CARROTS AND RELATED *APIACEAE* CROPS

2nd Edition

Edited by Emmanuel Geoffriau and Philipp W. Simon

CROP PRODUCTION SCIENCE IN HORTICULTURE

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Carrots and Related *Apiaceae* Crops, 2nd Edition

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Carrots and Related *Apiaceae* Crops, 2nd Edition

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Introduction: Contributions of the *Apiaceae* to the Agricultural Economy and Global Cuisines

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A HIGHLY DIVERSIFIED AND IMPORTANT FAMILY

The *Apiaceae* family (formerly called *Umbelliferae*) includes about 470 genera and 3800 species. The taxonomy definition of the *Apiaceae* family is currently evolving – recent taxonomy studies have changed the boundaries of the family with new species (Downie *et al*., 2010; Banasiak *et al*., 2016; Plunkett *et al*., 2018) – and will probably change in the coming years as it is still a complex family and molecular data are progressively available.

Lincoln Constance (1971) posited that the *Apiaceae* were familiar to prehistoric cultures 'because of their distinctive chemistry, reflected in odour, flavor, esculence, or toxicity' and the global familiarity and appreciation of this notable plant family continues today. The diversity of 'odour, flavor, esculence' is what attracts global connoisseurs to apply the *Apiaceae* to distinctive cuisines that have come to typify foods as 'Mexican' or 'Indian', for example, and delight consumers of all nations.

David French (1971) estimated that 'between two and three hundred species' of the *Apiaceae* have had some historical ethnobotanical use, and he provided an annotated list. In most cases the *Apiaceae* included in that review were wild plants used for their perceived health and medicinal benefits rather than crop sources of nutrients or flavour. An expanding scope of research on medicinal properties of apiaceous plants continues today.

About 50 taxa are being used as crops today (Table i). Most apiaceous crops originate from the Mediterranean area and are produced and used worldwide.

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Table i. Edible *Apiaceae* crops used as vegetable or condiment. (Reviewed by J.P. Reduron.)

Botanical name	Common name	Uses[a]	Plant portion used[b]
Aegopodium podagraria	Bishop's weed	V	L, St
Anethum graveolens	Dill	C, V	S, L
Anethum graveolens subsp. *sowa*	Indian dill, sowa	C, V	S, L
Angelica archangelica	Garden angelica	C, V	St, S, R, L
Angelica atropurpurea	Purple angelica	V	St, S, R, L
Angelica edulis	Japanese angelica	V	Stk, L
Anthriscus cerefolium	Salad chervil, French parsley	V, C	L, S
Anthriscus sylvestris	Cow parsley	V	L, Sh
Apium graveolens var. *dulce*	Celery	V, C	L, S
Apium graveolens var. *rapaceum*	Celeriac	V	R
Apium graveolens var. *secalinum*	Smallage	V, C	L, S
Arracacia xanthorrhiza	Arracacha	V	R, L, St
Bunium bulbocastanum	Great earthnut	V, C	T, L, F
Bunium persicum	Black cumin	C	S
Carum carvi	Caraway	C	S, R, L
Centella asiatica	Asiatic or Indian pennywort	V	L
Chaerophyllum bulbosum	Tuberous-rooted chervil	V	R
Conopodium majus	Pignut	V	T
Coriandrum sativum	Coriander, cilantro, Chinese or Mexican parsley	V, C	S, L
Crithmum maritimum	Samphire, rock samphire, sea fennel	V	L
Cryptotaenia canadensis	Hornwort, white or wild chervil, honewort, Canadian honewort	V	L, St, R, F
Cryptotaenia canadensis subsp. *japonica*	Japanese hornwort or mitsuba	V	L, St, R
Cuminum cyminum	Cumin	C	S
Daucus carota var. *sativus*	Carrot	V	R, L
Eryngium foetidum	Culantro, Java coriander	V	L
Eryngium maritimum	Sea holly	V	R, Sh, L
Ferula assa-foetida	Asafoetida or giant fennel	C	R, Sh, L

(*Continued*)

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Table i. Continued.

Botanical name	Common name	Uses[a]	Plant portion used[b]
Ferula communis	Common giant fennel	C, V	S, L, F
Foeniculum vulgare var. *azoricum*	Florence fennel	V, C	L, S
Foeniculum vulgare var. *dulce*	Fennel	C, V	S, L
Heracleum lanatum (*H. maximum*)	Cow parsnip	V, C	R, L, S
Heracleum sphondylium	Common cow parsnip	V	Sh, L
Levisticum officinale	Lovage, garden lovage	C, V	L, S, R, St
Ligusticum scoticum	Scotch lovage	V	L, Sh, R, S
Lomatium cous	Cous biscuitroot	V	R
Lomatium macrocarpum	Bigseed biscuitroot	V	R, S
Malabaila secacul	Sekakul, Arabian hartwort	V	R
Myrrhis odorata	Sweet cicely, garden myrrh, sweet chervil, myrrh	C	L, S, R
Oenanthe javanica	Water dropwort or water celery	V	L, Sh
Pastinaca sativa subsp. *sativa*	Parsnip	V	R, L
Perideridia bolanderi	Bolander's yampah	V	R
Perideridia gairdneri	Epos, yampah	V	R, S
Petroselinum crispum subsp. *crispum* var. *crispum*	Crisped-leaved parsley	V, C	L
Petroselinum crispum subsp. *crispum* var. *neapolitanum*	Italian parsley, Neapolitan parsley	V, C	L
Petroselinum crispum subsp. *crispum* var. *vulgare*	Flat-leaved parsley	V, C	L
Petroselinum crispum subsp. *tuberosum*	Rooted parsley	V, C	R, L
Pimpinella anisum	Anise	C	S
Pimpinella major	Greater burnet saxifrage	C	R, L, S
Pimpinella saxifraga	Burnet saxifrage	C	S, L, R
Sium sisarum	Skirret	V	R
Smyrnium olusatrum	Black lovage, horse parsley or alexanders	V, C	L, R, Sh
Trachyspermum ammi	Ajowan or ajwain	C	S, L

[a]V, vegetable; C, condiment.
[b]F, flowers; L, leaves; R, roots; S, seeds; Sh, shoots; Stk, stalks; St, stems; T, tubers.

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They correspond to herbaceous plants providing mainly essential oils and flavour, only a very few provide significant amounts of energy. All parts of the plant can be valorized, depending on the taxon.

GLOBAL PRODUCTION OF APIACEOUS CROPS

Global production statistics of Apiaceous crops recorded by the Food and Agriculture Organization of the United Nations (FAO) are sparse. The only *Apiaceae* production tracked by the FAO (FAO, 2018) is presented as 'carrots and turnips' grouped together and 'anise, badian, fennel, and coriander' grouped together. The fact that production data are mixed with crops outside the *Apiaceae* – carrot with turnip, which is in the *Brassicaceae*; and badian, or star anise, in the *Schisandraceae* family, with three apiaceous crops, namely anise, fennel and coriander – makes it difficult to make firm statements about production trends. Simon (2019) recently presented data indicating that global turnip production has been less than 2% that of carrot production in the USA.

Production of carrot and turnip has consistently been 30- to 50-fold higher than that of the anise, badian, fennel and coriander group (Fig. i). Interestingly, the recorded area harvested for carrot and turnip is only two- to threefold that of anise, badian, fennel and coriander (FAO, 2018), with the vast majority of the latter group being in Asia (Fig. ii), especially India. Since carrots are a root crop while anise, badian, fennel and coriander are spice crops often grown for seed, the dramatic difference in global production between these two groups is not surprising, even when the area of production of anise, badian, fennel and coriander is much more similar to that of carrots and turnips.

Per capita production of carrots and of anise, badian, fennel and coriander has more than kept up with a growing global population since 1960 (Fig. i), with both total production and per capita production of both crop groups rising especially in Asia during that period (FAO, 2018).

More of the apiaceous crops are grown for their savoury flavour and grown as spices and herbs, rather than as vegetable crops (Rubatzky *et al.*, 1999), and those crops are more widely grown in Asia, like anise, badian, fennel and coriander (Fig. ii). Given the more regional concentration of production of many apiaceous spice crops, production trends by individual country rather than global or regional statistics is a more meaningful approach. Chapters on several spice crops later in this book provide that approach.

The contributions of apiaceous spices and herbs to global cuisine cannot be readily measured in terms of agricultural production since individual serving size is often very small. Similarly, while many apiaceous spices contain numerous natural compounds that contribute to a healthy diet, their health impact is difficult or impossible to measure quantitatively. Like ornamental

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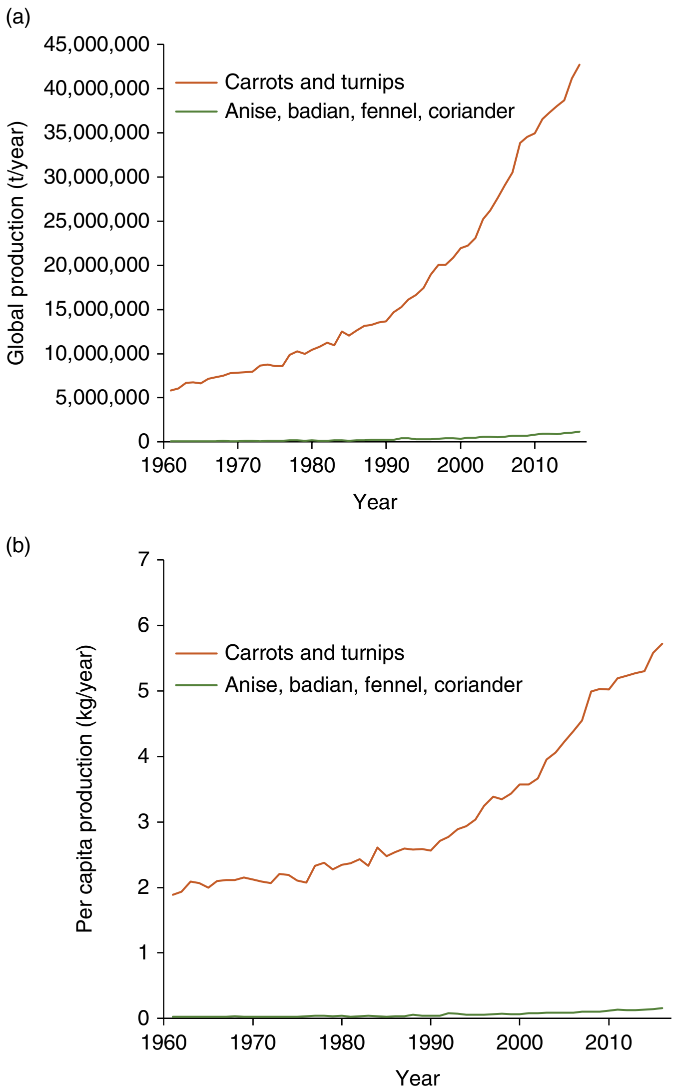

Fig. i. Global production in total (a) and per capita (b) of carrots and turnips and anise, badian, fennel and coriander since 1960. (Data from FAO, 2018.)

crops, their impact is more in the realm of aesthetic value and quality of life. Personal, ethnic and regional preferences and trends weigh in significantly on the value of apiaceous spices and herbs, but as globalization expands, their popularity does not seem to have been diminished.

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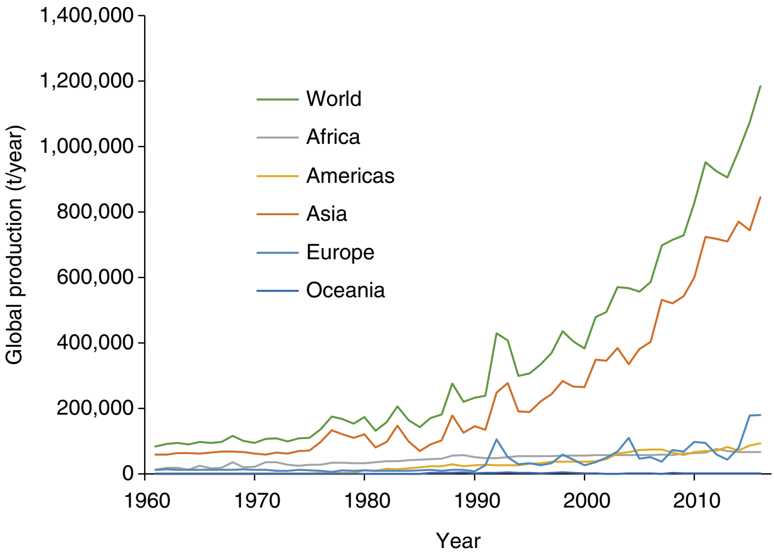

Fig. ii. Global production of anise, badian, fennel and coriander across regions of the world since 1960. (Data from FAO, 2018.)

FUTURE OUTLOOKS FOR APIACEOUS CROPS

Given the great breadth of diversity of apiaceous crops in terms of global production and crop use, future prospects are certain to be quite variable across crops and global production areas. Based on production statistics of the last 50 years, supply has more than kept up with demand, even as the global population has continued to grow. Future population growth is projected to level off and, given increasing demands on agricultural land, especially in Asia, the success of increased crop production in the last 50 years may not be realized into the future unless the projected levelling off of population growth is realized.

The impacts of environmental stress on crop production are anticipated to become more variable, often with a trend to hotter and drier climates. The impact of changing climates on sustained production of apiaceous crops has only minimally been studied, with no studies reported for most of those crops. Genetic diversity can provide some cushion to the threats of abiotic or biotic stressors, but systematic evaluations of genetic diversity in most apiaceous crops have not been reported either. Phenotypic diversity is broad in many apiaceous crops and many of them were domesticated in relatively warm and dry environments, so given their ancestral home in warm, dry climates, the prospects of meeting future production demands to feed growing populations with changing climates may be somewhat optimistic. Within this global trend,

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crops will need to adapt to erratic climate changes already observed: temperature evolutions with high amplitude in short periods of time; alternating of periods of very dry and very humid weather etc. Consequences are important in terms of undesirable bolting, crop cycle duration, disease management and yield consistency.

Apiaceous crops face important challenges regarding the reduction of input use. The use of chemical protection will be reduced due to a growing societal demand but also because all apiaceous crops are considered as minor by chemical companies. Fewer and fewer chemical products are homologated on apiaceous crops and some of them are considered with no solutions for chemical crop protection. With a global trend of careful use of resources, the efficiency of crops regarding fertilizer and water use will be an important criterion, and more research and experimentation are needed in this field.

Apiaceous crops are renowned for their product quality as healthy foods, condiments or essential oils. However, a better consideration of product quality (nutritional, sensory and sanitary) in crop management and commercialization chains is needed and can contribute to increase the added value of crops. Heavy metals and human allergies are concerns of increasing importance worldwide regarding apiaceous crops.

Crossing experience and knowledge between crops is valuable to address these challenges, which is also the reason for including a large range of apiaceous crops in the present book. An integrative, systemic approach of cropping systems and food systems, and an application of both classical and modern approaches to evaluate and apply the broad range of technologies to improving apiaceous crops to meet those future challenges will be critical.

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1

Taxonomy, Origin and Importance of the *Apiaceae* Family

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The *Apiaceae* (or *Umbelliferae*) is a plant family comprising at the present time 466 genera and about 3800 species (Plunkett *et al.*, 2018). It is distributed nearly worldwide, but is most diverse in temperate climatic areas, such as Eurasia and North America. It is quite rare in tropical humid regions where it is limited to high mountains. Mediterranean and arid climatic conditions favour high species diversification. The *Apiaceae* are present in nearly all types of habitats, from sea-level to alpine zones: aquatic biotopes, grasslands, grazed pastures, forests including their clearings and margins, cliffs, screes, rocky hills, open sandy and gravelly soils, steppes, cultivated fields, fallows, road sides and waste grounds.

The largest number of genera, 289, and the largest generic endemism, 177, is found in Asia. There are 126 genera in Europe, but only 17 are endemic. Africa has about the same total with 121 genera, where North Africa encompasses the largest occurrence of 82 genera, 13 of which are endemic. North and Central America have a fairly high level of diversity with 80 genera and 44 endemics, where South America accommodates less generic diversity with 35 genera, 15 of which are endemic. Oceania is home to 27 genera and 18 endemics (Plunkett *et al.*, 2018).

The *Apiaceae* family appears to have originated in Australasia (region including Australia, Tasmania, New Zealand, New Guinea, New Caledonia and several island groups), with this origin dated to the Late Cretaceous/early Eocene, *c.*87 Ma (Nicolas and Plunkett, 2014). The *Apiaceae* subfamilies (see below) then diverged in the Southern Hemisphere between 45.9 and 71.2 Ma: *Apioideae* and *Saniculoideae* in Southern Africa, *Azorelloideae* in South America and *Mackinlayoideae* in Australasia (Calviño *et al.*, 2016).

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1.1 TAXONOMY AND ITS HISTORY

The *Apiaceae*, or plants of the 'Carrot Family', were known by man since the most ancient times. Many local plants of this family were indeed used in primitive cultures because people soon noticed their odour, flavour, esculence or toxicity. The names 'coriander', 'cumin' and 'fennel' were recognized in a Mycenian text dating from 17th to 15th century BCE (Chadwick, 1958). Several *Apiaceae* are known in the early languages of China (*Materia medica*) and in Sanskrit (Constance, 1971). A utilitarian basic classification was developed by the native Americans of Mexico, long before the discovery of the New World (Rodriguez, 1957).

Theophrastus of Eresus, the Greek botanist and disciple of Aristotle, named the *Apiaceae* '*Narthekodes*' (Greene, 1909). He clearly defined anise, coriander, dill, cumin and fennel, in addition to other *Apiaceae* scattered in his books. Later, Dioscorides, in his *Greek Herbal*, cited about 50 *Apiaceae* under his general heading of 'Herbs' (Gunther, 1959), 40 of which are now well identified with substantial documentation (Evergetis and Haroutounian, 2015).

In the 16th century, the Herbalists improved the grouping of umbelliferous plants based upon vegetative resemblance, but still including many external elements from several other plant families. Cesalpino (1583) made the first overall grouping as '*Universum genus Ferulaceum*' which comprised about 60 herbs. At the same time, Dodoens (1583) used the designation '*De Umbelliferis Herbis*', and a short time later Daléchamps (1586–1587) gave the name of '*Plantae Umbelliferae*' to this group of plants. The '*Umbelliferae*' were born!

The next achievement was an important moment in the history of botany. The first monograph of a plant group independent of their uses was carried out by Morison (1672) who chose the *Umbelliferae* as a model where he proposed a classification based mainly on fruit morphology. After this the Linnaeus classification of *Umbellatae* was based on inflorescence features, most important being the presence of involucre (bracts) and involucel (bracteoles), contrary to Morison's system. Von Crantz (1767) reacted then to the Linnaean system, bringing back the use of habit and fruit. Many classifications arose during the 19th century including those of Hoffmann (1816), Koch (1824), Lagasca (1826), Reichenbach (1828), de Candolle (1829, 1830), Lindley (1836) who proposed the alternative name '*Apiaceae*', and Bentham and Hooker (1862–1883). The most widely used classification from this century is the one of Drude (1897–1898) written for *Die natürlichen Pflanzenfamilien*, often considered a basic work by later workers, where Drude divided the family into three subfamilies and 12 tribes. The 20th century started with the contribution of Koso-Poljansky (1916). The prolific German 'apiologist' H. Wolff (1910, 1913, 1927) revised many important genera like *Bupleurum*, *Eryngium* and *Pimpinella*. Cerceau-Larrival (1962) proposed a very original classification founded on pollen and seedling (cotyledon) morphology. L. Constance (1909–2001) from UC Berkeley USA carried out a huge work on *Apiaceae*,

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publishing many taxonomic and geographical monographs for North and South America and Asia. He published a 'History of the classification of *Umbelliferae*' (Constance, 1971) ranging from their origin to 1969. Hedge and Lamond (Edinburgh) included a treatment of the *Apiaceae* in the *Flora of Turkey and the East Aegean Islands* (Davis, 1972) and in *Flora Iranica* (Rechinger, 1987). Pimenov and Leonov (1993) updated Drude's system, adding four new tribes. Nowadays, some of the main workers on this family include M. Pimenov (Moscow), G. Plunkett (New York), S.R. Downie (Urbana-Champaign, Illinois), K. Spalik (Warsaw), B.-E. van Wyk and P. Tilney (Johannesburg).

The scientific taxonomy of *Apiaceae* started using morphological criteria but added afterwards were new diagnostic elements coming from several disciplines: anatomy, karyology, seedling morphology, palynology and phytochemistry. The current classification of *Apiaceae* takes now into account many molecular data and associates them with morphological features, still often including fruit anatomy. The family is at present divided into four subfamilies:

1. *Apioideae* have vittae extant in the valleculae and on the commissure, and rib oil ducts generally very small or lacking. All the main *Apiaceae* cultivated as vegetables or spices belong to this subfamily. Vegetables include carrot, celeriac, parsnip, alexanders, great pignut, pignut, skirret, tuberous-rooted chervil, Canadian honewort, Indian parsley, squaw root, arracacha, celery, fennel, angelica, chervil, coriander, dill, parsley and sweet cicely. Seeds include ajowan, anise, caraway, celery, coriander, cumin, dill, fennel and zira.
2. *Saniculoideae* have distinct (often very large) rib oil ducts and usually no vallecular vittae, and diverse outgrowths on their exocarps (scales, bristles or prickles). Only sawtooth coriander (*Eryngium foetidum*), used as an aromatic herb, belongs to this subfamily.
3. *Azorelloideae* have endocarps of fibre-like sclereids, vallecular vittae lacking, rib oil ducts present but not large, and dorsally compressed fruit (broadening of the two lateral ribs). No commonly cultivated plant used as a vegetable or spice is included.
4. *Mackinlayoideae* have endocarps of fibre-like sclereids, vallecular vittae lacking, rib oil ducts present but not large, and laterally compressed fruit. No commonly cultivated plants used as vegetables or spices are included.

At the present time, clear recognition and circumscription of tribes remains unsettled, because botanists face the lack of morphological discontinuities, reinforced with the convergences and parallelisms frequently occurring for many morphological characters.

Despite the great number of descriptive and taxonomic publications, the identification of many species remains difficult. Many species show a similar habit. Moreover, many species have a range of infraspecific morphological variations, peculiarly in the leaf dissection, which is confusing for identification. The floral morphology is often weakly detailed and rarely taken into account (if not merely forgotten) in the identification keys. Ripe fruits are in many cases

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essential for an undoubted determination, the young (green) fruits being misleading because of incomplete characters (such as ribs and wings). Moreover, several species demonstrate a great complexity due to high variability, hybridization and introgression processes, and influence of domestication.

Despite the use of molecular data coupled with morpho-anatomical features, the *Apiaceae* family remains marked by a large amount of very small genera, with 40% of the genera being monospecific, and over three-quarters have only five or fewer species (Plunkett *et al.*, 2018).

In contrast, there are several large genera. The largest one is *Eryngium* (*c.*250 species) present in the Old and New Worlds. *Bupleurum* (*c.*200 species) is mostly present in Eurasia. The next three largest genera, *Ferula* (*c.*185 species), *Pimpinella* (*c.*180 species) and *Seseli* (*c.*140 species), are all distributed in the Old Word. *Heracleum* (*c.*130 species) and *Angelica* (*c.*120 species) are widespread across north temperate areas. *Lomatium* (*c.*86 species) is limited to North America. The next genera encompass about 50 species: *Azorella* (*c.*58) from South America and New Zealand, *Arracacia* (*c.*55) from Mexico to South America, and *Ferulago* (*c.*50) from Europe, South-west Asia and North Africa.

Beyond these elements, phylogenetic studies have shown that many large genera (e.g. *Angelica*, *Heracleum*, *Lomatium* and *Pimpinella*) are composed of unrelated organisms descended from more than one ancestor (referred to as polyphyletic or paraphyletic groups), consequently still requiring progress to achieve reliable circumscriptions (Downie *et al.*, 2010).

1.2 ECONOMIC IMPORTANCE, PROPERTIES AND USES

The phytochemical diversity of the *Apiaceae*, early noticed by man by odours and flavours, led to a large range of uses: foods, beverages, flavourings, remedies and industrial uses. In many countries, the carrot family plants are still collected from the wild. In contrast, the main utilitarian species have been cultivated for a long time and were improved for agronomical processes.

The root vegetables are quite important since some of them are commonly consumed. The most well-known are carrots (*Daucus carota*), celeriac (*Apium graveolens*) and parsnips (*Pastinaca sativa*). Less known are parsley root (*Petroselinum crispum* subsp. *tuberosum*), alexanders (*Smyrnium olusatrum*), great earthnut (*Bunium bulbocastanum*), pignut (*Conopodium majus*), skirret (*Sium sisarum*) and tuberous-rooted chervil (*Chaerophyllum bulbosum*) in Eurasia. In North America, people sometimes eat the subterranean parts of Canadian honewort (*Cryptotaenia canadensis*), Indian parsleys (*Lomatium* spp.) and epos or yampah (*Perideridia gairdneri*). In South America, the roots of arracacha (*Arracacia xanthorrhiza*) are commonly cooked. A few *Apiaceae* root vegetables are extant in Africa, belonging to the genera *Annesorhiza* and *Chamarea*.

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Leaf parts are commonly used in many countries, notably the fleshy swollen parts which can be found in celery (*A. graveolens*) and fennel (*Foeniculum vulgare*). More numerous are *Apiaceae* for which the foliage is used as an aromatic herb. The main examples are: alexanders (*S. olusatrum*), angelica (*Angelica* spp.), chervil (*Anthriscus cerefolium*), coriander (*Coriandrum sativum*), dill (*Anethum graveolens*), parsley (*P. crispum*) and sweet cicely (*Myrrhis odorata*).

Many *Apiaceae* yield edible fruits, generally wrongly named 'seeds' in the marketplace. The most common are: ajowan (*Trachyspermum ammi*), anise (*Pimpinella anisum*), caraway (*Carum carvi*), celery (*A. graveolens*), coriander (*C. sativum*), cumin (*Cuminum cyminum*), dill (*A. graveolens*), fennel (*F. vulgare*) and zira (*Elwendia persica*).

The most well-known flavouring species used for beverages including alcoholic drinks are anise (*P. anisum*), giving the typical aniseed flavour in anisette, ouzo and raki; caraway (*C. carvi*), in kümmel and akvavit; and garden angelica (*Angelica archangelica*) in Chartreuse and vermouth.

One must keep in mind that the geographic origins of many commonly used *Apiaceae* are not or only doubtfully known, i.e. where their native populations were located at their first time of use. This is the case for ajowan, anise, coriander, cumin, dill, fennel and parsley. These were used since ancient times, exchanged, cultivated and marketed, so that it is therefore quite impossible to trace them. Consequently, the 'wild' populations are generally composed of plants escaped from cultivation and afterwards naturalized, becoming apparently spontaneous. The position of such populations in secondary habitats is generally linked with a non-native status.

Since most of the *Apiaceae* (if not all) are rich in chemical compounds, a great number of these compounds are used in local to more or less widespread pharmacopoeias. Their active properties lead to antispasmodic, carminative, cosmetic, diuretic, laxative, sedative or stimulant, stomachic and topical applications. A great number of the above-mentioned *Apiaceae* are also used in such a way. One must add others, restricted to pharmacological interest: bullwort (*Ammi majus*), Asiatic or Indian pennywort (*Centella asiatica*), hare's-ear (*Bupleurum* spp.), Siberian phlojodicarpus (*Phlojodicarpus sibiricus*), and toothpick-plant or khella (*Visnaga daucoides*). Some of them produce oleo gum resins: gum-ammoniac or vasha (*Dorema ammoniacum* = *Ferula ammoniacum*) and several giant fennels (*Ferula* spp., including *F. assa-foetida*, *F. galbaniflua* = *F. gummosa*, *F. tingitana*) producing the galbanum.

In contrast, many *Apiaceae* are more or less strongly toxic, such as hemlock water-dropwort (*Oenanthe crocata*), poison hemlock (*Conium maculatum*) and water hemlocks (*Cicuta* spp.). Some species are also known to cause dermatitis when the damp skin is exposed to bright sunlight (*Heracleum*, *Pastinaca*).

Finally, one can see now more and more *Apiaceae* used as ornamentals in gardens, especially belonging to the genera *Angelica*, *Astrantia*, *Bupleurum*, *Eryngium* and *Heracleum*.

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2

Botany of the Family *Apiaceae*

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The *Apiaceae* family is a complex group of plants in which many species are similar and difficult to identify. Once the species is identified, it is often still quite complex at the infraspecific level because of many existing variations (habit, leaf, umbel organization, sexuality of flowers). This chapter gives the main features of *Apiaceae* morphology and biology useful for identification checking, reproductive biology, cultivation, interest about wild relatives and biodiversity conservation.

2.1 MORPHOLOGICAL AND ANATOMICAL DESCRIPTION

The plants belonging to the family *Apiaceae*, sometimes merely designated as 'Umbellifers', are mainly herbs, although some woody subshrubs, shrubs or rarely trees are extant in this plant group. Almost all vegetable and aromatic cultivated *Apiaceae* belong to subfamily *Apioideae*, with only a very few members of *Saniculoideae* and no *Azorelloideae* or *Mackinlayoideae*; so, the description given here focuses on the plants of the *Apioideae* and *Saniculoideae*.

