Organic Seed Alliance

Advancing the ethical development and stewardship of the genetic resources of agricultural seed

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How to Breed Carrots for Organic Agriculture

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I. Introduction

Carrots have long been an important fresh market crop around the world. The breadth of regional preferences has ensured that a wide ***variety*** of types and varieties exist across cultures that use this nutritionally important vegetable as an everyday staple of their diet. Worldwide, there are dozens of different market types of carrots, each with hundreds of unique varieties that have been important to some segment of the market over the last century. When European carrots were imported to North America, they were grown primarily as a fall-harvested vegetable, stored through winter and used for cooking. As carrots gained popularity as a fresh market crop for all seasons in early 20th century America, there was a need for bunching carrots sold with their tops intact. This need demanded thinner, sleek rooted carrots without large shoulders that push the roots apart at odd angles when bunched. A new era of innovation in plant breeding delivered new types of carrots that represent combinations of the different types from around the world. This innovation has been heightened in the last 20 years with the reintroduction of older, uniquely colored carrots into the marketplace.

A century ago, carrot seed production and breeding was the domain of serious carrot growers and the small regional seed companies that were the norm in North America and in many places around the world. By the mid-20th century, both seed production and breeding became more specialized, and most commercial farmers in North America no longer considered producing their own carrot seed. The commercial open-pollinated (OP) carrot varieties bred and maintained from the 1920s until well into the 1970s were successful in supplying the various needs of both the fresh market and processed vegetable trade. The seed companies growing the best strains of these varieties were quite competent at maintaining a selection of each OP variety with a high degree of uniformity, while avoiding the pitfalls of inbreeding by selecting too narrowly. With the advent and subsequent commercial dominance of hybrid carrots beginning in the 1970s, fewer seed professionals had the skills to select and maintain high-quality OP varieties.

The goal of this manual is to explain simple methods for developing an OP carrot variety. While carrot breeding programs at large seed companies have largely abandoned OPs, there are a number of reasons why OPs are best suited to serve farmer breeders as well as independent seed companies that address regional needs. By breeding an OP variety that retains adequate genetic variability while selecting for uniformity for all of the important market traits, it is possible to produce a variety that can subsequently be selected for the varied climates and cultural needs of different regions.

II. Introduction to Breeding

We recommend that farmer breeders first develop breeding goals. In Organic Seed Alliance's (OSA) ***Introduction to On-Farm Organic Plant Breeding***, we outline the genetic concepts of breeding and provide farmer breeders a template for breeding crops. These are the basic steps for breeding crops on your farm:

1. Develop your breeding goals

2. Identify parental material, including conducting trials to find the best parents

3. Make crosses

4. Select and recombine your selected breeding material

III. Breeding Goals

The first step of any breeding project is to develop breeding goals. Below is a list of the most important traits for commercial carrots, including the foliar traits that are particularly important for organic growers. These traits will be discussed further in the **Selection** section.

- Germination/strength of emergence
- Seedling vigor

*Definitions for technical words that are italicized and bolded can be found in the glossary

- Canopy development and weed competitiveness
- Maturity slot
- Top attachment
- Disease resistance
- Color intensity
- Core color
- Root shape
- Root tip fill
- Flavor
- Sweetness
- Harshness
- Storability

IV. Germplasm

Germplasm is a collection of genetic resources in a species, and is the raw material that a plant breeder uses to develop new varieties. Breeders often use the term germplasm to refer to sub-groups of the entire germplasm that exists for a crop. For instance, carrot breeders refer to the "purple carrot germplasm" or the "Alternaria blight resistant germplasm" as a way to specify the crop's breeding material used in their work. While a breeder will probably never use more than a fraction of this material for breeding purposes, you should learn as much as possible about available material that includes traits that help you meet your desired breeding objectives. However, no one is ever fully aware of all the germplasm that may be useful for any particular breeding project, which is why learning about the crop that you are interested in breeding is a lifelong pursuit.

In the modern world where most of the newer carrot varieties are F1 hybrids, plant breeders should be on the lookout for good OP material. There are a few common OP varieties still commercially available in North America, and a number of older varieties can be requested through the Germplasm Resources Information Network (GRIN) of the U.S. Department of Agriculture or in heirloom seed collections. Unfortunately, carrots have a limited germplasm pool compared to other common vegetable crop species, as biennial root crops are harder to reproduce than most annual seed crops. Also, if OP carrot varieties are not maintained through diligent selection when seed is increased, their phenotypic constitution usually degenerates rapidly.

