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CARROT SEED PRODUCTION

*Affected By
Insect Pollination*

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E. H. Toole
W. P. Nye
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Carrot Seed Production
As Affected By Insect
Pollination

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Cover picture: Nectar collecting honey bee on carrot umbel in receptive stigma stage. When collecting pollen, the bee carries her abdomen low enough to be in close contact with the stamens.

CARROT SEED PRODUCTION AS AFFECTED BY INSECT POLLINATION

L. R. Hawthorn, G. E. Bohart, E. H. Toole,
W. P. Nye, and M. D. Levin

A CARROT field in bloom usually attracts large numbers of pollinating insects including honey bees. No fewer than 334 species representing 71 families were collected on carrot flowers during the course of these studies (Bohart and Nye, 1960). Little attention has been given in the past to the effect such insects actually have on yields and quality of carrot seed. The effect of harmful insects, particularly *Lygus* spp., has been studied by Flemion and co-workers

(1950, 1956). Robinson (1954) in a comprehensive review of the problems related to the germination of umbelliferous seeds, including harmful insects, cites over 100 references, but does not mention pollination. In 1954 experiments were begun at Logan, Utah, to determine the relation of different levels of insect pollination to carrot seed yields and quality. A resume of these findings was included in a preliminary report of these studies (Hawthorn *et al.*, 1956).

Materials and Methods

FROM 1954 to 1957 inclusive, four distinct pollination levels on carrots were established each year on different sites near Logan by treating plots as follows: (1) caged to enclose a colony of honey bees; (2) uncaged (open pollination); (3) caged to admit only tiny insects; and (4) caged to exclude all insects. The cages were placed over plots soon after the carrot seed stalks began

to elongate. In 1956 and 1957 an attempt was made to maintain two levels of honey bee populations, by using large and small colonies. However, the number of bees on the flower heads was not greatly different. There were 4 replications of each treatment each year.

The cages of the type described by Pedersen *et al.* (1950), were 21½ feet long, 11 feet wide, 6 feet high, and covered with 12-mesh lumite. Those excluding all insects had a cheesecloth cover over the lumite (fig. 1). As soon as flowering began in late June, the cages were erected and a small hive of bees was placed in each replicate of the first treatment. These bees were supplied with water and sugar sirup every few days as necessary. The cages remained in place until about September, when the carrots ceased flowering.

This bulletin is a report of cooperative experiments conducted by the Agricultural Research Service, United States Department of Agriculture, and the Utah Agricultural Experiment Station.

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Fig. 1. Carrot pollination plots in 1955. Foreground; open; left background, 12- x 12-mesh lumite screen cage; right background, cheesecloth cover over lumite screen

Each plot in 1954 contained four rows of carrots spaced 27 inches apart and with stecklings 12 inches apart within the rows. In the following 3 years, to avoid pollination through the sides of the cages, three rows were used, spaced 36 inches apart, but the stecklings were still spaced at 12-inch intervals within each row. Only 19 stecklings were planted per row to allow a space of 18 inches from the ends of the cage. The outer rows were 30 inches from the sides of the cages.

In 1954 and 1957 medium-sized stecklings of Red Core Chantenay were used exclusively. In 1955 and 1956 a mixture of Red Core Chantenay and White Belgian was used to determine the amount of crossing between plants various distances apart. The number of stecklings of each variety was the same in each plot within any given replication

so that the overall yields in these treatments were comparable. The stecklings were of uniform size, ranging from 1 to 1½ inches in diameter at the crown.

The carrots were harvested for seed in early September when the second-order umbels began to turn brown. In 1954 seed yields were recorded on only the two center rows, but in the following 3 years entire plots were used. As soon as the harvested plants were dried sufficiently the seed was threshed with a small experimental thresher of the beater-bar type. A 4-screen, 2-air suction mill and a gravity separator were used for processing. This was satisfactory only for the normal-sized seed from the open plots and the ones with bees enclosed. Consequently, samples of all lots were finally cleaned by a laboratory air-blast separator, hand screens, and handpicking in order to put them on a comparable

basis. The percentage of cleaned seed obtained from this final hand-cleaning was used to calculate the final yields.

Samples of the cleaned seed were subjected to standard germination tests in the Vegetable Seed Investigations laboratory of the Agricultural Research Service at Beltsville, Maryland.

The data were analyzed statistically by analyses of variance, and the significance of mean differences was determined by the application of Duncan's (1955) Multiple Range test. When differences did not exist at the 1 percent level, they were indicated at the 5 percent level.