Among these plants, hairiness is quite often absent (glabrous) but can also be scabrous to densely hispid, and sometimes glandular. Most of the *Apiaceae* are aromatic, due to a network of secretory ducts throughout the plant. Plant heights vary considerably, from very dwarf plants (few centimetres) to giant plants reaching 3–5 m (*Heracleum*, *Ferula*). Stems are often erect, but they can also be creeping (*Helosciadium repens*, *Centella asiatica*), prostrate, decumbent or ascending; they can be hollow or solid, and the presence of pith is quite frequent. Apiaceous plants are generally branched, with rare unbranched examples. Subterranean plant parts are very diverse, ranging from rootstocks to taproots and rhizomes, which are sometimes swollen and tuberiform.

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Leaf arrangements are usually alternate (Fig. 2.1), rarely opposite or in a whorl around the stem (verticillate), usually not stipulate. The petioles are generally present and typically sheathing at the base, with the sheaths quite often inflated (*Ferula*). Leaf blades are very frequently compound, usually much incised or divided, giving the classical aspect of 'Umbel' leaf, but they can also be lobed (*Astrantia*, *Sanicula*), or even simple and entire (*Bupleurum*) to toothed. Perfoliate leaves (the stem passing through the blade) can be seen in some genera (*Bupleurum*, *Smyrnium*). A surprising leaf gradient can be observed in several genera (*Coriandrum*, *Petroselinum*, *Pimpinella*).

The inflorescences of most *Apiaceae* are compound umbels, what inspired the early name of the quite properly circumscribed family, '*Umbelliferae*', but members can be less frequently simple-umbellate (*Astrantia*), capitulate (*Eryngium*) or capitate (*Sanicula*). The umbels are typically subtended by bracts inserted at the base of the rays, forming an involucre; the bracts are often entire but can be toothed or dissected (*Daucus carota*, Fig. 2.2), or sometimes absent which is a useful feature for identification. The umbellules (or umbellets) are typically subtended by bracteoles inserted at the base of pedicels forming an involucel (quite rarely absent, and again a good feature for identification); the bracteoles are usually entire, rarely dissected. In some cases, the involucral bracts are enlarged, with bracts often coloured (*Astrantia*, *Bupleurum*).

The flowers (Fig. 2.3) of the *Apiaceae* are perfect to staminate, epigynous, 5-merous and actinomorphic (but sometimes zygomorphic for the outer flowers of the umbel or umbellule). Calyx lobes are typically short, and sometimes very small or obscure; developed calyx lobes are ovate, triangular, lanceolate to linear, sometimes spiny, and rarely pinnatisect (*Lagoecia*). The morphology of petals is greatly diverse (Reduron, 1978) to the point that it can, in part, be used for identification and floral biology. Petals are equal or unequal on the umbel, usually basally clawed and generally having a narrowed inflexed apex; their outline is frequently cordate, but also lanceolate, ovate, rounded and often enrolled (*Bupleurum*, *Pastinaca*), ending in a margin entire, shortly notched to bifid for the peripheral enlarged ones (*Coriandrum*, *Heracleum*, *Tordylium*, *Artedia*, *Orlaya*), rarely linear or deeply dissected; the range of their colour is quite wide: white, pale to dark yellow, yellowish-green, green, pink, red, purple, blue (*Eryngium*), useful character for identification; the petals are glabrous to puberulent, and sometimes with several secretory ducts. The five (rarely four or six) stamens are alternate with petals. Anthers are diversely coloured: often white, pink, crimson or yellow, less frequently green, dark green, violet blue or almost black. The ovary is inferior, with two (rarely one, or two to four) unilocular carpels. The two styles are ended by stigmata and frequently reflexed in fruit (rarely erect or very short). The base of styles is generally swollen into a nectariferous disc named a stylopodium. The stylopodium can have diverse morphologies (e.g. flat, low-conical, narrowly conical, hemispheric, annular) and colours (white to cream-coloured, yellow to green, dark red, blackish). It can be reduced in many *Apiaceae* of the New World.

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Fig. 2.1. *Apium graveolens*, the type species of the family *Apiaceae*. A, lower part; B, top part; 1, bud; 2, flower, with cordate petals and the green stylopodium in the centre; 3, stamen; 4, longitudinal section of fruit, showing the two carpels and the stylopodium and styles at the top; 5, dorsal face of fruit; 6, commissural face of fruit; 7, carpophore (axis bearing the two mericarps); 8, transverse section of fruit showing the five ribs and the vittae (in dark). (Adapted from Thomé, 1885.)

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Fig. 2.2. Flowering umbel of *Daucus carota* var. *mauritanicus* showing the dissected bracts; Saverne, Bas-Rhin, France. (Photo by J.-P. Reduron.)

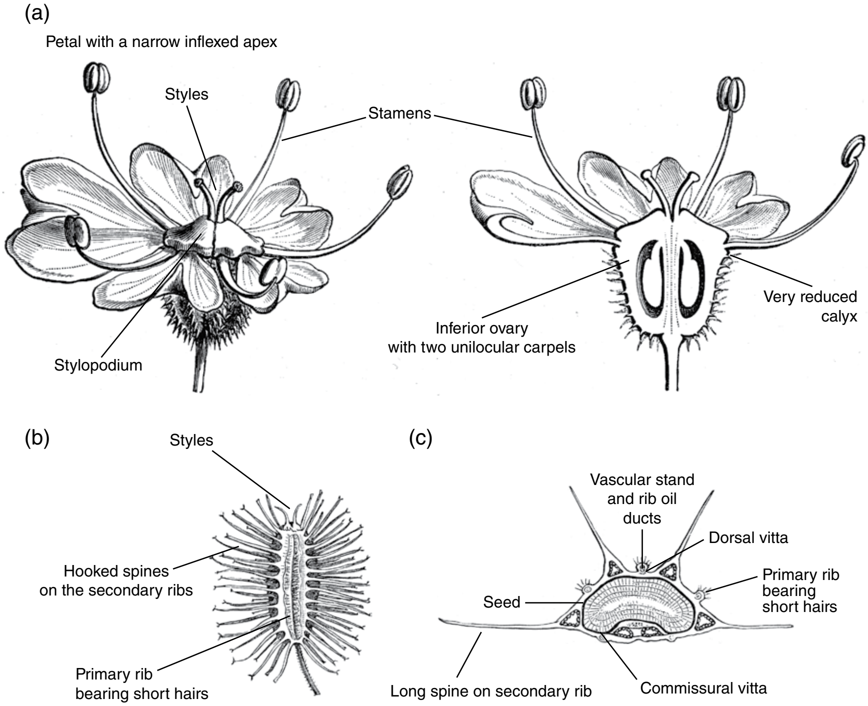

Fig 2.3. (a) Flower morphology of *Daucus carota*. (Adapted from Baillon, 1879.) Fruit morphology of (b) *Daucus involucratus* and (c) *Daucus carota* (transversal section). (Adapted from Drude, 1897–1898.)

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The fruits of *Apiaceae* are dry (very rarely fleshy, *Apiopetalum*, *Mackinlaya*), splitting when ripe into two usually equal mericarps attached to a thin axis called a carpophore, bifurcated or entire. The contact face of mericarps is the commissural one, the opposite face being the dorsal one. The commissural face can be narrow (*Torilis*, *Visnaga*, *Smyrnium*), when the fruit is laterally compressed, or can be very broad (as wide as the mericarp) when the fruit is dorsally compressed (*Pastinaca*, *Peucedanum*). Some fruits are almost spherical (*Coriandrum*) or two-lobed (*Bifora*). A beak can extend the mericarp at its upper part (*Anthriscus cerefolium*, *Scandix*). The dorsal face has five primary ribs, three dorsal and two marginal ones. These ribs can be filiform, prominent, keeled, corky, dentate, winged, spiny, or sometimes obscure, and even indistinct (*Ridolfia*). In several genera, secondary ribs are developed, often expanded into wings (*Laserpitium*, *Thapsia*) or bearing prickles (*Daucus*). Between the primary ribs (intercostal space), the formed furrows are named valleculae. The fruits can be glabrous, scabrous, puberulent, pubescent to hispid. There are one or more secretory ducts in association with the vascular strands (rib oil ducts, sometimes obscure) and distinct vesicles (specific to *Apiaceae*) named vittae, present in the valleculae and on the commissural face. The endosperm in the seed can be at commissural face plane to more or less concave to sulcate. Features of apiaceous fruit, including shape, compression degree, rib development, presence of wings or prickles, and number of vittae, were used extensively to develop the classifications of the family (Fig. 2.3).

2.2 BIOLOGY

2.2.1 Vegetative stage

Plants of the *Apiaceae* are annual, biennial or perennial. The annuals and biennials are always monocarpic (flowering and fruiting only once, then dying). The perennials are usually polycarpic (fruiting many times, not dying upon its first fruiting). The overall habit of the plant can be more or less strongly adapted to its habitat. Some species are totally prostrate and rooting at the nodes (*Helosciadium repens* living on the ground in wet meadows). True hydrophytes also exist (*Lilaeopsis*). Other species are practically leafless (*Deverra*) thus resisting very arid climates. There are also plants forming a caudex at, or just beneath, the surface of the ground. To withstand the salinity of the air on the seashore, several *Apiaceae* have glossy leathery or fleshy leaves (*D. carota* subsp. *gummifer*, *Crithmum maritimum*). Leathery leaves can also be found in plants living in dry climatic conditions (*Bupleurum rigidum*, *Cervaria rivini*, *Eryngium*). A number of genera include plants with 'rachis-leaf' morphology where the leaflets have disappeared and the remaining rachis is septate, compressed or inflated (*Lilaeopsis*, *Oenanthe*, *Tiedemannia*). Most of these plants live in aquatic habitats.

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Many species are spiny, a defence against herbivores (*Eryngium*, *Echinophora*, *Aciphylla*). The leaves can rarely be reduced to phyllodes (*Anginon*).

The aerial parts of the *Apiaceae* are very often moderately to strongly aromatic (*Apium graveolens*, *Foeniculum vulgare*, *Anethum graveolens*, *Levisticum officinale*, *Coriandrum sativum*, *Angelica archangelica*, *Myrrhis odorata*), and this characteristic has inspired diverse uses. Aromatic compounds are produced by schizogenous secretory canals found inside the endodermis, near the phloem and xylem vessels. Most of these compounds play a biological role, being repellent, attractive, toxic, acting as a biocide.

2.2.2 Flowering stage

The compound inflorescence of the *Apiaceae* provides the plant with two types of attractivity: visual and olfactory. Visual attractiveness results from the aggregation of the flowers into umbellules and umbels. The attractiveness of the resulting conspicuous floral discs is reinforced by flower density and bright colours (white, pink, yellow). For instance, *D. carota* subsp. *maximus* blooms have umbels up to 40 cm in diameter, and umbels of the giant hogweed (*Heracleum mantegazzianum*) are up to 60 cm in diameter.

Olfactory attractiveness results from volatile compounds spread by the flowers. The odours are very diverse, ranging from very pleasant (honey-like) to unpleasant (sweat odour, decaying fish). This range of odours attracts diverse insects (e. g. bees, flies).

Floral attractiveness is, of course, associated with the floral biology of the plant. Species having a prevailing allogamy show an overall attractive habit with umbels clearly emerging from the vegetative parts, in bright colours of floral organs, with dense umbel and strong smell. This allogamous syndrome (Owens, 1974; Jury, 1978) consists of floral zygomorphy (outer flowers with enlarged petals), high numbers of umbels on the plant, marked dichogamy (separation between stamen and style maturation time), long-exerted stamens opening on the outside, plentiful large-sized pollen, and very long styles.

In contrast, there are also species which are globally ‘discreet’ due to their prevailing autogamy where umbels consist of few unequal and divergent rays that do not form a disc, dull or dark colours of floral organs (greenish, purplish), and lacking or very low smell. This autogamous syndrome consists also of actinomorphic tiny equal flowers, few and not very dense umbels with lacking or weak dichogamy, short stamens opening towards the inside of the flower, low pollen production with small pollen grains, and short styles. The occurrence of the geitonogamous syndrome is quite frequent whereby the flowers of a given plant are fertilized by pollen coming from another flower on the same plant.

Many apiaceous species are andromonoecious, i.e. with male and bisexual flowers on the same plant, but without female flowers. These species can also quite frequently be completely hermaphroditic, rarely gynodioecious, i.e. with

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some plants bearing only bisexual flowers and other ones, female flowers (*Gingidia*, *Lignocarpa*, *Scandia*) or dioecious (*Aciphylla*, *Arctopus*, *Anisotome*, *Trinia*).

The compound inflorescences of *Apiaceae* are generally regarded as being uniform, but species vary in spatial and temporal arrangement of their flowers and umbels, and they exhibit diverse patterns of sex distribution and flowering sequence. In some cases, all umbels are synchronous. A commonly observed flowering system is clearly asynchronous, where plants bloom in successive phases. The first phase generally consists only of a single umbel which terminates the main axis. This umbel is usually large and composed of primarily, if not completely, perfect flowers. In the subsequent flowering phases, a progressively larger proportion of male flowers is observed. The second phase includes the production of perfect flowers, where many flowers are still fertile, so a high percentage of seeds are viable. These phases are then followed by umbels with functionally male flowers which appear to be perfect but without well-developed female organs, so they are unable to produce fruit. In the last phase, the umbels are quite completely male, without seeds. Consequently, for seed sampling, the agronomist must only take the fruiting umbels of the phases 1 and 2.

The flowering process *within an umbel* is again asynchronous, and in general it is centripetal, developing from the margin of the umbel towards the centre wherein there can be found entirely male flowers or even umbellules.

Flowers of most of the *Apiaceae* are protandrous, shedding pollen before the stigmata are receptive. With this, the flower is first functionally male, and later is functionally female. In several species, this phenomenon applies also the whole umbel which is first entirely male and afterwards entirely female. In synchronous flowering *Apiaceae*, the plant can initially be entirely male and afterwards be entirely female (*D. carota*). Protogyny is quite uncommon, observed mainly in North American species (*Thapsium*, *Zizia*).

Relevant papers about the reproduction biology patterns of *Apiaceae* subfamily *Apioideae* are Bell and Lindsey (1978), Doust (1980), Erbar and Leins (1985), Leins and Erbar (2004), Reuther and Claßen-Bockhoff (2010) and Schlessmann (2010).

The *Apiaceae* are mainly insect pollinated. A great diversity of insects has been observed visiting the flowering umbels, for nectar and pollen, and including predators of the foragers (Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera). Therefore, the *Apiaceae* were a long time considered as 'promiscuous' plants. But more in-depth studies have shown that few of the visitors are effective pollinators (Bell, 1971; Lindsey, 1984; Lindsey and Bell, 1985).

2.3 CARYOLOGY

Pimenov *et al.* (2003) gathered chromosome counts for a majority of the *Apiaceae*. The smallest haploid number was found to be $n = 3$ (*Sium suave*) while the highest number observed was $n = 77$ (*Lomatium columbianum*, $2n = 154$).

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The most widespread count is $n = 11$, giving the most common diploid level of the family: $2n = 22$. There are several series of polyploidy deriving from the base number. One series includes species having $2n = 44, 66, 88$, up to a maximum of 132 (*Lomatium suksdorfii*, *Seseli mucronatum*). A second series has the base number $x = 8$ leading to $2n = 16, 32, 48, 64$. A third series is based on the number $x = 10$ for species having $2n = 20, 40, 60, 80$. Polyploidy is quite rare in the vegetable *Apiaceae* and was only found in *Daucus montanus* ($2n = 66$) and in several North American species of *Lomatium* and *Perideridia*. Aneuploid and dysploid series occur in the family, with several genera exhibiting dysploidy (*Bunium*, *Bupleurum*), while some large series are uniform (e.g. *Ferula* includes *c.*185 species with $2n = 22$). The *C*-value is very variable ranging from 0.63 pg (*Oenanthe fistulosa*, $n = 11$) up to 5.18 pg (*Astrodaucus littoralis*, $n = 10$) and 5.48 pg (*D. montanus*, $n = 3x = 33$). B chromosomes were found in 24 genera and 40 species (Pimenov *et al.*, 2003).

2.4 FRUIT DISPERSAL

The morphology is usually taken into consideration along with the type of fruit dispersal. Fruits that are strongly compressed or winged (*Laserpitium*, *Thapsia*) are expected to be dispersed by wind. The same applies for plants with very light corky fruits (*Prangos*). Plants yielding spiny fruits are considered as dispersed on fur of animals (*Daucus*, *Torilis*). In some cases, the entire compound inflorescence is the dispersal unit (*Falcaria*, *Petagnaea*, *Trinia*).

On the other hand, several types of vegetative dispersal can be observed including natural cuttings (aquatic *Apiaceae*), stoloniferous roots (*Aegopodium*), creeping rhizomes and bulbules (e.g. *Cicuta bulbifera*, *Sium ninsi*).

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3

Apiaceae Seed Production

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INTRODUCTION

Most vegetable and condiment crops from the *Apiaceae*, including the major crops celery, carrot, coriander, fennel, parsley and parsnip, are propagated from seed. Perennial crops such as arracacha, water dropwort, Japanese hornwort and the pennyworts are capable of seed production but are most commonly propagated using vegetative methods. Carrot is the most important *Apiaceae* seed crop grown for propagation in terms of crop area and total value.

In this chapter, the principles and practices of *Apiaceae* seed production are described. While much of the information presented relates directly to carrot seed production, it is also relevant to production of most other *Apiaceae* seed crops. Where possible, information and examples from other crops have been included.

3.1 REPRODUCTIVE BIOLOGY

Seed production of carrot and other biennial *Apiaceae* follows a near annual cycle. Planting occurs in summer or autumn and seed is harvested in late summer or autumn of the next year. After the plant has developed beyond a period of juvenility, flowering is induced by a period of low temperature (vernalizing) conditions during winter. Following induction, elongation of the flowering stem, called bolting, is promoted by long days (Atherton *et al*., 1984). Development to flowering becomes faster with increased chilling units during vernalization and at higher temperatures after bolting has commenced (Craigon *et al*., 1990). In carrot, length of juvenility, chilling requirement for vernalization and temperature range over which vernalization can occur vary widely for different genotypes. Juvenility is completed in most temperate

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cultivars when eight to 12 leaves have been initiated (Atherton *et al.*, 1990), which approximates to accumulated thermal time from sowing of 800 to 1200 day-degrees above 0°C (Spurr and Geard, 2010). Vernalization requires 2–10 weeks' exposure to cold temperatures of 0–14°C (Dickson and Peterson, 1958; Spurr and Geard, 2010). Plants which have been induced to flower but have not yet begun stem elongation can be de-vernalized by several days of high temperatures between 28 and 35°C (Hiller *et al.*, 1979).

The *Apiaceae* inflorescence is a series of compound umbels borne terminally on the seed stalk branches. The central main stem terminates in the primary or first-order 'king' umbel. Secondary lateral branches form in succession from the top with each terminating in a secondary umbel. The system of branching usually continues for at least four orders, with smaller umbels in each successive order (Hawthorn *et al.*, 1961).

Flowering begins in the primary umbel and then progresses through the secondary and higher-order umbels. Individual umbels flower for 7–10 days and there is generally some overlap in flowering of successive umbel orders (Hawthorn *et al.*, 1961; Hiller and Kelly, 1985). Individual flowers are usually bisexual. They are also protandrous (Koul *et al.*, 1993) which facilitates outcrossing. Self-pollination occurs to varying degrees due to the overlap of flowering between different umbels but is generally undesirable except for plant breeding purposes.

The total period of crop bloom is typically 4 to 6 weeks (Hiller and Kelly, 1985) with flowering, seed setting and seed development occurring simultaneously on individual plants. This results in highly variable seed maturity which has important implications for seed yield, seed quality and timing of harvest.

3.2 OPEN-POLLINATED AND HYBRID SEED PRODUCTION

In 2000, approximately 60% of worldwide carrot seed production was of hybrid varieties with the balance made up of open-pollinated seed (Schreiber and Ritchie, 1995; Simon, 2000). It is likely that the market share occupied by hybrids has increased further given that almost all new varieties entering the market are hybrids. Hybrid seed is generally preferred because of the vigour and uniformity of the resulting crop but it is also more expensive to produce.

In open-pollinated seed crops, the resultant seed is the progeny of cross- and self-pollinations within and between plants of a population. Hybrid carrot seed production involves crossing a pollen-producing (male fertile or pollinator) line with a male-sterile line. After flowering, the pollinator line is destroyed to prevent contamination with sib-seed and the hybrid seed-bearing male-sterile parent line is retained for harvest. Before a hybrid seed crop is grown, each parent line is inbred for several generations to improve genetic uniformity. The progeny of the hybrid cross inherit characteristics from both parents and

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benefit from hybrid vigour. Commercial hybrid carrot varieties are often the progeny of a three-way cross, in which a single-cross (F1) hybrid male-sterile seed parent is first produced from two inbred parents and this is then crossed with an inbred pollinator line, since F1 male-sterile parent lines typically produce more reliable seed yields than inbred male-sterile parent lines (Erickson and Peterson, 1979). Single-cross hybrids are more uniform than three-way crosses, and do not require an additional year to produce F1 parent stock seed. Thus, if seed productivity of a single-cross hybrid is adequate, it is used in preference to a three-way cross.

The basis of male sterility for hybrid carrot seed production is genocytoplasmic male sterility (CMS). Two types of CMS are used commercially: brown anther and petaloid. Pollen of brown anther lines is aborted during microsporogenesis (Zenkteler, 1962). The anthers shrivel prior to opening of the flower (Welch and Grimball, 1947). In petaloid lines the anthers are replaced with petal-like or filamentous structures (Eisa and Wallace, 1969). While the flowers of brown anther lines retain the white coloration typical of open-pollinated cultivars, petaloid flowers are usually white or various shades of green (Erickson and Peterson, 1979). Individual petaloid male-sterile parent lines may contain both white and green phenotypes. Petaloid is generally preferred because of less frequent reversion to male fertility (Hansche and Gabelman, 1963) but seed yields from brown anther lines are often higher.

Because of the large genetic variation in material produced and the influences of environmental and cultural variables on seed crop performance, carrot seed yields vary widely. Generally open-pollinated yields range from 600 to 1200 kg/ha. Hybrid seed yields are typically 200 to 700 kg/ha but yields in excess of 1 t/ha are occasionally produced in three-way crosses. Hybrid seed yields are usually lower than open-pollinated yields because there are fewer seed-bearing plants in the field, flowering of the two parent lines is not always completely synchronous and pollen must be transferred from the pollinator to male-sterile lines to effect seed set, whereas in an open-pollinated line pollen transfer between flowers on the same plant or between plants in the same line can also effect seed set. Too few and/or ineffective pollinating insects and reduced vigour within parent lines are additional factors that can contribute to lower hybrid seed yields.

In addition to carrot, hybrid seed crops of fennel, parsnip and celery are also produced. Male sterility in celery is based on a defective tapetum that degenerates prematurely resulting in anthers lacking in pollen (Quiros *et al.*, 1986).

3.3 PRODUCTION LOCATIONS

Apiaceae seed production is located in areas where reliable yields of high-quality seed can be achieved. Seed yields and quality are generally favoured by warm

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and dry summer and autumn conditions, which promote pollination and seed maturation and minimize disease incidence. Low winter temperatures are required for *in situ* vernalization of many species, but temperatures must not be so low as to cause freezing damage. In some locations soil mulching or cloth covers are used to reduce the risk of freezing damage. Access to irrigation as well as a low incidence of wild *Apiaceae* species, which can reduce genetic and physical purity of the resultant seed lot, are also important factors in site selection.

In the northern hemisphere the main carrot seed production areas are located in the Pacific north-west of the USA (Oregon, Washington, Idaho and northern California) and in southern France. Significant production also occurs in Italy, Israel and Japan. Many vegetable breeders use counter-season production in the southern hemisphere to manage production risks and ensure continuity of seed supply. The main southern hemisphere production locations include south-eastern Australia, New Zealand and Chile. Many other countries also produce seed, mainly for domestic use.

3.4 PRODUCTION METHODS

Apiaceae seed crops are grown using seed-to-seed, root-to-seed or seedling transplant methods. For seed-to-seed crops, parent line stock seed is sown directly into the field in late summer or autumn and the resulting plants vernalize *in situ* over winter. In the root-to-seed method parent lines are established from seed in nursery beds. The resultant plants, known as stecklings, are lifted and then transplanted into a seed production field in spring. Lifting allows for rogueing of the parent lines based on root characteristics and culling of diseased and damaged plants. Root-to-seed crops can be vernalized *in situ* or during cool storage between lifting and transplanting.

Seed-to-seed production is less expensive and allows greater planting densities than root-to-seed production. It is generally preferred for large-scale production of biennial species, particularly carrot. Stock seed with high genetic purity is required because there is little opportunity to rogue the parent lines for root characteristics.

Although rarely used for large-scale seed production, root-to-seed production is still widely used for breeding purposes and for stock seed production where rogueing for root characteristics is essential. The main crops that can be grown using the root-to-seed method include carrot, celery, celeriac, parsnip and Hamburg parsley.

Celery, fennel and parsley seed crops can be sown from seed but are more commonly established from seedling transplants raised in a nursery. The main benefits of transplants are rapid establishment in the seed production field and improved crop uniformity which can simplify timing and improve effectiveness of subsequent crop husbandry practices.

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3.5 SITE SELECTION, PREPARATION AND PLANTING

Commercial seed production requires geographic isolation between sites to reduce the risk of unwanted cross-pollination between parent lines in different fields. Depending on the production standard required, isolation distances for carrot seed production are typically 1–2 km for crops of similar root type and 3 km or more for crops differing in root colour or shape and for stock seed production. Less stringent isolation standards are required for other *Apiaceae* seed crops except where different cultivars vary markedly in key traits, for example smooth and curly leaf parsley.

Production fields should also be isolated from weedy *Apiaceae* species such as wild carrot, which readily cross-pollinates with domesticated carrot. *Apiaceae* weeds and volunteers within the production field also present a significant risk for contamination of the seed line with foreign seed.

Apiaceae seed crops generally perform best on freely draining soils with high organic matter content such as peat, or soils with a silt loam or sandy loam texture. Optimum soil pH is 6.5 and there is generally a low tolerance for overly acidic and saline soils. Depending on the site characteristics and the type of irrigation used, some crops are grown on raised beds. Planting of seed-to-seed and transplant crops is normally done with tractor-mounted precision pneumatic seed drills or transplanter units. Root-to-seed crops are generally planted by hand with the stecklings distributed into furrows from a tractor-drawn bin.

Plant density has a significant effect on crop canopy architecture which can influence seed yield, seed quality and disease pressure within the crop. At low plant density, branching is increased. Individual plant yields are higher and the contribution of higher-order umbels to seed yield is greater (Table 3.1). The overall flowering period is extended, which can result in uneven crop maturity or loss of mature seed from shattering of lower-order umbels before seed in the higher-order umbels is mature. At greater density, branching is reduced, the bloom period is shorter and the contribution of higher-order umbels to seed yield is less (Gray *et al.*, 1983). The reduced spread in maturity can simplify harvest timing and result in improved seed quality, but individual plant yields are also reduced. In general, target stand densities between 12 and 18 reproductive plants/m^2 with inter-row spacings from 45 to 90 cm are used in commercial seed-to-seed production of carrot. At these spacings more than 70% of total seed yield is typically produced in the first two umbel orders with secondary umbels accounting for about 50% of the total yield (Table 3.1). Typical densities for root-to-seed carrot and transplanted fennel and celery seed crops range from 3 to 12 plants/m^2.

In hybrid seed crops, pollinator and male-sterile lines are grown in alternating strips through the field to facilitate destruction of the pollinator line after flowering (Fig. 3.1). The ratio of pollinator to male-sterile plants and the distance between adjacent pollinator strips are important yield determinants.

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Table 3.1. Plant density effects on total seed yield and percentage contributed by each of the primary, secondary and tertiary umbel orders for open-pollinated and hybrid carrot. (Adapted from Noland *et al*., 1988.)

Plant density (plants/m²)	Total seed yield (kg/ha)	% seed yield contribution by weight			% seed yield from first two umbel orders
		Primary	Secondary	Tertiary	
Open pollinated					
47	7134	20	60	20	80
12	2235	17	54	29	71
6	1458	17	55	28	72
3	986	13	52	35	65
Hybrid					
47	4148	22	63	15	85
12	744	22	54	24	76
6	424	20	60	20	80
3	358	15	59	26	74

Fig. 3.1. A commercial hybrid carrot seed crop near Naracoorte, South Australia. The crop is organized in a repeating arrangement of three rows of pollinator plants followed by six rows of male-sterile plants. (Photo by G. Fitzgerald, South Pacific Seeds.)

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Pollinator to male-sterile plant ratios within crops largely depend on the relative fecundity of the two parent lines. Generally, male-sterile to pollinator plant ratios vary from 2:1 to 4:1. Pollen transfer rates to male-sterile flowers decline sharply with distance from the pollen source (Spurr, 2003), so the width of male-sterile strips in hybrid crops is usually kept to between 3 and 8 m. In most production systems pollinator strips must be of sufficient width to enable mechanical destruction with a tractor-mounted mulcher after flowering.

3.6 CROP NUTRITION AND IRRIGATION

Fertilizer applications are largely determined on the basis of soil and plant testing. Depending on the nutritional status of the soil and varietal requirements, between 70 and 150, 40 and 70, and 80 and 120 units in total of nitrogen, phosphorus and potassium, respectively, are typically applied to carrot seed crops. This is divided between a base dressing of fertilizer at planting (commonly with N:P:K ratio near 1:2:2) and combinations of side dressings and foliar applications after winter when the crop is growing rapidly. Calcium and various trace elements may also be applied during reproductive growth. For celery, nitrogen applications must be undertaken with care when the risk of frost is high.

In most production locations, access to a reliable source of irrigation is essential. Careful management of soil moisture during establishment and flowering is important as these events represent stages when the crop is particularly sensitive to moisture stress and, for seed-to-seed crops, generally correspond with periods of high evapotranspiration.