A good breeder must be open to finding commercial OP varieties from around the world that are still being actively maintained. This is often the most valuable breeding material, as it can most rapidly be developed into new varieties. Some breeders have also used F1 hybrids for parental material in their breeding work. The details of hybrid carrot breeding are beyond the scope of this manual, but note that F1 hybrid carrot seed is produced using naturally occurring ***cytoplasmic male sterility (CMS)*** in the female parent. Seed collected from F1 progeny or subsequent generations will have ***cytoplasm*** with these sterility factors that could result in future sterility problems. Therefore, it may be best to start a breeding project with OP material. That said, if the progeny from an F1 hybrid variety exhibits good fertility in the F2 and F3 generations, the progeny of this existing F1 hybrid likely had plenty of ***nuclear restorer genes*** to adequately restore the sterility of the CMS, and the material may be used in developing an OP variety.

While plant breeding discussions often begin with which parents are best to cross-pollinate for creating a breeding population, all breeders should remember that the breeding process sometimes begins with an already existing population of the crop. In this situation, breeders find an existing OP population that has adequate genetic variation for the desired traits, which allows them to bypass the steps of choosing parents and making a cross. There are also cases where a breeder discovers a diverse population that has occurred due to an unintended cross in the field and realizes that it holds promise as a breeding population. The point is that germplasm is wherever you find it, and all good farmers and plant breeders learn to recognize good germplasm for specific breeding needs over time as they gain experience with the crop.

V. Reproductive Biology

Carrots are a biennial cross-pollinated species that rely on insect pollination. Many species of pollinating insects are attracted to carrot flowers, including wasps, Syrphid flies (also known as hover flies), wild bees, and domestic bees. Flowers are borne on a series of compound umbels, starting with a single central ***inflorescence***, known as the primary or king umbel, followed by a few secondary umbels, and then many more tertiary umbels. In most climates, the best seed is harvested from the primary and secondary umbels, as they will have the longest period of time to fully mature their seed. The multiple-flowered umbelets on each compound umbel usually have at least a dozen small perfect flowers with five stamens, five pistils, and five sepals. The ovary of each blossom has two locules, each producing a single seed when successful fertilization has occurred. While carrots are fully self-fertile, a majority of the seed produced is due to cross-pollination between plants in the population. Much of this cross-pollination is due to the fact that carrots are protandrous: the ***anthers*** on any particular flower shed pollen before the ***stigma*** of that same flower is receptive to fertilization. This decreases the chances of self-pollination, as insects will fly from umbel to umbel in an attempt to find mature flowers. ***Protandry*** is an evolutionary mechanism to enforce a majority of cross-pollination in carrots, as this species is more susceptible to potential ***inbreeding depression*** from excessive self-pollinations than most agricultural crops.

Producing carrot seed on the farm is usually done across two seasons, which is natural for the crop when growing in its native habitat. Carrot roots for plant breeding purposes are produced during one growing season, and are dug up and evaluated for root characteristics at the end of the first season. These carrots should be planted later in the year. That way the roots grow to marketable size as late as possible at the end of the first season, minimizing winter storage time. Overwintering can also be done in situ, or in the field, in milder climates, but the roots must be vernalized in either case. As with all ***biennial*** crops, carrots need to be vernalized in order to flower. ***Vernalization*** is a process where the biennial plant (in this case the carrot root) is exposed to at least 8 to 10 cumulative weeks of temperatures at approximately 50F (10C) or below between their first season of vegetative growth and their second season of reproductive growth. This is accomplished either by allowing the roots to overwinter in the ground in regions with mild winters or by storing the roots at ideal storage conditions -- 35F (2C) and 95% humidity -- through winter months. The steps for preparing and storing the roots in a cold room are covered in *Principles and Practices of Organic Carrot Seed Production in the Pacific Northwest*, available at www.seedalliance.org.

VI. Plant Breeding

Mating systems for seed production

There are basically two ways that carrot varieties are produced, either as ***open-pollinated*** varieties or as F1 hybrids. Producing open-pollinated varieties is relatively easy to do if the grower is (1) in a climate suited to the reproductive phase of carrots, and (2) willing to put in the time to learn the intricacies of working with a biennial seed crop and learn the discipline of selecting for a set of traits in an OP without overly narrowing the genetic base of the population. Producing hybrid carrot varieties, on the other hand, requires maintaining a series of parental ***inbred*** lines. These include both sterile and fertile male lines for each female parent, as well as a fertile male parental line for each hybrid. To produce hybrid seed, you must first produce seed of each of the parent lines in separate isolated fields at least a year before hybrid production. Then, when the hybrid seed crop is produced, the hybrid seed is harvested only from the female parent, as all of the male parent rows are destroyed. This process is much more costly and time-consuming than producing OP seed, and is usually outside of what most farmer breeders are willing to do in both the breeding and the production of a carrot variety.