Conditions Affecting the Experiment

Plants. Red Core Chantenay predominated in 1954 and 1957; this variety and White Belgian were about equally divided in 1955, and White Belgian predominated in 1956. This probably affected yields between years. White Belgian grew larger and had slightly larger umbels than Red Core Chantenay. Yields between plots were probably not affected by the carrot stocks used except in 1955 when all plants but one in two replications were of the White Belgian variety, and all but four in the other two replications were Red Core Chantenay. Plant growth was generally uniform from plot to plot and year to year, except as affected by the conditions noted in the following paragraphs.

Soil. There was a conspicuous soil gradient in 1955. The plots toward the east had progressively shallower, stonier soil that dried out more quickly. This condition was obviously reflected in poorer growth and lower seed yields.

Harmful insects. In 1954 (Hawthorn *et al.*, 1956) aphids became numerous in the caged plots, especially in one of the plots protected with cheesecloth. A treatment with TEPP severely damaged the plants in this plot and its yields had to be eliminated in the analyses. In 1955, grasshoppers which hatched within the

plots were moderately abundant, but they fed primarily on small cruciferous weeds and concerned us only in connection with their possible function as pollinators in the no-insect cages. In 1957, mirid bugs (*Lygus* spp. and *Orthops scutellatus*) were troublesome in a small carrot seed field about one quarter mile away, but a thorough chemical control program prevented them from building up a large population in our plots. However, adult bugs migrated in from time to time and these were somewhat more abundant in the open plots than in the caged ones.

Cages. In 1957 the two types of cages used had little effect on air, soil temperature, or relative humidity (table 1). However, light was decreased 39 percent by the 12- x 12-mesh screen cover and 68 percent by the screen plus cheesecloth. Air movement was measured by blowing a fan in a closed room to create an artificial breeze of about 500 feet per minute. The 12- x 12-mesh screen reduced the air flow by 45 percent and the screen plus cheesecloth reduced it by 75 percent. Apparently, the reduced air movement in the cages offset the shading effect and kept the temperature and humidity nearly the same as in the open.

Table 1. Measurements of ecological factors affecting carrot pollination plots, 1957

Type of cage	G.E. light meter readings	Relative humidity	Soil temperature	Air temperature
		percent	°F	°F
No cage	22.5 A	20 a	100 A	86.6 Aa
12- x 12-mesh lumite cage	13.8 B	20 a	98 A	87.6 AaB
Lumite cage covered with cheesecloth	7.2 C	22 a	93 B	87.8 Bb

Means followed by the same letter are not significantly different. Means not followed by the same letter are significantly different at the 1 percent level where letters are capitalized and at the 5 percent level where lower case.

Floral Development

IN 1955, detailed observations were made on floral development with and without insect pollination and in both caged and uncaged plots. In general, the significant blooming period lasted about 1 month, and 3 orders of heads contributed nearly all harvested seed. The peak of bloom occurred in the middle of the cycle, or about July 23 in 1955.

Dehiscence within the umbels lasted for 6½ days and stigma receptivity began on the fifth day of anthesis. Within an umbellet dehiscence lasted 4½ days and stigma receptivity began on the fifth day. Within a floret dehiscence (fig. 2) lasted from one to two days and stigma receptivity (fig. 3) began on the fourth day. The foregoing is based on the assumption that stigma receptivity begins when the styles separate. If the stigmas

are receptive when the styles are extended but not separated (fig. 2), the beginning of receptivity was 1 day earlier than indicated. The period of stigma receptivity appeared to last more than a week. In the Red Core Chantenay variety the stigma began to turn brown about 2 weeks after first becoming receptive. In the White Belgian variety the stigma remained apparently receptive until the ovaries were full-sized and the hairs fully developed (fig. 4). In view of these facts, it appears that under the conditions of these experiments a limited but significant opportunity existed for self-pollination from one umbellet to another by jarring or wind action, and a greater opportunity (on a time basis) for cross-pollination by accidental rubbing together of umbels on adjacent plants.

Pollination Levels

Pollinators in open plots. The activities of the many pollinators on the open plots were discussed in detail by Bohart and Nye (1960). As shown in

table 2, the average numbers of all insects per open plot per observation from 1954 to 1957 were as follows: 2662, 472, 1175, and 666. The density of these

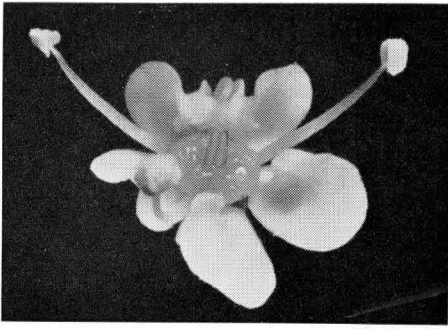


Fig. 2. Floret with anthers dehiscing and style elongating but not fully extended or separated