In the USA, most crops are grown using drip or flood/furrow irrigation whereas in Australia and New Zealand overhead centre-pivot irrigation is commonly used. Drip and flood irrigation have the advantage of being able to apply water without wetting the crop canopy. This is beneficial for control of some foliar and seed-borne diseases such as bacterial and fungal leaf blights (Strandberg, 1977, 1988; Crowe *et al.*, 2006). In low rainfall environments, establishment of seed-to-seed crops and incorporation of post-plant residual herbicides are generally more reliable under overhead irrigation. Daytime overhead irrigation is undesirable during flowering as it can compromise pollen viability and deter pollinating insects (Spurr, 2003).

Irrigation management during establishment of seed-to-seed crops such as carrot is focused on maintaining adequate soil moisture for germination in the seeding zone 0 to 20 mm beneath the soil surface. In light soils, moisture retention is improved by rolling the seedbed before seeding. It is important that irrigation is managed so that surface structure does not deteriorate to a crust that can impede water penetration and seedling emergence. Under overhead irrigation these objectives are best achieved with frequent, low-volume applications.

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During flowering of carrot, reduced nectar production is often the first obvious indicator of moisture stress within the plant. Consistent nectar production is important to maintain attractiveness of the crop to pollinating insects to maximize pollination (Spurr and Geard, 2011). Moisture stress can also impair seed development, resulting in reduced seed size and vigour (Steiner *et al.*, 1990). Excessive watering is also undesirable as it promotes seed development in high-order umbels and extends the period of seed maturation within the crop. As a result of these considerations, irrigation strategies that provide low moisture stress conditions during flowering and seed development for the primary and secondary umbel orders, followed by accumulating moisture stress for several weeks prior to harvest to prevent seed development on high-order umbels are generally recommended for carrot seed crops (Steiner *et al.*, 1990). In general, the same principles apply to other *Apiaceae* seed crops, but it is notable that celery has a shallow root system and generally requires more frequent watering than other crops.

3.7 WEED CONTROL AND ROGUEING

Contamination of the seed crop with weed seeds is expensive as it can result in additional seed cleaning and grading processes to remove the weed seeds and a corresponding loss of yield. Furthermore, the quarantine requirements of some markets may prevent sale of contaminated seed lots.

Early weed control in seed crops is generally similar to that used in the corresponding vegetable crops but there are additional challenges. Seed crops are grown for a longer period of time over which weed control must be maintained. Inbred hybrid seed parent lines often display increased herbicide sensitivity resulting in a reduced range of chemical options for weed control and lower rates that can be safely used.

In-field rogueing is an essential aspect of seed production to ensure genetic quality. Most rogueing is undertaken during the reproductive growth stages. Plants differing in morphology or phenology from the parent line standard are removed including plants displaying atypical foliage, root or inflorescence characteristics, early bolters and, in male-sterile lines, pollen-producing plants. Rogueing is also used to remove volunteer plants from previous *Apiaceae* crops and weeds that have escaped earlier control measures.

3.8 MANAGEMENT OF FLOWERING AND POLLINATION

Synchronization of flowering between parent lines, referred to as nicking, is an important element for achieving satisfactory yields from hybrid seed crops. Within carrot, large variation exists in traits that determine onset of flowering including length of juvenility, cardinal and optimal temperatures for vernalization, chilling unit requirement for vernalization and daylength response

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(Spurr and Geard, 2010). The impact of each on determination of flowering time varies in different environments such that parent lines that nick well in one production location may have poor nicking in another. Recent growth in production of hybrid carrot seed from crosses of early flowering tropical (Kuroda or Brasilia) lines and later flowering European Nantes lines has also increased the need for flowering time adjustment, in some cases by as much as 3 weeks. Furthermore, in some hybrid crosses, the length of flowering period of the pollinator line is less than its corresponding male-sterile line and, in this situation, the pollinator line should be managed to extend its flowering period.

Carrot seed producers generally employ two strategies to manage nicking issues. The first is to delay sowing or transplanting of the early line relative to the late line. Split sowing or transplanting of a pollinator line can also be used to lengthen the overall period of pollen production. In seed-to-seed crops, adjustment of sowing time is generally most effective for easy-bolting lines because more bolting-resistant genotypes may fail to flower from a late sowing. The second and more widely applied strategy is to trim the early umbels and promote branching and development of later-flowering, higher-order umbels.

In addition to managing flowering time, highly vigorous crops may be trimmed to reduce reproductive canopy height and risk of lodging. Stem-shortening plant growth regulators including ethephon and mepiquat chloride combinations are used by some producers to prevent lodging.

While wind pollination occurs in some species, the large majority of pollination of *Apiaceae* seed crops is performed by insects. The flowers of these crops are unspecialized in structure and can be pollinated by a wide range of insects. Three hundred and thirty-four insect species were observed in a study of insect visitors to carrot flowers in North America (Bohart and Nye, 1960) and over 100 morphological groups of insects were reported in flowering carrot crops in Tasmania (Gaffney *et al.*, 2011). Despite this diversity, comparatively few species are frequent and reliable visitors and also carry enough pollen to contribute significantly to pollination of commercial carrot seed crops (Gaffney *et al.*, 2018). In general, the most important pollinators are bees, syrphid, calliphorid and muscid flies, and nectar beetles (Spurr, 2003; Gaffney *et al.*, 2011). Reliance on wild pollinator populations alone is risky, so most producers introduce European honeybee colonies into crops at the onset of flowering. Stocking rates of about five (open-pollinated crops) to ten hives (hybrid crops) per hectare are typically used. In breeding operations, flies are commonly used to pollinate caged plants.

While there are few problems attracting honeybees to crops such as fennel, carrot flowers are not particularly attractive to honeybees. This may be partly attributable to poor nectar production, which is most commonly an issue in some CMS hybrid seed parent lines (Erickson and Peterson, 1979; Spurr and Geard, 2011), and the composition of carrot nectar, which is reportedly low in

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sucrose (Broussard *et al.*, 2017). Nectar production is positively correlated with temperature and sensitive to plant moisture stress (Spurr and Geard, 2011).

In hybrid crops, pollinator line removal provides an opportunity to manage uniformity of seed maturation. As a general rule, the pollinator line is removed during flowering of the tertiary umbels, but this may be delayed if conditions for pollination during early flowering were poor.

3.9 PESTS AND DISEASES

Apiaceae seed crops are subject to the same insect pests and diseases as their corresponding vegetable and condiment crops and similar management practices are applied. Seed-feeding insects and seed-borne diseases must also be effectively managed to ensure high-quality seed is produced.

Some insects within the *Lygaeidae* family of true plant bugs (Hemiptera) including various species of lygus bug and the Rutherglen bug, *Nysius vinitor* (Fig. 3.2), are known to feed on developing seeds of carrot and other *Apiaceae*, causing damage to the embryo and loss of seed viability (Robinson, 1954; Spurr, 2003). Damaged seeds cannot be identified on the basis of external appearance or removed by grading. In general, control is achieved by crop monitoring and application of pesticides in response to infestation events.

Seeds of carrot, coriander, dill, fennel and parsnip are also damaged by the parasitic seed wasp *Systole albipennis*, commonly known as the parsnip or

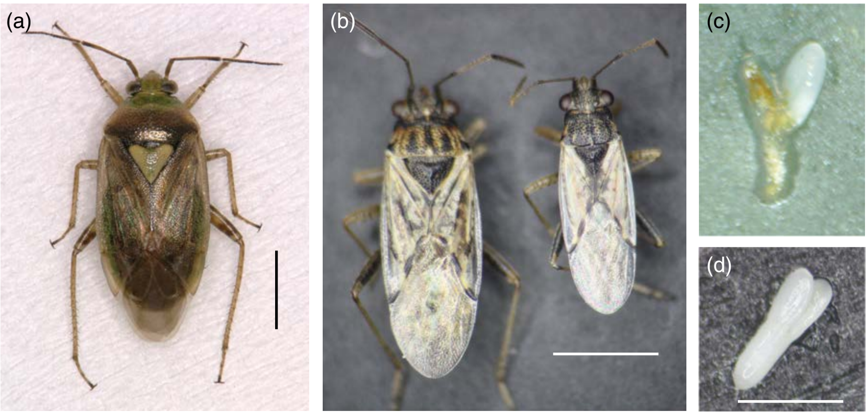

Fig. 3.2. (a) Lygus bug (adult *Lygus rugulipennis* pictured) and (b) Rutherglen bug (*Nysius vinitor*; adult female pictured on the left and adult male on the right) feed on developing seeds of carrot and other *Apiaceae* causing embryo damage and loss of viability. Excised embryos from (c) damaged and (d) viable seeds. Scale bars in (a), (b) and (d) indicate 1 mm. (Photos by C. Dias, Bejo Zaden BV and D. Spurr, SeedPurity Pty Ltd.)

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fennel wasp. *S. albipennis* is widely distributed and periodically affects most seed production areas to varying degrees. Most in-field control is a by-product of pesticide applications for other seed-feeding insects. Larvae and pupae are eradicated from some higher-value, low-volume seed lines after harvest by short-term storage at freezing temperatures.

In addition to diseases that also affect vegetable and condiment crops, several pathogens require management to ensure that effects on seed yield and quality or incidence of seed-borne disease is minimized. These include the fungal pathogens *Alternaria* (e.g. *Alternaria radicina* black rot of carrot and *Alternaria petroselini* leaf blight of parsley), *Cercospora* and *Septoria*; and the bacterial pathogens *Xanthomonas hortorum* pv. *carotae* (which causes bacterial leaf blight of carrot) and *Candidatus* Liberibacter solanacearum. Fungi from the genus *Phomopsis* (*Diaporthe*) have also more recently emerged as significant pathogens (Zalewska *et al.*, 2013) of crops such as caraway, dill, fennel and parsnip with potential to affect seed production. Management strategies used by growers to minimize disease incidence include long cropping rotations of up to 8 years (for *A. radicina*) between host crops in the same field, use of disease-free stock seed, stecklings or transplants, avoidance of overhead irrigation in areas affected by bacterial leaf blight, destruction of crop residues to prevent dispersal to adjacent fields, and application of bactericides and fungicides (Du Toit, 2004; Farrar *et al.*, 2004; Crowe *et al.*, 2006).

3.10 SEED DEVELOPMENT AND TIMING OF HARVEST

Decisions on when to harvest *Apiaceae* seed crops are complicated by their prolonged period of flowering and a pattern of seed development where most embryo growth occurs late in seed development, coupled with a tendency for mature umbels to shatter. Germination and vigour are positively correlated to embryo size, and shattering can occur on the most mature umbels before the seed lot as a whole reaches an acceptable germination standard (Fig. 3.3).

Various indicators of harvest maturity are used. The most common is based on the physical appearance of the umbels, with harvest typically occurring when the secondary umbels are brown and the seeds of the tertiary umbels are starting to turn brown. In addition to managing the length of the flowering period to improve uniformity of seed maturation, polymer-based glue sprays are sometimes used to delay the onset of shattering.

In large-scale seed production, a single mechanized harvest is performed. Prior to harvest the crop is either sprayed with a desiccant or cut and windrowed. After the plants have dried, a combine harvester (Fig. 3.4) is used to thresh the seed free from the plants and provide basic separation of seed from the coarse plant trash and dust. The harvested seed is transported to drying and cleaning facilities where seed lots with unacceptably high field heat or

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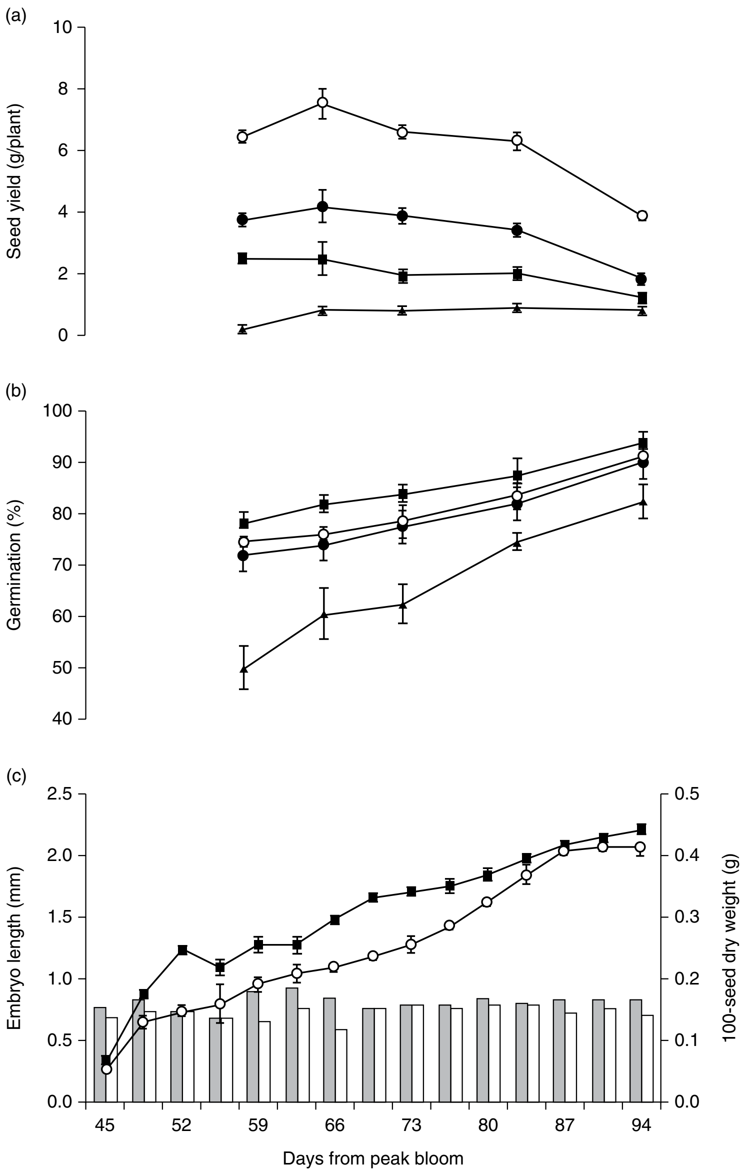

Fig. 3.3. Effect of time of cutting on (a) yield and (b) mean germination percentage of seed from the primary (■), secondary (●) and tertiary (▲) umbel orders and all umbel orders combined (○) in a hybrid carrot seed crop grown in Tasmania, Australia. (c) Corresponding changes in mean embryo size in seed from the primary (—■—) and fourth secondary (—○—) umbels and 100-seed dry weight in seeds from the primary (■) and fourth secondary (□) umbels. Error bars indicate standard errors, $n = 4$. Least significant difference values ($P < 0.05$): combined umbels yield = 0.48 g; combined umbels germination percentage = 1.2%. (Adapted from Geard *et al*., 2007.)

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Fig 3.4. Harvesting a windrowed carrot seed crop with a combine harvester. (Photo by C & J Spencer Agriculture.)

moisture levels above 12% are ventilated with dry air prior to storage for subsequent cleaning and grading.

Seed cleaning is performed with a combination of air screen cleaning, indent cylinder and gravity grading equipment which can achieve high levels of seed lot purity and precise size or density grading of the seed. Seeds of carrot, dill and caraway have spines that must be removed to enable the seed to flow freely and for accurate sizing. This is achieved with milling equipment that rubs the seed. Seeds of celery, parsley and fennel are ribbed but not spined, and do not require milling. Parsnip seeds have small wing-like ribs, but these do not interfere with seed separation. Chlorophyll fluorescence sorting is used in some low-volume or high-value seed lines to grade out immature seed.

Industry standards for seed lot purity and germination vary between varieties and target markets but, over time, improving production practices and demand for high-quality seed have increased standards. For carrot seed production minimum purity and germination standards of 99.9% and 80–90%, respectively, are typical.

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After cleaning, the seeds are dried to their optimum storage moisture content which is normally in the range of 7 to 9%. *Apiaceae* seed will typically maintain viability for 3 years or more in cool, dry storage conditions but parsley and parsnip seeds lose viability quite rapidly and are normally stored for only 1 year.

3.11 SEED TREATMENTS

Many seed treatments for *Apiaceae* are intended to reduce the impact of *Alternaria* and other fungal pathogens on seed germination and to prevent transmission into the developing crop. Fungicides such as iprodione and thiram have commonly been used in seed dressings (Farrar *et al.*, 2004) but have now been withdrawn from registration in the European Union. Hot water (50°C for 30 min) or hot sodium hypochlorite (0.1 or 1.0% at 50°C for 30 min) seed treatments have been shown to eradicate *A. radicina* with minimal reduction in seed germination (Pryor *et al.*, 1994). Hot-water treatment is also used to eradicate the bacterium *C.* Liberibacter solanacearum from seed of *Apiaceae* hosts as it is considered a quarantine pest in some markets.

Pre-germination soaking, priming and growth regulator seed treatments are used to improve germination percentage and speed and uniformity of germination of carrot and other *Apiaceae*, particularly when environmental conditions are suboptimal for germination. Soaking seed in aerated water at low temperature improved germination in celery (Finch-Savage, 1984) and parsnip (Gray and Steckel, 1977), while priming in aerated 30% w/v polyethylene glycol for 72 h improved germination of carrot seed under high-temperature stress at 35°C (Nascimento *et al.*, 2007). Under high-temperature conditions, germination of celery seed is affected by phytochrome-mediated thermo-dormancy (Thomas, 1989) and requires light for germination. Osmotic priming and incorporation of growth regulators (GA4, GA7, ethephon and cytokinins) into the priming medium was effective in overcoming this light requirement and improving germination rates (Thomas *et al.*, 1975; Brocklehurst *et al.*, 1982).

After priming, seed can be dried to allow for storage. The drying conditions that are used can affect both the storage life of the seed and the extent to which the benefits of priming are retained in the dry seed. In general, the storage life of primed seed is shorter than that of untreated seed.

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4

Apiaceae, A Family of Species Rich in Secondary Metabolites: Aromatic Compounds and Medicinal Attributes

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The *Apiaceae* family consists of a copious number of different species distributed quite worldwide but most diversified in Eurasia, the Mediterranean area and North America. Members of these species are an important trait of the global diet as exemplified by their use as species in cuisines around the world due to their content of essential oil and non-volatile compounds (Maxia *et al*., 2009; Prachayasittikul *et al*., 2018). Nevertheless, the value of *Apiaceae* plants extends to traditional medicine too with application against several disorders, and this popularity has fostered the isolation of their secondary metabolites and detection of the biological activities including toxicity when it occurs. This family is a producer of various phytochemicals such as terpenoids, phenylpropanoids, polyacetylenes and alkaloids with potential implications for drug discovery and industrial use which endows these plants a relevance that goes beyond the simply alimentary association (Bruneton, 1999a; Sayed-Ahmad *et al*., 2017).

4.1 ESSENTIAL OIL COMPOSITION

Apiaceae are one of the major essential oil-bearing plant families. The complex mixture of constituents obtained by hydrodistillation can be deeply influenced by exogenous factors such as light exposure, temperature, latitude, humidity, soil type and fertilizer (Capasso, 2011). The moment of the day or the time of the year can influence the yield of essential oils (EOs), leading to intrinsic difficulty to standardize the extract.

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4.1.1 *Ammi visnaga* (L.) Lam. = *Visnaga daucoides* Gaertn. (toothpick-plant, toothpicked, bisnaga, khella)

Ammi visnaga L. is an annual or biennial plant from the Mediterranean area (Hashim *et al.*, 2014). The EO obtained by fruits distillation is used as a support treatment for bronchial asthma, bronchitis, cough and whooping cough. Khadhri *et al.* (2011) have analysed two samples of khella collected in different locations in northern Tunisia: Ichkeul and Djebba. Each distillate afforded a yield of 0.2% v/w, based on dried weight (Khadhri *et al.*, 2011). Like many EOs enriched in linalool (23.6–32.0% of the total), they should be used only if the limit of peroxides is kept under 20 mmol/l (IFRA, 2009); linalool oxidation products are skin-sensitizing. Due to the minimum amount of furanocoumarins detected in some samples (marmesine and 8-hydroxybergapten), khella EO could be phototoxic (Tisserand and Young, 2014).

4.1.2 *Anethum graveolens* L. (dill)

Anethum graveolens L. is the only species accepted in the genus *Anethum*. *A. graveolens* fruits find application in ethnopharmacology for gastrointestinal disorders and nose bleeds (Sharopov *et al.*, 2013). The distillation yield obtained from aerial parts, mostly fruits, is 1.05% v/w (Kazemi and Abdossi, 2015). According to the part of the plant, the relative yield of the same constituents can differ considerably: β-limonene ranges from 35.9 to 68.4% in fruits and between 22.5 and 24.9% of the total in the entire herb; α-phellandrene from 1.0–2.3% in fruits and 18.2–30.2% of the total; and (Z)-dihydrocarvone from 0.8–1.4% and 2.9–3.7% respectively (Tisserand and Young, 2014).

4.1.3 *Apium graveolens* L. (celery)

Celery can be easily found worldwide in cuisine as stalks, leaves or hypocotyl. Seeds and stems were traditionally used as a diuretic for bladder/kidney complaints or an adjuvant in arthritic and rheumatic disease. Hydrodistillation of Tunisian celery (*A. graveolens* var. *dulce* L.) leaves, stems and roots afforded respectively 0.6, 0.2 and 0.1% v/w of EO as reported by Sellami *et al.* (2012). The volatile analysis shows a significant concentration of phthalides like 3-*n*-butylphthalide (2.0–14.8% of the total), (Z)-3-butylidenephthalide (30.5–34.8%) and 3-butyl-4,5-dihydrophthalide (12.3–34.2%). (Z)-3-Butylidenephthalide is characteristic even in lovage (*Levisticum officinale* Koch) (Tisserand and Young, 2014).

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4.1.4 *Carum carvi* L. (caraway, meridian fennel, Persian cumin)

Beyond the common use as a spice, caraway is recommended in folk medicine for diarrhoea, gastrointestinal disorders and as a stimulator of the salivary gland, stomach acid and bile. Most of these activities are attributed to the high percentage of carvone in the EO that can reach almost 80% of the total yield (Samojlik *et al.*, 2010). (+)-Carvone (23.3%), limonene (18.2%), *trans*-dihydrocarvone (14.0%), carvacrol (6.7%) and (*E*)-anethole (3.3%) are detected as major constituents of the 5.8% v/w yield in EO oil of caraway (Iacobellis *et al.*, 2005).

4.1.5 *Coriandrum sativum* L. (coriander, cilantro, Chinese parsley)

The EO obtained from the fruits of *Coriandrum sativum* L., an annual herb species cultivated in Europe and Asia, is dominated by linalool (59.0–87.5% of the total), α-pinene (5.94%), (+)-2-bornanone (4.73%), α-terpinene (6.79%) and geranyl acetate (2.46%) (Hassan and Elhassan, 2017). Usually, fruit maturity and loam soil can deeply influence the amount of linalool in the final product (Capasso, 2011). The distillation yield reported by Hassan and Elhassan (2017) is 0.8% v/w for fruits. Used in Ayurvedic medicine for systematic asthenia, digestive atony and cystitis, coriander is even appreciated as a flavouring agent in spirits and beverages. Leaves are, instead, used as a sedative and anti-inflammatory but the significant occurrence of aliphatic aldehydes, like (*E*)-2-decenal (26.8–46.5%), decanal (4.4–18.0%), octanal (0.5–11.2%) and (*E*)-2-dodecenal (2.7–10.3%), can concur with irritation of mucous membranes (Nicoletti, 2007; Tisserand and Young, 2014).

4.1.6 *Cuminum cyminum* L. (cumin)

Cumin is an aromatic plant used worldwide as a spice and in Ayurvedic medicine for the treatment of dyspepsia, diarrhoea and jaundice. Preliminary studies on cumin seed decoction showed a hypoglycaemic effect (Dhandapani *et al.*, 2002). Seeds hydrodistillation afforded 0.72% v/w of EO. The major components are cuminaldehyde (52.56% of the total), carenal (24.53%) and cuminic alcohol (13.26%) (Saha *et al.*, 2016). Cumin oil is associated with a moderate risk of phototoxicity and, for this reason, it has been fixed a limit of use of 0.4% w/w in dermal products (Tisserand and Young, 2014).

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4.1.7 *Daucus carota* L. subsp. *sativus* (wild carrot, bird's nest, bishop's lave, Queen Anne's lace)

Since the 16th–17th century, the leaves, roots, flowers and fruits of *Daucus carota* L. have been consumed in base nutrition. The EO obtained by fruits distillation (0.5–0.8% v/w) can change considerably according to the area of cultivation, establishing several chemotypes like carotol (≤77.5% of the total), geranyl acetate (≤81.2%), sabinene (≤60.4%), α-pinene (≤55.5%), geraniol (≤50.0%), β-bisabolene (≤35.0%), β-caryophyllene (≤29.0%), γ-bisabolene (87.0%, China) and (*E*)-asarone (40.3%, Japan) (Mockute and Nivinskiene, 2004; Flamini *et al.*, 2014). Carrot fruits oil is traditionally considered a contraceptive and its antigestational effects in mice and rats have been described in the literature (Dong *et al.*, 1981).

4.1.8 *Foeniculum vulgare* Mill. (fennel)

Like many other *Apiaceae*, fennel EO (2.4–6.2% v/w) is commonly used in phytotherapy as a carminative to prevent and/or reduce formation of intestinal gas. It is even useful in menstrual cycle regularity, premenopausal syndrome, as a galactagogue in primiparous females or to treat musculoskeletal-associated pain (Festy, 2008). Oestrogen-like activity is due to high percentage of (*E*)-anethole and estragole; for this reason fennel EO, like chervil, should be avoided by pregnant women, people affected by hormonal-dependent tumours (e.g. breast, uterus), toddlers and children under 5 years old (Firenzuoli, 2008). There are four chemotypes of fennel: anethole, β-limonene, estragole (methylchavicol) and estragole/fenchone type, but just the first one is used for commercial production (Krüger and Hammer, 1999). In order to prevent photo-dependent dermatitis, the International Fragrance Association (IFRA) suggests to not exceed 0.2% w/w of EO in dermal products (Tisserand and Young, 2014). Major EO phytochemicals of 23 samples extracted from plants from Iran, Poland, Albania, Spain and England resulted in (*E*)-anethole (≤ 90.38% of the total), estragole (≤ 3.25%), fenchone (≤ 4.5%) and *p*-anisaldehyde (≤ 2.71%) (Salami *et al.*, 2016).

4.1.9 *Petroselinum crispum* Mill. (parsley, garden parsley)

Parsley is one the most common herbs used in cuisine. Hydrodistillation of the fruits affords an EO with 0.05% v/w yield, while fresh roots give 0.5% v/w. The most abundant compounds (% of the total) are β-phellandrene (17.2%), terpinolene (7.1%), 1,3,8-*p*-menthatriene (17.7%), myristicin (19.4%), apiole (15.5%) and carotol (7.4%) (Ascrizzi *et al.*, 2018). There are three chemotypes of parsley seed oil: apiole, myristicin and allyltetramethoxybenzene types.

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General contraindications are in pregnancy, breast-feeding and hepatotoxicity, especially for children under 6 years old. Maximum adult daily oral intake corresponds to 538 mg for leaves due to high concentration of apiole (Tisserand and Young, 2014).

4.1.10 *Pimpinella anisum* L. (anise, aniseed)

Anise fruits and its EO find application as a flavouring in liquors, foods and cosmetics all over the world. Like fennel, anise is used as a carminative, for menstrual cramps and colic, with the same contraindications reported. Distillation of the fruits can yield from 1.5 to 3.5% v/w, according to environmental conditions. The most abundant compounds are anethole (*Z*/*E* ratio equal to 0.43; 88.13% on total extract), estragole (1.52%) and γ-himachalene (4.15%). Maximum adult daily oral intake corresponds to 70 mg while the IFRA-suggested concentration in leave-on products is 0.2% w/w (Tisserand and Young, 2014; Fitsiou *et al.*, 2016).

4.2 NON-VOLATILE ORGANIC COMPOSITION

The non-volatile organic composition is characterized by non-distillable compounds with low vapour pressure under existing conditions due to their huge molecular weight.

4.2.1 Polyphenolic compounds

Flavonoids, tannins, catechins and coumarins are the major classes of these secondary metabolites that can be located in seeds, flowers, stems, leaves and roots in varying concentrations depending on species and variety (Bettaieb *et al.*, 2010; Gupta, 2013). Major flavonoids identified as aglycones and glycosides of different *Apiaceae* plant parts are rutin, isoquercitrin and quercetin, astragalin, apigenin, rhamnetin, kaempferol, luteolin, isoorientin and isovitexin (Shahat *et al.*, 2011; Sayed-Ahmad *et al.*, 2017). They are associated with ultraviolet-screening functions and with the inhibition of both production and action of pro-inflammatory mediators through antioxidant and free-radical scavenging capacity preventing the generation of reactive oxygen species by a mechanism not completely discovered yet (Ambriz-Perez *et al.*, 2016). The examination of *Apiaceae* composition cannot ignore coumarins: simple, prenylated, furanoid and hydroxyisopropylfuranoid, linear and angular (Bruneton, 1999a). Conversely to simple coumarins, linear furanocoumarins are endowed with significant phototoxicity. Responsible of such reaction are psoralen, bergapten, peucedanin, xanthotoxin and related phytochemicals (Nigg

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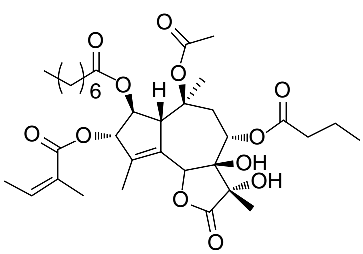
et al., 1993). Dietary consumption of vegetables containing these derivatives such parsnip, parsley, celery, angelica, khella and lovage rarely causes photosensitivity. Instead, contact or topical application of furanocoumarins followed by sun exposure could cause dermatitis of variable intensity (Bruneton, 1999b; Lombaert *et al.*, 2001). However, psoralens find application as PUVA treatment: a phototherapy that combines furanocoumarin, like khellin from *A. visnaga*, with ultraviolet radiation of 320–400 nm wavelength (UV-A), used for a variety of skin disorders such as psoriasis, mycosis, vitiligo and eczema (Parrish *et al.*, 1974; Morison, 2005). Other significant constituents are prenylated coumarins, especially ferulenol and ferprenin, different concentrations of which in *Ferula communis* L. roots have been known for a long time to be related to the anticoagulating toxicity linked to this species (Appendino *et al.*, 1988). The volatile constituents of the genus *Ferula* are reviewed by Sahebkar and Iranshahi (2011).

