Organic Seed Alliance
Supporting the ethical development and stewardship of seed
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Principles and Practices of Organic Carrot Seed Production in the Pacific Northwest

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Crop History, Lifecycle, and Basic Biology

Carrot (*Daucus carota* L.) is a widely grown root vegetable of the Apiaceae family. It is an important source of *alpha*- and *beta*-carotene, precursors of vitamin A in human nutrition, in many cultures worldwide. Carrot is grown as an annual for its fleshy root, but is a true biennial requiring two years for flowering and seed production. Carrot seed is planted the first year to produce roots which are then either lifted and stored under cool conditions or left in the field to acquire vernalization (chilling required to induce floral initiation). In the spring of the second season of growth flowering is initiated and seed is produced during the subsequent 3 to 6 months. Commercial carrot seed production in the USA is limited to areas free from wild carrot, also known as Queen Anne's Lace (*Daucus carota* var. *carota*). Central Oregon and the Columbia Basin of Washington are leading regions in carrot seed production. Seed growers in these districts can expect seed yields of 700 to 900lbs/ac (780-1000kg/ha) for open-pollinated carrot varieties and 350 to 400lbs/ac (390 to 450kg/ha) for hybrid carrot seed crops.

The first certain recorded use of carrot roots as a vegetable is from the 10th century in what is now Afghanistan. From the Middle East carrots gradually spread north to Europe and also travelled east to China and Japan, presumably via the Silk Road, over the next several centuries. From the earliest documentation in the Middle East till the 16th century in both Europe and Asia cultivated carrots were less refined than our modern crop and were either purple or yellow in color. Orange carrots first appeared as a genetic variant in Europe in the 16th century and soon after became very popular. From then until present much of the breeding in this crop has concentrated on eating qualities and the intensity of orange color. These more refined orange carrots quickly spread around the world and by the early 20th century became the predominate color of carrots in most growing regions of the world.

Carrots can be placed into two basic types. The western type includes the orange, white, purple, and yellow forms originating and developed in the Mediterranean Basin and Europe. Alternately, the sub-tropical carrot type is adapted to the hotter, sub-tropical conditions of China, Japan, and South-east Asia. These may be yellow, purple to reddish-purple, or red in color and sometimes have leaves with a fine pubescence and a grayish-green color with leaflets that are less divided and more compound than the more common western type. The sub-tropical carrots also have a propensity for early bolting or flowering before producing an edible root in both North American and European production areas due to a lower vernalization requirement. This has created a problem for seed companies wanting to improve some of these subtropical carrots with unusual colors for use in the temperate north. In general, "colored" carrots have received much less breeding effort when compared with the orange types and for this reason have more of a "rustic flavor," which in some includes strong, even soapy, off flavors. While recent breeding efforts that started in the 1990's have resulted in some improved colored carrot varieties on the market there is still plenty of room for improvement in this crop category.

A variety of colored carrots at a modern farmers market stand.

Climatic requirements

The best climate for carrot seed production includes a fairly mild spring and a dry summer with temperatures that routinely reach 86F (30C) and above, but generally don't reach above 95F (35C) until late in the summer, after the seed is set and near maturity. For seed maturation and harvest, a dry Mediterranean climate with low precipitation from late June until mid September, is best as it significantly lowers the chances of any diseases forming on the seed heads as they mature. Precipitation late in the season as seeds are maturing can significantly reduce yields and affect seed quality.

Soil and fertility requirements

Carrots are best grown on loose, well drained, deep loamy or sandy loam soils with good fertility. Carrot seed crops require high fertility for optimum yield and seed quality. Optimum root growth is important for plant health and the ability to select for root shape and quality without significant environmental effects. Good drainage is essential for prevention of bacterial soft rot. Crop rotations of at least three years should be practiced between any crops susceptible to *Sclerotinia sclerotiorum* and *Botrytis cinerea* (including beans, cabbage, endive, lettuce, and tomato).

Planting and Cultivation

Carrot seed is produced using two different methods, the "seed-to-seed" or "root-to-seed" method depending on your goals. The seed-to-seed method is the most efficient if you have well selected stockseed and feel confident that you can produce a genetically uniform crop without root selection. The root-to-seed method on the other hand affords you the chance to select the crop based on the root characteristics, replanting only the roots that meet your selection criteria, thus improving the variety. Root-to-seed also allows the ability to plant the root crop in a smaller nursery plot during the first season of growth and then transplant the roots to a larger field for seed production in the second season of the biennial cycle. Drip or furrow irrigation is preferred especially in the seed maturation phase as overhead irrigation may promote disease in the seed heads.

Seeding

Planting seed for the seed-to-seed or root-to-seed method should be sown into well-prepared soil with good moisture holding capacity. Seed is planted in summer, usually the tenth of July through the third week of August, depending on carrot type and location in the Northwest. As the crop is sown in the hottest, driest time of year you will need to assure even, adequate moisture to achieve a good stand. In desert production of carrot roots in California where seeding is frequently done in late summer at temperatures around 100F (35.5C), growers apply overhead irrigation daily for evaporative cooling in the top horizon of the soil until germination and emergence is achieved.