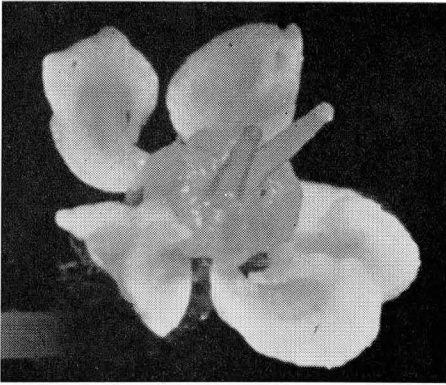


Fig. 3. Floret with stamens gone, styles fully extended, and stigma receptive

insect populations can be judged from the number of open umbels, which ranged between 500 and 800 during the peak of bloom. The large number and variety of insects on the plots can be accounted for by the varied terrain in the area and the small size of the plots, which tended to concentrate the existing populations. In 1954 and 1956 the experiment was conducted in a locality that offered greater ecological diversity and thus harbored a greater diversity of insects than the sites used in 1955 and 1957.

Pollination indices, arrived at by mul-

tiplying populations by pollination efficiency ratings of the component species, emphasize the variation under open-pollination conditions from year to year. For the years 1954 to 1957, the pollination indices in the open plots were as follows: 3125, 695, 1268, and 412 (table 3). Although based on somewhat subjective estimates¹ of efficiency, the pollination indices are much more meaningful from a pollination standpoint than figures for pollinator populations.

Based on pollination indices shown in table 2, sphecoid wasps appeared to be the most important pollinators in 1954 and 1956, various bees other than honey bees in 1955, and larger species of true

¹Ratings were based on the quantity of loose pollen on the body, together with the size, hairiness, and activity of the insect on the umbels. For further details, see Bohart and Nye (1960).

Fig. 4. Developing seed of White Belgian variety showing styles still fresh appearing

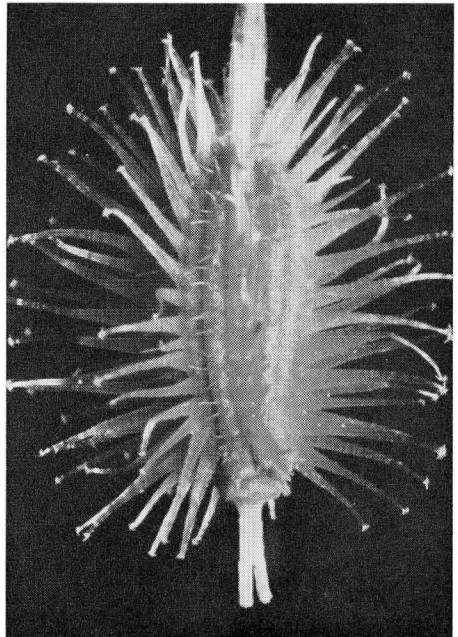


Table 2. Numbers and pollination indices* of various kinds of pollinators in the open plots.

Category of insect	1954		1955		1956		1957		Average	
	Number per plot	Index	Number per plot	Index	Number per plot	Index	Number per plot	Index	Number per plot	Index
Honey bees	14	70	5	25	4	20	11	55	9	43
Other bees	178	432	44	180	53	175	18	68	73	214
Sphecoid wasps	368	1021	27	82	185	380	43	82	156	391
Other Hymenoptera	100	163	11	23	47	57	23	30	45	68
Larger Diptera	348	767	41	98	78	230	46	106	128	300
Syrpitta pipiens	478	478	274	274	264	264	11	11	257	257
Tiny Diptera	984	84	62	8	385	29	86	9	379	33
Other insects	192	110	8	5	159	113	428	51	197	70
All insects	2662	3125	472	695	1175	1268	666	412	1244	1375
Insects less honey bees	2648	3055	467	670	1171	1248	657	357	1236	1333

*Number per plot per observation x efficiency rating of component species within each group.

Table 3. Pollination indices* for the four principal carrot pollination treatments

Pollination level	1954†	1955	1956	1957	Average
Bees‡	2962	1050	1282	2030	1831
Open pollination	3125	695	1268	412	1382
Tiny insects	108	342§	64	40	139
No insects	15	0	10	0	6.3

*Number per plot per observation x efficiency rating of each species. Figures for different treatments on different years not based on equal numbers of observations.

†Discrepancies with figures for 1954 in Hawthorn et al. (1956) result from changes in assigned efficiency ratings and a revised estimate of the numbers of umbels per plot (600 instead of 400).

‡Since differences between the two honey bee treatments were not achieved, the pollination indices were based on an average of both.