4.2.2 Sesquiterpenoids

Sesquiterpenoids have a wide botanic distribution located in leaves, stems, inflorescences, fruits and seeds. Examination of *Apiaceae* chemical diversity has led to the identification of one of the most peculiar sesquiterpenes: the hexaoxygenated guaianolide lactone thapsigargin (**1**, Fig. 4.1) located in the fruits and root of *Thapsia garganica* L. used in folk and traditional medicine against rheumatic pain (Christensen *et al.*, 1982). Thapsigargin is a potent skin irritant



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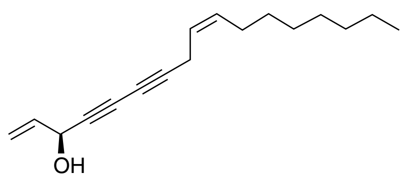

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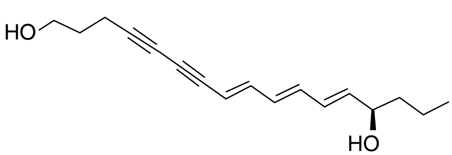

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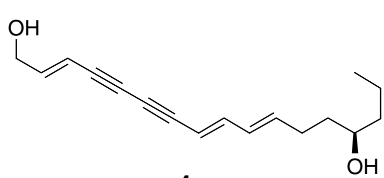

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Fig. 4.1. Thapsigargin (**1**), falcarinol (**2**), cicutoxin (**3**) and oenanthotoxin (**4**) molecules. (Drawing by F. Pollastro.)

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able to cause histamine release from mast cells (Patkar *et al.*, 1979). Nowadays it could be considered the most widely used molecular probe in the study of calcium homeostasis, elucidating the mechanisms of intracellular Ca^{2+} signalling (Treiman *et al.*, 1998; Navarrete *et al.*, 2006). Moreover, the importance of thapsigargin is raised by the development of its prostate cancer-specific prodrug capable of inducing cellular apoptosis via endoplasmic reticulum stress (Denmeade and Isaacs, 2005).

4.2.3 Phytosterols

Apiaceae oilseed could be considered a respectable source of phytosterols. Of these organic compounds, the main constituents are β-sitosterol and stigmasterol while other ones like Δ5-avenasterol, lanosterol, brassicasterol and campesterol are present in minor quantity (Sayed-Ahmad *et al.*, 2017). The implications of phytosterols are various and considerable. From a nutritional point of view, they are active additives in functional foods as anti-cholesterol agents; from a pharmaceutical viewpoint they are endowed with anticancer properties. In fact, β-sitosterol can delay and improve prostate hyperplasia symptoms by acting as an inhibitor of 5α-reductase (Bruneton, 1999a; Cabeza *et al.*, 2003; Sayed-Ahmad *et al.*, 2017).

4.2.4 Carotenoids

Carotenoids are a class of tetraterpenoids with at least ten conjugated double bonds that are biosynthesized in plants, fungi, bacteria and algae, but not in animals and humans, which acquire them from their diet (Tapiero *et al.*, 2004). From a health point of view, some populations depend mainly on the locally available plant materials to cure various health disorders (Raju *et al.*, 2006). Carotenoids represent natural pigments from yellow to orange and accumulate widely in leaves, flowers, fruits and roots (carrot) (Raju *et al.*, 2006).

The interest in carotenoids has multiple justifications but one of the most relevant for human health is their ability to act as strong antioxidants (Khoo *et al.*, 2011). Among the various carotenoids, the primary forms are α- and β-carotene that play a key role in the human diet: in intestinal mucosa, carotene is degraded via an intermediate peroxide to retinol (vitamin A), deficiency of which causes considerable health problems like xerophthalmia (WHO *et al.*, 1997; Tapiero *et al.*, 2004; Khoo *et al.*, 2011). Another implication of β-carotene is cancer preventive activity for lung, colon, breast and prostate cancer; the mechanism of action consists in oxidative protection against singlet molecular oxygen and a synergistic interaction with other biological antioxidants (Tapiero *et al.*, 2004).

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4.2.5 Polyacetylenes

An emblematic example of secondary metabolites that could be considered desirable in edible plants, but only in low concentration due to their toxicant properties, are polyacetylenes found in 72 species of 41 genera of *Apiaceae* (Chen *et al.*, 2015). In particular, falcarinol (**2**, Fig. 4.1) and falcarindiol are the two most frequently occurring dietary polyacetylenes found in the family and especially in carrot. In the plant, they act as a constitutive and inducible fungicide inhibiting spore germination of different fungi (Christensen and Brandt, 2006), but in animals they are responsible for different biological activities. They can exhibit remarkable cytotoxic effects against various cancer cell lines *in vitro*, showing the strongest activity towards gastric adenocarcinoma cancer cells, but their mechanism of action is not yet completely identified. They exert a significant antibacterial, antiplatelet aggregation and anti-inflammatory effect, acting with a 5-lipooxygenase inhibitory action (Zidorn *et al.*, 2005; Christensen and Brandt, 2006; Chen *et al.*, 2015). Unfortunately, polyacetylenes are also responsible for allergic contact dermatitis and irritant skin reactions mainly due to the ability of falcarinol to form a hapten–protein complex recognized as an antigen. Curiously, this undesirable biological response could explain the general falcarinol bioactivity (Christensen and Brandt, 2006).

If carrot polyacetylenes could concur to explain their healthy dietary properties, different consideration must be attributed to the neurotoxic polyacetylenes of *Cicuta virosa* L. and *Oenanthe crocata* L., respectively cicutoxin (**3**, Fig. 4.1) and oenanthotoxin (**4**, Fig. 4.1), characterized by poisonous deathly effects like convulsion and respiratory paralysis. The neurotoxicity of these natural compounds is based on their ability to penetrate in the haematoencephalic barrier and potently block the GABAergic responses in neuronal cell cultures (Appendino *et al.*, 2009; Chen *et al.*, 2015). Falcarinol is not completely devoid of neurotoxicity, the symptoms of which are comparable to those of oenanthotoxin, although no alimentary poisoning has been reported due to the higher dose required (Christensen and Brandt, 2006).

Considering toxicity, a special mention is due to water hemlock (*Conium maculatum* L.): one of the most poisonous species among the *Apiaceae* family. Every part of the plant contains piperidine alkaloids; the main ones are coniine, *N*-methyl-coniine, conhydrine, pseudoconhydrine and γ-coniceine. These natural compounds are extremely dangerous by ingestion and responsible for human and animal toxicosis affecting the nervous system, with paralysis of motor nerve endings leading to death in severe intoxications (Vetter, 2004).

4.3 CONCLUSION

Apiaceae is ranked as one of the most important families best known as a source of important culinary herbs and spices, although their importance cannot be

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exhausted by a unique alimentary use. The phytochemical diversity of *Apiaceae* members is yet to be explored adequately but the distinctive secondary metabolites already discovered classify this family as an incredibly rich source for industrial application, essential micronutrients and drug discovery. However, those very same edible plants are not lacking in toxicity resulting from their inappropriate use and destination. Definitely, a phytochemical knowledge of their secondary metabolites is necessary for completely appreciating the fruitfulness of their different potentialities.

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5

Genetic Diversity and Main Carrot Types

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Tremendous progress has been achieved during the last decade in the knowledge of carrot genetic diversity thanks to the availability of molecular tools, but also due to renewed interest in carrot wild relatives for evolutionary genetics, breeding and taxonomy reasons.

5.1 CARROT DOMESTICATION AND EVOLUTIONARY GENETICS

Daucus species and *Daucus carota* subspecies originated from the Mediterranean region and wild carrot was originally present in Europe and Asia, but it has become clear today that domestication took place in Central Asia, probably in the region around present-day Afghanistan as promoted by Vavilov (1926). Based on historical and morphological data, Small (1978) has proposed that cultivated carrot is divided between Western and Eastern groups. Clotault *et al.* (2010) have demonstrated a structure in two groups based on molecular markers, as supported by several other studies (Baranski *et al.*, 2012; Iorizzo *et al.*, 2013; Grzebelus *et al.*, 2014). This subdivision between Western and Eastern carrots suggests that two migration events occurred from the domestication site, in accordance with historic literature (Laufer, 1919; Mackevic, 1929; Banga, 1957). The existence of an intermediate group specific to Central Asia (Iorizzo *et al.*, 2013; Soufflet-Freslon *et al.*, 2013) confirms with molecular data the origin of domesticated carrot in Central Asia.

The level of diversity reduction between wild and cultivated carrot is still discussed (Iorizzo *et al.*, 2013; Rong *et al.*, 2014) but it seems to be limited, with 85% of wild diversity retained in the Western cultivated carrot for example. Moreover, the domestication pressure was evaluated as moderate (Soufflet-Freslon *et al.*, 2013). The domestication process was therefore probably progressive with a moderate bottleneck.

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The domestication process should translate to signatures of selection, especially for domestication traits such as biennial habit, root morphology and colour. Focusing on carotenoid biosynthesis genes, Clotault *et al.* (2012) have shown significant selection constraints upstream of the carotenoid biosynthesis pathway, especially with a diversity reduction of the phytoene desaturase gene (*PDS*), which supports the hypothesis of domestication effect on the biosynthetic flow. Controlling chromoplast development, the *Or* gene sequence diversity is associated with the presence or absence of carotenoids in cultivated and wild carrots, respectively, demonstrating the domestication effect on this trait (Ellison *et al.*, 2018). On the contrary, genes related to lycopene in the centre of the pathway correspond to a diversifying selection model, which suggests post-domestication selection (Clotault *et al.*, 2012) in response to anthropological pressures.

Among 900 markers covering the carrot genome, Grzebelus *et al.* (2014) found 17 markers with signatures of domestication. One, in particular, corresponds to the *Vrn1* gene responsible for early flowering, confirming the biennial growth habit as a primary domestication trait. *Vrn1*, along with *Or*, the carotene hydroxylase gene *DcCYP97A3*, the root thickening gene *DcAHLc1*, and the Y and Y_2 genes associated with carotenoid accumulation were also among the signatures of selection observed by Ellison *et al.* (2018). Through root transcriptome analysis, Rong *et al.* (2014) suggested that several genes were downregulated in the domestication process, affecting traits such as root water content and transport, carotenoid accumulation and allergy reduction. All these data support the existence of domestication or post-domestication traits affecting plant development (biennial growth habit), root morphology (fleshy roots, reduced lateral branching, shape) and root quality (colour and carotenoid presence, reduced allergy).

5.2 CARROT HISTORY

The carrot has not always been orange; it is even the most recent coloured type in the history of this species, while we see a reappearance in the market of carrots of different colours. A domesticated form distinct from the current wild carrot is mentioned from the 2nd century by Galen (Stolarczyk and Janick, 2011). Charlemagne thus recommends the carrot in the *Capitular De Villis* (year 800). De La Quintinie writes that ‘carrots are a sort of root, some white, others yellow’ in ‘Instruction for fruit gardens and vegetable gardens’ published in 1690. Until the Middle Ages, some confusion with parsnip exists in the writings, since it can be referred to as ‘Pastinaca’ for both plants. The writings of Ibn-Al-Awam (12th century), on the situation in Asia Minor, mention two types of carrot, ‘one is red, it is the most juicy and tasty, and the other has a green colour that blends in yellow’ (cited by Banga, 1957).

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Iconographic sources (market scenes, still lives) are also very useful to reconstruct this story, especially in Europe. The first assured representation of a cultivated carrot comes from the Roman world in the *Juliana Anicia Codex* around 512 (Stolarczyk and Janick, 2011). The root is clearly orange but slightly divided, which shows an old form of the vegetable (Fig. 5.1). However, the orange colour can be discussed, the colour of the original painting having faded with time. Representations are not found before the 11th century in illustrations of medieval manuscripts. It was at this time that the carrot was widely distributed in Spain, Italy, then France, and finally Germany, Holland and England (Banga, 1957), following trading routes or invasions by the Moors. The yellow and purple carrots were thus probably reintroduced into Europe from Central Asia.

Fig. 5.1. Ancient representation of carrot from the *Juliana Anicia Codex*. (From Ḥunayn ibn Isḥāq al-ʿIbādī *et al.*, 1889–1890.)

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It is only really in the Renaissance with the Flemish and Spanish painters that we have unequivocal representations of the carrot, first yellow and purple, then orange. A still life by the Spanish painter Juan Sànchez Cotàn in 1602 includes yellow and purple carrots. Similarly, in a market scene in Holland by the painter Nicholaas Maes in 1660, there are clearly purple and yellow carrots, elongated and pointed (Fig. 5.2). These paintings show that these two coloured types were common at this time, yellow carrots being more appreciated than purple ones known to 'dirty the soup' due to the hydrosolubility of anthocyanins. Based on iconographic sources (painters Aertsen, Bueckelaer, Dou, van Rijck, Wtewael), the modern form of the orange carrot is considered to have appeared in Holland in the 16–17th centuries, probably from a natural mutation and selection (Banga, 1957). Sometimes yellow and yellow-orange carrots are mixed, which may indicate a gradual transition from yellow to orange.

As a result of spreading east from their site of domestication, specific pink and long-rooted types were developed in China and Japan (Laufer, 1919; Takagi *et al.*, 2017). The Japanese orange carrot is largely influenced by the Western orange germplasm (Soufflet-Freslon *et al.*, 2013) whereas the Chinese orange carrot would derive from local carrot (Ma *et al.*, 2016). Extensive trading between Europe and the New World, then between Europe and Asia in the 18th

Fig. 5.2. Carrot representation in paintings. Long purple and yellow carrots in a market scene by Nicholaas Maes (1660). (Source: Rijksmuseum, Amsterdam.)

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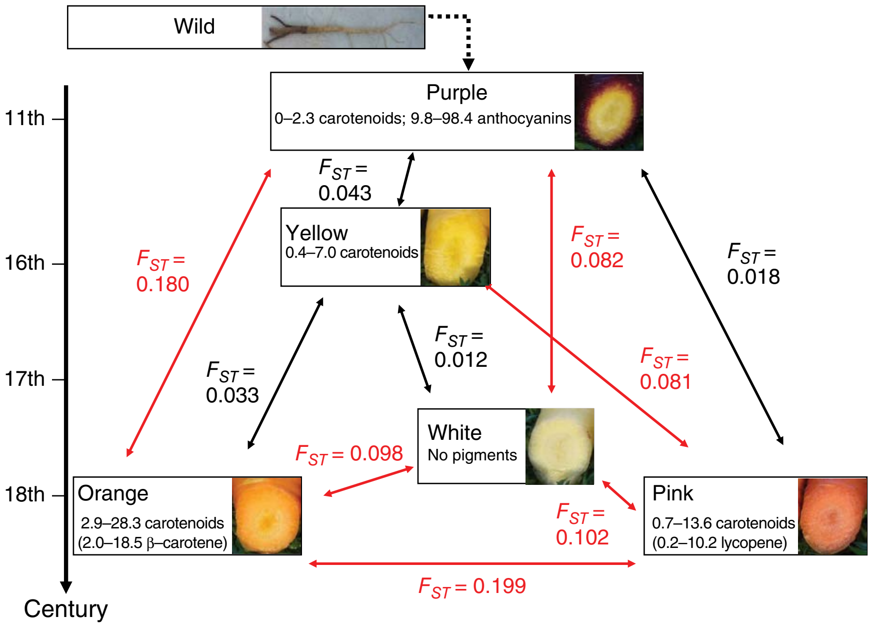

Fig. 5.3. History of carrot colour types based on carotenoid gene genetic distances. F_{ST} are distance indices: in black, indicates non-significant, low genetic distance; in red, indicates significant genetic distance. Pigment content variation is indicated in mg/100 g fresh weight. (Elaborated from Geoffriau *et al*., 2010.)

century and between the USA and Japan in the 19th century explains the broad genetic mix in today's carrots (Banga, 1963; Simon *et al*., 2008).

This history of coloured types is confirmed by molecular markers, especially based on carotenoid genes (Fig. 5.3).

5.3 CULTIVATED CARROT DIVERSITY

Understanding diversity structure is critical for appropriate genetic resources management, studies such as association mapping and for heterosis prediction when breeding for hybrids. It is now established that the overall cultivated diversity is structured in three main groups, Western, Eastern and Central Asia groups (Clotault *et al*., 2010; Baranski *et al*., 2012; Iorizzo *et al*., 2013; Soufflet-Freslon *et al*., 2013; Grzebelus *et al*., 2014). The level of differentiation (F_{ST}) between the Western and Eastern groups has been evaluated as from 0.072 to 0.160 depending on the material and markers used. The diversity in the Eastern group seems higher and with less signature of selection (Baranski *et al*., 2012; Soufflet-Freslon *et al*., 2013). The Western group is constituted of accessions from Europe and America but also some from Japan. The Eastern

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group is represented by accessions originating from the Middle East, southern and eastern Asia, and some from Japan. Accessions from countries such as Afghanistan, Kirgizstan, Uzbekistan and Kazakhstan correspond to the Central Asia group, the position of which varies between the Western and Eastern groups depending on the study. Most orange-rooted cultivars, even cultivated in Asia, belong to the Western group.

A large diversity is displayed in the cultivated carrot as shown by many studies, at the global level but also at the local level, with a significant structuration in three to five clusters depending on the study: cultivars in India (Jhang *et al.*, 2010; Amin *et al.*, 2012; Singh *et al.*, 2017), local purple carrots in Turkey (Ipek *et al.*, 2016), local yellow carrot in Iran (Kasiri *et al.*, 2013). A large diversity exists in globalized types such as Nantes, Chantenay and Kuroda. Within varieties, the diversity can be important in carrot and even higher than between-variety diversity, accounting for 62 and 38% of total variation, respectively (Shim and Jørgensen, 2000; Maksylewicz and Baranski, 2013), but in a study focusing on yellow carrot populations the intrapopulation distance value was somehow lower than the interpopulation one with 10–31 and 12–55%, respectively (Le Clerc *et al.*, 2005). Both levels of diversity need to be considered when exploring diversity in carrot.

5.4 MAIN CARROT TYPES

The Western orange carrot types are derived from four initial orange types (Banga, 1957): Long Orange and three Horn types (Late, Half Long and Short). The Long Orange led to late types and long roots such as Flakkee, whereas the Horns led to all other types with higher-quality roots. In Japan, the Kokubu Oonaga type is considered to be bred from Long Orange (or Long Rouge) and the Kuroda type from Half Long Horn (Takagi *et al.*, 2017) as Nantes for example. Nowadays, the Nantes type is the most cultivated worldwide. Distinguishable by the convenient cylindrical shape of the root, it corresponds actually to a large genetic mixing as a result of extensive breeding: the Nantes type has been classified into seven subtypes by the International Union for the Protection of New Varieties of Plants (UPOV) for variety registration.

Logically, several countries in Europe can be considered as secondary diversification centres as shown by the resulting types (Table 5.1, Fig. 5.4), but specific types are from North and South America and Japan. Some types were developed for specific conditions such as Kuroda and Brasilia for subtropical areas. Other types are dedicated to processing: Imperator (cutting and peeling, slicing), Danvers and Berlicum (dicing), Amsterdam (canning), and Flakkee and Colmar (shredding). Chantenay has been bred as an early type for fresh market and also for storage and processing (dicing). Nantes and Kuroda types are mainly for fresh market.

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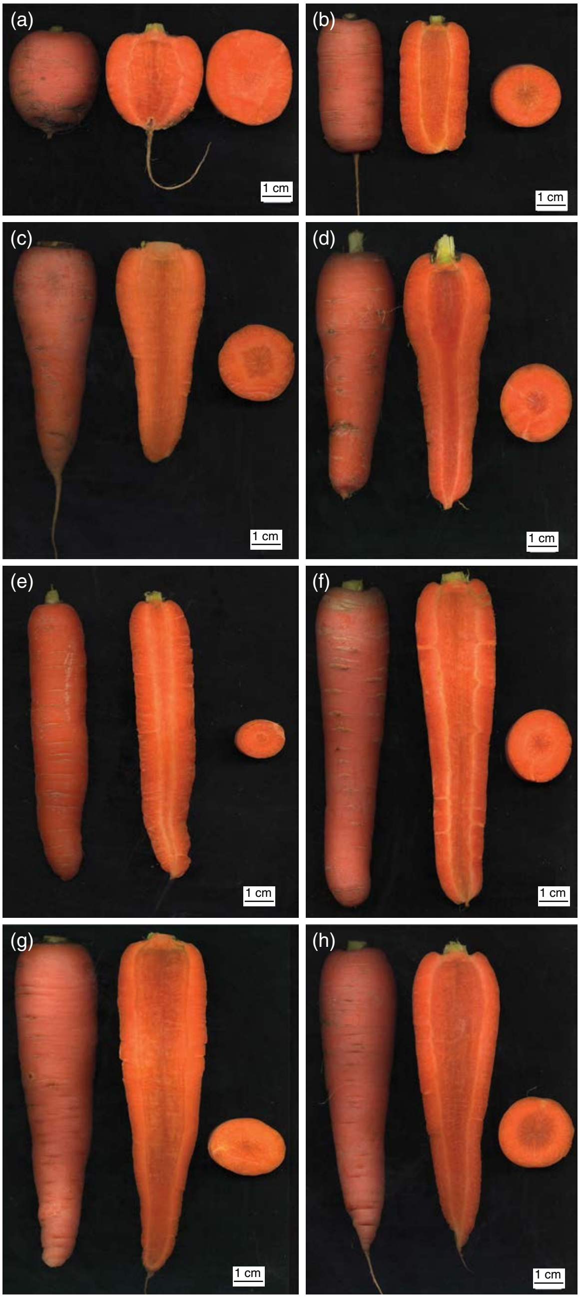

Fig. 5.4. Examples of carrot types: (a) Paris Market 2; (b) de Saint Fiacre; (c) Royal Chantenay; (d) Kuroda; (e) Amsterdam 2; (f) Nantes improved 4; (g) Autumn King; (h) Danvers. (Photos by E. Geoffriau.)

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Table 5.1. Main carrot types and country of origin[a].

Description	Type/Accession name
Short root, early type	Europe: Paris Market (FR), Oxheart (UK), Bellot (FR), Davanture (FR), Forcing Nantes (FR)
Half root, season	Europe: Nantes (FR), Chantenay (FR), Amsterdam (NL) Asia: Kuroda (JP)
Long large root, late type	Europe: Flakkee (NL), Colmar (FR), Saint Valery (FR), Meaux (FR), Tilques (FR), Berlicum (NL), Altringham (UK), Autumn King (UK), Brunswick (DE) America: Danvers (US), Brasilia (BR)
Long narrow root	America: Imperator (US) Asia: Oonaga (JP), Kintoki (JP)

[a]BR, Brazil; DE, Germany; FR, France; JP, Japan; NL, The Netherlands; UK, United Kingdom; US, United States.

5.5 CARROT CROP WILD RELATIVES

Carrot wild relatives can be found within *D. carota* L. and intercross easily with the cultivated carrot, or correspond to other *Daucus* species which intercross depending on the chromosome number, varying from $2n = 18$ as in the cultivated carrot to $2n = 20$, 22 or 44 (Pimenov *et al.*, 2003; Iovene *et al.*, 2008; Grzebelus *et al.*, 2011). Actually, the taxonomy of the *Daucus* genus has been revised (Spooner *et al.*, 2013; Arbizu *et al.*, 2014b; Lee and Park, 2014) and its perimeter has evolved significantly: from 20 species, the genus now includes 40 species with the inclusion of *Agrocharis*, *Athamantha*, *Cryptotaenia*, *Melanoselinum*, *Monizia*, *Pachytecnium*, *Rouya* and *Tornabenea* (Banasiak *et al.*, 2016). The previous species *Daucus capillifolius*, which hybridizes easily with the cultivated carrot, is now considered a subspecies within *D. carota* (Arbizu *et al.*, 2014a). The complex *D. carota* has been thoroughly studied with morphological and molecular markers. Based on fruit descriptors, Saenz Lain (1981) split the complex into five subspecies (*carota*, *maximus*, *hispanicus*, *gummifer* and *maritimus*) but most studies agree on a subdivision into two entities (considered as subspecies or subgroups depending on botanists): *carota* (previously *eucarota*) and *gummifer* (previously *gummiferi* or *gingidium*). *Carota* subdivision includes the taxa or subspecies *sativus*, *carota*, *maximus* and *maritimus*, whereas *gummifer* subdivision includes *gummifer*, *drepanensis*, *commutatus*, *hispanicus* and *gadecaei* (Thellung, 1926; Nehou, 1961; Small, 1978; Reduron and Muckensturm, 2007; Spooner *et al.*, 2014).

Gummifer taxa are distributed mainly in coastal areas whereas *carota* taxa are found in inland areas. Carrot wild relatives are mainly distributed around the Mediterranean Sea even if the taxon *carota* is obviously distributed worldwide. Some taxa or species have specific distribution areas such as *gummifer* and *capillifolius* in northern and southern Mediterranean countries, respectively. *Commutatus* and *drepanensis* are from southern countries but are present

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in Corsica. The protected *gadecaei* is found only in the north-west of France. *D. syrticus* and *D. sahariensis* for example are from northern African countries.

Diversity structure based on morphological descriptors does not reflect geographic patterns but taxa logically (Mezghani *et al.*, 2014; Geoffriau *et al.*, 2017), whereas molecular markers reflect geographical structure within the interfertile *D. carota* taxa. At the global level of diversity structure, wild relatives are well separated from cultivated forms but structured quite similarly, with Europe–USA, North Africa, Middle East and Central Asia groups (Iorizzo *et al.*, 2013).

The cultivated carrot diversity is probably not fully valorized but wild relatives have regained interest for breeding for disease and pest resistance, or adaptation to stresses. Sources of several resistances have been identified in carrot wild relatives: resistance to the carrot fly (*Psyla rosae*) from *D. capillifolius* (Ellis *et al.*, 1993), to powdery mildew from *D. carota* subsp. *dentatus* Bertol. (Bonnet, 1983), to *Alternaria dauci* from several *Daucus* species and *D. carota* subspecies (Arbizu *et al.*, 2017; Nothnagel *et al.*, 2017), to nematodes from *Daucus azoricus* (Kraus, 1992) and *D. carota* subsp. *hispanicus* (Frese, 1983) and to xanthomonas from subsp. *commutatus* (Christianson *et al.*, 2015).

Importantly, the petaloid male-sterile system discovered by H.M. Munger in 1953 in wild carrot (Peterson and Simon, 1986) has been transferred to adapted material and is now being widely used. Several other male sterility systems have been identified in wild relatives of carrot (subspp. *gummifer*, *maritimus*, *gadecaei*) and could be an alternative to existing systems (Nothnagel *et al.*, 2000). Contrary to what could be expected, wild relatives are not necessarily a source of tolerance to salinity as shown by Bolton and Simon (2019) at the germination stage. Nevertheless, wild carrot is also of interest for essential oil composition and extracts (Tavares *et al.*, 2008; Jabrane *et al.*, 2009) although the large diversity in wild taxa has not been sufficiently explored so far.

5.6 ACCESS TO GENETIC RESOURCES

Carrot genetic resources are mainly conserved as seeds in *ex situ* collections. The conservation is facilitated since carrot seed is small (500–700 seeds/g) and orthodox. Quality untreated seeds can be stored for about 20 years under stable conditions of 4°C and 35% relative humidity in the storage room but can also be frozen after lowering seed water content. However, germination management of seeds of wild relatives is more problematic since they exhibit some dormancy and can be sensitive to mechanical seed-cleaning processes (spine removal).

Many collecting missions have been conducted over the years, and more recently targeting wild relatives. Carrot genetic resources are available in many collections worldwide: 7116 accessions from 28 species are reported in 77 genebanks from 49 countries (FAO, 2019). In Europe only, 4282 accessions (60%

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of the total) are held in 42 genebanks from 25 countries. However, only 35 to 50% are considered unique. When searching for genetic resources, the general information system 'Genesis PGR', connecting databases worldwide, can be surveyed, or the Eurisco database for European collections. Main collections for *Daucus* resources are the Vegetable Genebank in Warwick University (UK), the US Department of Agriculture in Ames, Iowa (USA), the Leibniz Institute in Gatersleben (Germany), the Vavilov Institute in St Petersburg (Russian Federation), Genebank in Olomouc (Czech Republic), the national carrot collection in Agrocampus Ouest IRHS in Angers (France), the Institute of Vegetable and Melon Growing in Kharhiv (Ukraine), the National Genebank in Tunis (Tunisia) and Embrapa (Brazil). Major collections exist also in China and India.