For the seed-to-seed method seed is sown sparingly so that only a cursory thinning is necessary to achieve the desired within row spacing. Seed should be planted to produce one live sprout per inch (2.5cm) with the seeding rate corrected for germination percentage of the seed lot. This planting rate allows for winter kill and the ability to select for the strongest, most vigorous seedlings the following spring. Thinning in spring can be achieved by blocking with a hoe or by "cross-cultivating" with a spring tooth harrow across the field at a perpendicular angle to the rows of carrots when they are young, but well established, seedlings. The goal is to achieve a within row spacing between roots of 4 to 8in (10 to 20cm). The spacing between rows can be from 22 to 36in (55 to 90cm).

With the root-to-seed method carrots are sown much as a grower would for producing the vegetable. As the crop is planted in mid-summer you should be particularly careful to plant at a spacing which will insure that roots achieve their optimum characteristic size and shape for selection upon lifting in the fall. Upon replanting stecklings in the spring the within row spacing is 8 to 12in (20 to 30cm) between plants as fully grown stecklings often produce larger plants. The spacing between rows is routinely between 24 and 36in (60 to 95cm).

Spacing and Staking

Carrot seed crops benefit from staking. Staking helps avoid lodging (plants falling over) and increases airflow which helps reduce incidents of disease.

The spacing between plants within the row is partly dependent on the type of carrot you're producing. If you are producing seed of Amsterdams, Paris Market types, or true Nantes types (or inbred lines for hybrid production) it is possible to plant them at a closer spacing as they all have flowering plants that are of a smaller stature than most other carrots. These types are frequently planted at 4in (10cm) apart within the row for the seed-to-seed method and at 8in (20cm) apart for the root to seed method. Other types of carrots, like Imperators, Chantenays, Flakkees, or Kurodas usually have larger frames and are planted at 8 to 12in (20 - 30cm) spacing, respectively for the two methods.

The density of the planting also influences which class of umbels will yield the highest proportion of seed. The carrot seed produced by the primary and second order umbels is universally regarded as superior to later forming seed of the third and fourth order umbels, due to its size and degree of maturity. In many temperate regions third and fourth order umbels commonly have a large percentage of their seed that is small, that hasn't fully matured, and has a lower germination rate. Under higher density plantings the development of the later forming third and fourth order umbels are restricted, thereby benefiting the development and quality of seed from primary and secondary order umbels.

Seed-to-Seed Method of Planting

The vast majority of large-scale production of carrot seed is done using the seed-to-seed method, which requires that the crop be sown in mid to late summer in the field in which the seed crop will be produced the following year. The crop is left in the field through winter where it will grow and flower during the next growing season with seed harvested the following August or September. This exposure to cold also serves to vernalize the crop, which is required to induce flowering during the second season. Vernalization is a cold treatment for a given number of hours below a temperature of approximately 50F (10C). The vernalization time required for carrots is generally a total of from 6 to 8 weeks below 50F (10C). In some warmer temperate areas it is important to make sure that there are enough vernalization hours during the course of the winter for all of the carrots in the population to bolt. Otherwise, only the least bolt hardy roots will flower and produce seed, which is the equivalent of selecting for easier bolting carrots. This can shift the population to become more bolt sensitive resulting in premature bolting of roots during the root production phase of the life cycle.

There are at least two main challenges with the use of the seed-to-seed method. First of all the carrots must be over-wintered without excessive damage from freezing or rodents. One of the main reasons for sowing the crop as late as mid to late summer is so the carrots won't be too large to go through the winter successfully. Carrot roots with a diameter of approximately 0.75in (2cm) or less at the shoulder will usually survive through the cold of winter better than full size carrots. Carrots at this size can generally withstand temperatures at or slightly below 14F (-10C) if there isn't excessive freezing and thawing throughout the winter. There are however varietal differences in the ability to withstand winter conditions among carrots, with subtropical types being especially sensitive to low temperatures.

Some growers will mechanically throw a layer of soil ("soil mulch") onto the row in fall for winter protection, although this may hinder regrowth in the spring and promote rotting in the crown. It is important to limit this soil mulch to only 0.5–2in (1.3-5cm), depending on your climate. Alternately, floating row covers can be used for cold protection, giving many winter crops an environment that is several degrees F warmer than ambient conditions. On a smaller scale growers have mulched the tops with straw or other organic materials to create a warmer environment for the crowns. However, in some cases the mulch can create a welcoming environment for rodents to build nests among an ample winter food supply that won't be evident until the roots are uncovered in spring. Also, the mulch needs to be removed promptly in spring so as not to promote rot at the crown.

The main drawback with the seed-to-seed method is for the grower or seed company not being able to evaluate and select the roots that will make seed. Many of the open pollinated carrot varieties that are available are of poor varietal quality because of lack of selection through numerous generations of seed-to-seed production.

The Root-to-Seed Method of Planting

The root-to-seed method requires that the carrot roots are "lifted," selected, and either replanted soon after the selection process or stored in a cooler or root cellar and planted the following spring. The advantage of this method is the ability to evaluate each root and decide if it is worthy of contributing to the next generation. The grower using this method must make sure that all the roots that are retained; 1) receive adequate vernalization to bolt the following season, 2) conform to the standards set by the selection criteria, and 3) are free of growth cracks, splits, disease, or any insect tunnels or damage. It is important to remember the old adage "one rotten apple spoils the whole barrel" as rot in stored root crops can have the same effect. The main disadvantage of this method is that some types of carrots, notably Nantes, do not vernalize dependably unless storage conditions are for an adequate duration.