§The index was much higher for the period when *Halictus confusus arapahonum* entered the cages.

flies (Diptera) in 1957 (Bohart and Nye, 1960). Taking all years together these three insect groups and a single species of small syrphid (hover) fly, *Syrpita pipiens*, were apparently responsible for over 80 percent of the pollination on the open plots. By contrast, honey bees, which were efficient but relatively scarce on the open plots, appeared to account for only about 3 percent. In 1957 honey bees were more than twice as abundant as in the preceding years and appeared to account for about 12 percent of the pollination. (See Bohart and Nye (1960) for further details.)

Plots admitting only tiny insects.

Except in 1955, only tiny, relatively inefficient pollinators were found in significant numbers in the plots protected by 12- x 12-mesh screen. Most of the insects observed were tiny Diptera of the families Heleidae, Chloropidae, Cecidomyiidae, and Sciaridae. In number per plot per observation, these minute insects varied from 1954 to 1957 as follows: 980, 210, 685, and 365 (see table 2 for comparative figures in open plots). Since most of these insects were ex-

tremely inefficient they were given a pollination index equal to only one-tenth the population observed.

In the latter half of the 1955 season, significant numbers of the small sweat bee, *Halictus confusus arapahonum*, were found collecting pollen in the "tiny insect plots." On July 27 they averaged 156 per plot and increased the pollination index for that day from 34 to 654. These bees were moderately abundant in the cages for about 1 week and during this period may have pollinated more carrots than are indicated by the figures based on seasonal averages (table 3).

Plots caged with honey bees.

Populations of honey bees in the cages enclosing bee colonies were generally satisfactory. The average number of bees per plot per observation from 1954 to 1957 were as follows: 592, 210, 256, and 406. The pollination indices (arrived at in the case of honey bees by multiplying the population by 5) were as follows: 2962, 1050, 1282, and 2030 (table 3).

In 1956 and 1957 we tried to regulate the number of honey bees in the

plots by using larger and smaller colonies. However, the number of bees that visited the umbels was not associated with the strength of the colonies used. Average population on the "high" bee plots was slightly lower in 1956, and only slightly higher in 1957 than on the "low" bee plots. On the other hand the range between all bee plots was considerable (68 to 289 in 1956 and 375 to 800 in 1957).

Plots excluding all insects. Exclusion of pollinators from the cheesecloth-covered plots was adequate in 1955 and

1957. In 1954, (Hawthorn *et al.*, 1956), adults of the onion maggot were present in the cheesecloth cages in small numbers during the first week of bloom. In addition a small amount of unwanted pollination may have occurred on some of the umbels which pressed against the sides of the cage and attracted a number of insects. In 1956, grasshoppers which hatched within the cages spent considerable time resting on the cupped-in umbels, but they moved little when undisturbed and probably pollinated few florets.

Influence of Pollination Level

On floral development. Apparently plants in the plots without pollinators (in cheesecloth cages) reached their peak of bloom a few days earlier and held it more than a week longer than the ones in the open or in cages with

bees (fig. 5a, b). In the years when sweat bees did not enter the cages the "tiny insect plots" bloomed more like the "no insect plots" than like the "honey bee plots." In view of the foregoing, the level of pollination rather than cage

Fig. 5a. Carrot umbels photographed on the same day: below, in a "tiny-insect plot (low pollination), next page, in an open plot (high pollination).





Fig. 5b. Carrot umbels in an open plot (high pollination). Photographed same day as umbels in low pollination plot

effect was apparently responsible for the earlier and more extended bloom. A probable explanation for the earlier peak of bloom observed under conditions of low pollination is that the petals of unpollinated flowers of many kinds of

plants remain attached for a longer period than those of pollinated flowers. Furthermore, in the plots with low pollination large insects were not present to dislodge petals. Thus the petals of the early flowers remained attached

Table 4. Effect of various levels of insect pollination on yields per acre of processed carrot seed

Pollination level	1954	1955	1956	1957	Average
	pounds	pounds	pounds	pounds	pounds
Bees — high	771 A	1037 A	844 A	708 A	840 A
Bees — low			1086 AB	688 A	
Open pollination	601 A	1018 AB	998 AB	226 B	711 AB
Tiny insects	327 B	864 AB	369 C	225 B	453 BC
No insects	100 C	214 C	65 C	132 B	128 C

Means followed by the same letter are not significantly different.

Means not followed by the same letter are significantly different at the 1-percent level.

longer than under conditions of high pollination and created the illusion of an earlier peak of bloom.

On seed yields. Seed yields tended to be positively associated with the pollination levels established by the four basic treatments (compare tables 3 and 4). Differences between the plots enclosing bees and the open plots were relatively small, as might be expected from the previously discussed large populations of pollinators in the open plots. In 1954 the calculated pollination index was actually higher on the uncaged plots than in the plots caged with bees (table 3). Only in 1957, when populations of efficient species of pollinators were much lower than in previous years, were yields in the open plots conspicuously lower than those in the cages with honey bees.