Major access limitations and issues are the discrepancy in passport data, the lack of characterization and evaluation data, and also the sometimes-unclear juridical status of accessions. The regulation framework is evolving regarding the use not only of genetic resources but also of related compounds and genomic information. Carrot (*Daucus*) is included in the Annex I of the International Treaty on Plant Genetic Resources for Food and Agriculture, which simplifies sample exchange based on the standard material transfer agreement (sMTA) under the multilateral system for signing countries. For other conditions not included in the Treaty, then one needs to comply with the Nagoya protocol of the Convention on Biological Diversity implemented in 2014. However, specific regulation and implementation dates may exist depending on the country, as each country remains sovereign on the regulation framework to be applied to its own genetic resources and diversity.

5.7 CONCLUSION

There is large and underexploited carrot diversity, especially in crop wild relatives. These resources are critical for carrot breeding and adaptation to new needs and conditions. They are also valuable for new methods of studying trait determinism based on a large genetic background (i.e. association genetics), as done on carotenoid content and root colour (Arango *et al.*, 2014; Jourdan *et al.*, 2015) and chromoplast differentiation in relation with carotenoid accumulation (Ellison *et al.*, 2018). The knowledge on carrot genetic diversity has increased significantly recently but there is still more to know on the evolution genetics of the species and better characterization and evaluation of accessions are needed to valorize and safeguard these critical resources.

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6

Carrot Genetics and Breeding

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6.1 CARROT SEED PRODUCTION AND CULTIVAR DEVELOPMENT FOR GLOBAL CLIMATES

6.1.1 Carrot reproductive biology

Carrot is a diploid outcrossing root crop grown primarily in temperate (40° to 60°) and subtropical (23.5° to 40°) latitudes, but also in humid and arid tropical (0° to 23.5°) and northern cold (60° to 90°) latitude climates. Since carrot is relatively cold-tolerant it is categorized as a cool-season vegetable crop. Exposure to cold temperature is the primary stimulus to initiate carrot flowering, with temperatures less than 10°C contributing to the vernalization process in temperate cultivars (Simon *et al.*, 2008). Storage of harvested roots at 1–4°C for 6–8 weeks is also adequate to vernalize most breeding stocks for temperate production regions. Exposure of vernalized carrots to short-day photoperiods or to temperatures exceeding 28°C when planted in the field or greenhouse before stem elongation can suppress flowering, or devernalize plants, while exposure of plants to long-day photoperiods in early stages of stem elongation can accelerate flowering (Linke *et al.*, 2019).

Carrot is an insect-pollinated crop. Breeding programmes use flies to pollinate flowers in small isolation cages (Fig. 6.1) whereas commercial seed producers pollinate the crop with bees (Rubatzky *et al.*, 1999). Most carrot flowers are perfect and carrot has no self-incompatibility, but self-pollination leads to inbreeding depression which, in some genetic backgrounds, can be severe.

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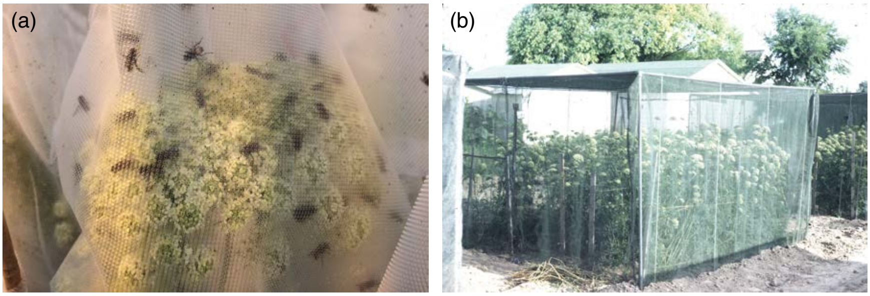

Fig. 6.1. Carrot seed production (a) in a small screen cage showing housefly pollinators and (b) in large cage isolations. (Photos by (a) P.W. Simon and R. Kane; (b) D. Maynard, University of Florida.)

6.1.2 Sources of genetic variation

Carrot is a genetically and phenotypically diverse crop with over 6500 germplasm accessions held in collections around the world (Allender, 2019). Cultivated carrot is classified as *Daucus carota* L. subsp. *sativus* whereas the most common form of wild carrot is *D. carota* subsp. *carota* (Spooner, 2019). Vavilov (1992, translated) noted that wild carrot 'invades gardens, vineyards, and vegetable plots, as well as borders between fields, just as if inviting itself to be cultivated'. The cultivated carrot crop is in the vegetative phase of its life cycle since, with the initiation of flowering in the production field, carrot root quality deteriorates quickly as the succulent, crisp storage root of commerce becomes lignified, woody and unmarketable.

6.1.3 Breeding history

The recorded history of carrot as a root crop is relatively recent. Storage root colour was the primary trait used to differentiate cultivated carrots before 1600, with yellow and purple root colour noted first in Afghanistan, then Persia and northern Arabia in the 10th century based on research summarized by Banga (1963). Banga discussed the possibility of carrots being recorded in the Roman Empire but concluded that the root crop described was parsnip rather than carrots. More recently Stolarczyk and Janick (2011) evaluated texts from Dioscorides in the 1st century CE that they concluded described carrots, and images from the 6th and even back to the 2nd century CE that they concluded depict orange carrots, to point to the possibility of an earlier history of carrots as a root crop. The only other trait noted in the early written history of carrots is flavour, with an indication that yellow carrot flavour was inferior to that of purple carrots in Persia and Asia (Clement-Mullet, 1866). An

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expansion of the scant history of the carrot awaits new discoveries and interpretations of the biological and agricultural history of the crop, and additional written historical records of early carrots.

6.1.4 Breeding goals

In more broad-based carrot breeding programmes that intercross non-bolting temperate biennial breeding stocks with early-bolting subtropical annual cultivars to generate new breeding stocks, the selection for uniform floral induction is paramount. Reliably non-bolting reproductive habit for temperate production areas, or early-bolting reproductive habit for subtropical production areas, is essential for successful cultivar development in these respective crop production areas since early-bolting plants occurring during production of the root crop cannot be sold in temperate markets, and non-bolting plants occurring after production of the root crop will not contribute to the seed crop in subtropical/semi-arid markets. Intercrosses to introgress useful genes from wild carrots to either category of cultivated carrots can create additional challenges since wild carrot germplasm often bolts much more readily than most subtropical breeding stocks. Given the challenge of breeding for reliable bolting behaviour, breeding programmes often avoid intercrosses between temperate and subtropical cultivated carrots, and rarely use wild germplasm.

Storage root appearance is the most critical trait in breeding stocks where reliable bolting behaviour is fixed. Orange carrots account for the majority of global carrot production today and root shape is used to categorize orange cultivars (Rubatzky *et al.*, 1999). The development of the various root shapes in modern orange carrot cultivar classes and their use are discussed in Chapter 5 (this volume).

6.2 TRAIT GENETICS AND CANDIDATE GENES

6.2.1 Vernalization and floral induction

Given the importance of targeting carrot cultivar development towards either the non-bolting, temperate, biennial production areas, or the early-bolting, subtropical, annual production areas, most carrot breeding efforts treat these as separate breeding pools. To utilize the full range of cultivated carrot germplasm diversity, intercrosses between these breeding pools demonstrate a strong annual habit. Genetic control of floral initiation has recently been reviewed (Linke *et al.*, 2019). As the genetics of vernalization and floral induction are further elucidated, marker-assisted selection will undoubtedly improve the ease of selection.

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6.2.2 Cytoplasmic male sterility

The widespread use of hybrid cultivars for carrot production has relied upon the incorporation of cytoplasmic male sterility (CMS), controlled by the mitochondrial genome (Linke *et al.*, 2019) into breeding stocks. The development of reliable breeding stocks for hybrid production involves backcrossing of the recurrent parent into the petaloid or brown anther cytoplasms to create male-sterile lines. To be successful, the nuclear genome of the recurrent parent cannot bear any restorers of fertility which, in carrot, can be dominant or recessive (Linke *et al.*, 2019). Phenotyping for CMS and its restoration is performed on flowering plants, making selection a lengthy process. Molecular makers for the mitochondrial genome are also being developed and as marker technologies advance, selection efficiency can be expected to improve (Linke *et al.*, 2019).

6.2.3 Uniformity and productivity

Like most crops, uniformity is critical to maximize productivity; and like most horticultural crops, phenotypic uniformity is critical to maximize carrot marketability and market value. The development and application of CMS to commercial production of hybrid carrots provides growers with a uniformly vigorous crop with a high pack-out, where pack-out is the proportion of carrots coming from the field able to fit the requirements for delivery to markets (Rubatzky *et al.*, 1999; Simon *et al.*, 2008). Like other crops, combining ability among hybrid combinations varies widely, and the identification of superior hybrid combinations requires extensive field testing of many combinations to identify those elite combinations. The necessity to develop multiple inbred parent lines with reliable CMS and seed yield requires several more years to begin testing experimental hybrid combinations, in comparison to classical open-pollinated breeding strategies. But in spite of these challenges, hybrid carrot cultivars account for most of today's large-scale production.

6.2.4 Root shape and appearance

The development of a fleshy tap root is one of the distinctive domestication traits of carrot (Ellison, 2019) and variation in carrot root shape was first definitively recorded in the 1600s in European artwork depicting what became known as the 'Horn' and 'Long Orange' types. In the 1700s and 1800s roughly ten more root shapes were described (Fig. 6.2), and, for the 'Half Long Horn' type, both early and late versions were noted (Banga, 1963).

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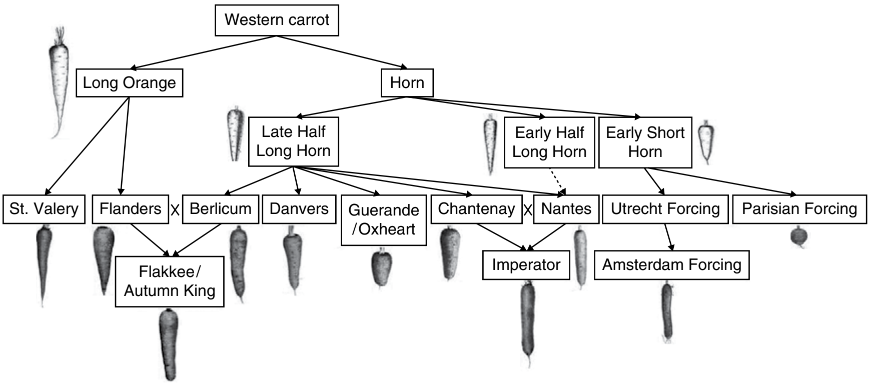

Fig. 6.2. Names, shapes and likely origins of major types of Western carrots.

Since carrot is a root crop, the genetic basis of root development and shape has been the focus of several studies. In an analysis of wild carrots, which have relatively slender tap roots, and domesticated carrots, which have larger storage roots, a polymorphic indel on the long arm of chromosome 2 named *cult* was associated with these two contrasting *D. carota* gene pools. A quantitative trait locus (QTL) analysis of a wild × cultivated mapping population identified a candidate gene, *DcAHLc1*, that belongs to the AT-hook motif nuclear localized (AHL) gene family previously reported to be involved in the regulation of root development (Macko-Podgórni *et al.*, 2017). Further evaluation of the gene function will be of interest across diverse environments and genetic backgrounds. In a recent genome-wide association study using more than 300 plants from 103 open-pollinated cultivars and almost 82,000 single-nucleotide polymorphisms (SNPs), a 600 kb-long region on chromosome 1 associated with root diameter was identified (Macko-Podgórni *et al.*, 2019). Turner *et al.* (2018) provided evidence that root shape is probably under relatively simple genetic control that is just beginning to become characterized. Using genetic mapping and QTL analysis they identified six QTLs for root length, two QTLs for root shape and two QTLs for root weight localized on chromosomes 1, 2 and 7. That the *DcAHLc1* gene did not overlap with the QTL on chromosome 2 was likely because the 'cultivated' variant of that gene was identified in a wild × cultivated segregating population (Macko-Podgórni *et al.*, 2017), while it is almost fixed in the cultivated carrot gene pool. Interestingly, another gene belonging to the AHL family was reported by Turner *et al.* (2018) within the QTL interval on chromosome 2. Possibly, a suite of tightly linked genes on chromosomes 1 (root diameter and root length) and 2 (root diameter, root length and root biomass) are involved in determination of root development and are inherited together (Turner *et al.*, 2018).

Orange carrot cultivars account for most of the global production of carrots and variation in root shape continues to be the primary basis for differentiating

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cultivars. Among the roughly ten to 15 root shapes recognized in orange carrots today (Fig. 6.2), the larger-rooted cultivars are primarily targeted for processing and the smaller-rooted cultivars for fresh market. Yellow and white cultivars, historically bred for farm animal feed, also vary in root shape and, as novel colours of carrots become more popular, red, purple, yellow and white cultivars in these shapes, and perhaps new shapes, can be expected (Rubatzky *et al.*, 1999).

6.2.5 Carrot colour and flavour

Carrot root colour has received extensive breeding and research attention. This reflects the prominent role of colour in crop domestication (Ellison, 2019), the important nutritional impacts that carrot pigments impart (Arscott and Tanumihardjo, 2010) and the striking phenotypic variation in carrot colour (Fig. 6.3).

Candidate genes have been identified for several major carrot root colour traits. Several genes have been proposed to control carotenoid content in carrot roots as a result of classical genetics studies and two of those genes, *Y* and Y_2, have been thoroughly investigated (reviewed by Simon *et al.*, 2019). A candidate for the *Y* gene has been indicated as a result of the carrot reference genome sequencing and subsequent genetic analyses. The *Y* gene candidate (DCAR_023551) is a homologue of the *Arabidopsis thaliana* gene *PSEUDO-ETIOLATION IN LIGHT*, responsible for the regulation of photomorphogenesis. Mutations resulted in frameshifts turning off the repression of downstream genes associated with light-induced photosystem and plastid biogenesis in the roots, which in turn facilitated accumulation of carotenoids (Iorizzo *et al.*, 2016). The *Or* gene, related to plastid biogenesis, has recently been described as the key component of the carotenoid accumulation (Ellison *et al.*, 2018). Besides the above-described key regulatory genes, structural genes constituting the carotenoid biosynthesis pathway have also been characterized and their regulation investigated (for a review, see Simon *et al.*, 2019).

Three major genes governing anthocyanin accumulation in the roots of 'black' carrots, labelled *P1*, *P2* and *P3*, have been proposed, controlling root pigmentation, node pigmentation and root/petiole pigmentation, respectively (reviewed by Cavagnaro and Iorizzo, 2019). R2-R3-MYB genes at these loci have been proposed as candidates governing anthocyanin accumulation in carrots (Xu *et al.*, 2017; Iorizzo *et al.*, 2019c). Recently, Iorizzo *et al.* (2019c) and Bannoud *et al.* (2019) proposed *DcMYB7* as a key gene and a candidate for *P3*, while the other two MYB genes (*DcMYB6* and *DcMYB11*) are likely involved in anthocyanin accumulation, depending on the genetic context or providing tissue specificity.

Beyond the visual and nutritional impacts of pigments that carrots deliver to consumers, flavour is the other major carrot trait that influences consumer

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Fig. 6.3. The historical development of carrot has generated a diverse array of colours of interest for breeders today.

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quality. Sweetness, harsh flavour and texture are the three major organoleptic variables in diverse carrots for flavour consumption (Simon *et al.*, 1982). Not surprisingly, sugars account for much of the variation in carrot sweetness while the distinctive flavour of carrots is attributable to volatile mono- and sesquiterpenoids (Buttery *et al.*, 1968). The genetic control of carrot volatile terpenoid and sugar biosynthesis and accumulation is discussed in Chapter 14 (this volume) and has recently been reviewed (Ibdah *et al.*, 2019; Simon *et al.*, 2019). Recently 30 QTLs controlling volatile terpenoid content have been reported and candidate genes identified (Keilwagen *et al.*, 2017). Total sugar content varies more than tenfold in diverse carrot germplasm (Baranski *et al.*, 2011) and carrot breeders typically perceive increased sweetness to be desired by consumers. High volatile terpenoid content can mask sweet flavour, so selection for carrot flavour in a fresh market breeding programme typically involves flavour evaluation of individual carrots for harshness and sweetness.

The *Rs* locus controls the balance of free sugars in the storage root, and the gene encoding acid-soluble invertase isozyme II is the candidate gene identified for this trait. A 2.5 kb insert near the 5′ end of the first and largest intron of *rs*/*rs* plants disrupts RNA processing and reduces invertase activity. With the identification of a candidate gene for the *Rs* locus, marker-assisted selection has been exercised for carrot sugar type with high accuracy (reviewed by Cavagnaro, 2019).

6.2.6 Disease and pest resistance

Selection for genetic resistance to several foliar diseases of carrot has received much attention. Most prominently, Alternaria leaf blight (*Alternaria dauci*) is often considered the most serious disease of carrot globally, especially in more humid growing regions. Root-knot nematodes are also a significant pest in most production areas. Resistance genes have been identified for these biotic threats to carrot production, as well as several others (Chapter 10, this volume; Du Toit *et al.*, 2019). Selection techniques involve field screening combined with greenhouse or laboratory evaluation for diseases and pests of primary importance. With well-established loci for nematode resistance, marker-assisted selection has been successfully initiated to improve carrot root-knot nematode resistance (Boiteux *et al.*, 2004).

6.2.7 Abiotic stress tolerance and weed competitiveness

Relatively little carrot breeding effort has been directed to improving abiotic stress tolerance but as carrot production has increased dramatically in Asia and warmer growing conditions have been experienced in several global production areas, an increased interest has developed in identifying genetic sources

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of salinity, heat and drought tolerance in diverse germplasm (Grzebelus, 2019; Bolton *et al.*, 2020). Both wild carrot and cultivars from more stressful growing regions demonstrated stress tolerance, making the prospects for improvement hopeful.

Global production of carrot under organic management conditions has increased in well-developed European and North American markets (Chapter 16, this volume), and this has led to a heightened interest in durable disease and pest tolerance, as well as in more rapid stand establishment and top growth to improve weed competitiveness. This has resulted in efforts to characterize the genetic basis of top growth.

6.3 MOLECULAR BREEDING AND GENETICS

6.3.1 The carrot genome

Carrot has nine pairs of chromosomes and a relatively small genome that was sequenced in 2016. The haploid genome size is approximately 473 Mb (Iorizzo *et al.*, 2016) or around 1.0 pg of DNA in 2C nuclei of most cultivated carrots, while it ranges from 0.9 to 1.1 pg in the wild *D. carota* subspecies (Nowicka *et al.*, 2016b). Carrot metaphase chromosomes are small and poorly differentiated in length and morphology (Iovene *et al.*, 2008; Nowicka *et al.*, 2012) and include four subtelocentric, one submetacentric and four metacentric pairs with the nucleolar organizer region localized at the end of the short arm of chromosome 4 (Nowicka *et al.*, 2016a).

The carrot genome comprises 32,113 non-redundant gene models, most of which (almost 99%) were demonstrated to be expressed, with the mean coding sequence size of 1183 nt and *c.*5 exons per gene on average. The majority of genes (89%) were functionally classified. Almost half of the carrot genome was attributed to repetitive DNA, mostly transposable elements (TEs), of which 67% were assigned to class I (retrotransposons) and 30% to class II (DNA transposons). Tandem repeats (TRs) occupied 3.6% of the assembled genome, while they were more abundant in the non-assembled fraction, probably constituting more than 7% of the carrot genome (Iorizzo *et al.*, 2019b).

Recent advances in the suite of tools facilitating molecular breeding of carrot include the development of simple sequence repeat (SSR) (Cavagnaro *et al.*, 2009, 2011; Iorizzo *et al.*, 2011), Diversity Arrays Technology (DArT) (Grzebelus *et al.*, 2014) and SNP (Iorizzo *et al.*, 2013, 2019a,b) genotyping platforms providing rich sources for reliable molecular markers. Another promising and technically simple genotyping system, based on intronic insertions of miniature inverted repeat transposable elements (MITEs) for the group of carrot *DcSto* (*Daucus carota Stowaway*-like), has been developed recently (Stelmach *et al.*, 2017). Dubbed DcS-ILP (*DcSto* intron length polymorphism),

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it allows for genotyping hundreds of gene-associated *DcSto* insertion polymorphisms (Fig. 6.4). These technical developments provide means for the identification and chromosomal localization of many agronomically and nutritionally important carrot genes.

6.3.2 Tissue culture and genome engineering

Carrot is commonly acknowledged as a species well-responding to tissue cultures. It has been a model for plant protoplast cultures, following first successful cultures derived from carrot roots (Kameya and Uchimiya, 1972) and cell suspensions (Grambow *et al.*, 1972), and subsequent plant regeneration via somatic embryogenesis. More recently, a direct somatic embryogenesis system from leaf- and hypocotyl-derived protoplasts was developed (Grzebelus *et al.*, 2012). Protoplast cultures were used to perform intraspecific, interspecific and intergeneric somatic fusions (Dudits *et al.*, 1977, 1987; Han *et al.*, 2009; Maćkowska *et al.*, 2014) and for *in vitro* selection against biotic stressors via medium supplementation with bacterial and fungal elicitors (Barański *et al.*, 1997; Grzebelus *et al.*, 2013). Also, protoplast reaction to abiotic stress, i.e. increased salt concentration in the medium, was investigated (Kiełkowska *et al.*, 2019).

Efficient protoplast culture protocols are essential for the application of clustered regularly interspaced short palindromic repeats (CRISPR)-associated protein 9 (Cas9) genome editing. The first case of successful genome editing in carrot was reported by Klimek-Chodacka *et al.* (2018) using the CRISPR/Cas9 system. Two single-guide RNAs targeting the flavanone-3-hydroxylase (*F3H*) gene in the anthocyanin biosynthesis pathway knocked out that gene to block accumulation of anthocyanin pigments in originally purple callus lines. Xu *et al.* (2019) utilized a similar approach to edit *DcMYB113-like* gene, that also conditions anthocyanin biosynthesis to block purple colour, and to edit the *PDS* gene in the carotenoid biosynthetic pathway to block carotenoid biosynthesis in purple and orange callus lines, respectively. Both experiments proved that carrot genome editing can be efficiently performed, providing means for verification of the function of other candidate genes. However, no reports

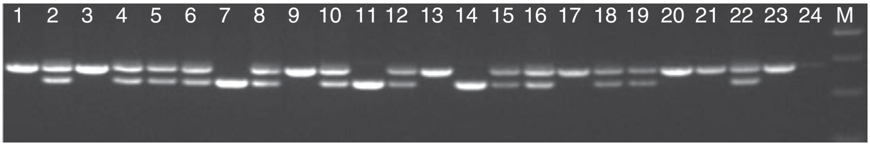

Fig. 6.4. An example of DcS-ILP (*DcSto* intron length polymorphism). Lanes 1–23, carrot plants of different origin; lane 24, DH1 reference line carrying homozygous insertion; M, size marker. Upper band is amplified from the intron variant with insertion of a *DcSto* (*Daucus carota Stowaway*-like) element, lower band is derived from an unoccupied variant, both variants are present in heterozygotes.

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have yet been published on the regeneration and performance of carrot plants bearing these edited genes.

Recently, Dunemann *et al.* (2019), following earlier reports on *A. thaliana* (Ravi and Chan, 2010), edited the centromeric histone H3 (*CENH3*) gene, aiming at the development of 'haploid inducers', i.e. plants with mutated CENH3 that, when used as parent, facilitate generation of haploid progeny. In their preliminary report they demonstrated accumulation of the mutated CENH3 protein in regenerated plants, but no haploids have been produced yet (Dunemann *et al.*, 2019). This subject is vital for carrot breeders, as no efficient protocols for the production of haploids/doubled haploids using conventional tissue culture systems (anther cultures, microspore cultures, ovule cultures) have been developed, despite numerous efforts (Kiełkowska *et al.*, 2014).

The functional CRISPR/Cas9 genome editing system adds to the range of techniques available for carrot breeders in the field of genetic engineering. Earlier, *Agrobacterium tumefaciens*-mediated genetic modifications proved to be useful in producing carrots with enhanced resistance to pathogens, increased tolerance to abiotic stresses, modified carotenoid composition and production of recombinant proteins (reviewed by Baranski, 2008). However, no genetically modified (GM) carrots have been evaluated in advanced field trials and no commercial GM carrot cultivars are available.

6.4 CONCLUSIONS

Progress in carrot breeding was accelerated in the middle of the last century by the development of a CMS-based system to produce hybrid cultivars. The development of genomic tools is beginning to have applications to advance carrot breeding in this century. New production challenges in the form of biotic and abiotic stress, and growing consumer demand can be expected. The diversity of genetic variation in carrot germplasm combined with an expansion of genomic information and tools to improve performance can provide an important foundation to address these challenges.

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Carrot Growth and Development

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The cultivated carrot is a biennial plant: in the first year, it produces a rosette of leaves and carbon reserves located in the storage root; in the second year, it uses these reserves after vernalization to produce a floral stem. In that year, the plant can reach a height of up to 1.5 m.

7.1 THE FIRST PHASES OF DEVELOPMENT

Just after seed germination *stricto sensu* (radicle exit from the seed), both the root and hypocotyl contribute downward growth, a crook then forms, and all subsequent hypocotyl growth is upward while all root growth is downward. The results of White and Strandberg (1978) concerning the American Imperator carrot show that the growth rate of the root is about 1 cm/day at 16°C under controlled conditions and with organic soil. In Normandy (France), Roche *et al.* (1991) observed lower growth rates for Nantes-type seedlings planted in May–June: around 0.8 cm/day at about 14°C.

Before the first leaves appear, the young carrot plants show a clear delineation between the storage root and the hypocotyl. When the first leaves appear, while this distinction tends to fade (Esau, 1940), the lateral roots begin to develop into four longitudinal lines.

For the Nantes carrot type, the distribution of biomass (fresh and dry) between the shoot and the storage root seems different depending on the sowing period. For early sowing (November to January), no difference is observed up to 1000 degree-days (base 0°C) between foliage and storage root. Then the storage root grows exponentially, while foliage development is greatly reduced (Fig. 7.1). There is no significant difference between November and January sowings. For later sowing (April to July), storage root growth occurs earlier than for the so-called early carrots (Fig. 7.1).

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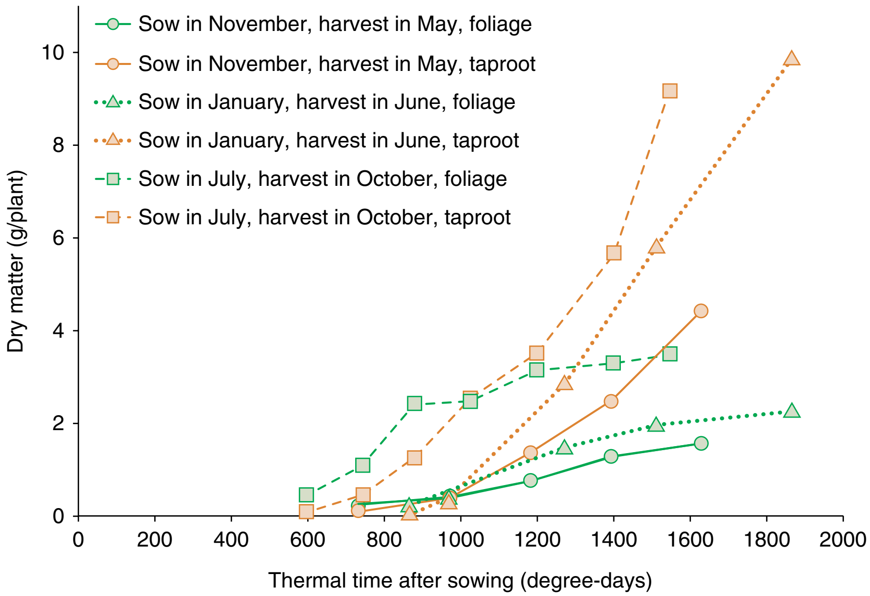

Fig. 7.1. Seasonal growth pattern of carrot foliage and storage root for Nantes-type varieties in Landes area (France): early sowing in November or January, variety Nanda; sowing in July, variety Maestro. (C. Raynal, unpublished results, 2005.)

The distribution of dry matter between shoot and storage root is primarily determined by genotype at early stage (Stanhill, 1977; Hole *et al.*, 1983).

A decimal scale for the coding of phenological stages has been developed, called the BBCH scale, used for authorization of plant protection products in Europe. The different phases of plant development are divided into ten main stages numbered from 0 to 9 and clearly recognizable (Fig. 7.2).

Formation of storage root secondary structure starts with meristematic activity between the primary xylem and phloem (Fig. 7.3). Towards the end of the first month after sowing (spring sowing), a complete cambial sheath forms around the central primary xylem (Esau, 1940). The cambium produces phloem tissue to the outside and xylem tissue to the inside. The secondary phloem zone is covered by periderm, the storage root protective layer, and contains phloem elements and cells of phloem parenchyma.

Phan and Hsu (1973) indicate that the first organs to develop rapidly are leaves that can reach a length of 13 to 18 cm in 2 weeks for the Imperator type. During this foliar growth, as the number of lateral roots increases, the diameter of the storage root hardly changes; it takes another month before the diameter evolution is visible. In the meantime, the foliar system reaches its full development. From this stage, the growth of the storage root accelerates to the detriment of the foliage.