Generating breeding populations

As with all breeding projects, you should choose the right parents to cross to create an effective population with the potential of generating progeny with the combination of traits you are seeking. This requires some care in the selection of parent varieties or other germplasm to find or create a useful breeding population. Most importantly, this process begins with the breeder having a good working knowledge of the traits in potential breeding stocks. Identifying these traits requires growing field trials of existing carrot material under conditions that are similar to those used by growers. Trials need to start before the first crosses are made to allow you to evaluate existing material for the traits you have identified as important (see

Carrot crossing in outdoor pillow tubes: Initial single crosses can be made outdoors with homemade muslin fabric and small round metal frames that surround carrot flowers. Note the small black plastic tube with a cork on top where you can add fly larvae weekly that will hatch in the pillow tubes. Only seed produced inside of the pillow tubes is used for breeding.

Carrot pollination by flies: The common house fly and blue bottle fly are often reared and used by carrot breeders as they are effective pollinators.

Selection). To learn more about conducting variety trials, refer to OSA's *On-farm Variety Trials: A Guide for Organic Vegetable, Herb, and Flower Producers*, at www.seedalliance.org.

When good breeding material has been identified, most breeders will make a number of crosses, incorporating several different combinations of the best material available. Initial cross-pollinations are often made in a greenhouse between single plants in small muslin or perforated plastic pollination "pillow tubes" that cover the flowers of the two plants. Insect pollinators must be introduced into these pollination bags. These insects are typically houseflies or blue bottle flies that can be purchased in the larval stage. Some small-scale breeding projects use feather dusters in the event that finding a fly source is problematic. The downside of this single-plant by single-plant crossing method is that you will get a limited sample of the genes from each of the parental populations. This is because no one plant in a cross-pollinated crop species variety contains all of the genetic variation present in that variety. This may not be a problem in commercial hybrid breeding programs where many crosses are made with the expectation that only a few will result in finished varieties or inbreds. However,

House flies in carrot pillow tubes: For an isolated carrot pollination it is recommended that you use a high density of flies. Pillow tubes here are made from a perforated plastic mesh used by cheese makers.

*Isolation tents can be purchased from Redwood Empire Awning at www.redwoodempireawning.com.

most farmers are not willing to manage a number of crosses. In most farmer-led breeding projects, the goal is usually to create a finished variety by performing only one or two crosses between two well-chosen parents.

In order to capture more of the genetic variation from the initial cross between any two parents, we recommend a technique used by forage breeders known as a "***strain cross***." A strain cross is the crossing of two small populations of the chosen parent varieties. To use this technique, select a number of carrot roots from each of the two parental populations. The advantage of farmer breeders using a strain cross is that by using a number of selected individuals from each of the two parents you are capturing a greater number of possible genetic combinations from the overall genetic breadth of both parents. Strain crosses can be done in a small, mesh pollination cage or in an open field if isolated from other flowering carrots or ***feral*** Queen Anne's Lace (*Daucus carota*), which will readily cross with cultivated carrots.* The advantage of making a strain cross in an open field is that in most locations there will be ample wild pollinators, native wasps and bees, to ensure adequate pollination.

Making the cross-pollination

Make certain that carrot roots have been vernalized so that they flower. Refer to the **Reproductive Biology** section above for instruction on how to vernalize carrot roots.

When making a carrot cross, either between two plants in a pollination pillow tube or with two parent populations in a strain cross, label the different parent roots with a pedigree stake. That way, the crossed seed that results can be harvested separately from the different parents.