The open plots yielded much more seed than those admitting only tiny insects, except in 1955 and 1957. In 1955 the large number of small sweat bees that entered the cages increased the pollination level to nearly that of the open plots. In fact, the plot invaded by the largest number of sweat bees actually produced 1279 pounds of seed per acre which was comparable with any yield produced that year. In 1957, yields in

the open plots were no higher than those in the plots admitting only tiny insects in spite of the considerably higher pollination index in the open plots. The lower-than-usual pollination level in the open that year probably accounts only in part for such a low yield. Apparently a migration of adult mirid bugs into the open plots for short periods augmented the effect of low pollination.

As evidenced by the high yields in the cages with honey bees (and in one instance with sweat bees), the reduction in light and air movement brought about by the screen had no apparently adverse effect on yield. Possibly the cages exerted a beneficial effect by protecting the plants from injurious insects. In 1957, this protection appeared to be significant.

In all cases the plots admitting only tiny insects yielded considerably more seed than those deprived of all pollinators. The variation in yield from year to year in the plots without pollinators may have been accounted for in part by differences in maturity at the time of harvest. As discussed on page 11, seed development was delayed in the plots with low pollination. Varietal differences in self-pollinating ability apparently were not involved since the highest and low-

Table 5. Germination of carrot seed harvested 44 and 40 days after first flower opened on umbel as influenced by pollination level

Pollination level	Germination			
	When fully mature		When harvested early	
	1955	1957	1955 (44 days)	1957 (40 days)
	percent	percent	percent	percent
Bees	92	93	94	74
Tiny insects	94	76	86	46

est yields without insects were recorded in the two years when White Belgian was grown.

Since we did not confine bees in cheesecloth cages, the possibility exists that reduction in light or air movement or both were responsible, at least in part, for the low yields in the plots without insects. However, the cheesecloth did not produce adverse effects on plant growth. The plants bloomed a little earlier than those in the other plots. Furthermore, they exhibited none of the tall, spindly growth or poor flowering usually associated with inadequate light.

On rate of seed development.

Every year seed in the plots admitting only tiny insects matured at least 10 days after that produced in the plots caged with bees. Similarly, seed in plots where insects were entirely absent matured 5 to 6 days later than that which had the benefit of small insects. In some years the carrot seed in cages with bees was noticeably more mature on any one date than that growing in the open. In 1957 the heads in the open plots were not mature enough to harvest until 6 days after those in the plots with bees. Here again is evidence that

low pollination was important in the open plots that year.

In 1955 and again in 1957 an attempt was made to verify these observations by tagging 5 second-order umbels, each of about the same size and vigor but each on a different plant. These were chosen at random in each plot with honey bees and in each plot caged to admit only tiny insects. Forty-four days later in 1955 and forty days later in 1957 these umbels were harvested, cured, and dried for later germination studies.

The most clear-cut results were obtained in 1957 when the interval between tagging and harvest was only 40 days. In that year 74 percent of the carrot seed from tagged umbels produced in cages with bees germinated as compared with only 46 percent for similar seed produced in cages with only small insects (table 5). Such a result indicates that under a high level of pollination, such as that created by a plentiful supply of honey bees, carrot seed matures more rapidly than where the pollination level is low. Apparently, the change in harvest date from 44 to 40 days after first flowering resulted in a considerable reduction of viability, re-

Table 6. Effect of various levels of insect pollination on yields per acre of abnormally large processed carrot seed

Pollination level	1954	1955	1956	1957	Average
	pounds	pounds	pounds	pounds	pounds
Bees — high	0 A	17 A	0 A	25 A	10 A
Bees — low	.....	.....	0 A	31 A	16*
Open pollination	0 A	14 A	0 A	57 A	18 A
Tiny insects	100 B	149 B	138 B	73 AB	115 B
No insects	77 C	122 C	74 C	105 B	94 C

Means followed by the same letter are not significantly different from each other. Means followed by different letters are significantly different at the 1 percent level.

*This figure was not included in the analysis of the average.

ardless of pollination level. However, the effect was much greater where the level was low.

On seed size. Each year while the seed was still green, we found abnormally large seed in plots in which pollinators were scarce or absent. At harvest abnormally large seed reached 149 pounds per acre in one of the low pollination treatments. For the 4 years the yield of the abnormally large seed was about one-third as great as that of the normal seed in the "tiny-insect" plots and three-fourths as great in the "no-insect" plots (table 6).