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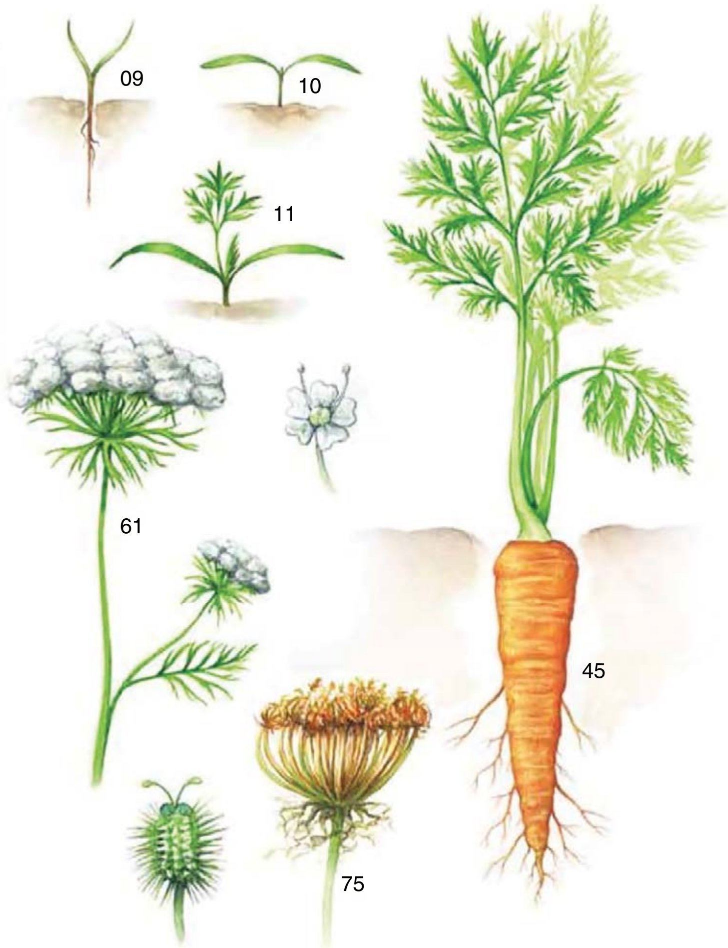

Fig. 7.2. Illustration of carrot development stages. Each precise growth stage is identified by a 2 digit number. The first digit number from 0 to 9 corresponds to main growth stages, which are subdivided in substages with the second digit number. For example, '09' corresponds to emergence, with cotyledons breaking through the soil surface, and is the last substage of the main growth stage '0' (germination). (From Villeneuve, 2014.)

The diametrical extension of the storage root begins slowly, accelerates and finally reaches its maximum at a stage sometimes called 'biochemical maturity'. The cessation of root development depends on leaves left and seems to occur when temperatures fall below 3°C (Suojala, 1999).

Several growth models have been worked on to approach the partitioning of dry matter between the aerial system and the roots, to see the possibilities of adaptation such as for climate change or specific conditions (Benjamin and Sutherland, 1992; Reid, 2019).

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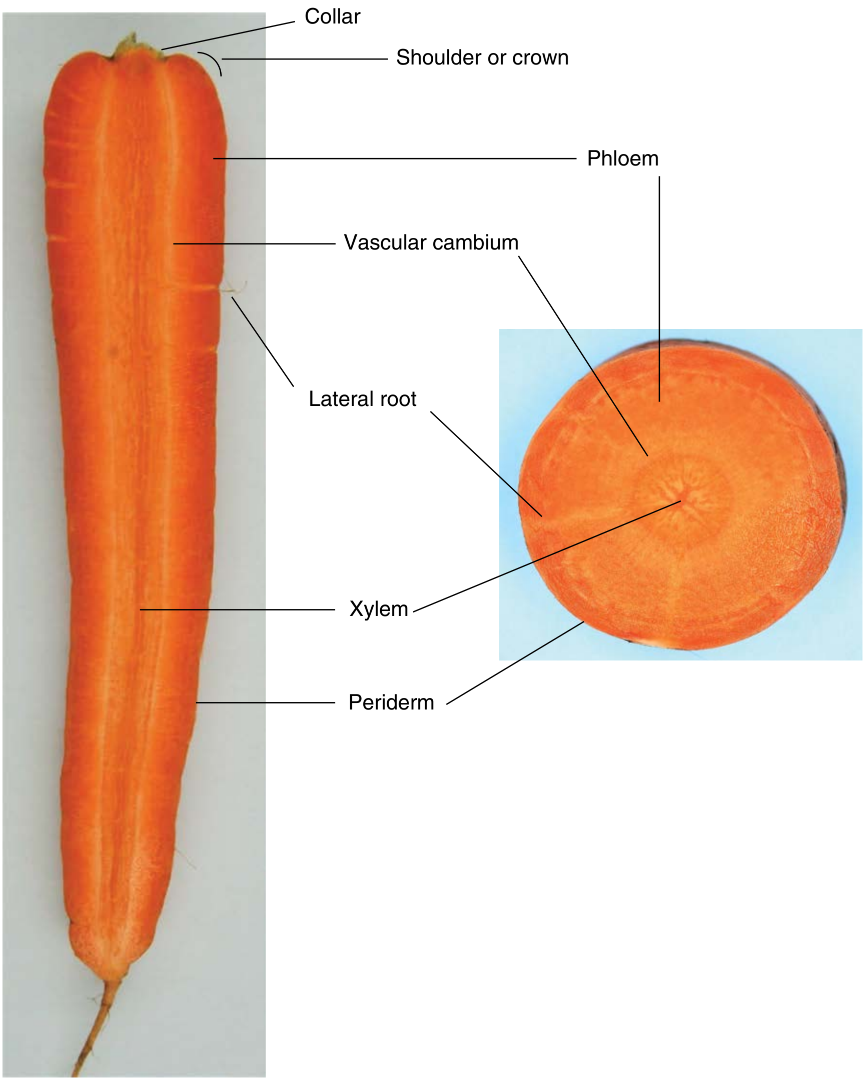

Fig. 7.3. Longitudinal and transversal sections of a carrot storage root. (Photos by F. Villeneuve.)

The sowing density and the design of sowing (one to three rows of seedlings side by side) influence foliage height and reduce per plant biomass accumulation in carrot (Bleasdale, 1967; Benjamin and Sutherland, 1992).

The carrot sensitivity to frost will depend on the stage of development of the plant and the conditions under which frost occurs. When storage roots are fully developed at the harvest stage, frost damage can occur with temperature as low as –2.5°C (Tucker, 1974). Nevertheless, there is a tremendous variation in sensitivity between varieties, due to sensitivity to ice crystal formation or

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the position of the crown relative to the soil surface (Palta and Simon, 1993). Young plants have a much higher frost resistance, making it possible to use the seed-to-seed production technique, sowing in late summer or early autumn of the first year and harvesting seeds the next year. Carrot at rosette stage can withstand temperatures down to –15°C. However, the alternation of freezing and defrosting and the duration of the frozen period can reduce this resistance.

Carrot is classified as a salt-sensitive plant and there is a 7% growth reduction for every 10 mM increment in salinity above 20 mM salt. Salt stress results in reduced leaf gas exchange and a reduction in apparent photosynthetic capacity in cultivated carrot crops (Gibberd *et al*., 2002).

7.2 MORPHOLOGY OF THE ROOT AT HARVEST TIME

The carrot we eat is, in fact, the storage part of the plant root system. It is possible to differentiate several areas (Fig. 7.3):

- a very thin area on the outside, a real epidermis of the root called a 'pericycle';
- an intermediate zone constituted by the phloem, commonly referred to as 'carrot flesh';
- a thin ring made up of the generating bases that make up the cambium; and
- a central zone that corresponds to the xylem of the root.

The root diameter can range from 1 cm to as much as 10 cm at the widest part. The root length ranges from 5 to 50 cm, although most roots are between 10 and 25 cm long (Rubatzky *et al*., 1999).

The 'harvest' maturity of the carrot is more a function of root morphology or market conditions than of biochemical composition criteria. Various attempts have been made to define them, for example the refractometric index or the simple sugars/sucrose ratio, but none of these parameters is fully satisfactory (Villeneuve *et al*., 2002). As long as climatic conditions allow, the main root of the carrot continues to grow.

Depending on variety type, the root tip can have different forms at harvest time: round or blunt, slightly pointed, and pointed. Blunt tip is an expression of root maturity for Nantaise type.

The structure of the periderm and outermost layer of the phloem zone may be closely related with storage root resistance to splitting (McGarry, 1995).

7.3 EVOLUTION OF CARROT ROOT BIOCHEMICAL COMPOSITION

7.3.1 Composition of soluble sugars

Analysis of the soluble carbohydrate composition of the carrot storage root mainly revealed the presence of sucrose, glucose, fructose and, in lesser amounts,

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galactose and raffinose. Sucrose is by far the most important carbohydrate reserve formed in the storage root. Carrot has been considered for a long time as containing negligible amounts of starch and malto-oligosaccharides, and sucrose was proposed as the major transport and storage carbohydrate. However, microscopy analyses revealed that amyloplasts are present in parenchyma cells around the phloem of freshly harvested carrots and disappear following cold storage. So, starch may play a role in sugar reserves in carrot, representing a mobilizable energy source to face preharvest and postharvest stresses (Bufler, 2013).

During the root growth period, the total soluble sugar load increases gradually. However, detailed analysis of the various sugars shows that the content of reducing sugars (glucose and fructose) decreases during this same period while sucrose accumulates rapidly until it reaches about 5.5% of fresh weight at the beginning of December for carrots of the Nantes type for a June sowing (Le Dily *et al.*, 1994). This last aspect is greatly dependent on the area of production. As many authors have shown (Goris, 1969), this results in a steady increase in the ratio of sucrose to reducing sugars during this period.

The winter rest period when the storage root remains in the field is reflected in December and January in the northern hemisphere by a reduction in metabolic activity (linked to meteorological phenomena: drop in temperature, decrease in daylength). Thus, the sugar content no longer changes significantly

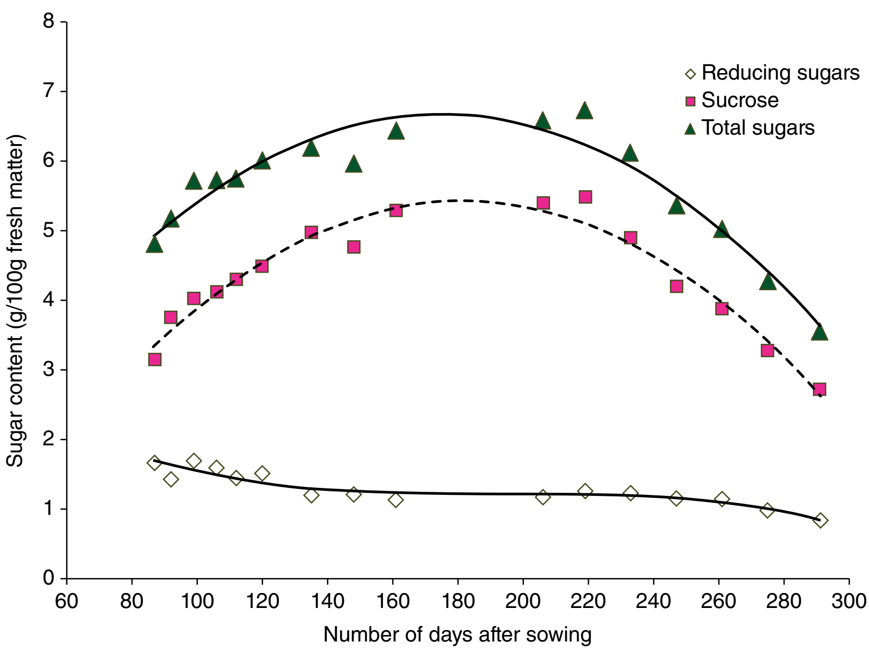

Fig. 7.4. Evolution of sugars in carrot roots in the field, variety Nandor – Nantaise type – sown on 25 June.

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following a more or less significant loss of foliage and the absence of new shoots (Fig. 7.4). The cold storage completely changes the pattern of sugars evolution.

The remobilization of free sugars for vegetation recovery can be observed from mid-February and begins with the hydrolysis of sucrose accumulated in the autumn. By March, all carbohydrate reserves are significantly depleted, the rapid consumption of sucrose leading to a drop in the ratio of sucrose to reducing sugars (Le Dily *et al.*, 1994).

7.3.2 Evolution of the carotenoid content

The production of carotenes in the root is characteristic of the maturation phase. Analyses conducted throughout root development (June sowing) showed a gradual increase in carotene content during the autumn period, before falling with the recovery of vegetation (Le Dily *et al.*, 1994; Fig. 7.5). For early varieties, there is a ceiling that coincides with the slowing down of the fraction of total dry matter allocated to roots. According to Lee (1986), this seasonal evolution is also reflected in the vitamin A content of the root.

A delay in maturity results in a low carotene content as well as early harvest (Aubert, 1981), although some varieties are able to accumulate carotenes earlier than others (Fleury *et al.*, 1994).

7.3.3 Evolution of the total fibre content

From a purely nutritional point of view, plant ‘fibres’ can be defined as the insoluble organic fraction, composed by hemicelluloses, cellulose and lignin.

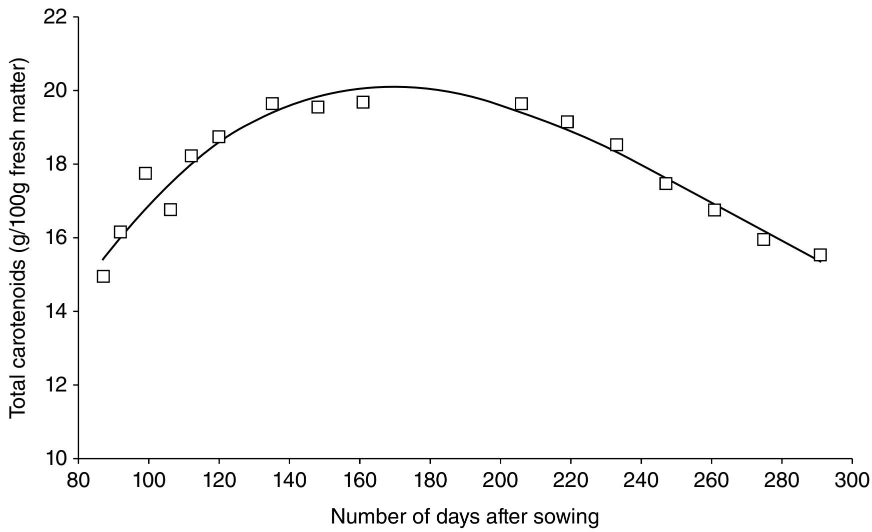

Fig. 7.5. Evolution of total carotenoids in carrot roots in the field, variety Nandor sown on 25 June.

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The fibrosity of the core can be assessed overall by means of different 'indices': either chemical (insoluble alcohol substances, crude fibre, neutral detergent fibre) for its nutritional value, or physical (penetrometry) for its mechanical strength and texture.

The determination of the neutral detergent fibre index (dry matter insoluble in detergent) shows a decrease in fibre content during the growing season. In reality, this apparent decrease in fibre content is caused by the considerable increase in soluble dry matter (total sugars) that carrot root records during this same period (Robertson *et al.*, 1979).

Spring regrowth results in an increase in fibre content, probably linked to an incipient lignification linked to floral induction.

7.4 FLORAL INDUCTION AND VERNALIZATION

Regarding floral induction, the development cycle of the carrot is divided into three distinct periods:

- The so-called 'juvenile' period, a phase during which the plant is not receptive to photo- and thermo-induction stimuli: consequently, there can be no floral induction.
- The period known as 'adolescence' and 'sensitivity to vernalization': carrots gradually acquire sensitivity to floral induction (or vernalization maturity). Maximum sensitivity is achieved when carrots reach the eight- or nine-leaf stage, with a pivot diameter of 4 to 8 mm (Atherton *et al.*, 1990; Samuolienė *et al.*, 2009). Before this stage, the vernalization is more or less reversible. During this period, the plant always differentiates leaves in a rosette form. The root grows larger as the cambium becomes functional.
- The period known as the 'maturation' or 'sexual reproduction' period, during which the stem, until then short-notched (vegetative rosette), elongates, then flowers and bears fruits.

In carrots, floral initiation is the result of a photo- and thermo-induction that do not necessarily interact and can occur at different times (Samuolienė *et al.*, 2008). The work of Duchovskis (2000) shows that the photo-induction occurs earlier (five-leaf stage) than thermo-induction (nine-leaf stage).

The effect of cold, perceived by the meristem cells, is the major factor in stimulating floral induction in carrots, particularly for the biosynthesis of the necessary phytohormones (Samuolienė *et al.*, 2009). The response of plants to temperature is given by the combination of the temperature during vernalization and the duration of the vernalization period, measured in terms of the number of days of effective vernalization. An effective vernalization day is reached when the plant is exposed for 24 h to the optimal temperature.

Based on the results of Atherton *et al.* (1990) on Chantenay Red Cored variety, Yan and Hunt (1999) calculated the cardinal temperatures regarding

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plant response to temperature: minimum temperature 0°C, optimal temperature 6.6°C and maximum temperature 14.6°C (Fig. 7.6).

The length of the juvenile period is very strongly dependent on the variety as well as the length of the vernalization period. The 'late-flowering' varieties need 10 to 12 weeks to be vernalized in a non-reversible way and 'early-flowering' varieties, only 1 to 4 weeks (Alessandro and Galmarini, 2007; Alessandro *et al*., 2013). Vernalization requirement is under the genetic control of two main genes (*Vrn-A* and *Vrn-B*) with three alleles (Wohlfeiler *et al*., 2019). Annual behaviour is dominant and the 'late flowering' character is recessive.

Bonnet and Aubert's work (1987, 1989) showed that there is a large variability in the Nantes type, with some varieties or lines showing 'less sensitivity to cold', but it is still unclear whether this is due to a longer juvenile period or to higher cooling requirements. These results, as well as those of Alessandro and Galmarini (2007) and Alessandro *et al*. (2013), suggest that there are certainly genetic mechanisms complementary to the two major genes. Work on the *Arabidopsis* model plant has shown that its vernalization is under epigenetic control.

However, the photoperiod also plays a role, especially after vernalization; in particular flowering can be suppressed by continuous low intensity light (Atherton *et al*., 1983).

It should be noted that vernalization poses some problems of observation due to its invisible nature. The beginning of stalk elongation can be observed (Fig. 7.7).

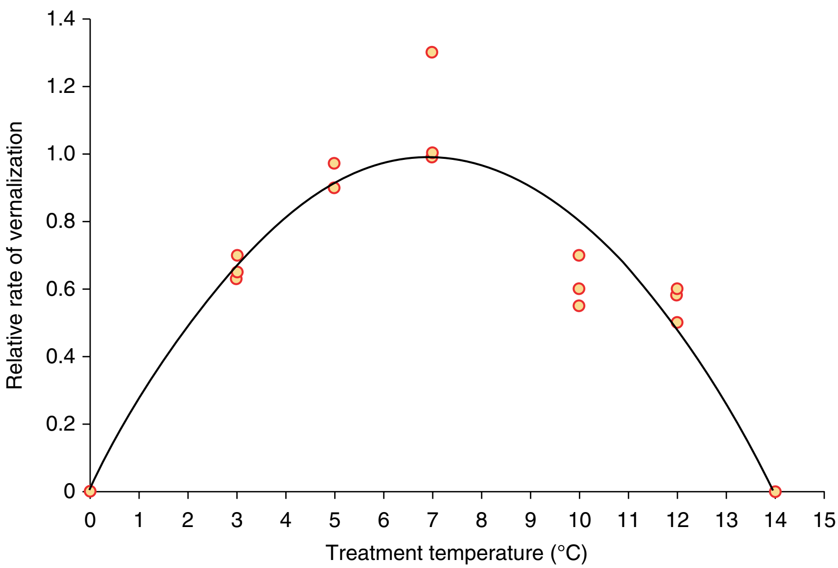

Fig. 7.6. Temperature response curve for carrot vernalization, Chantenay Red Cored variety. (Elaborated from Yan and Hunt, 1999.)

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Fig. 7.7. The shape of the terminal meristem tissues changes after vernalization and at the beginning of stalk elongation: (a) unvernalized carrot; (b) vernalized carrot. (Photos by F. Villeneuve.)

7.5 BOLTING, FLOWERING AND FLORAL BIOLOGY

The beginning of bolting can be considered as the time when the stem (apex) is visible to the naked eye, i.e. greater than 8 mm. The bolting is characterized by a very high degree of heterogeneity between plants with regard to the appearance of the stem, without any systematic link with the size and internal fibrosity of the roots (Bonnet and Aubert, 1989). Stalk elongation blocks the growth in root thickness; the two phenomena are therefore totally antagonistic.

The carrot inflorescence consists of flowers grouped into umbellets with bracts, which in turn are grouped into umbels with 20–40 small, arched and converging rays at maturity. The colour of flowers is white for orange, white and yellow carrots, and purple for some purple varieties. The primary umbel, which is located at the top of the main axis, can consist of about 1000 flowers, while the secondary umbels (at the end of the branches inserted on the main axis, called primary branches), tertiary (at the end of the branches inserted on the primary branches, called secondary branches) and quaternary ones have respectively fewer and fewer flowers. It is common to have several flower stems for a single plant. The floral development is centripetal with a spiral arrangement.

Thus, the first mature flowers are those found at the outer edge of the outer umbellets. The proportion of sterile flowers increases from primary to quaternary umbels.

The flowering of the umbels follows one another over time with a delay of several days between each order.

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The number of days between the anther and the maturation of the stigmas can range from 1 to 11 days. Nectar is secreted from a swollen disc on the upper surface of the ovary and is easily available to all types of insects.

The carrot is protandrous and flowers include five small sepals, five petals, five stamens and two carpels.

Physiological maturity has been characterized as the moment when the seeds reach maximum dry matter accumulation, approximatively 35 days after anthesis (Hawthorn *et al.*, 1962; Steckel *et al.*, 1989).

7.6 SEED CHARACTERISTICS AND EMERGENCE

Carrot seed is an endospermic achene. It is a dry fruit comprising the seed itself, consisting of a large mass of endosperm and an embryo, surrounded by thick integuments. The seminal reserves are located outside the embryo.

Seeds begin to respire almost immediately after imbibition of water and the subsequent respiratory patterns are closely associated with seed vigour and responses of germination to environmental and hormonal signals.

Eighty-seven per cent of root size differences can be attributed to different emergence dates, for sowing in July (Benjamin, 1990).

Each seed lot has its own characteristics; these heterogeneities result for the producer in a spreading of emergence over time, in varying final germination percentage and in differences in vigour and growth of young seedlings. The seed lot can therefore be the basis of poor crop establishment.

The behaviour of seeds depends on many factors: genetic characteristics, conditions of development (harvesting, preparation and storage), seed health status before and after harvesting, germination conditions and possible dormancy.

However, much of this information is not available to the producer. Nevertheless, producers can implement specifications with specific requirements for the required seed quality.

The carrot is not sensitive to the presence or absence of light to germinate. The main factors influencing germination are:

- The possible presence of pests and diseases causing seedling damping-off like *Pythium* spp., *Rhizoctonia solani*, *Alternaria* spp. and *Delia platura*.
- Temperature.
- Soil oxygen content. Carrot seeds germinate with even greater difficulty when the oxygen content of the atmosphere is lower. A slight hypoxia (15% oxygen) is sufficient to slow down germination, or even reduce the final percentage of germination. Even a transient anoxia (1 or 2 days) affects the germination and growth of the hypocotyl (Corbineau *et al.*, 1995).
- Osmotic pressure. The phenomenon of germination starts with what is called ‘water imbibition’, a process that actually corresponds to a three-phase

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sequence involving both the seed and water (Bradford, 1990): Phase I, rapid initial water uptake; Phase II, a plateau phase during which there is little change in the amount of water contained in the seeds; and Phase III, a further increase in the amount of water in the seeds that coincides with radicle growth.

For these three steps to be achieved, the environment must have a quantity of water that is not only sufficient, but also accessible to seeds, which depends on respective water attraction between soil and seeds.

This exchange of water between soil and seed may be modified according to their respective content in saline elements. The higher the concentration of soluble salts in the soil, the lower the water absorption by the seed. Soil preparation affects seed imbibition by favouring evaporation and upwelling of water loaded with saline elements. This causes the accumulation of soluble salts in the soil surface, resulting in an increase in osmotic pressure which interferes with seed germination.

Both germination and seedling growth were reduced by soil moisture potentials of 0.01 MPa, although osmotic potentials as low as 0.5 MPa had no effect on these stages of growth (Maas and Hoffman, 1977). Schmidhalter and Oertli (1991) concluded that germination and seedling growth are affected differently by comparable matric and osmotic stresses and that water stress exerts a more negative effect on carrot than salt stress. A wide range of phenotypic variations for salt tolerance is identified; some accessions were identified as salt-tolerant accessions (Bolton and Simon, 2019).

The impact of temperature on germination has been the subject of various studies (Hegarty, 1973; Corbineau *et al.*, 1993). Carrot seeds can germinate in a wide temperature range from 3 to 40°C. The optimal temperature is 25°C. At extreme temperatures (low and high) the percentage of germination is reduced, and in the case of low temperatures the germination time is greatly extended. Germination stops at seedbed temperatures of 32 to 35°C, but restarts as soon as the temperature drops, inducing emergence spread and root size differences at harvest. Nascimento *et al.* (2008) showed that thermotolerant varieties can have good germination at 35°C, as well as the relationship between thermotolerance and ethylene production during carrot seed germination at high temperature.

It is possible to calculate a sum of soil temperatures from the sowing date using 3.5°C as a basis. It is necessary to reach a temperature sum of 60 degree-days to obtain 50% germination, and 130 degree-days for 50% emergence, if water potential is not a limiting factor. More detailed modelling should take account of both temperature and water potential (Rowse and Finch-Savage, 2003). The forecast of the emergence date is important for the producer to schedule application of non-selective herbicides before emergence. It would be relatively simple to predict this date from ground temperature, but it does not take into account the water potential of the seedbed. Several studies have integrated these data into models (Finch-Savage *et al.*, 2001); however, it is still

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difficult to know the acquisition of the water potential of the seedbed on a routine basis at the producer level.

For a seed lot, there are often significant differences in size and weight between seeds in the same lot, and between seed lots from different sources. Seeds are generally calibrated and graduated before marketing. In the case of carrots, sizing consists of sorting the seeds according to their width and grading over their length. However, these operations, which are necessary for the homogenization of seeds from the same seed lot, do not entirely reduce the variability between seeds.

The different sizes of the same seed lot do not have the same aptitudes with regard to the limiting factors that can occur when a crop is planted. These differences in sizes have various origins for the carrot; it is possible to quote the position on the umbel, the order number of the umbel, the rate of setting, the water supply and the date of harvest of the seed, for example.

Seeds are generally calibrated before marketing. Large-calibre seeds have a slightly slower germination rate than small calibres, but they perform better at low temperatures while the opposite is true for high temperatures (Villeneuve *et al.*, 1993). Since large seeds have more reserves, it is possible to sow deeper, compensating for the significant decrease in the emergence strength of the seedlings during the underground life cycle. Similarly, large seeds have a higher capacity when facing obstacles such as clods or crust. On the other hand, the use of reserves during the emergence phase leads to less growth after emergence (Tamet *et al.*, 1994).

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8

Carrot Production Practices

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8.1 CLIMATIC REQUIREMENTS

Carrot is a cool-season crop that grows best at temperatures of 15 to 21°C. Temperatures of 18 to 21°C are ideal for optimum colour and flavour of the carrot roots. However marketable carrots can be grown in a rather wide range of temperatures (13 to 35°C). Seeds germinate at soil temperatures of 4.5°C or higher. Carrot seedlings grow rapidly during cool growing conditions, producing their mature length taproots within the first 3 weeks of growth. Root colour can deepen rapidly when temperatures are within the 18–21°C range 3 weeks before harvest.

Above 30°C, canopy growth is reduced and strong flavours develop in the roots, reducing their market quality. Conversely, carrot root and foliage growth are slowed below temperatures of 10°C. Carrot seedlings will tolerate warm temperatures early in the growing season and mature carrots can tolerate light frosts but will be injured by hard frosts. Air temperatures near 35°C or above can injure young seedlings at the soil line, causing death of seedlings. Hard freezes can lift the soil, causing breaking of the tender roots of seedlings, resulting in stubbed and forked roots.

8.2 SOIL REQUIREMENTS

Carrot root growth is best in loam to sandy loam mineral soils. Carrots can also be grown in muck soils due to their light textures. These types of soils allow for the best development of the carrot root length, shape and colour. Clay soils tend to produce rough and stubby roots. However, in dry climates where irrigation is required, the soil moisture can be managed to produce marketable carrots in slit loams and heavier clay soils.

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The upper 30 cm of soil should be uniform, loose and well drained. Soils that crust easily should be avoided or managed carefully to ensure good seed germination. The soil should be free of stones or other debris that may inhibit normal root growth. Compacted soils will result in stubbed or shortened roots and prevent water penetration.

Soil pH of 6.0 to 6.5 is ideal for most vegetables including carrots, but carrots can be grown on slightly alkaline soils as well. Soils of pH 7.8 are known to produce excellent carrot roots.

Carrots are considered sensitive to soil salinity. Yield loss can be expected to occur above 1.0 dS/m, with increasing yield loss with increasing soil salinity.

Previous crop history should also be considered before planting carrots into a particular field. Cavity spot of carrots is a major disease of carrots. Although lucerne is not affected by this fungal disease, it can harbour and reproduce on the roots of lucerne plants. Soil populations of *Rhizoctonia* species can also be high following lucerne, which can reduce stand populations of carrot seedlings. Herbaceous root crops such as potatoes, turnips and sweet potatoes can increase the amount of soft rot bacterial pathogens if not allowed to be fully decomposed before planting of carrots. Planting small grains before carrots is a method to reduce disease issues from the previous crop if there is a concern.

