile, meiosis had occurred and there were some completely sterile anthers and some with nearly all fertile pollen. However, in sterile plants, sporogenous tissue was abnormal, and there was no evidence of meiosis, similar to the brown anther sterile line B9668. The fine-foliage brown anther sterile had hypertrophied sporogenous cells, different from the other brown anther steriles. In mature stages, the locular contents of all brown anther steriles was collapsed.

The 3 examples of brown anther male sterility found in carrot all fail to enter meiosis, like male sterility in petunia (4). In this way, those 3 carrot lines differ from onion (8), beet (14), barley (11), and maize (9), where microsporogenesis usually is normal and male sterility is manifested during microgametogenesis. It is interesting to note that in both carrot (12) and petunia (7), the brown anther type of male sterility is subject to partial restoration to fertility under certain environments. Since high temperature also has been reported to partially restore fertility in onion (16), further work is needed to examine the relationship between pre-meiotic expression of male sterility and predisposition toward partial restoration to fertility.

Literature Cited

1. Banga, O., J. Petiet, and J.L. van Bennekom. 1964. Genetical analysis of male-sterility in carrots, *Daucus carota* L. Euphytica 13:75–93.
2. Borthwick, H.A. 1931. Development of the macrogametophyte and embryo of *Daucus carota*. Bot. Gaz. 92:23–44.
3. Eisa, H.M. and D.H. Wallace. 1969. Morphological and anatomical aspects of petaloidy in the carrot (*Daucus carota* L.). J. Amer. Soc. Hort.Sci. 94:545–548.
4. Frankel, R., S. Izhar, and J. Nitsan. 1969. Timing of callase activity and cytoplasmic male sterility in *Petunia*. Biochem. Genet. 3:451–455.
5. Hansche, P.E. and W.H. Gabelman. 1963. Digenic control of male sterility in carrots, *Daucus carota* L. Crop Sci. 3:383–386.
6. Hansche, P.E. and W.H. Gabelman. 1963. Phenotypic stability of pollen sterile carrots, *Daucus carota* L. Proc. Amer. Soc. Hort. Sci. 82:341–350.
7. Izhar, S. 1977. Cytoplasmic male sterility in petunia: II. The interaction between the plasmagene, genetic factors, and temperature. J. Hered. 68:238–240.
8. Jones, H.A. and S.L. Emsweller. 1936. A male-sterile onion. Proc. Amer. Soc. Hort. Sci. 34:582–585.
9. Laughnan, J.R.and S. Gabay-Laughnan. 1983. Cytoplasmic male sterility in maize. Annu. Rev. Genet. 17:27–48.
10. McCollum, G.D. 1966. Occurrence of petaloid stamens in wild carrot (*Daucus carota*) from Sweden. Econ. Bot. 20:361–367.
11. Mian, H.R., J. Kuspira, G.W.R. Walker, and N. Muntjewerff. 1974. Histological and cytochemical studies on five genetic male-sterile lines of barley (*Hordeum vulgare*). Can. J. Genet. Cytol. 16:355–379.
12. Michalik, B. 1978. Hybrid breeding of carrots in Poland. Biuletyn Warzywniczy 22:157.
13. Morelock, T.E. 1974. Influence of cytoplasmic source on expression of male sterility in carrot, *Daucus carota* L. PhD Diss., Univ. of Wisconsin, Madison.
14. Owen, F.V. 1945. Cytoplasmically inherited male-sterility in sugar beets. J. Agr. Res. 71:423–440.
15. Thompson, D.J. 1961. Studies on the inheritance of male-sterility in the carrot, *Daucus carota* L. var. *sativa*. Proc. Amer. Soc. Hort. Sci. 78:332–338.
16. Van der Meer, Q.P. 1978. Results of recent investigations on male sterility in onion (*Allium cepa* L.) Biuletyn Warzywniczy 22:73–79.
17. Welch, J.E. and E.L. Grimball, Jr. 1947. Male sterility in the carrot. Science 106:594.
18. Zenkteler, M. 1962. Microsporogenesis and tapetal development in normal and male-sterile carrots (*Daucus carota*). Amer. J. Bot. 49(4):341–348.

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EXPERIMENTAL PROTOCOLS

Controlled Pollinations of Carrot

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Genetic experiments with carrot require controlled pollinations to produce seed. Seed production with carrot varieties has recently been described (Peterson and Simon, in press). This protocol includes the principal features and points of interest which may be useful to researchers' need to produce seeds from carrots.

Procedures

1. *Grow relatively vigorous plants.* Weak or diseased plants are subject to storage loss during vernalization and they set few seeds. Plants with pencil-sized roots may be large enough (particularly for undomesticated germplasm) but larger plants are preferable. Plants regenerated from tissue culture, like those transplanted or grown in compacted soil, often develop deformed roots. Such plants can be used for seed production as long as storage roots are at least 5 cm long.

2. *Vernalize roots.* Biennial plants generally require 6 to 8 weeks cold storage (2 to 5°C) for floral induction. Cool growing conditions and passage through tissue culture can reduce the cold storage requirement. Segregating undomesticated germplasm can range from plants with annual habit to those with vernalization requirements exceeding 12 weeks. Roots can be vernalized in two ways: One is to simply place plants growing in pots into a cold room with a 12 to 16 hour photoperiod, watering as necessary (too little water encourages fungal attack, too much drowns plants). Dead or dying leaves must be removed promptly and tops can be cut back to 5 cm to reduce transpiration. Storage losses are often very high with this method. Another metho[d] is to harvest plants and trim tops back to 2 to 4 cm, dip them in a fungicid[e] mixture, dry until *no* surface moisture remains, pack in paper bags with a[n] equal volume of wood shavings, and place paper bags in closed polyethylen[e] bags at 2-5°C. Puncture plastic bags after several weeks when water droplet[s] accumulate inside the polyethylene film. Better storage survival is realized i[f] lateral and fibrous roots are removed, soil is removed by washing gently, an[d] senescing leaves are removed. Even with these precautions wild species ar[e] often very susceptible to pathogen infection during storage.

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3. *Grow vernalized plants.* Place vernalized plants in a cool greenhouse (13° t[o] 15°C) or field until seed stalk development is evident in 4 to 6 weeks. Warme[r] conditions (18° to 23°C) are then preferable for more rapid development Control of microbial (*Alternaria*, *Cercospora*, aster yellows, motley dwarf) an[d] insect pests (aphids, spider mites, lygus bugs) is essential to assure seed production.

4. *Make crosses.* Isolate umbels from 1 to 5 plants in small cloth cages whe[n] first flowers dehisce. Stigmata are receptive when they split. Because of pro[tandry], umbels representing several stages of floral maturity should be included to assure pollen availability when the pistil is receptive. Pollination i[s] best performed by introducing housefly pupae on a regular 3-4 day schedul[e] to insure the presence of adult flies for continuing pollen transfer during th[e] period of receptivity. As an alternative, pollen movement is possible by han[d] or brush but seed set will be very low. Hybridization can be accomplished b[y] hand-emasculation but this is very tedious. Unreceptive flowers are emasculated, and all other flowers are removed. Umbels with emasculated flower[s] are caged with the desired pollen parent and live flies. In 4 to 6 weeks th[e] developing seed turns brown. Harvest (before the seed shatters) into pape[r] bags to dry completely. Remove spines by rubbing. Heat treat for *Xanthomonas* if necessary. Seed is now ready to plant.

References

Peterson, C.E. and P.W. Simon. Carrot breeding. In: *Breeding Vegetable Crops.* M.J Bassett (Ed.), Westport, CT: AVI Publishing Co. In press.

Goldman