From 1955 to 1957 seeds of three classes (abnormally large, normal, and abnormally small)² were weighed in lots of 500. Even within the class of normal-size seed (that accepted by the trade), it was apparent that the various pollina-

tion levels had a noticeable effect on weight (table 7). The seed harvested from the open plots and those caged with bees varied but little from the 605 milligrams calculated from the seed weights published by the Association of Official Seed Analysts (1959). In all three years the normal-sized seed from the plots with only small insects weighed distinctly more than that from the uncaged plots and those caged with bees. Likewise, each year the normal-sized seed from the plots with no insects was the heaviest.

Abnormally large and abnormally small seeds were always associated with the two low pollination treatments. Only in 1955 and 1957 were such seeds harvested from the other treatments. Their presence was noticeable in 1957 in the open-pollinated plots, and is further evidence that pollination was poor in those plots that year.

The presence of large seeds in plots with insufficient pollination is probably explained by the lack of competition between adjacent developing embryos, thus allowing the few fertilized seeds to develop to their fullest size. The principle would be the same as that in thinning

²The three sizes of seed were separated as follows: abnormally large seeds were held by screen with circular apertures of 6/64-inch diameter; normal-sized seeds passed through this screen, but were held by apertures of 1/12-inch diameter (in 1956 and 1957 by apertures of 1/14-inch); and abnormally small seeds passed through the first two screens but were held by apertures of 1/22-inch diameter.

Table 7. Average weights of 500 carrot seeds as influenced by different pollination levels

Pollination level	1955	1956	1957
	milligrams	milligrams	milligrams
Bees — high	746 A	647 Aab	725 A
Bees — low	.....	737 Ab	698 A
Open pollination	777 A	632 Aa	871 AB
Tiny insects	1033 B	1274 Bc	1007 BC
No insects	1474 C	1538 Cd	1078 C

Means followed by the same letter are not significantly different from each other. Means followed by different letters are significantly different at the 1 percent level where letters are capitalized, and at the 5 percent level where lower case.

fruit trees. In 1957 sections made of developing embryos³ and seeds showed that the only difference between normal and abnormally large seeds was in the number and size of the cells. The excessive growth was most evident in the fruit tissue and gave the seeds a corky appearance. Seeds of normal size are usually flinty and hard.

In 1957 weights of abnormally large seed from the various treatments were statistically analyzed. As with regular sized seed, the abnormally large seed averaged larger with each reduction in the pollination level. Five hundred large seeds from the open plots, the "tiny-insect plots," and the "no-insect plots" weighed 1440, 1563, and 1816 milligrams, respectively. At the 5 percent level the differences between any pair of these figures is valid. Even at the 1 percent level the difference between

1816 and either of the other weights is significant.

Except in 1957, the quantity (but not percentage) of abnormally large seed was always greatest in the plots caged to admit small insects only (table 6). Such yields indicate that pollination was sufficient in these plots to fertilize a moderate number of ovules, many of which, because of reduced competition, developed into abnormally large seeds. In 1955, when small sweat bees entered the "tiny insect plots" and were responsible for excellent yields in two replications, abnormally large seed was still abundant. Apparently the sweat bees did not enter the cages until the primary umbels had finished blooming and abnormally large seed had started to develop. The viability of such seed was usually about the same as that of regular seed. The large seed from plots with no insects was often more viable than the normal-sized seed.

Abnormally small seeds were always found mixed with considerable inert matter. By the time such matter was removed, the number of seeds was often too small to obtain an accurate weight

³The sections of developing embryos were made by Ralph W. Anderson, a graduate student under the direction of Dr. W. S. Boyle, professor of botany at Utah State University. The latter's observations on these sections plus those of the senior author are the basis for statements made in the paragraph above.

Table 8. Germination percentages of processed carrot seed produced under different levels of pollination

Pollination level	1954	1955	1956	1957
	percent	percent	percent	percent
Bees — high	96 A	92 A	93 A	91 Aa
Bees — low	.....	.....	91 A	93 Aab
Open pollination	94 A	92 A	94 A	78 Aabc
Tiny insects	88 A	94 A	92 A	76 Abc
No insects	67 B	94 A	69 B	70 Bc

Means followed by the same letter are not significantly different from each other. Means followed by different letters are significantly different at the 1 percent level where capitalized, and at the 5 percent level where lower case.