Controlled pollination

For a simple cross between two carrot plants from different varieties, plant the two parental roots in separate pots in the greenhouse or in the soil (if making the cross in a small pollination tent or pillow tube outdoors). As the plants send out flower stalks and form flowers, cover them with a cloth, plastic pollination bag, or tent. These enclosures need to be secured before the first flowers open and are receptive to pollination. Pollinating insects must now be introduced. Houseflies and blue bottle flies are most commonly used for this purpose. The larvae of these fly species must be introduced weekly at the onset of flowering, approximately a half- teaspoon per pollination bag or tube. They usually survive for one week in these cages. These flies will seek pollen and nectar and pollinate with their movement across the flowers. By adding a cotton ball soaked in sugar water every two days, the lifespan of the flies can be extended by several days. This method is used extensively by commercial carrot breeders who may make hundreds of crosses per year. Pollination enclosures provide the advantage of allowing you to make a number of crosses in one location without the threat of cross-pollination.

Strain cross

Most farmer breeders are unlikely to make more than one or two crosses after identifying good material and deciding on a specific set of breeding goals for a desired ***phenotype***. The strain cross method is often used for a single, isolated cross. In a strain cross of a root crop like carrots, select at least 20 to 30 of the best roots from each of the two parents and plant them in two separate rows, side by side, with the intent of harvesting, cleaning, and bagging the seed as separate lots in the first year. The seed in lot A contains seed of two different constitutions, with both A x B and pure A (from crosses between A plants and some A plant self-pollinations). Likewise, the seed in lot B contains both B x A and pure B. In plant breeding, you denote the pedigree of the cross by putting the maternal parent first and the paternal parent second, hence A x B denotes A as the maternal seed parent and B as the paternal pollen parent.

In the second year, seed from the two lots will be planted into separate beds, preferably in two replications (two beds of each). The lots are kept separate, as there can be a phenotypic difference between the roots of the reciprocal hybrid crosses: A x B and B x A. While there is no easy genetic explanation for this, in rare cases there can be a discernable difference between the reciprocal hybrids. When harvesting roots at the end of the first season, evaluate the two populations for general performance and root shape. If it is obvious which population is superior in performance, make this one population the breeding population and discard the others. Otherwise, the hybrid roots from both can be selected and combined. Upon further evaluation, the difference between the hybrid roots (A x B and B x A) and the pure roots (A x A and B x B) will become obvious. The roots that have resulted from cross-pollination are often different in several ways, especially if the phenotypic difference of the two parents is pronounced. In general, the hybrid roots will often demonstrate a marked increase in vigor with increased root and/or top size. The hybrids may also exhibit a marked difference in shape or color, as well as an obvious hybrid shape that is intermediate between the two parents. In contrast to hybrid roots resulting from crosses between the two parents, pure roots resulting from self- or sibling pollinations will be phenotypically similar to the original parental material. The obvious hybrid roots should be selected and saved for the next phase of the breeding program.

Mass selection

Once you have created a breeding population through controlled pollination or the use of a strain cross, the next step is to begin selection. ***Mass selection*** in carrots can be done following the basic principles outlined in OSA's *Introduction to On-Farm Organic Plant Breeding*. Selection begins by producing the crop under uniform field conditions and with the use of gridded selection to select evenly across the breeding population. Fortunately, in biennial root crops, it is possible to grow the roots to full vegetable maturity and then select the desired phenotype before replanting for the reproductive phase of the life cycle. Only the desired, selected plants will cross-pollinate to contribute their genes to the next breeding cycle. You can also select plants as they re-grow foliage and form flowers in their second season. Abnormalities in the formation and development of umbels and flower structures are more common than many carrot growers realize. These abnormalities should be eliminated when obvious, preferably before the onset of pollination. Selecting before pollination increases the efficiency of mass selection. Selecting for healthy, reproductive features and bountiful seed production is an important and often forgotten part of the breeding process. When practicing mass selection in carrots, maintain as large of a population as possible, saving seed from at least 100 to 120 healthy plants in each breeding cycle.

Family selection

Family selection can be used to make rapid gains in breeding cross-pollinated species, and carrots are no exception. Refer to OSA's *Introduction to On-Farm Organic Plant Breeding* for the basic concepts of family selection in cross-pollinated crops. The breeding method described here for carrots is ***half-sibling*** (half-sib) family selection. Another method is to use pollination bags to make a series of self-pollinations on individual plants with flies, which would make self-pollinated, or ***S1***, families.

A half-sib family is produced by saving seed from a single carrot plant that has been openly pollinated by other plants of a selected population. The seed from this single plant all share the same mother, while the paternal inheritance may come via pollen from any of the other plants in the population. By systematically selecting half-sib families for several generations, you can retain favorable traits while avoiding severe inbreeding.