The root to seed method may follow several modifications depending on the climate and goals of the seed grower. If your situation necessitates replanting the roots immediately after lifting and selection (thus over-wintering them in the field), then it is best to grow roots of a comparable size to the seed-to-seed method. This is especially true in the areas where the winter lows approach and exceed temperatures at or below 14F (-10C) and even smaller diameter carrots may frequently be damaged by the cold. If a grower is going to lift and store the roots through the winter months or they are replanting immediately after evaluation in a mild winter location (temperatures not dropping below about 28F (-2C) then they may want to grow the carrots to the size in which they are normally harvested for eating. The great advantage of this is that you can select the carrot traits at precisely the point in their life cycle that corresponds to their true use as a vegetable. Many carrot varieties used on the organic market are larger rooted types like Nantes, Chantenays, Flakkees, and Kurodas that don't fully attain their distinctive shape until they are mature. Maturity is measured by the extent to which their "tip" (the point from which the taproot emanates) has filled and their tips appear "blunt." This "blunting" as carrot breeders refer to it, along with the overall size and taper of the root, determines the characteristic shape of each carrot type. Hence, using the root-to-seed method and selecting roots at their full size and "tip fill" for each variety is the only way to maintain good shape in a carrot variety. Other traits that are best selected at full maturity include color, bolt tolerance, foliar disease resistance, and very importantly flavor.

Proper storage of carrot roots for the root-to-seed method is very important as some growers may need to store the roots for upwards of five months before replanting in the spring. Roots of biennial crops like carrots that are stored for seed production are known as “stecklings.” Environmental conditions for carrot stecklings stored for seed production are essentially the same as for storing carrots for food. The storage temperature should be between 35-38F (1.5-3C) to slow the roots’ physiological processes, but avoiding freezing with errant temperature swings that can occur when the cooler is set closer to 32F (0C). This exposure to cold must be for at least 8 to 10 weeks in order to fully vernalize the roots and promote flowering and subsequent seed production for most carrot varieties. For most Nantes and many Amsterdam types the vernalization period must be at least 10 weeks in duration with some carrot seed growers holding them in cold storage for 12 weeks to insure full vernalization. If carrots are not fully vernalized they will not flower. As all carrot varieties are populations with genetic variation for such traits, an inadequate vernalization period will result in only a percentage of the population flowering. By harvesting seed from only the plants that bolt with the least vernalization you will be selecting for the “earliest bolters.” If this is done over several generations it will result in a population with a much shorter vernalization requirement which can cause premature bolting of the crop when exposed to cool weather during its first season of growth.

Carrot roots must also be stored at 90-95% relative humidity to remain in good condition for subsequent growth when replanted. These two environmental requirements are most easily met with an electric cooler with humidity control. If using this type of cooler, clean, sound stecklings can be stored in wooden totes with small openings between the slotted planks on the sides to allow the free flow of humidity to reach the roots. Covering the totes with a two to three inch layer of *clean* wood shavings (not sawdust!) will keep the roots free of standing water that can accumulate on the surface of the uppermost roots under high humidity conditions. This helps eliminate a source of potential rot. Cedar wood shavings may be superior for this purpose, if available, as cedar is reported to have a higher level of anti-microbial factors than most woods.

Carrot stecklings can also be stored in traditional root cellars, which benefit from cold temperatures and high humidity of the earthen walls or floor at varying depths in many temperate zones. In root cellars carrot roots or stecklings are traditionally stored in moist, clean sand or clean, undecayed deciduous leaves (in New England growers sometimes use maple leaves), where the roots are laid carefully between layers of this material so as not to touch each other. This can slow the spread of rot through the lot of roots. It is crucial that you wait till the temperature of the cellar is about 40F (4.5C) or below for proper storage, which will also insure a higher humidity.

Alternately, stecklings can be placed into plastic bags that will create a high humidity environment for the roots. Make sure that there is a series of small penny sized holes, 3 to 4 rows consisting of 6 to 8 holes for a 18 by 36in (45 by 90cm) bag used for 25lbs (10kg) of carrots. Place three large handfuls of wood shavings into each bag attempting to spread them evenly amongst the carrots. These shavings will soak up much of the condensation that forms and the holes will allow for excess moisture to slowly escape out of the bags. Do not place warm roots from the field into any of these various cold storage situations directly, as this will cause excessive condensation that may promote rot.

Prior to storage carrots must be cleaned gently of soil clinging to the roots, which is best done *without* the use of water. It is preferable to harvest the roots during cool, dry weather, when the soil has had a chance to dry to the point where it readily crumbles and falls away from the root surface. Avoid rubbing soil vigorously against the surface of the root while cleaning, as sand or small rocks in the soil may abrade and damage the surface of the carrot, thus allowing an avenue of fungal or bacterial infection during the long storage period. Healthy soil has many beneficial microbes that will discourage the growth of root rot under most conditions; therefore it is not necessary to remove all of the soil before storing the stecklings. If possible it is best to not wash the roots and avoid getting them wet in any way before storage, as this will only encourage the growth of rots.