Because soil-borne pathogens of carrots can survive in the soil, it is recommended that a 3- to 5-year crop rotation be used. The longer rotation is especially required for organic carrot production.

8.3 PLANTING AND SPACING

Fields intended for carrot production should be deep ploughed to turn under previous crop debris and loosen the top 30 to 35 cm of soil. If soil compaction or hard pan below this depth is suspected, then loosening of the soil to 90 cm with a chisel tillage implement may be necessary.

Carrots are normally grown on raised beds or ridges to increase soil drainage. Bed shapes and widths can vary greatly and can depend on local tradition, available equipment, planter spacing, and harvest equipment size and configurations. Carrot market type also determines bed width, plant spacing and plant density. Bed widths of 76 to 180 cm have been used by various carrot producers in the world. In the USA, bed width is typically 96 to 102 cm.

Carrot seeds are small compared with most other vegetable seeds, and emergence is slow and irregular. Seed weight can range from 0.42 to 1.40 g for 500 seeds. Due to the irregularity in seed size within a cultivar and seed lot, the seed is normally sized into large and medium sizes. Larger sized seed generally produces more vigorous seedlings. Nevertheless, young seedlings are small, weak and fragile until the first true leaves appear. For these reasons, sowing techniques are extremely important.

Sowing techniques vary greatly depending on bed size, carrot type, market type and planting equipment being used. Because carrot seed size is so small and

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even distribution of the seed on the bed is critical for uniform root formation, precision seeders are required to achieve proper seeding. Pelleted seed is required on some types of planters while others may be able to use raw seed. However, even with seeders that can use raw seed, a seed coating enhances even flow of the seed from the seed hopper to the soil.

The use of precision planters also requires proper seedbed preparation (Fig. 8.1). Whether planting on raised beds or on the flat, the top of the bed must be smooth and free of clods or other debris. Raised beds are shaped ahead of the planting unit with bed shapers attached to the front of the planter unit, so that bed-shaping and planting occur as one field operation.

Belt planters require pelleted seed to attain good singulation of seed. Some vacuum planters may also require pelleted seed although many can use raw or coated seed as well. Because of the high density requirements of carrots grown for short-cut carrots, many growers have gone to spider planters that can plant multiple seed lines on a bed. Each spider planter may be able to plant up to six seed lines. Multiple spider planters can be used per bed to plant as many seed lines as required for each bed.

No matter the type of planter used, the design of the planting shoe is critical in achieving proper spacing of the seed (Fig. 8.2). A properly designed scatter shoe can be used to plant a uniform seedbed in a 10 cm wide band. Otherwise multiple-row planter shoes are used to plant up to six seed lines in a 10 cm wide band. Normally a set of seed rows is planted on each shoulder

Fig. 8.1. A planter in action in the USA. (Photo by J. Nunez.)

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Fig. 8.2. Scheme of planting design with uniform 10 cm bands. (Photo by J. Nunez.)

of the bed. On very wide seedbeds several bands of seed rows may be used on the top of the beds. However, maintaining an open space between seed bands is important to allow air flow within the canopy as the canopy expands. This will help reduce moisture on the foliage and reduce possible foliar disease issues that may arise.

Carrot seed should not be planted deeper than 1.3 cm in mineral soils. In fields where irrigation will be used the seed should be planted at a depth of 0.32 to 0.64 cm to promote quick emergence (Fig. 8.3). Muck soil fields may require planting down to a depth of 2.5 cm.

How much seed to plant depends greatly on the carrot type being grown and the market type (Table 8.1). There are four types of carrots that are grown commercially and in gardens. Nantes is a major fresh carrot type grown worldwide. It is a short carrot type with a blunt tip and is favoured for its sweetness and crisp texture. Danvers is another short carrot but is slightly broader in size. Danvers is used extensively for processing such as for slicing and dicing. Chantenay carrots are very large but short carrots that are not grown extensively commercially but are popular with gardeners. Imperator type carrots are grown extensively in North America. This is a much longer and thinner carrot that can be used for multiple purposes: juice, fresh and lightly processed. Cut-and-peel or 'baby carrots' are normally produced from Imperator carrots.

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Fig. 8.3. Correct seed emergence at plantlet stage. (Photo by J. Nunez.)

Table 8.1. Suggested sowing rates depending on carrot type.

Carrot type	Plants per hectare	Plants per metre row
Processing (dicing)	444,600 to 617,500	32 to 49
Cello (fresh market)	864,000 to 1,111,500	65 to 81
Slicer	1,111,500 to 1,358,500	65 to 98
Cut-and-peel (baby carrots)	3,211,000 to 4,693,000	260 to 309

Imperator types are normally planted in high density to achieve a long narrow root at harvest. Imperator hybrids that are designed for the cut-and-peel market are planted at a very high density, typically at 3,211,000 to 4,693,000 seeds per hectare. Imperator grown for fresh market are planted at a lower density than cut-and-peel carrots to achieve a carrot with a broader shoulder but still produce a long root. Fresh market Imperator carrots are planted at a density of 864,000 to 1,111,500 seeds per hectare. Conversely, Danvers varieties that are grown for processing are planted at a much lower density to achieve maximum size and yield. Typically, Danvers are planted at a density of 444,600 to 617,000 seeds per hectare.

8.4 GERMINATION

Overhead sprinkler irrigation is required in many areas of the world where carrots are produced (Fig. 8.4). Irrigation is applied within 24 to 72 h of planting. This initial watering phase to achieve germination is often referred to as 'germination water' or 'germ water'. The first application of the 'germ water' is to thoroughly wet the soil profile down to the effective root zone. This may range from 0.6 to 1.2 cm of water depending on soil type and soil moisture content at time of planting. After the initial 'germ water' the newly planted fields are watered daily to ensure the soil surface remains moist at all times. Depending on weather conditions, it may require more than one short watering period

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Fig. 8.4. Overhead irrigation with sprinklers of a planted carrot field. (Photo by J. Nunez.)

per day to maintain soil moisture at the soil surface until the field achieves 100% germination. Carrot seed is planted very shallow, 0.32 to 0.64 cm in depth, so maintaining soil moisture at the soil surface is critical during the germination phase.

Also, it is during this germination phase that herbicides, fungicides and insecticides may be applied through the water system.

Overhead irrigation is not employed in some carrot-growing regions. Instead rainfall is adequate and timely enough to rely on for germination and growth of the crop. Sometimes overhead sprinklers are used for the critical germination phase of the crop and then water can be applied by furrow irrigation or again rely on natural rainfall events. Drip irrigation is not a common method of irrigating carrots due to costs and impracticality for germination and harvest.

8.5 IRRIGATION AND FERTILIZATION

The amount of water required to grow a crop of carrots is very similar to most other vegetable crops. A carrot crop season will require 61 to 76 cm of water. Actual amounts will vary from field to field according to soil types and weather

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conditions. Applying enough water and at the correct time will yield the best-quality carrots. Stressing the crop will cause bitter-tasting compounds to be produced by the carrot root. For this reason, carrots that are on irrigation systems tend to be of more consistent quality than carrots that rely on natural rainfall events which may or may not occur at the correct frequency or amount (Fig. 8.5).

As a deep-rooted crop, carrots are able to extract nitrogen from a depth of 60 to 90 cm. Carrots do not require large amounts of nitrogen applications for maximum yield. Amounts of nitrogen application can range from 110 to 170 kg/ha. In California, rates of 100–135 kg/ha are typical. Nitrogen rates greater than 170 kg/ha typically will not increase yields and can cause excessive cracking at harvest and postharvest handling. Irrigation water should be tested for nitrogen content because that can potentially be a significant source of nitrogen.

Phosphorus and potassium should be applied according to soil tests (Table 8.2). Soils with neutral or alkaline soils with 30 ppm phosphorus by the bicarbonate extraction method will likely not respond to added phosphorus application. A value of 70 ppm phosphorus by the Bray extraction method for acid soils will also likely not benefit from added phosphorus. Fields testing with a value of greater than 200 ppm exchangeable potassium will also not likely respond to added potassium fertilizer.

Fig. 8.5. Central pivot irrigation system in a carrot field in France. (Photo by E. Geoffriau.)

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Table 8.2. Recommended phosphorus and potassium application rates for carrot according to soil phosphorus and potassium levels.

	Soil phosphorus level					Soil potassium level			
	Low	Med	High	Very high		Low	Med	High	Very high
P_2O_5 (kg/ha)	168	112	56	0	K_2O (kg/ha)	168	112	56	0

The full amount of phosphorus and potassium fertilizer requirements are typically applied during soil preparation phase. A small amount of the intended amount of nitrogen is also applied during the soil preparation process. The remaining amount of the nitrogen intended for the season is applied as a side dressing or though the irrigation water during the course of the season. If the nitrogen is applied by irrigation water, it is applied over several split applications during the course of the growing season and not all at once. Nitrogen is applied several times during the course of the season in small amounts to achieve slow, even growth. Rapid growth from excessive nitrogen can cause deformed and split roots.

Once the planted field reaches 100% emergence the crop can be irrigated to meet its water requirement. Water demand will increase as the crop grows and reaches maturity. Cultivation is often conducted at the five-leaf stage of growth at which point the irrigation is stopped to allow the field to dry enough so that cultivation equipment can be used. Many growers feel that drying the soil somewhat at this time also forces the roots to grow longer in search of water. It is debatable if that is actually the case and no studies have been done to confirm or refute this practice.

Carrots should be checked on a weekly basis to ensure they are growing properly and without any issues. Scouting the fields regularly will help prevent unexpected problems from arising. Nutritional disorders and plant diseases can be caught early and rectified before they become costly and difficult to resolve.

8.6 CARROT HARVEST

Carrot harvest is done after the carrot roots reach the intended size that the crop was grown for. Imperator carrot varieties grown for the fresh market reach maturity when they reach 20 to 24 cm in length and 3 to 4 cm in width at the shoulder. They often reach maturity after 120 days from planting. Imperator carrots grown for the cut-and-peel market are longer and more slender, at 22 to 28 cm in length and 2 to 3 cm in width at the shoulder. These varieties can be at maturity in 100 to 110 days after planting. Nantes carrots will be much shorter at 15 to 18 cm in length and 5 cm in width. Danvers carrot varieties used in processing will be short and blunt at 15 to 20 cm in length at maturity.

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Carrots grown commercially are normally harvested by machine (Fig. 8.6). Most carrots grown for fresh market or cut-and-peel are harvested in the same way. Carrot harvesters will lift the soil just below the carrot root to loosen the soil around the root. The roots are then lifted out of the soil by a series of rubber belts that clamp on to the carrot leaves. The carrots are lifted to the top of the harvester where the tops are removed from roots by a series of cutters. The roots then are sent to a bin or trailer being pulled alongside the harvester by way of a conveyer belt. The carrot tops are dropped back to the field. Carrot harvesters are manufactured by various manufacturers but are often custom-built by some of the larger carrot companies. The mechanical harvester can be self-propelled or be pulled along by a separate tractor.

Carrots grown for the processing market (e.g. Danvers, Flakkee) are often harvested with modified potato diggers. They use closer-spaced chains than normal potato harvesters to reduce the amount of roots that may fall through the chains. The tops are removed at the soil level or slightly below soil level with a flail mower. The roots are then undercut with a soil lifter at the front of the digger and lifted on to the chain conveyer belt. Once lifted the roots are dumped into a bin or trailer that is pulled alongside the harvester.

Bunched carrots are harvested by hand crews in the field. Normally an area the size that the hand crew can harvest in one day is lifted by a soil lifter. The roots are pulled by hand from the loosened soil with the tops intact. Six to

Fig. 8.6. Mechanical carrot harvest. (Photo by J. Nunez.)

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ten roots with the tops still attached that are of uniform size are tied together with a wire twisty. They are either placed in bins or on to a flatbed truck or trailer. The bunched carrots are then sent to a processing facility where the carrot bunches are washed and placed in waxed carton boxes. At this point it is important to remove the field heat by placing them in refrigeration. It is also critical to get the bunched carrots to the marketplace as quickly as possible. This is due to the fact that bunched carrots respire at a higher rate than carrots without leaves. They are more prone to drying and stress, both of which can cause the carrots to become bitter.

8.7 POSTHARVEST HANDLING

Fresh market carrots are taken to processing facilities where they are dumped into large tanks of water to remove field soil still on the roots. They are quickly moved by conveyer belts to a sorter that separates the roots into different sizes. Once sorted, the roots are hydrocooled to quickly remove any field heat. The carrots are bagged according to size of the carrot root. All jumbo carrots are bagged together while the medium sized carrots are bagged as cellos. Small or damaged carrots are culled during the sorting process and can be used as shredded, coins or crinkle-cut carrots. They may be also used for juicing.

Cut-and-peel carrots also go through the same process but are cut into 5 cm sections, go into a peeler drum and then a polishing drum. Once the carrots are cut, peeled and polished they will usually be sorted again so the finished product contains the same size carrot pieces.

Fresh market carrots are normally not stored for any period of time. Once they are harvested, the roots are processed in the packing facility within 24 h. This is especially true for cut-and-peel carrots. Once the finished product is bagged it is refrigerated and sent to market in a refrigerated container.

There are areas of carrot production where fresh market carrot roots are stored. In many parts of Europe, carrots may be field stored over the winter and not harvested until the following spring. In Canada the carrots may be harvested in early autumn, stored in cold storage facilities during the winter and then processed in packing facilities in the spring. Normally the carrot roots are stored without washing to reduce storage decay.

Processing carrots are often stored for several months until they are sent to a facility that uses them for dehydration, dicing or purée.

FURTHER READING

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9

INTEGRATED WEED MANAGEMENT IN CARROT

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INTRODUCTION

Weed management remains one of the greatest challenges in carrot production despite advances in integrated control strategies. In fact, Van Heemst (1985) reported that carrot was the most sensitive to weed interference of the 26 crops included in a global literature review. This sensitivity is largely related to inherent crop growth characteristics that include slow and variable crop emergence, relatively poor seedling vigour and slow early-season canopy development. Adequate weed management without compromising carrot root yield or quality requires an integration of preventative, cultural and direct strategies (Peruzzi *et al.*, 2007). Recent developments in robotic weeders utilizing artificial intelligence, biostimulants and competitive varieties that favour carrot growth over weeds, and utilization of organic mulches in strip tillage systems may improve carrot weed control.

9.1 WEED INTERFERENCE IN CARROT

Weed interference in carrot reduces root yield, decreases quality by stimulating misshapen root development and hinders mechanical harvest. Weed species spectrum varies by production region, but most often includes common annual broadleaf and grass species that emerge after pre-plant tillage (Fig. 9.1). Marketable carrot root yield loss from season-long weed competition is often greater than 90% (Bellinder *et al.*, 1997; Coelho *et al.*, 2009; Freitas *et al.*, 2009).

Established perennial weeds can be particularly problematic in carrot production as they are challenging to manage with available methods such as cultivation, often have extensive root systems that disrupt carrot root growth and easily out-compete weak carrot seedlings. For example, William and Warren (1975) documented purple nutsedge (*Cyperus rotundus*) density of 1600

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Fig. 9.1. Weeds left unmanaged dominate carrot production, effectively eliminating root yield. (Photo by J. Colquhoun).

plants/m^2 in Brazilian carrot production. Additionally, parasitic weeds such as dodder (*Cuscuta* spp.), Egyptian broomrape (*Phelipanche aegyptiaca*) and crenate broomrape (*Orobanche crenata*) attach to and draw water and nutrients from carrot plants. Depending on the density and timing of parasitic infection, damage from parasitism can range from aesthetic blemishes, where the broomrape weeds in particular physically attach to the carrot root, to reduced root sugar content and total yield loss (Konieczka *et al*., 2009; Cochavi *et al*., 2015).

Carrot is often grown in rotation with other specialty crops and as such is subject to unique volunteer crops that act as weeds when growing in the carrot season, such as potato (*Solanum tuberosum*) from tubers that persist in soil. These crops are often more competitive for water, nutrients and light than carrot, and as such can cause crop loss even at very low population densities. For example, Williams and Boydston (2006) reported that carrot root yield was reduced by 5% when volunteer potato was left season-long at a low density of 0.06 plants/m^2. Two potato plants per square metre reduced carrot yield by 5% when growing for the first 430 growing-degree-days (GDD; calculated beginning at 50% carrot emergence and with a base temperature of 7.2°C).

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9.2 NON-CHEMICAL WEED MANAGEMENT

9.2.1 Crop rotations and systems to favour carrot over weeds

Carrot weed management can be improved by adequately managing weeds in rotational crops and utilizing a cropping system that favours carrot over weeds. In particular, perennial weeds such as nutsedge (*Cyperus* spp.) should be eradicated prior to carrot seeding. The carrot production system and seeding configuration are also important in determining weed competitiveness. For example, drip irrigation allows water and nutrients to be placed nearby carrot plants for optimal use while depleting inter-row weeds of these resources. The carrot row configuration itself can influence weed growth, where early crop canopy formation is enhanced when seeding rows are narrower, thus reducing light available to young weeds (Fig. 9.2).

9.2.2 Planting timing to favour rapid early-season carrot growth and competitiveness

Carrot crops that are seeded into warmer soil and during warmer weather conditions typically emerge and grow faster than early carrot seeded in colder conditions. In cool conditions, carrot emergence occurs 2 to 3 weeks after

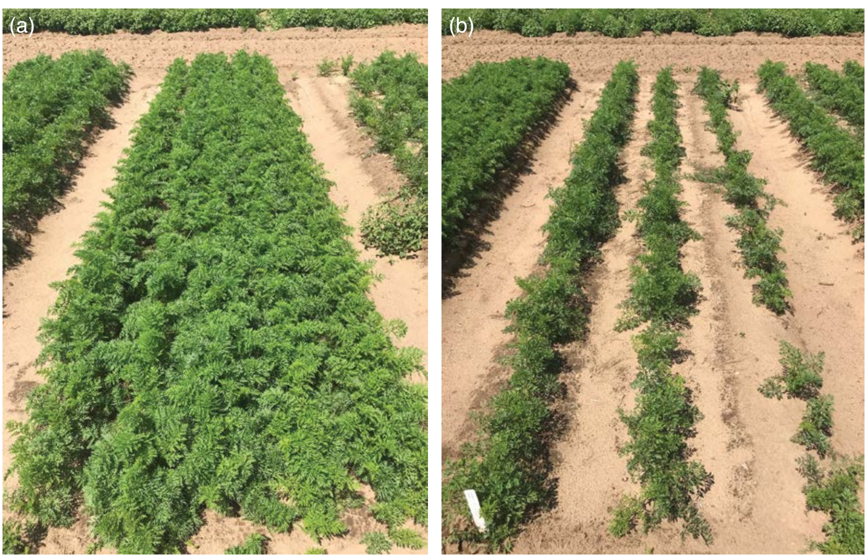

Fig. 9.2. Carrot competitiveness with weeds is enhanced in a narrow-row system with five seeding rows per bed (a) compared with a traditional three-row system (b). (Photos by J. Colquhoun).

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seeding and carrot plants take 35 to 45 days to reach the five-leaf growth stage (Bellinder *et al.*, 1997). Swanton *et al.* (2010) investigated the carrot critical weed-free period, or the period of time where the crop is required to be weed-free to minimize yield reduction, at two seeding dates. The critical weed-free period was 414 to 444 GDD (accumulated from seeding date and with a 5°C base temperature) when carrot was seeded in mid- to late May. The critical weed-free period was extended to 930 GDD when carrot was seeded in late April. This weed-free period is somewhat dependent on planting configuration as noted by Freitas *et al.* (2009). They compared 15 and 20 cm inter-row spacing and reported that the narrower rows decreased the critical weed-free period by 7 days.

9.2.3 False sowing

Delayed seeding also allows use of the false sowing or stale seedbed technique, where the soil is tilled to a finished seedbed and allowed to rest fallow for 1 to 3 weeks while weeds germinate and emerge. Young weeds are then destroyed with shallow tillage, flame burning or a non-residual, non-selective herbicide. While the strategy effectively eliminates the first flush of weeds that will compete with carrot, dormant weed seed is not affected and perennial weed vegetative tissue can be spread by tillage.

9.2.4 Competitive carrot varieties to suppress or tolerate weed infestations

A competitive difference between carrot varieties was reported in Brazilian carrots infested with high populations of purple nutsedge. Carrot root yield reduction was 39% where Kuroda variety was grown and 50% where Nantes was grown (William and Warren, 1975). With such observations in mind, Colquhoun *et al.* (2017) compared the ability to tolerate and suppress weeds among nine carrot varieties. They reported that emergence rate varied greatly among varieties and affected canopy development and subsequently weed interference.

9.2.5 Mechanical or physical weed management

Cultivation is a mainstay of many carrot integrated weed management programmes. The focus has been on tools and strategies that mechanically remove or destroy weeds growing as close to the carrot row as possible, without crop damage, to limit weed competition and hand-weeding needs, but this selectivity is challenging. In a laboratory study, Benjamin and Wren (1978) demonstrated

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that cutting the taproot of 2-week-old carrot plants stimulated lateral root thickening near the cut end, resulting in bifurcated or 'forked' carrots that are often not marketable depending on end use. Ascard and Mattsson (1991, 1994) noted misshapen carrot roots where cultivation was used close to the crop row, likely as a result of this damage.

Numerous cultivator types have been evaluated in carrot production, with some tools developed specifically to meet crop needs. Peruzzi *et al.* (2007) compared a conventional cultivator on a bed with five banded carrot rows to a precision cultivator used on a bed with ten single carrot rows. Both systems were also flame-weeded and hand-weeded. Labour savings were noted where the precision cultivator was used in the ten-row system, but hand weeding was still needed. The authors concluded that a programme that integrates the stale seedbed technique, flame weeding, precision cultivation, hand weeding and competitive seeding configuration was needed for effective control and acceptable crop yield and economic margins.

The brush hoe cultivator was not developed specifically for carrot production but has been a focus of much research and grower interest. Ascard and Mattsson (1994) compared a conventional cultivator to the brush hoe and two untilled strip widths over the crop row (10 or 5–6 cm). They reported no yield differences in any cultivator or row width configuration, but cultivation increased prime carrot yield in two of three years compared with non-cultivated carrot. However, they also reported that cultivation resulted in a higher proportion of branched carrots in two study years.

9.2.6 Thermal weed management

Flame weeding has been used in organic carrot production in particular. Propane-powered burners are directed towards newly emerged weeds at a rate that damages cell wall integrity, noted by a water-soaked appearance. Carrot plants can be rather severely damaged; hence the practical application has focused on pre-emergent flame weeding during the long period between carrot seeding and emergence when the first flush of weeds is often observed (Turner *et al.*, 2000; Anyszka and Golian, 2017). Flame weeding is not a stand-alone weed management strategy but can be effective when combined with mechanical methods supplemented with hand weeding. Anyszka and Golian (2017) observed more weeds and less carrot yield when flame weeding was used alone compared to hand weeding and mechanical methods.

9.2.7 Reduced tillage, cover crops and mulch

Reduced soil tillage systems utilized in other cropping systems recognize several benefits, including reduced weed seed germination and increased weed

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seed predation. These benefits are further emphasized and expanded when reduced tillage is combined with cover crops that serve as an in-season mulch and a windbreak against blowing soil that damages sensitive carrot seedlings. Cover crops are seeded in the autumn prior to the carrot season and often winter-killed in colder climates or with a herbicide or mowing prior to carrot seeding. However, reduced tillage can be challenging systems in which to grow root crops sensitive to soil structure and compaction, often shift the weed species spectrum towards wind-blown perennials such as common dandelion (*Taraxacum officinale*) and largely eliminate the potential to use cultivation as a weed management strategy.

Brainard and Noyes (2012) compared carrot production with conventional tillage to a strip tillage system with and without compost additions in three processing carrot varieties. Barley (*Hordeum vulgare*) that was established prior to carrot seeding was left as a windbreak in the strip tillage system. Annual weed control, carrot root yield and grower net return were similar or greater in the strip tillage system compared to conventional tillage. The addition of compost yielded less clear results.

Similarly, Borowy (2004) compared a system where rye (*Secale cereale*) was grown in the autumn prior to the carrot crop, killed in the spring with glyphosate herbicide and carrot seeded without tillage ('no-till') to a conventional tillage system without a cover crop. The author noted the challenges around seeding carrot into 80% rye residue cover and hard, non-tilled soil, but the rye mulch reduced the weed species number by 96 to 100%. However, a shift towards the perennial common dandelion was observed, where this single species made up 30% of the weed population in the non-tillage system by carrot harvest. Carrot yield did not differ between production systems, but the study appears to have been conducted only in a single growing season. Additionally, the work was conducted on a low-organic-matter (1.6%) loess soil that remains loose and more conducive to carrot root growth than a heavier soil.

In subsequent work, Borowy *et al.* (2015) investigated autumn seeded white mustard (*Sinapis alba*) that was killed by low winter temperatures and provided residue cover during the early portion of the carrot season in particular. The authors relied on significant amounts of hand weeding for the remainder of weed control and suggested the system would benefit from integration with herbicides for season-long weed control. Carrot emergence was greater where white mustard was grown but carrot plant growth was slower for the remainder of the season. As a result, total root yield and roots greater than 20 mm were reduced compared with where conventional tillage was used without cover crops. With somewhat similar crop yield results, Gruszecki *et al.* (2015) reported that living mulches grown between carrot rows reduced root yield and increased the number of small diameter (<20 mm) and forked carrots compared with where linuron herbicide was applied without cover crops. Chopped and dried mulch of legume cover crops may show more promise. Santos *et al.* (2011) found that pigeon pea (*Cajanus cajan*) and gliricidia

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(*Gliricidia sepium*) mulch increased carrot root yield and diameter, and weed populations were 300% less compared with non-mulched carrot.

With these observations in mind, further research is warranted on systems that integrate the benefits of strip tillage with herbicides banded over the carrot row for in-row weed control and cover crop mulch for between-row weed control. Main *et al.* (2013) reported that linuron herbicide could be banded over the crop row and combined with between-row cultivation to reduce herbicide use by 66% compared with broadcast application, without compromising weed control or carrot root yield. The potential to integrate such herbicide banding with cover crops and reduced tillage has not been reported in the literature.

9.2.8 Hand weeding

In many production systems and particularly those where synthetic herbicides are not broadcast to eliminate in-row weeds, hand weeding to some extent is inevitable to prevent significant carrot yield reduction. However, as Bishop (2002) noted, hand weeding is often too costly and time consuming. Labour availability has also become a constraint in many global production regions. Melander *et al.* (2005) reported that even production systems that integrate multiple weed management strategies still require 100 to 400 h of hand weeding per hectare.

9.3 HERBICIDES FOR WEED MANAGEMENT

9.3.1 Linuron

Linuron has been the mainstay of carrot herbicides for many years. Many studies have demonstrated the broad utility of linuron in carrot crops. For example, carrot yield in weedy plots without herbicide was often 15% or less than where linuron was applied (Henne and Guest, 1973; Henne and Poulson, 1980). Bell *et al.* (2000) also reported carrot yield about six times greater where linuron was applied pre-emergent, post-emergent or at both timings compared with weedy carrot. In two study years, net profit where linuron was applied ranged from US$980 to US$6426 per hectare compared with US$740 to US$2852 per hectare where the carrot crop was hand-weeded.

Linuron is applied pre-emergent and post-emergent in carrot and controls several annual grass and broadleaf weeds, including some species when newly emerged. Linuron use is restricted on coarse-textured, low-organic-matter soils to mitigate crop injury and groundwater contamination risk and as such the herbicide has now been banned in some production regions. Linuron is a urea herbicide that inhibits photosystem II in susceptible plants. Limited populations of several weed species common in carrot, such as redroot

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pigweed (*Amaranthus retroflexus*) and common lambsquarters (*Chenopodium album*), have been identified with linuron resistance (Heap, 2018).

9.3.2 Metribuzin

Geminiani *et al.* (2008) found metribuzin to be a useful alternative to post-emergent linuron, except in fields where solanaceous weeds were prevalent. Metribuzin is applied post-emergent in carrot, most typically at crop growth stages beyond when linuron is applied, to extend soil residual weed control and mitigate risk of injury to young carrot plants. The herbicide can be readily leached in sandy soils with low organic matter content. Metribuzin is a triazinone family herbicide that inhibits photosystem II in susceptible plants, resulting in both pre-emergent and early post-emergent weed control. Resistance to metribuzin is somewhat common among weed species such as common lambsquarters and redroot pigweed.

9.3.3 *S*-Metolachlor

S-Metolachlor controls primarily annual grass weeds and some annual broadleaves when applied pre-emergent in carrot. Carrot injury is sometimes observed when cool, wet weather occurs around the time of or soon after herbicide application. This herbicide is a member of the chloroacetamide family that inhibits very-long-chain fatty acid synthesis. Minimal weed resistance development has been observed.

9.3.4 Pendimethalin

Konieczka *et al.* (2009) found pendimethalin to be the only effective herbicide for swamp dodder (*Cuscuta gronovii*) management, noting greater than 80% control 56 days after carrot planting. Like *S*-metolachlor, pendimethalin controls several annual grasses and some annual broadleaves in a pre-emergent application. Pendimethalin is a microtubule inhibitor herbicide. Despite over four decades of use, resistant weeds are not widespread.

9.3.5 Prometryn

Prometryn herbicide is applied both pre- and post-emergent in carrot in a similar use pattern to linuron and controls several annual broadleaf weeds and selected grasses. Prometryn also inhibits photosystem II in susceptible plants. Carrot injury can be observed at higher use rates and when applied at early

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carrot growth stages. Resistant weeds have been sporadically reported among weeds common in carrot, such as *Amaranthus* spp. and common lambsquarters (Heap, 2018).