Breeding timeline

The following timeline is based on OSA's approach to breeding cross-pollinated crops using population improvement via two approaches: *family selection* and *mass selection*. The family selection method is an alternative to the pedigree breeding used in most modern carrot breeding programs. Since carrots are a biennial crop, each breeding cycle in this timeline takes two growing seasons to complete. A breeding cycle is a single generation in the reproductive lifecycle.

Year 1

Root year – Cycle 1: Determine your breeding objectives and evaluate potential parents or breeding populations. Your preliminary investigation into which carrot varieties are best suited as potential parents to meet your breeding goals, as well as which varieties are adapted to your environment and production needs, is time well-spent, especially when conducting a meaningful trial. This preliminary step is very important, especially if you can identify an existing population with desired characteristics to select from or two parents that are phenotypically similar but have different desirable traits. Either of these cases will usually save time when performing on-farm breeding with a biennial crop. If good parental material is identified in a trial, it can be used as a source for roots of the selected parents and allowed to flower and intermate in the second year. In order to potentially use trial roots at the outset of a breeding project, produce a large enough population of each accession in the trial to select and harvest at least 60 to 80 roots from to use as parents. While only 20 to 30 roots are needed to perform a strain cross in the second year, it is important to store at least twice as many roots as you predict will be needed, since a percentage of stored roots will rot or begin sprouting excessive secondary roots. Selected roots should be healthy and undamaged with minimal to little sprouting when examined the following spring. Roots that haven't sprouted, and that appear in good condition (free of damage, injury, or disease), can be good breeding stock when developing carrot varieties to market after long-term storage.

Year 2

Flower year – Cycle 1: In this second season of the first breeding cycle, you will plant at least 20 to 30 parental roots of each variety after a final selection for their storability. Follow the steps for making a strain cross described in the **Making the cross-pollination** section. At seed maturity, harvest seed from the two rows separately into two separate bags marked appropriately: A x B or B x A.

Year 3

Root year – Cycle 2: Seed harvested from the two separate parental rows in year 2 should be sown into separate rows and grown to vegetable maturity for evaluation. Evaluate both the foliar characteristics and the roots of both rows at full maturity. If the reciprocal **hybrids** are similar in all characteristics, combine them into a single population. If there are discernable differences between the two populations, choose the superior population for selection and discard the other. Each of these rows will produce two basic types of roots: those that are obvious hybrids between the two parents, and those that are recognizable as the parental type (see **Strain cross** section above). Select as many healthy hybrid roots (at least 100 if possible) for storage and replanting in year 4.

Strain cross hybrid progeny: Pictured here are six hybrid roots from a strain cross, flanked by the two parents of the cross. The six hybrid roots in the middle exhibit a phenotype that is intermediate between the parents. The hybrid roots also demonstrated notable vigor in their foliar growth in the field. Interestingly, the hybrid roots are obviously later in their root maturity as a vegetable crop.

Year 4

Flower year – Cycle 2: After storage, select at least 40 to 60 of the healthiest roots in spring. Plant these roots as soon as spring conditions stabilize and there is no threat of hard frosts. Plant these roots in an open, isolated field at least one mile from other flowering carrots or Queen Anne's Lace. Alternatively, plant these roots in a mesh isolation tent with introduced pollinating insects. The plants are then allowed to freely intermate (openly pollinate). Plants should be evaluated regularly as they come to full flower for any abnormalities in their growth or reproductive traits. Carrot plants will often produce a small percentage of flowering plants with obvious deleterious traits, such as leaves originating in umbels or umbels borne on jointed flower stalks, and these need to be eliminated.

Mass selection: At this point, if you prefer to only practice mass selection, harvest seed at the end of the season from all healthy plants without obvious flaws as a "balanced bulk." This means that a roughly equal quantity of seed is harvested from each plant in the population and is cleaned and mixed together into one "bulked" population.

Family selection: At the end of the season, harvest seed from all remaining healthy plants without obvious flaws, and then clean and bag separately. Each of the resulting seed packets will contain seed that are largely the result of sibling mating and each is considered a half-sibling (half-sib) family. There will also be a percentage of seed in each half-sib family packet that is the result of self-pollination of that plant. These seed packets are numbered sequentially.

Year 5

Root year – Cycle 3: see specifics for mass selection and family selection as follows.