In some cases carrot roots are grown in hot southern areas in winter and transported to the Northwest for storage and subsequent seed production during the growing season. As the roots are harvested in hot weather during late winter in the desert southwest they often need to be hydro cooled to remove field heat. Some seed companies have had success with hydro cooling, gently washing, disinfecting with a peroxide wash, and then thoroughly drying the roots before transport and storage. Under most circumstances this more elaborate cleaning procedure is not necessary or practical for many farmers or smaller seed companies.

Carrot steckings on left are prepared for short term storage. Stecklings on the right are prepared for long term storage.

Proper removal of the tops from carrot stecklings is very important for long-term storage. The leaves and petioles (stems holding the leaves) are collectively called the tops and are often the most susceptible part of a carrot plant to rot. Removing as much of the tops without destroying the growing point within the crown is crucial. For 8 to 10 week storage before transplanting (which is often used primarily to vernalize the crop) the tops are literally twisted at about 1 to 1.5in (2.5 to 3.8cm) above the crown which tears the petioles, but doesn't usually promote significant rot in this shorter storage time period. If you are going to store the stecklings through the winter, which can be for upwards of 5 to 6 months, then you should trim much more of this easily decaying tissue.

The above photos demonstrate preparation of stecklings for long term storage by trimming tops in three upward-angled cuts.

Trimming will require a sharp knife, steady hand, and a little bit of knowledge of where the new top-growth will come from when the steckling is transplanted. All new shoot growth upon replanting emanates from the crown or the stem apex. This is the point where the petioles connect to the carrot and the shoot apical meristem creates all new foliar growth.

It is possible to trim most of the petioles off, about 0.25 to 0.3in (0.6 to 0.75cm) above the crown and not damage the growing point (hence not hindering subsequent leaf and flower stalk development).

You should then be able to see very small fern-like leaves below the point where you have cut and not see the round outline of an orange-white stem. If you see the outline of a stem you have either cut too close or that particular root has already started flowering and you have cut off the emerging flower stalk. It is a good idea to practice this technique on roots that you will not use for seed production until you get the hang of it.

Carrot stecklings are often prepared for replanting in two steps, though the second step is only necessary when selecting for root quality. The first step, removing the tops at the time of harvest, should always be practiced whenever pulling carrot roots for replanting. This cuts the transpiration flow from the plant and preserves moisture in the root. Upon transplanting the steckling the carrot will regrow new foliage soon after reestablishing new “feeder” or adventitious roots. If transplanting fully vernalized root within 3 to 4 weeks then the tops can be removed easily by twisting the tops a full 1.5 – 2in (3.8 – 5cm) above the crown until they snap off. Serious decay of petiole material won’t occur within this timeframe if they are stored properly. If storing roots any longer than this see *Preparation of Stecklings for Storage* above.

The second step, cutting the roots in preparing stecklings, is used when the seed company or grower wants to select for several quality traits like color, core size, flavor, and texture. However there are many instances where carrot roots from good genetic stock are dug for transplanting and don’t require any further selection for quality traits before transplanting. In this case whole roots can be planted as long as adequately deep holes or furrows are dug to accommodate the length of the roots, as soil needs to be firmed around each root up to the crown.

Cutting the roots when preparing carrot stecklings serves two primary purposes; 1) it allows the grower to evaluate for quality characteristics, and 2) it shortens the length of longer carrot types, e.g. Imperators, Amsterdams, Flakkees, and some Nantes, for easier transplanting.
When cutting the goal is to cut no more than 1/3 to 1/2 of the root off at the bottom or taproot end of the carrot. This gives you a chance to see both the intensity of the color of the carrot and the core size and a piece that can be used for taste and textural analysis (see Selection below.) Some breeders also use these cut pieces for nutritional and pigment analysis. The cut should be made cleanly, with a sharp knife, and at a slight angle latterly (15 to 30 degrees from a straight diagonal cut). This allows for quicker healing of the wound and the root will meet with less resistance when it is pressed into the soil upon transplanting. These cut roots are then placed, one deep, in a cool, airy area for several hours to allow the wound to heal or suberize, forming a scar-like protective layer on the cut surface. Stecklings must be at least 3 to 4in (8 to 10cm) long to successfully regrow and are usually 4 to 6in (10 to 15cm) long. This length easily accommodates replanting into furrows as compared to full size carrots.

Hybrid Seed Method of Planting

Producing hybrid seed on contract with a seed company can potentially be lucrative for an organic grower; however it is necessary to understand the process and potential risks in order to manage the crop successfully. Almost all of the hybrid seed production in carrot relies on a form of cytoplasmic male sterility (cms) which occurs naturally and was originally derived from wild carrot populations. To produce hybrid seed using this system the female parent is a male sterile inbred carrot line that doesn’t produce viable pollen but has fully functional female parts and will accept pollen from the male parental inbred line. The male parental carrot is fully fertile and will supply plenty of pollen to pollinate the female parent. The sterile female line is

usually monitored and rogued for the occasional presence of male, pollen producing plants. It is important to note that many of the inbred lines are poor seed yielders. For this reason many carrot F1 varieties are three way crosses that use a single cross for the female parent to take advantage of hybrid vigor for increased seed yield.
The specific protocols and responsibilities of planting and roguing should be clearly communicated in a contract with the seed company, but in general the following procedures are followed. The parent populations are commonly planted in a ratio of 8 female rows to 2 male rows to maximize the amount of hybrid seed that is harvested. The seed company should make recommendations of timing of planting. In some cases the male and female may require a staggered planting dates to ensure that the timing of pollen release coincides with timing of receptivity of the female inbred. In some cases removing the first flowers to emerge of the earliest flowering parent will help to synchronize the cross-pollination between the parental lines. Commonly the seed company will monitor and rogue the sterile female line for presence of pollen producing plants. Once the effective pollination period has passed the male rows are then mowed and incorporated to avoid mixing with seed from the female rows at harvest. The female rows, once mature are harvested in the same manner as in standard seed production (see section on Maturation and Harvest).