Table 9. Percentage* reduction in yield of normal-sized seed resulting from final stages† of cleaning and from calculating the amount of non-viable seed

Pollination level	1954		1955		1956		1957	
	During final cleaning	On basis of 100% viable seed	During final cleaning	On basis of 100% viable seed	During final cleaning	On basis of 100% viable seed	During final cleaning	On basis of 100% viable seed
	percent	percent	percent	percent	percent	percent	percent	percent
Bees — high	2.7 A	6.6 A	1.7 A	9.4 A	1.6 A	8.3 A	7.2 A	13.5 A
Bees — low	-----	-----	-----	-----	2.5 A	10.9 A	5.3 A	14.1 A
Open pollination	3.4 A	9.0 A	1.6 A	9.9 A	1.7 A	7.7 A	89.4 Bb	60.3 Bb
Tiny insects	36.8 B	46.4 B	15.4 B	22.4 B	32.1 B	37.8 B	43.4 Bbc	56.9 Bbc
No insects	70.5 C	80.2 C	38.1 C	42.0 C	76.9 C	84.1 C	62.2 Bc	76.4 Bc

Means followed by the same letter are not significantly different. Means followed by different letters are significantly different from each other at the 1 percent level where letters are capitalized, and at the 5 percent level where lower case.

*Analyses of variance of percentages made according to arc sin percentage method (Snedecor, 1956).

†Cleaning operations after the initial cleaning with the 4-screen 2-air blast mill had been completed.

to use in statistical analysis. However, judging from the limited data obtained, this class of seed was not distinctly lighter (therefore, probably denser) than seed of normal size. Some of the small seeds were fertilized but still immature. Others were probably partially developed ovaries enclosing unfertilized ovules.

On germination. The largest reduction in germination usually occurred between the treatment admitting tiny insects and that excluding all insects (table 8). For example, in 1954 and 1956, the germination percentage dropped from 88 to 67 and 92 to 69, respectively. In 1955, when the White Belgian variety predominated, yield and viability were higher than usual in the plots with no insects and germination was reduced little as a result of any lowering of pollination level. White Belgian grows larger than Red Core Chantenay and may have had more opportunity for cross pollination when umbels of adjacent plants rubbed together in the wind.

Low viability of carrot seed has been primarily attributed to injury by lygus bugs (Flemion and Hendrickson 1949, Flemion and Olsen 1950), and undoubtedly these insects do injure developing carrot seed. The results of our study indicate that an insufficient number of pollinating insects is sometimes the principal cause of low germination. It is noteworthy that in 1957 germination of seed from the open plots was as low as that from the plots protected from insects. Although hemipterous insects may have been partially involved, the appearance of abnormally large seed from this treatment indicates that poor pollination was also a contributing factor.

On shrinkage from processing and reduced viability. The yields recorded in table 4 are all of normal-sized seed; that is, seed generally accepted by the trade. As indicated previously, abnormally large seed represented a high proportion of the total yield in the low pollination plots (tables 6, 9). However, other forms of unacceptable material, including trash and abnormally small seeds, were also more abundant in the low pollination plots. Each year the progressive shrinkage in weight following the various cleaning processes was accelerated with every decrease in pollination level, as indicated for 1954 in the previous report (Hawthorn *et al.*, 1956).

Even after cleaning with the 4-screen, 2-air suction mill, trash was noticeably present in the seed lots from the low pollination plots. As indicated by table 9, the percent of such trash ranged in 1954 from 2.7 in the honey bee plots to 70.5 in the "no-insect" plots. In 1956, the range was from 1.6 to 76.9. The large amount of unacceptable material in the "trashier" lots would present an almost insurmountable problem to a seed company. Such seed could not be satisfactorily processed without considerable additional losses in both processing time and labor, and also in further loss of acceptable seed. Such losses might exceed those resulting from the actual shrinkage in yield.

The reduced viability associated with low pollination as previously discussed was another factor adding to the total shrinkage (table 9). However, in normal commercial practice, germination is not a factor in shrinkage since seed of 100 percent viability is never offered for sale.

Discussion

THE RESULTS of our studies make it apparent that, although limited quantities of carrot seed can be grown without insect pollination, even a few pollinators increase yields considerably. Moreover, the results show that a good supply of efficient species of pollinators is necessary to insure high yields of quality seed. In addition to benefiting yields, appearance, and germination of the seed, rapid pollination hastens seed maturity and thus shortens the period for protection from harmful insects and gives more flexibility to the harvesting schedule.

Under the cultural conditions of our experiments, a honey bee population of 8 per square yard (the lowest average number for the season in our cages) is apparently as high as the plants can use to advantage. Probably a somewhat smaller number would do just as well, although we have no direct evidence to support such a conclusion.

Low yields coupled with abnormally large seed, poor germination, and late development in the open plots in 1957 point strongly to inadequate pollination, although moderate but transitory populations of mirid bugs that year may have further reduced the yield and germination. The calculated pollination index for the open plots in 1957 was 412, which is about two-thirds the 695 index recorded for the open plots in 1955 and one-third of the 1282 figure for the honey bee cages in 1956, both of which produced normal yields (table 3). Such facts indicate a sharp breaking point in yields at a pollination level not far below the last two figures. On the other hand, it could point to substantial inaccuracy in our evaluation of the pollinating effi-

ciencies of the species involved, especially those on the open plots in 1957 when a high proportion of insects with low but relatively unknown efficiencies were involved. The actual pollination level on the open plots that year may have been considerably lower than that calculated.