Mass selection: Plant seed of the bulked population into uniform field conditions, paying attention to soil type, fertility, and irrigation. Plant a large enough plot to produce at least 1,000 to 1,200 carrots. In mass selection of a root crop like carrots, a large population of at least 1,000 roots provides for good selection opportunities. Grow the crop to the stage of vegetable maturity that fits the market you are addressing in your breeding. Harvest and select the crop for both root and foliar characteristics using the gridded selection technique described in *OSA's Introduction to On-Farm Organic Plant Breeding*. Store at least 200 to 300 well-selected roots.

Family selection: Plant the seed of these 40 to 60 families into short rows (6 to 9 ft/2 to 3 m) in the fashion of a replicated trial, with at least two randomized replications preferred. These progeny rows can be evaluated for all of the important foliar traits, from seedling vigor, canopy development, and foliar disease resistance throughout the season. At root harvest, evaluate all root traits. The most promising families will exhibit superior traits in a majority of the roots (at least 60 to 65%) for a number of the breeding goals. This is often only a fraction of the half-sib families that are originally produced in the previous year. In our experience, this will be about 20 to 25% of the families, or 4 to 5 families for every 20 families produced. The best roots from these superior families are then selected after eliminating at least 25 to 35% of the "less-than-ideal" roots. Selected roots from the superior families are then stored in individual family bags for continued selection and breeding in year 6.

Year 6

Flower year – Cycle 3: see specifics for mass selection and family selection as follows.

Mass selection: Evaluate the roots for their storability and select the best 150 to 200 roots for replanting in isolation. Select roots that have some combination of the traits of interest, but know that you will probably not find a large percentage of roots that have all or nearly all of the traits you are trying to isolate in your desired ***ideotype***. Plants should also be evaluated for any foliar or flowering abnormalities. Eliminate these plants before pollination occurs. Harvest seed at seed maturity as a balanced bulk as you did in year 4.

Family selection: The stored roots from the superior selected families in year 5 are planted in an open field in individual family rows. As before, during flowering, eliminate any individuals from these families that exhibit aberrant reproductive growth. If a family has a large percentage of plants with aberrant foliar or reproductive growth, eliminate the entire family row. Allow all healthy families to openly pollinate using native or introduced pollinators. At the end of the season, harvest,clean seed from each of these families separately.

Year 7

Root year – Cycle 4: At this point you will essentially repeat the procedure followed in years 5 and 6 for both mass selection and family selection.

Mass selection: Plant the bulked population again as you did in year 5 with at least 1,000 roots for selection. The crop produced this year should have a higher percentage of roots that exhibit characteristics you are trying to combine through selection. Select and store at least 200 of these roots as you did in year 5.

Family selection: Repeat the procedure of year 5 by evaluating the selected superior families from the previous cycle based on foliar and root characteristics. A predictable outcome at this point in half-sib family selection is to find only 1 or 2 families from the approximately 4 or 5 selected families that are worthy of continued breeding. This is especially true if the phenotypes of the parents are similar as discussed below. As the families are narrower at this point, you can increase the selection pressure you apply to the roots of the selected families. If family selection reveals that one family is clearly superior, selecting from this point forward will be the same as is used in mass selection. If selecting down to one family, retain at least 100 to 150 roots before proceeding. If two or more families are worthy of selection, proceed as in year 5 by storing roots of the selected families separately. For two or more families, store at least 80 to 100 roots for flowering in the next year.

Year 8

Flower year – Cycle 4: Repeat the procedure for seed production of the selected roots as in year 6 for both mass selection and family selection. If you have selected down to a single half-sib family using family selection in this cycle, harvest seed as a balanced bulk and proceed to the next cycle. Practice mass selection with this family.

Year 9 and 10 (and beyond)

If practicing mass selection, continue as in the previous two-year cycles until you have achieved a degree of uniformity in the population that meets your needs. In family selection you will have easily narrowed your choice to a single half-sib family by now, if not before. With either method, you may now have a useful OP population that serves as a unique carrot variety. Be sure to maintain the population by growing at least 100 to 200 roots each cycle and selecting at least 100 to 150 roots for seed production for subsequent generations. Vigilant selection pressure is needed to maintain a high-quality OP variety.

Breeding summary

The number of breeding cycles depends on 1) how similar the two parents are, and 2) the degree of uniformity you need for your production and/or market demands. In the first instance, the more similar the parental phenotypes, the faster you may be able to attain uniformity in relatively few breeding cycles. Conversely, the more dissimilar the parental phenotypes are, the more breeding cycles you may need to attain a distinct, uniform phenotype. These two-year cycles must be repeated until the desired phenotype is attained.