Flowering and Pollination

Carrots are insect pollinated and like most crops in the Apiaceae they are very attractive to a wide diversity of pollinator species. This is relevant, as carrots grown for seed in most temperate climate settings will attract insects from a broad perimeter around the field in which they are planted. If diverse insect habitat exists in the area then wild pollinators can supply a substantial amount of pollination to the crop. Depending on location, size of crop, and availability of pollinator species, the grower may need to manage pollination by placing honeybee hives in the field. When producing seed in an isolation tent honeybees or flies such as the blue bottle fly must be introduced for pollination.

Carrot flowers attract a wide range of pollinators.

Isolation Requirements

Carrot seed production requires that there is no wild carrot or Queen Anne’s Lace (*Daucus carota* var. *carota*) within a one to two mile area of the potential production field. This common weed will readily cross with cultivated carrots resulting in off-types of gnarled, white roots. The only effective way to produce pure carrot seed in the vicinity of wild carrot is with well-maintained pollination cages equipped with a mesh material specifically designed for insect pollinated crops. These cages are usually too expensive for commercial seed production and are generally only used by breeders or seed banks for research or preservation needs respectively.
The rare occurrence of wild carrot in eastern Washington, eastern Oregon, and southern Idaho, combined with ideal climates for carrot growth and reproduction accounts for the predominance of this region for commercial carrot seed production in the USA.

The standard recommended *minimum* isolation distance of one mile (1.6km) between carrot seed crops of the same “crop type” should be observed. In cases where significant barriers, e.g. hills, forest, dense vegetation, or significant structures, dominate the landscape then it is possible to diminish this distance to one half mile (0.8km) if the two carrot seed crops are of the same crop type. Major crop types in carrots include Nantes, Imperators, Chantenays, and each of the unusually colored carrot types (purples, reds, yellows, and whites). Other minor carrot types like Flakkees or Danvers are included into one of these major crop types (e.g. Flakkees and Amsterdams are in the Nantes crop type, while Danvers and Kurodas are in the Chantenay crop type). It is always possible to have some crossing at these recommended minimum isolation distances. Hence the idea is that two carrot varieties within a particular carrot crop type will suffer less varietal "damage" if crossed than if a Chantenay is crossed with an Imperator in the production of commercial seed. If you are producing carrot seed that is of a different crop type than the nearest neighboring carrot seed field you will need to double the isolation distance to a minimum of 2 miles (3.2km) to insure a high level of genetic purity. If there are significant barriers to pollen flow then a minimum isolation of 1 mile (1.6km) should be adequate. It is also important to use this increased isolation when isolating any of the different colored carrots from one another and also serves as the minimum distances to be used when there is any wild carrot in the production region. It should be noted that concerns have been heard in the central Oregon carrot seed production area that these isolation distances were not adequate between dissimilar carrot types, resulting in too high of a rate of out-crossing and indicating that a minimum isolation of 3 miles (4.8km) under normal conditions might be more effective.

Genetic Maintenance and Improvement

Maintaining the genetic integrity of open-pollinated carrot varieties that are good performers requires attention to details, knowledge of carrot traits, and a higher level of commitment to selection than for many other vegetables. As with many cross-pollinated species even well selected carrot varieties with a high degree of uniformity are genetically heterogeneous and may have an appreciable amount of variation in the traits that are routinely selected. Carrots are more prone to inbreeding depression from "over selection" (selecting too narrowly) than most cross-pollinated crops. When selecting a cross-pollinated species like carrots the goal is to establish the amount of variation that is acceptable for each trait of interest and not select so narrowly that you jeopardize the genetic integrity of the variety. A minimum of 150 roots and preferably over 200 should be retained in the final intermating population to maintain adequate genetic variability. The art of the selection process is for the breeder to understand the breadth of variation for the traits of interest that can be retained while still producing a variety that is selected for a level of uniform that satisfies the farmers who will produce the crop and the markets they serve. Following are suggested traits to consider in the selection process.

Evaluating carrot trials in the field.

Selection for Foliar Characteristics

Selection in carrots begins before the roots are lifted. As with all root crops the carrot tops are an important constituent of the crop, especially for the organic grower. Selection for vigorous seedling growth and the early establishment of a robust full set of leaves can be instrumental in developing a carrot for the organic market that is able to compete with weeds early in the season. Selection for this foliar canopy that will better compete with weeds can be done early in the season, long before the roots are fully formed. Also important is the stature of the carrot's foliage. Selection for carrot tops that stand erect with minimal contact with the soil is important in slowing the potential spread of both fungal and bacterial foliar diseases that are soil borne. Foliar diseases can decrease the yield and eating quality of the carrot root crop by diminishing the amount of energy (and sugars) that is fixed through photosynthesis. They can also severely affect the yield and quality of the seed crop. If a disease is transmitted via the seed then it requires special consideration (see Seed Borne Diseases in Diseases of Carrot Seed Crops section below).