The high yields obtained in 1955 from the plots admitting only tiny insects is clearly attributable to the large number of small sweat bees found in the cages for about a week. Since the seasonal pollination level in these cages was considerably below that of the open plots in 1957, there is an indication that timing is important. During the week in which the sweat bees were abundant they apparently brought the overall pollination to a satisfactory level.

In spite of the relative scarcity and consequent unimportance of honey bees on the open plots during our experiments, they rated high in efficiency and are probably the most important pollinators in areas where they visit carrots more readily. Since bee colonies were moderately abundant near the experimental plots, and honey bees were abundant on blossoming alfalfa in surrounding fields, it appears that competition with more attractive bloom was the principal reason for the low honey bee populations on the carrots. Probably the most practical solution to the problem of inadequate pollination on carrots would be to increase the number of colonies in the area and remove or avoid as much competing bloom as possible. Limitation of the carrot seed acreage may also be advisable if the number of colonies cannot be increased sufficiently.

The attractiveness of carrot bloom to

a wide variety of insects and the pollinating efficiency of many of these species were clearly shown in our studies, but populations of wild pollina-

tors cannot generally be depended on from year to year, and many problems must be solved before their numbers can be successfully manipulated.

Summary

FROM 1954 to 1957, inclusive, carrots were grown for seed at Logan, Utah, under four pollination levels by establishing plots as follows: (1) caged with a colony of honey bees; (2) uncaged (open pollination); (3) caged to admit only tiny insects, and (4) caged to exclude all insects. There were four replications. Each cage covered a plot 21½ feet long, 11 feet wide, and 6 feet high, and consisted of clear 12 x 12-mesh lumite screen over an aluminum frame. For the "no-insect" treatment a cover of cheesecloth was placed over the lumite cage. Evidence indicates that caging had no adverse affect on plant growth or that the various yield and germination results were noticeably affected by soil, harmful insects, or any variables among treatments other than pollination levels.

Red Core Chantenay and White Belgian varieties of carrots were grown (the former exclusively in 1954 and 1957). The two varieties responded similarly to the treatments, but the White Belgian tended to grow larger and produce more seed.

Plants reached their peak of bloom earlier and held it longer under conditions of low pollination, especially where there were no insects (in cheesecloth cages). Petals remained attached over a long period of time because of the lack of insects to dislodge them.

Higher yields were consistently associated with higher pollination levels. From 1954 to 1956, inclusive, with abundant insect pollinators in the open plots,

yields were about the same as in the plots caged with honey bees. In 1957, when insects in open plots were scarce, yields were much lower than in the plots caged with bees. Yields in the plots with only tiny insects were much lower than those in the open plots except in 1955 when small sweat bees entered the cages for a brief period during full bloom. Yields in the plots with no insects were always much lower than in any of the other plots.

High levels of pollination resulted in earlier seed maturity. In 1957, when umbels were harvested 40 days after their first flowers opened, 74 percent of the seed from the "honey-bee plots" and 46 percent from the "tiny-insect plots" germinated.

Low pollination levels were associated with unusual quantities of both abnormally large and abnormally small seed. In addition, the average weight per seed of each size category was greater at the lower pollination levels. The explanation for the abnormally large seed and higher weight averages in all classes is probably related to the reduced number of developing ovules and the lessened competition for nutrients. The many abnormally small seeds in the plots with the two lower pollination levels apparently consisted of both fertilized, immature seeds and unfertilized, undeveloped ovaries.

Seed viability was increased by raising the pollination level. At the two high levels germination percentages were usu-

ally well over 90, but in 3 out of 4 years seed from the plots excluding insects germinated less than 70 percent. The greatest difference in viability usually occurred between the no-insect plots and those admitting only tiny insects.

Although significant differences in yield at the different pollination levels could be measured as soon as threshing was completed, they were accentuated with each cleaning operation, and also by taking into account the percentage of viable seed. The total shrinkage in yield ranged from 42 to 84 percent at

the lowest pollination level and from 7 to 13 percent at the highest level.

The results clearly indicate that an adequate supply of insect pollinators is necessary for high yield and quality of carrot seed. Yields and pollinator populations in the open plots and plots caged with bees indicate that insect populations under natural conditions are not always consistent with high yields. When the natural supply of pollinators is inadequate, the number of honey bee colonies should be increased and competing bloom reduced.

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