Plant breeders of open-pollinated varieties are always faced with the challenge of how uniform a variety must be to meet the standards of the market. The plant breeder and educator R. W. Allard states that, "trueness to type in an open-pollinated population is a statistical feature of the population as a whole; it is not a characteristic of individual plants" (Allard, 1999). In other words, breeders must make a value judgment on the number of cycles needed to attain the degree of uniformity required for their market or production system. At the point where the population produced through this process has sufficient uniformity for the most important production and market traits, with some degree of inherent variation for insignificant traits, the variety may be acceptable for release. The better you know your potential market, the better your chances of knowing when the breeding population is acceptable in the marketplace.

Seedling vigor can be rated as the size of the seedlings, either by rating the height alone or by rating both the height and width together at a set number of days after the planting date. We rate seedling vigor at 15 and 30 days in order to evaluate in the first half of the season. These ratings reflect the days to germination and the specifics of the planting depth and other environmental challenges.

Canopy development can be measured by tracking the rate of growth of both height and width of the canopy and its relationship with weed competitiveness. The rate of development, and size of the overall carrot leaf canopy from early in the season until final harvest, may have a marked effect on the crop's ability to compete with weeds in organic systems.

The *maturity* is measured in the number of days from planting until the root has filled out its full shape, including filling out the tip of the root (tip fill) and achieving its full marketable size and weight.

Top attachment is a subjective measurement based on how well the petioles are attached to the crown of the root. This is an important trait when evaluating prospective fresh market bunching types, and is important for a number of different mechanical harvesters used for carrots. The trait is often gauged under the real world challenges of bunching or harvesting the crop.

Disease resistance, including Alternaria leaf blight, Alternaria crown rot, Aster Yellows, Bacterial blight, Cavity spot (*Pythium* sp.), Cercospera leaf blight, and Root-knot nematodes (*Meloidogyne* spp.). These are pathogen species for which selection for resistance under field conditions has been demonstrated to be effective.

Color (orange, yellow, purple, and red types) is based on inherited major genes that control pigment types in carrots. The white root color, which is due to the absence of pigment, is simply inherited and dominant to the pigmented types, hence easily eliminated in the generation after an errant cross with Queen Anne's Lace occurs. All of the pigmented types have other genetic factors that can greatly enhance the intensity of the color. Enhancing color is achieved through repeated selection and inter-mating of high color material as intensity of color is a ***quantitative trait***.

Core color is the color of the xylem tissue of the root. Older carrot varieties often have cores that have a different color than the predominant phloem color of the root. The xylem can also exhibit less pigmentation than the ***phloem*** when they are of the same root color. Paler xylem (core) color can sometimes be predicted with the observation of pale-colored storage root tips (tails), but an accurate assessment of ***xylem*** color can only be done well by cutting the tip of the root off to view interior color. This practice does not interfere with seed production, since all the plant reproductive organs are derived from growing points in the crown of the carrot.

Root shape requires selecting for the general taper of the root, which is based on the diameter at the shoulder relative to the diameter at the tip or bottom of the root. Selecting for a strong "blunting" or filling of the root tip helps to enforce a shift to a less pronounced root taper.

Root tip fill is often used as an indication that a carrot has reached a marketable size. Selecting for "early blunting" is common in almost all modern carrot varieties to give growers more flexibility with harvest dates.

Root smoothness is most associated with the prominence and depth of the lateral secondary root scars, which are present along the entire length on carrots. When these root scars are prominent, it makes the root appear to be ribbed and rough as opposed to smooth and sleek.

Blunting of carrot roots: These 'Rumba' carrot roots exhibit different degrees of "blunting" or root tip fill, which is the rounding of the root tips that occurs in some varieties as the crop matures. Note that the third root from the right has the most well filled tip of these roots.

Flavor in carrots is quite complex, with a large number of volatile flavor compounds, mostly terpenoids, giving carrots their characteristic flavor. When terpenoids are in a favorable balance, the roots have a pleasant "carroty" flavor. If terpenoids are too prominent, the carrot can taste "harsh," sometimes described as soapy, piney, or overly floral. Flavor is rated as a subjective trait with trained tasters and should be considered separately from sweetness. There can be large differences between tasters in their ability to perceive the harsh flavors in carrots.

Sweetness is a prominent part of carrot flavor and is usually evaluated by breeders as a separate component of overall flavor during taste evaluations.