If foliar diseases are present when producing the carrot roots for seed production it is often possible to select for horizontal resistance to these pathogens. When present, there is usually a continuum of disease symptoms that can be observed from plant to plant in the crop. In this situation it is advised to rogue out the most susceptible individuals from the population. This can be done as early as symptoms arise to slow the spread of the pathogen and can be repeated throughout the season, including during the flowering cycle in year two.

Selection for Root Characteristics

With the root-to-seed method of seed production you will have a golden opportunity to select for many root characteristics. I will list the most important traits that are universally selected for realizing that for any particular carrot type or carrot variety there may be traits of import for that specific type or the market it serves.

The shape of a carrot variety is probably the most recognizable feature of that carrot. As stated earlier the shape, relative size, degree of taper and the extent of blunting of the tip determine the characteristic shape of each carrot variety. While there is a sizable amount of influence on these traits from the environment the seed grower must make the overall shape of the roots a top priority in the selection process as the shape of a carrot variety will become much too variable in very few generations if ignored. Another trait that is usually quite variable is the degree of smoothness of the surface of the root. The predominate feature on the exterior of a carrot root are the lateral root scars that appear as pale, off-white lines in small indented regions running perpendicular to the length of the root. Selection for small lateral root scars with a minimum of indenting will make the carrot appear smoother. It is also important to select against the presence of small adventitious roots that occasionally emanate from the root scars.

Scarlet Nantes carrots laid out for selection of root and foliar traits.

Carrot roots are very prone to producing additional lateral roots, a syndrome growers call forking. Sometimes this forking will result in as many as three, four, and even five additional lateral roots. There is a lively debate among researchers on whether these extra roots are due to early damage of the developing taproot from either a root rot organism, nematode feeding, or from hitting a rock. Regardless of the cause the consensus among carrot breeders is that the genetic background of a carrot can influence the degree of forking in a particular variety, hence it is possible to select against forking. Also common in carrots is the propensity of certain carrots to crack while growing and then fully heal. These "growth cracks" result in ugly scars in the mature crop that make the carrot unmarketable.

Alternately "shatter cracks" may occur at the time of harvest from any impact sustained by the root during the harvesting process. They appear as long, vertical cracks along the length of the root and also make the effected roots unmarketable. While both types of cracking are thought to occur due to excessive uptake of water it is agreed that genetic selection against both forms of cracking over time can lessen the propensity of a particular carrot variety or population to crack.

Breeding for color in carrots is a time-honored tradition, as described in the development of orange carrots. When the intensity of the color in a variety is relatively low, as it is with older orange varieties and in most of the unusually colored open-pollinated carrot varieties, then it is possible to select based on a visual inspection of the exterior of the root. However for improved accuracy in selecting for root color, it is important to make a smooth lateral cut and visually evaluate the internal color (as described in *Preparation of Stecklings for Storage*) to more accurately compare the intensity of color between roots. This is a highly heritable trait that will improve rather quickly through several cycles of selection. The added bonus is that all of the varied carrot pigments are nutritionally significant and any increase in pigment will be a health benefit to anyone eating the variety.

Selection for flavor is very important; as we all know how many bad tasting carrots there are in this world. Selecting for carrot flavor isn't easy for a couple of reasons. First it requires tasting each root in the carrot population you're reproducing. This is usually done with smaller breeding populations of 300 to 400 roots that are grown using the root-to-seed method where it's possible to taste the piece that's cut from each root in preparation of the stecklings. You will quickly learn to spit out each bite that you taste to avoid the stomachache that can come from over 300 bites of carrots. Secondly, carrot flavor is biochemically quite complex and there is no consensus among carrot lovers on what constitutes the ideal carrot flavor. Many people want the sweetest, mildest flavored carrots while others like a strong "carroty" flavor that isn't too sweet. Also, the genetics for the human ability to discern flavors is quite variable. Therefore, anyone selecting for carrot flavor must be confident in their own ability to assess the relative merits of carrot flavor.

Harvesting

The king or primary umbel is the first to ripen. The seed will turn from a dark green to brown and will actually begin to detach from the umbel, but because of the racemes, or little hooks that cover the seed, they often latch together and remain on the umbel surface. Much of this seed can still be lost to shattering. The secondary and tertiary umbels that form after the king umbel will ripen anywhere from a few days to a few weeks later. However, waiting until all of the late forming umbels ripen is seldom economically viable as this seed tends to be of lower quality and strong winds will begin to dislodge the seed from the king umbels which is generally the best seed.

Poor soil fertility, uneven soil water, excessive heat at flowering, inadequate pollination and Lygus bug damage can all effect the development of the embryo. Good quality seed is generally plump and heavy. One way to check initial seed quality is to rub a small sample in the palm of your hand using a fair bit of pressure on the seed. Good seed will remain intact while poor seed will crush and break apart. When about 80% of the total seed has turned brown and detached from the umbel the crop is usually swathed and left to lie in the field for 2-5 days to allow the stems to dry so that the crop can easily be threshed. The crop is very vulnerable to shattering due to high winds and rain at this stage so timing and being mindful of the weather is important in timing this step.

Cleaned carrot seed.

Proper threshing takes an experienced operator. Because carrot seed is light in comparison to the stems and other trash created by threshing with combine, it's difficult to get a clean seed crop using a combine. Further seed cleaning with screens and forced air is necessary to get a clean seed crop. It's not uncommon for the total weight that comes out of the combine to be less than 50% good, clean seed. Research and trials show that early harvest of carrot seed before the seed is physiologically ripe results in lower seed quality.

Harvest beyond mid-September is dangerous as it exposes the crop to the vagaries of wind and rain damage. If the crop is small and cover is available, cut the crop at the proper stage and then move it onto paper or plastic under cover until it can be threshed. The stems will still have a fair bit of moisture so make sure to manually turn the crop to get it uniformly dry. Don't pile the crop any higher than 2-3ft (61-91cm) deep and try to keep the pile loose and fluffy to allow airflow through the crop. Supplementary air from fans may be necessary to keep mold from forming on the mature seed until threshing.

Diseases and Insect Pests

Seed borne diseases

The seed borne diseases in which the seed is the primary mode of transmission are of high concern as they can significantly affect seed quality and the potential for infection of the following crop. The following diseases are seed transmitted and commonly tested for in commercial seed production, Alternaria leaf blight (*Alternaria dauci*), black rot (*Alternaria radicina*), carrot bacterial blight (*Xanthomonas campestris* pv. *carotae*). If the presence of one or more of these seed borne diseases is confirmed then hot water treatment is currently the most viable organically approved method of treating the seed to control the pathogen. For infected carrot seed a hot water treatment regime of 20 minutes at 122F (50C) is recommended. Directions for conducting hot water treatment can be found in a publication by Ohio State University found at: http://ohioline.osu.edu/hyg-fact/3000/3085.html Hot water treatment should be performed with caution as it poses the dual risks of damaging the seed if overtreated (i.e. seed is soaked at too hot of a temperature or for too long of a time period) or conversely not being effective if seed is undertreated. Hot water treatments can also vary in effectiveness based on the quality of the seed and the extent of pathogen infection. It is always best to test the treatment on a small portion of seed first to see if it has adverse affects on seed quality or is effective in controlling the pathogen on the infected seed lot. Once seed has been treated it may also lose longevity in storage, so it is also recommended that seed be treated in batches according to expected sale or use.

Fungal Pathogens

Alternaria leaf blight: (*Alternaria dauci*)
Alternaria leaf blight is common in seed crops grown across the Northwest region. This fungal foliar disease occurs in all carrot growing regions and is transmitted easily via the seed. *Alternaria dauci* survives in the overwintered crop, crop debris, in the soil, and on the seed. Symptoms appear first on older leaves 8 to 10 days after infection as greenish brown, irregularly shaped leaf spots usually by mid-season. Petioles can become infected under increasing pressure and spots may grow and coalesce causing petiole girdling and leaf die back. Under severe pressure the most susceptible varieties can loose a considerable amount of foliage by the end of the season, resulting in depressed yields. Preventative measures include using disease free seed, irrigating so that plants are dry by nightfall, crop rotation (at least one year), and plowing under plant debris after harvest. Partial resistance exists among some carrot varieties.

Black rot: (*Alternaria radicina*)
Black rot symptoms often first appear in the foliage of carrots as dark brown lesions on the lower portion of the petioles. From there it commonly attacks the leaf-stem base at the crown of the root in fall resulting in dark cankers on the root with defined margins between healthy and infected tissue. Root symptoms may not occur until late in the season, but black rot can damage crowns to the point where the foliage dies back and the apical growing point is damaged or dies. This can occur throughout the fall or winter and can destroy roots that are overwintered for seed production, either in the field or in storage. Infected plants with viable growing points may survive into the second season but may be stunted

and result in reduced seed yields. Seed harvested from fields with black rot present may have infected seed. It commonly overwinters in debris in the soil. While black rot is not as widespread as Alternaria leaf spot in the Northwest, it is seed borne and is easily spread in this way. All carrot seed crops should be monitored and tested for presence of the pathogen after harvest.

Preventative measures include using disease free seed, irrigating so that plants are dry by nightfall, crop rotation (at least one year), plowing under debris after harvest. The disease has been successfully eradicated from infected seed by treating with hot water at 122F (50C) for 30 minutes.

Bacterial Pathogens

Carrot bacterial blight: (*Xanthomonas carotae* pv. *Carotae)*
Carrot bacterial blight is found wherever carrots are grown in North America. Foliar symptoms start as small irregularly shaped, yellow, water soaked lesions. These spots become brown and necrotic over time with a yellow halo at their margins. As infections of *X. carotae* progress dark elongated lesions may be found on the petioles. This pathogen is problematic for the seed grower as flower stems of bolting carrot plants may be dwarfed, chlorotic and become brittle. Umbels are often reduced in size and flowers may not fully develop. As lesions develop on the flower stalk they will ooze a bacterial exudate and be sticky to the touch. When the disease becomes severe the growing points of new flower shoots will appear to melt in the bacterial exudate as they emerge. Seed is readily contaminated and the disease can be transmitted via the seed.