Succulence or texture is an important component of carrot eating quality. Consumers prefer carrots that are succulent, tender, and juicy rather than overly hard, tough, or soft. One negative production attribute that can accompany succulent carrots is a greater tendency for roots to break or crack. While breeding carrots for more sweetness or less harshness has not been found to have any accompanying negative production attributes, breeding for more succulence can introduce production challenges. *Storability of roots* is done by bringing carrots out of storage at regular intervals during the off-season to evaluate the roots for their firmness and ability to resist rot and not sprout lateral roots or shoots. Roots can also be evaluated for flavor and sweetness at these same intervals.

Glossary

Anther: male, pollen-bearing structures of the flower.

Biennial: the type of plant that normally produces only vegetative growth the first growing season, overwinters, and then produces a seed crop after which the plant dies. The plant requires two growing seasons to complete its life cycle.

Cytoplasm: the contents of a cell between the nucleus and the cell wall. In reproduction, the cytoplasmic constituents from the female parent become part of the cytoplasm of the offspring. There may be a transfer of traits determined by organelles contained in the cytoplasm not associated with chromosomes within the nucleus.

Cytoplasmic male sterility (CMS): Sterility of the male reproductive organs that is under extranuclear genetic control, usually genetic material in mitochondria or chloroplast organelles. This sterility is inherited maternally. It occurs naturally in many species and has been identified in well over 100 crop species, including carrots.

Family: a group of genetically related plants. Often the nature of the relationship is specified. As examples, see *half-sib families, full-sib families*, and *S1 families*.

Family selection: selecting individual plants or families based on the overall performance of a family.

Feral: a domesticated species that has reverted to a wild or untamed state.

Full-sib family: a family structure where plants in a family share the same mother and the same father.

Genotype: the genetic composition of the plant.

Germplasm: the entire collection of genetic material for any given crop species.

Half-sib family: a family structure where the plants in a family share the same mother.

Hybrid: the product of a cross between genetically distinct parents.

Hybrid vigor: the increase in vigor of hybrids over their parental types, also known as heterosis.

Ideotype: tor the purposes of this text, an imagined crop variety representing the ideal to be reached through a breeding project.

Inbred: a variety produced by successive inbreeding over a number of generations. Also called an inbred line.

Inbreeding depression: the decrease in a variety's fitness due to inbreeding.

Inflorescence: the arrangement of plant flowers, such as umbel, raceme, spike, tassel, and panicle.

Male sterility: an inherited factor useful in hybrid seed production. It prevents viable pollen from being produced.

Mass selection: a form of selection where individual plants are selected based on their individual performance.

Nuclear restorer genes: these are nuclear genes that can restore fertility in plants with cytoplasmic male sterility (CMS). These genes are usually dominant in their expression and when present will restore male fertility to plants with CMS. These genes are often abundant in wild populations of plants with naturally occurring CMS.

Open-pollinated: seed produced as a result of natural pollination as opposed to hybrid seed produced as a result of a controlled pollination. Also called an OP.

Phenotype: the observable, outward appearance of a crop.

Phloem: the vascular tissue in plants that transports sugars and other metabolites from the photosynthetic tissue to the rest of the plant. In carrots, the phloem constitutes the tissue surrounding the central core of the edible root.

Polygenic trait: relating to or controlled by multiple genes.

Protandry: the reproductive state of a flowering plant where the male reproductive organs or anthers come to maturity before the female flowering parts.

Reciprocal cross: two mirrored crosses made between a single set of parents where each parent serves as both the female and the male.

Quantitative trait: synonymous with polygenic trait (see *polygenic*).

S1 family: a family structure where the plants in the family all resulted from the same self-pollination.

Stigma: the upper part of the pistil that receives the pollen.

Strain: a term used by breeders that is essentially the equivalent of a variety, although strain is also used to describe a specific variant of a variety that is slightly different from the original variety in its phenotype or adaptation.

Strain cross: a term used by breeders to specify a cross between two different varieties or strains of a crop where multiple individuals of both strains are used to create the breeding population.

Variety: a group of plants of a particular species that shares a set of characteristics or traits that differentiates it from other varieties of the same crop. These characteristics must be distinct and relatively uniform across all of the plants of the variety. Variety is a synonym for cultivar.

Vernalization: the exposure to certain conditions of cold temperature and photoperiod to seed and young plants, which promotes floral induction without development of the plant.

Xylem: the vascular tissue in plants that transports water and dissolved nutrients from the root to all parts of the plant. In carrots, the xylem constitutes the central core of the edible root.

References and Resources

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