Carrot bacterial blight survives in the overwintering seed crop, plant debris, and in the seed. Water and warm conditions are required for infection and spread of the disease. Crop rotations and timely plow down of crop debris will help to control the incidence of this disease. Regular roguing of seed production fields for infected plants will slow the spread of the disease. Refrain from walking or driving through fields that are wet from irrigation water or dew as the bacteria is easily spread in water droplets from one plant to the next. Infected seeds should be treated with hot water at 124F (51C) for 15 minutes.

Other Pathogens

Aster yellows phytoplasma: (AYP)
Aster yellows is a phytoplasma, which are bacteria like organisms that parasitize phloem tissue and require insect vectors for their spread. AYP is distributed worldwide, has a wide host range of over 300 plant species, and is vectored by many species of leafhoppers (order Hemiptera). The leaf hoppers spread the disease anew each year as they bring the disease with them from the south as they are carried long distances on air currents from the south. Plants affected by AYP will often appear stunted and bushy, with a mass of shortened, profuse growth of spindly leaves. Leaves will also become yellow and chlorotic as the phytoplasma disrupts photosynthesis in the plant. Leaves can also take on a rusty, bronze-like hue. Petioles often become brittle and twisted. Root symptoms of AYP include prolific growth of lateral roots, pale pigmentation and woody texture. Reproductive structures can also be severely affected, sometimes causing flowers to produce leaf like structures and white carrot petals to turn green. Sterility may also ensue and serious seed yield losses are possible.

The aster yellows phytoplasma survives from season to season in overwintering carrots, perennial host plants, and in the adult leafhopper vectors. Interestingly, AYP is actually beneficial to the fitness and longevity of the leafhopper vector. It is possible to select for polygenic resistance to AYP. When the original Northrup King Seed Company grew their seed production carrot roots of ‘Scarlet Nantes’ and ‘Gold King’ in Minnesota during the mid-twentieth century they always rogued out all roots with prolific lateral roots. Over many cycles of selection the NK strains of these two OP varieties were found to have relatively strong partial resistance to AYP by Gabelman, Goldman, and Breitbach at the U. of Wisconsin. They released several AYP resistant carrot inbred lines derived from these varieties in 1994.

Beet leafhopper-transmitted virescence : BLTV This phytoplasma has only been reported in the western USA. It appears to have a large number of hosts, similar to AYP, and several new host crop species have been identified in recent years. The magnitude of the damage in PNW carrot seed crops has also steadily increased over time. The only known vector for BLTV is the beet leafhopper (*Circulifer tenellus*), although this is still being investigated. The impact of this disease on carrot seed crops seems to be greater than on carrot vegetable production. Symptoms include chlorotic foliage with older leaves that turn reddish purple and floral parts that are distorted, malformed, and can be sterile. Flowers will often bolt early and develop a green caste as the petals will turn green due to a loss of pigment in petal cells. Seed yields can suffer severe losses. BLTV overwinters and is spread in the same way as AYP. Eliminating infected plants as soon as they appear and controlling leafhoppers can slow the spread of the disease.

Insect Pests

Tarnished plant bugs: (*Lygus* spp.)
There are several species of tarnished plant bugs where both the adult and the nymph stage will feed during the reproductive phase, after petal fall, on the embryo of the developing carrot seed. The result is embryoless, barren seeds, which are the same size and close to the same weight as viable seed and therefore cannot be eliminated during the seed cleaning process. This leads to germination rates that can be considerably lower than normal. The use of any type of insecticide, even one those approved for use in organic production, to control tarnish plant bugs during their feeding cycle is dangerous as there are also pollinating insects present. In Western Europe there are four major species of parasitic wasps in Western Europe, belonging to the genus *Peristenus*, which attack nymphs of *Lygus* spp. Research is underway to determine a system to use these parasitoides for *Lygus* control.

Carrot Rust Fly damage

Carrot Rust Fly: (*Pslia rosae)*
The carrot rust fly is found in temperate carrot growing regions around the globe and also attacks celery, parsley, parsnips, and a number of wild Apiaceae relatives. This small black fly (0.3in/6-8mm) emerges in spring to lay their eggs in the soil near the crown of carrots or other Apiaceae hosts. As larvae emerge they burrow into the soil feeding on the host's roots. As they grow they often tunnel into the main storage root, leaving a trail of rust-colored "frass" that gives this species its unique name. Tunnel damage will often lead to secondary damage that can be severe enough to destroy carrot roots grown for seed production. In the Pacific Northwest there are usually three generations of the rust fly per year with the potential damage increasing in subsequent generations if there is plenty of host plants for them to feed on in the first and second generations. It is a weak flier, not being able to fly much higher than 24in (60cm) above the ground. Rust flies will usually not travel more than 1000ft (305m) in a generation. The first step in controlling the carrot rust fly is monitoring the adults. By learning when they the first generation emerges in your location through the use of sticky traps, you can then schedule the planting of carrots and other Apiaceae crops after the average first peak of emergence in subsequent years. Sticky traps should be placed relatively close to the ground, at a 45-degree angle, and in several spots in a carrot field that are relatively close to the edge of the field. Moderate levels of quantitative resistance in several carrot varieties has been found and resulted in the cultivar 'Fly

Away.' Further breeding work needs to be done to build stronger resistance into new carrot cultivars.

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