9.3.6 Trifluralin

Trifluralin controls many annual grasses and certain broadleaf weeds. The herbicide is applied prior to carrot planting and incorporated in the soil with tillage or water to reduce volatilization risk and compromised weed control. Trifluralin is a dinitroaniline herbicide that inhibits microtubule assembly. Resistant weeds, particularly grasses, have been occasionally reported but are not widespread. Trifluralin is ineffective on high-organic-matter soils where carrot is grown in some production regions.

9.3.7 Graminicides

Sethoxydim and clethodim herbicides control only emerged grass weeds that are actively growing, particularly when applied prior to tillering. The herbicides belong to the cyclohexanedione herbicide family that inhibits the acetyl CoA carboxylase enzyme. Resistance to the post-emergent graminicides is rather common and has been reported in 48 weed species globally (Heap, 2018).

9.3.8 Natural herbicides and biological control

Biological weed control attempts specific to carrot pests have been primarily limited to *Alternaria* spp. to control dodder (*Cuscuta* spp.). Bewick *et al.* (1986) reported 92% swamp dodder control, but the *Alternaria* spp. growth was limited by pesticides commonly used in carrot such as linuron herbicide and chlorothalonil fungicide. Subsequent research pointed towards instability in the biological control agent and the strategy never reached commercial application (J. Colquhoun, 2008, unpublished results). Clove oil and citrus oil have shown some promise as natural herbicides. For organic carrot production, Main *et al.* (2013) found these oils to provide marginally better weed control than acetic acid and flaming.

9.4 FUTURE CHALLENGES IN CARROT WEED MANAGEMENT

Weed management in conventional carrot production is particularly at risk because of herbicide-resistant weed development and pesticide regulations.

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The over-reliance on a few herbicide active ingredients for the majority of weed management has resulted in widespread weed resistance as noted above. Additionally, global regulatory pressures around pesticide use in general will impact carrot production. For example, the herbicide linuron was recently prohibited in Europe and is currently in the registration re-evaluation process in the USA. Environmental concerns will likely increase this regulatory pressure and could be particularly challenging for common carrot herbicides such as *S*-metolachlor and metribuzin that have been detected in groundwater.

9.5 CURRENT AND FUTURE AREAS OF CARROT WEED MANAGEMENT RESEARCH

Resistant weeds and global pressure to reduce pesticide use have stimulated renewed interest in the study of non-chemical weed management strategies that can be integrated into holistic, season-long programmes. In related small-seeded crops, such as leafy greens, studies are underway to investigate the combination of robotic technology, remote sensing and artificial intelligence as a potential replacement for human labour and hand weeding. Grower adoption of such a system is dependent on consistent selectivity, or the ability for the equipment to remove or destroy weeds growing among the carrot plants without significant crop injury. Additionally, researchers are investigating the ability to use natural biostimulants to favour carrot growth over weeds, such as gibberellic acid application to stimulate competitive carrot top growth and early canopy closure.

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10

Carrot Disease Management

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While chemical control is increasingly questioned because of its putative impact on environment and human health, the implementation of alternative solutions for crop disease management is imperative and the carrot does not escape this rule. In this chapter, we offer a quick overview of the main control methods used or which could be considered for carrots.

While the causal agents of carrot foliar diseases are numerous, few of them are responsible for important economic losses. Among them, *Alternaria dauci* is the most destructive one responsible for leaf blight. Similar symptoms may also be due to the bacterium *Xanthomonas hortorum* pv. *carotae* and the fungus *Cercospora carotae*. Among the major root diseases, cavity spot due to *Pythium* spp. is present all over the world. Sclerotinia soft rot and brown ring rot occur not only in the field but also during storage, and *Rhizoctonia solani*, responsible for crown or canker rot, may cause damage on carrot plants in various stages of growth from seedlings to mature roots (Sumner *et al.*, 2003). Black rot of carrot, caused by *Alternaria radicina*, is also a very important disease characterized by black necrotic lesions on taproots (Pryor *et al.*, 1998). For all these diseases, symptoms are recorded in Table 10.1 and extensive descriptions have been published by Davis (2004) and Villeneuve (2014).

10.1 DISEASE FORECAST MODELS

In order to reduce pesticide applications, the development and use of disease forecasting models have become widespread. This is particularly true for timing fungicide sprays to control fungal leaf blight diseases of carrot. Most of the models in carrot were developed to manage Cercospora blight (Carisse *et al.*, 1993) or Alternaria leaf blight but probably the most used

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Table 10.1. Major fungal and bacterial diseases on carrot crops. (Photos for images a, b, f, g, h by M. Briard; c by E. Dupas; d by V. le Clerc; e by A. Laffray; i by C. Beasse; and j, k, l, m by F. Villeneuve.)

Common and scientific name	Symptoms	Picture
Major foliage and stem diseases		
Alternaria leaf blight *Alternaria dauci*	Small greenish-brown lesions enlarging, leading to dark brown to black leaf or petioles, sometimes surrounded by a chlorotic halo. Cause foliage death when severe; umbel blight and damping-off. Possible symptoms on stem and umbels	
Cercospora leaf blight *Cercospora carotae*	Symptoms on aerial parts similar to *A. dauci* and *Xanthomonas* leaf blight. Leaf death when severe	
Bacterial leaf blight *Xanthomonas hortorum* pv. *carotae*	Gummy exudate on stems and petioles leading to necrotic lesions, dark brown to black with water-soaked edges and chlorotic halos. Similar to *A. dauci* and *Cercospora* leaf blight. Possible symptoms on roots and umbels	

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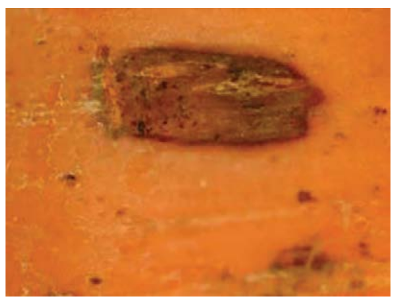
Common and scientific name	Symptoms	Picture
Powdery mildew *Erysiphe* spp., *Leveillula* spp.	*Erysiphe* spp.: powdery white rounded spots initially covering the entire leaflet. *Leveillula* spp.: yellowish spots on the upper side of the leaves and white felting on the underside	
Major root diseases		
Black crown or black rot *Alternaria radicina, Stemphylium radicinum*	Black decay of the petiole base and upper portion of the storage root. Black sunken lesions on the taproot. Symptoms of damping-off, foliar blight, and umbel blight similar to Alternaria leaf blight	
Cavity spot *Pythium violae, P. sulcatum, P. sylvaticum, P. ultimum, P. irregulare, P. intermedium, P. aphanidermatum*	Small, 1 to 10 mm in length, sunken, elliptical lesions orientated across the breadth of the root. Root cracking	
Sclerotinia soft rot *Sclerotinia sclerotiorum, S. minor, S. subarctica, Sclerotium rolfsii*	Translucent spots at crown bases. Root tissues becoming mouldy and covered with white silky mycelium evolving into white then black very resistant sclerotia	

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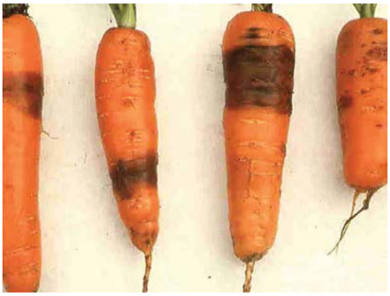
Table 10.1. Continued.

Common and scientific name	Symptoms	Picture
Brown ring rot *Phytophthora megasperma*	Ring watersoaked translucent bands across the root. Rapid extension to a black soft rot of root tissues, finally leading to the entire root decomposition	
Crown or canker rot *Rhizoctonia solani*	Damping off from cotyledon to the 3 true leaves stage. Bottle-shaped collar with a generally corky appearance. Band of dark brown necrosis, canker-like lesions around the root. Small pits enlarging into sunken brown crater lines with a white, flocculent mycelium	
Violet root rot *Rhizoctonia violacea* or *R. crocorum*, *Rhizoctonia* spp.	Superficial purplish rot evolving into reddish brown spots. Rusty root. Final complete rotting of the root. Pseudo sclerotia	

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Common and scientific name	Symptoms	Picture
Fusarium dry rot *Fusarium solani, F. avenaceum, F. culmorum, F. caeruleum*	More or less rounded, 3–4 cm sized black spots wherever on root surface. Evolution into soft rot or brown canker lesions. Black spot on crown bases	
Scab rot *Streptomyces scabies*	Corky, scablike lesions	
Bacterial soft rot *Erwinia carotovora* pv. *carotovora* or *Pectobacterium carotovorum* subsp. *carotovorum*	Soft, watery, and slimy decay of the taproot. Liquefied root core and epidermis/peel intact. Rotted tissues retain their natural colour until they completely decay.	

and well-documented is the TOM-CAST model used to manage both. Initially developed in 1988 to reduce early blight and Septoria leaf spot on tomato, it was adapted for carrot and makes it possible to replace systematic treatments by reasoned applications, based on the calculation of a daily disease severity value (DSV), using information on the duration of leaf wetness and temperatures during the wetness period (Pitblado, 1992). Treatments are then triggered when the cumulative daily DSV reaches a certain threshold and the DSV total is reset to zero. Comparing three disease-forecasting systems for timing sprays to control foliar blight on carrot, only TOM-CAST 15-DSV

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consistently provided disease control similar to weekly fungicide application and required five to seven fewer applications, resulting in fungicide savings (Bounds *et al.*, 2006).

Whatever the forecasting model, an important question to address is to optimize the timing of the first treatment to further limit fungicidal applications (Kushalappa, 1990; Abraham *et al.*, 1995; Bounds *et al.*, 2007). Treatments can be applied preventively before the onset of symptoms, considering a threshold of 5%, when a trace amount of foliar blighting is visible or when DSV index is between 40 and 55 points, the latter being more efficient.

While the older models relied on recorded weather data, new models should be more predictive. Initially developed for management of *Phytophthora infestans* on potato, the Plant-Plus system® developed by Dacom was extended to several diseases and pests on different crops (Ciancio and Mukerji, 2008). Relying on on-farm weather data and 4-day weather forecasts, the model gives the probable evolution of the risk for the coming days. It also includes adjustment variables (varietal sensitivity, field observations, loss of treatment efficiency over time, etc.) that modulate the risk calculation and recommends which type of chemical to use (S. Plas, Ychoux, 2018, personal communication).

Very little literature is available on disease-forecasting models to control soil-borne pathogens or pathogens occurring on both foliage and root. Two models have been developed by Foster *et al.* (2011) to control *Sclerotinia sclerotiorum* affecting both foliage and roots in carrot by predicting the occurrence of apothecia and ascospores, the start of epidemics. Relying on soil moisture, and occasionally soil temperature, architectural and phenological stages of carrot development such as the complete closure of the canopy, and the percentage of plants with one to two collapsed senescing leaves, over the course of two years, the forecasting model decreased the number of fungicide applications by up to 80%. Parker *et al.* (2014) showed that the number and location of ascospore sampling sites have to be adapted to cropping and environmental conditions. Preliminary work has been done on carrot cavity spot to understand the processes that induce the spatio-temporal kinetics of epidemics (Suffert, 2007; Suffert and Monfort, 2007) but up to now no predictive model is available to manage fungicide spray programmes.

10.2 BIOCONTROL

A wide variety of biological control agents (BCA) are emerging as safe and eco-friendly alternatives to chemical products to control plant pathogens while for some of them stimulating plant growth and improving soil structure at the same time. Plant resistance may be induced by treatment with different agents such as virulent or avirulent pathogens, cell wall fragments, synthetic chemicals

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and plant extracts, reducing incidence and severity of disease caused by many pathogens (Kuć, 2001).

Among them, *Bacillus subtilis* is currently commercialized to control multiple diseases and nematodes. Liquid formulation of *B. subtilis* IIHR BS-2 (5 l/ha) was tested under field conditions as seed treatment and soil application after enrichment in vermicompost (2 tons/ha). It resulted in an increase in carrot yield (28.8%) and decreases in nematode population of *Meloidogyne incognita* (69.3%) and disease incidence (70.2%) due to the soft rot bacterium *Pectobacterium carotovorum* subsp. *carotovorum*, one serious bacterial disease favoured by the nematode infection (Rao *et al.*, 2017).

Jayaraj *et al.* (2008, 2009) observed reduction in disease development due to *A. radicina* and *Botrytis cinerea* on carrot leaves following elicitor treatment with seaweed (*Ascophyllum nodosum*) extract, chitosan and Alexin. Natural algal extracts, among them commercial seaweed extract widely used in Australian agriculture, are applicable in controlling plant-infecting fungi with relatively negligible impact on the environment (Arioli *et al.*, 2015; Hamed *et al.*, 2018). Kolaei *et al.* (2013) reported a strong inhibition of *Pythium sulcatum* when spraying inoculated carrot roots with aluminium-containing salts (e.g. aluminium sulfate at 5 mM completely inhibited the development of cavity spot). To these authors' point of view, it is possible that the observed effects will include an elicited biochemical defence mechanism, this indicating that these salts may provide an alternative to the use of synthetic fungicides to control cavity spot.

El-Tarabily *et al.* (1997) first reported the use under controlled conditions of seven actinomycetes to control *Pythium coloratum*, a causal agent of carrot cavity spot. Some strains were capable of parasitizing *P. coloratum* oospores in addition to producing antifungal metabolites.

For all these products, timing of application is a key factor. El-Tarabily *et al.* (1997) noticed that *P. coloratum* could attack carrots at any stage of development after 3 weeks, suggesting that the antagonists may need to be established in the soil prior to pathogen infection.

McQuilken and Chalton (2009) demonstrated that foliar sprays of Contans® WG (a granular formulation containing conidia of *Coniothyrium minitans*) were able to reduce viability of *S. sclerotiorum* produced on diseased foliage however they failed to reduce disease severity perhaps due to a late application immediately after the appearance of the disease symptoms. Cheah *et al.* (1997) reported a putative utility of chitosan root coating as a postharvest treatment for the control of Sclerotinia rot during storage of carrots. Wang *et al.* (2015) confirmed that chitosan directly inhibited the growth of *S. sclerotiorum* and potentially induced a defence reaction in carrot.

While BCA have been applied successfully against soil-borne or foliar pathogens, consistent and reproducible results with single BCA are difficult to obtain as diverse microbial communities in diverse field conditions may affect them. Mixed cultures of compatible microorganisms may be more effective such as the widely used Effective Microorganism (EM) biofertilizer, a mixture

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of beneficial microorganisms including up to 80 different species of bacteria, yeasts and fungi. Several EM products are commercially available and widely used (Shin *et al.*, 2017). Carrot damping-off by *R. solani* was reduced by bokashi (an anaerobic fermentation product) + EM compared with bokashi alone. Observed suppression of *R. solani* was probably caused by specific microorganisms that survived in the soil amended with bokashi + EM. However, the authors suggested that field experiments on the application methods and rates are needed for a variety of soils and crops before EM application can be recommended for plant disease control due to conflicting results on different species. Here again, they suggest that to be efficient, EM amendment should take place several weeks before exposure of the plants to the pathogen (Shin *et al.*, 2017).

Combined mechanisms of action are expected when BCA are used together, conferring higher levels of protection, as observed by Nesha and Siddiqui (2017) when the two fungi *Paecilomyces lilacinus* and *Aspergillus niger* were combined to reduce soft rot disease complex and bacterial leaf blight incidence in glasshouse experiments. In field trials in Australia, sulfur, applied at 0.6 kg/ha, was the most effective product in controlling powdery mildew on carrot foliage when applied in a mixture with either botanical oil or paraffinic oil, being significantly more effective in reducing leaf blight due to *C. carotae* than when each product was applied alone (Watson *et al.*, 2017). Weiland (2014) stressed the importance of using multiple, representative pathogen isolates in preliminary biocontrol agent inhibition assays and highlighted that *Pythium* species and isolate diversity influence inhibition by *Streptomyces lydicus*.

However, resistance induced is broad spectrum but rarely provides complete protection, and information is required on the interaction between the use of resistance elicitors and other crop management practices as highlighted by Walters *et al.* (2005).

10.3 AGRO-TECHNICAL MEASURES

Suffert *et al.* (2008) showed that a reduction in mean planting density and a deficit of soil moisture were effective in limiting carrot cavity spot development. While increasing the mean root-to-root distance at a constant mean linear density is feasible, thus decreasing the potential for alloinfections, soil moisture is more difficult to control because of natural rainfall. Growers can only reduce soil moisture by methods such as drainage, soil ridging or raised beds. Reducing the incidence and severity of aerial and soil-borne diseases is feasible by means of rotation if the break period is longer than the survival time of the pathogen. Working on *P. sulcatum*, Davison and McKay (2003) emphasized the necessity to know the host range of the pathogen and the length of time it will persist in soil. They observed a significant reduction in the incidence of seedling infection by *Pythium* spp., including *P. sulcatum*, when carrots followed one, two or three broccoli crops. Davis and Nunez (1999) observed

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that populations of *Pythium* spp. were generally greater following lucerne and barley than other crops, while populations of *R. solani* were greater following lucerne and cotton. The management of the inter-crop period using biofumigation is experiencing increasing interest for its potential use in integrated pest management. Montfort *et al.* (2010) demonstrated that biofumigation with *Brassica juncea* during the inter-crop period led to an important reduction in soil infectivity over time, as well as reducing the incidence of crown rot disease at the end of the succession. Collier *et al.* (2017) showed that application of biofumigants containing isothiocyanates may also significantly reduce germination of sclerotia in soil of carrot crops. The best treatment was *Raphanus sativus* 'Terranova', where final percentage germination of sclerotia was 23% compared with 74% in the untreated control. Germination under three *B. juncea* treatments ranged between 37 and 43%, while use of *Sinapis alba* 'Brisant' resulted in 42% of sclerotia germinating. Authors reported that these effects were due to a direct effect of the isothiocyanates on *S. sclerotiorum* sclerotia and that these compounds also inhibit mycelial growth.

Optimized management of nitrogen fertilization can also be effective in controlling diseases. Indeed, several studies mentioned by Westerveld *et al.* (2008) showed an interaction between nitrogen fertilization practices and the severity of Alternaria leaf blight, which decreased when nitrogen applications increased, except for proven excess. Underlying assumptions are that nitrogen applications would delay leaf senescence and consequently decrease infections, with *A. dauci* firstly infecting older and senescent leaves. Nitrogen could also increase the production of new leaves, thus reducing the effects of the disease.

Saude *et al.* (2014) showed that the severity of Alternaria leaf blight and Cercospora leaf spot decreased with increasing nitrogen. High nitrogen application and no fungicide treatment gave equivalent yields, in some cases, to carrots treated with no nitrogen and five fungicide sprays.

Other control methods such as physical methods have been tested. Among them, foliage trimming allows changes in the microclimate of the canopy by improving the passage of air and reducing the moisture of the foliage, thus providing an environment not conducive to infection and the development of disease. It would improve the effectiveness of fungicides by promoting their penetration into the canopy, which would allow producers to reduce costs by reducing inputs. While McDonald *et al.* (2008) tested this practice successfully to stop the attack of *S. sclerotiorum* on carrots, it was ineffective to control the severity of foliar leaf blight due to *A. dauci* and *C. carotae* and no significant effect was obtained on total or marketable yield. Canopy clipping by cutting off overlapping leaves above the furrow and senescing foliage on the soil surface was able to reduce the quantity of *S. sclerotiorum* apothecia in carrot crops (Kora *et al.*, 2005). McIsaac *et al.* (2013) identified significant cultivar × trimming interactions. However, they reported the use of this method as becoming standard practice for carrot producers in North America.

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Abiotic factors such as ultraviolet-B radiation and wounding are known to cause the accumulation of phenolic compounds involved in plant defence. In field trials, although most of the ultraviolet and blow-drying treatments tested by Pickle (2009) reduced foliar burns, the use of fungicides was necessary to control the disease. The timing of treatment applications seems to be the most important factor for successful treatment.

10.4 TREATED SEEDS

The use of treated seed represents another alternative to pesticide treatments, providing early-season crop protection against a broad spectrum of seed and seedling diseases.

Seed treatments using conventional or biological products are available to protect the crop from pathogens such as *Pythium*, *Rhizoctonia*, *Fusarium* and other root-decaying fungi. However, new treatments with biopesticides or physical treatments are increasingly required (Mancini and Romanazzi, 2014). Available seed treatments of carrot are mainly directed against the two main seed-transmissible fungal pathogens, *A. dauci* and *A. radicina*. Among the physical methods, hot-water and hot-air treatments were as effective as chemical treatments to reduce or eradicate these pathogens while electron treatment was slightly less efficient (Koch *et al.*, 2010). Treatments with essential oils such as thyme oil, antimicrobial substances, BCA such as *Pseudomonas* or *Trichoderma*, or the combination between them, to name just a few, have proved their efficiency during *in vitro* tests or experimental field trials (Bennett *et al.*, 2009; Szopińska *et al.*, 2010). Results in production conditions may be less efficient depending on many environmental factors. However, it is certain that these alternatives will develop in the future.

10.5 VARIETAL RESISTANCE

While total resistance can fully control pathogen development, partial resistance will reduce symptom intensity by limiting the pathogen development. For foliar diseases, some major genes or genomic regions (quantitative trait loci) have been identified as being involved in carrot resistance against *C. carotae*, powdery mildew, *A. dauci* and *A. radicina*. Most of the research work has been done on carrot resistance to *A. dauci* (Pawelec *et al.*, 2006; Le Clerc *et al.*, 2015; Koutouan *et al.*, 2018) and partially resistant varieties are available for producers. While resistance to *C. carotae* and *X. hortorum* pv. *carotae* have been identified, commercial varieties are not available. On the contrary, partial resistance to powdery mildew conferred by a dominant gene identified in *Daucus carota* subsp. *dentatus* has led to the development of commercial varieties. For

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the root diseases, major work has been done on *Pythium*, leading to carrot varieties classification into subgroups from very susceptible to partially resistant (Guérin *et al.*, 1998; Cooper *et al.*, 2004). Due to the lack of a reliable biotest for carrot high-throughput screening and the huge diversity of *Pythium* species, varieties with a high level of resistance are difficult to obtain.

10.6 CONCLUSION

Integrated disease management relies on a combination of cultural methods from optimal fungicide application piloted by disease forecast models to the sowing of healthy seeds of varieties with increased resistance to pathogens, biological control agents and the use of agro-technical measures. In-depth knowledge about the targeted pathogen is also a key tool for efficient disease management. For example, as epidemiology and susceptibility to fungicides vary among *Pythium* species able to cause cavity spot (Hiltunen and White, 2002; Allain-Boulé *et al.*, 2004; Lu *et al.*, 2012), identification of the pathogen is required for better disease control. Several diagnostic PCR tools have been developed (Hiltunen and White, 2002; Klemsdal *et al.*, 2008); they should help reduce cavity spot incidence by avoiding highly contaminated soils and identifying causal species. As emphasized by Ben-Noon *et al.* (2003), a single control measure does not provide an acceptable level of disease suppression; for example, control efficacy of Alternaria leaf blight of carrots was optimized by combining chemical control and host resistance and to a lesser extent chemical and cultural measures such as drip irrigation. They also concluded that additive effects are the rule and antagonistic effects are the exception.

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11

Management of Carrot Pests

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Carrots are produced mainly in temperate climates but on several continents and obviously geographical location and climate have a considerable influence on the pest complex. China is the largest producer of carrots but unfortunately there is relatively little information available on pests and their control. Pest damage can be direct, affecting yield and/or quality, and some species also transmit plant pathogens. A number of important pests are listed in Table 11.1. This is unlikely to be an exhaustive list since so little is published about carrot production in certain parts of the world. Only a selection of these pests will be covered in more detail in this chapter.

Overall, management of most invertebrate pests relies on synthetic pesticides, with limited use of biopesticides or arthropod biological control agents. For pests and situations where effective pesticidal control cannot be achieved, use of physical control methods, such as crop covers, seems to be one of the most consistently reliable approaches. Cultivars with some level of resistance to pests, or the pathogens they transmit, are available in a few instances.

11.1 NEMATODES

More than 90 different species of nematodes can feed on carrot. Not all species have the same impact on the crop. The main pest nematodes of carrot are: cyst nematode (*Heterodera carotae*); root-knot nematodes (including *Meloidogyne incognita*, *M. javanica*, *M. arenaria* and *M. hapla*); free-living nematodes (e.g. *Pratylenchus* spp.); and stem nematodes (*Ditylenchus dipsaci*, *D. destructor*). Details of a range of species infesting carrot are reviewed in AHDB (2002) and Villeneuve (2014). Overall, root-knot nematodes have been the main focus of international research (AHDB, 2016). In addition to cosmetic damage, tissue injury also provides entry to *Pythium* and other fungal pathogens.

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Table 11.1. Phytosanitary problems affecting carrot crops.

Common name	Scientific name	Incidence
Nematodes		
Cyst nematode	*Heterodera carotae*	●● to ●●●
Root-knot nematodes*	*Meloidogyne incognita*, *M. javanica*, *M. arenaria* and *M. hapla* principally, but also *M. chitwoodi*, *M. fallax*, *M. enterolobii*	●● to ●●●
Free-living nematodes*	e.g. *Pratylenchus* spp.	●●
Stem nematode	*Ditylenchus dipsaci*, *D. destructor*	●
Other nematodes	*Longidorus* spp., *Paratrichodorus* spp., *Paratylenchus* spp., *Trichodorus* spp., *Tylenchorhynchus* spp., etc.	●
Invertebrates other than insects: root damage		
Slugs*	*Deroceras reticulatum*, *Arion hortensis*, *Milax gagates* and *Limax flavus*	● to ●●
Myriapods*	*Scutigerella immaculata*, *Blaniulus guttulatus*	●
Invertebrates other than insects: foliage damage		
Mites	Different species: *Panonychus ulmi*, *Petrobia latens*, *Tetranychus turkestani*, *T. ludeni*, *T. urticae*, *T. peruvianus*	●
Insects: root damage		
Mole cricket*	*Gryllotalpa gryllotalpa*	●
Carrot root aphid	*Pemphigus phenax*	●
Carrot weevils	*Liparus coronatus* *Listronotus oregonensis* *Listronotus texanus*	●
Wireworms	*Agriotes lineatus*, *A. sordidus* principally in Europe; *Limonius*, *Melanotus* and *Conoderus* spp. in North America	● to ●●
Common cockchafer	*Melolontha melolontha*	●
Cutworm*	*Agrotis ipsilon* and *A. segetum* principally	● to ●●
Carrot root fly	*Psila rosae*	● to ●●
Carrot mining fly	*Napomyza carotae*	●
Craneflies	Principally three species: *Tipula maxima*, *T. oleracea* and *T. paludosa*	● to ●●
Insects: foliage damage		
Thrips*	*Thrips tabaci*, *Frankliniella occidentalis*	●
Whiteflies	*Bemisia tabaci*, *Trialeurodes vaporariorum*	●
Aphids*	Many species of which some are vectors of virus, e.g. *Cavariella aegopodii*	● to ●●
Psyllids	*Dyspersa* (ex. *Trioza*) *apicalis* (complex of eight species)	● to ●●
	Bactericera trigonica, *B. nigricornis*	● to ●●

Continued

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Table 11.1. Continued.

Common name	Scientific name	Incidence
Leaf hoppers*	*Macrosteles fascifrons*	● to ●●
	M. quadrilineatus, Euscelis plebeja, Hishimonoides sellatiformis	
	Circulifer tenellus	● to ●●
	Scaphoideus titanus	● to ●●
	Hyalesthes obsoletus	
Bugs*	*Graphosoma italicum, G. semipunctatum, Orthops campestris, O. kalmii, Tingis auriculata*	● to ●●
	Lygus lineolaris, L. pratensis, L. rugulipennis, L. hesperus and *L. elisus*	● to ●●
Caterpillars*	*Autographa gamma, Helicoverpa armigera* principally	● to ●●
	Depressaria marcella	
	Agrotis exclamationis, Peridroma saucia, Feltia subterranea	● to ●●
Swallowtail butterfly	*Papilio machaon*	●
Vertebrates		
Voles and field mice*	*Pitymys subterraneus, P. duodecimcostatus*	● to ●●
Hare*	*Lepus europaeus*	●
Rabbit*	*Oryctolagus cuniculus*	●
Cervids*	Deer (e.g. *Capreolus capreolus*)	● to ●●
Wild boar*	*Sus scrofa*	● to ●●

● = minor pest; ●● = medium pest; ●●● = major pest (*infests most *Apiaceae*).

Root-knot nematodes are obligate endoparasites that complete most of their life cycle within their host roots. *H. carotae* larvae hatch in response to compounds released from their host plants and invade the roots, and can survive in cysts for more than 10 years. Species of free-living nematode reproduce in the soil.

Root-knot nematodes cause direct economic loss of the crop due to galling and forking of the carrot roots, making them unmarketable (Roberts, 1987). Carrots affected by *H. carotae* are small and the radicles are abnormal and numerous, giving the roots a characteristic bearded appearance (Fig. 11.1). Free-living nematodes feed on the root system and root hairs and can cause direct damage by affecting uptake of water and nutrients and by malformation of the root (fanging), and *Pratylenchus* may also enter root cells and leave a wound that can be invaded by other organisms (AHDB, 2016).

Limited control of root-knot nematode is possible through crop rotation and non-chemical management (Parsons *et al.*, 2015), but this can be difficult due to wide host ranges, including many weed species (Hunt and Handoo,

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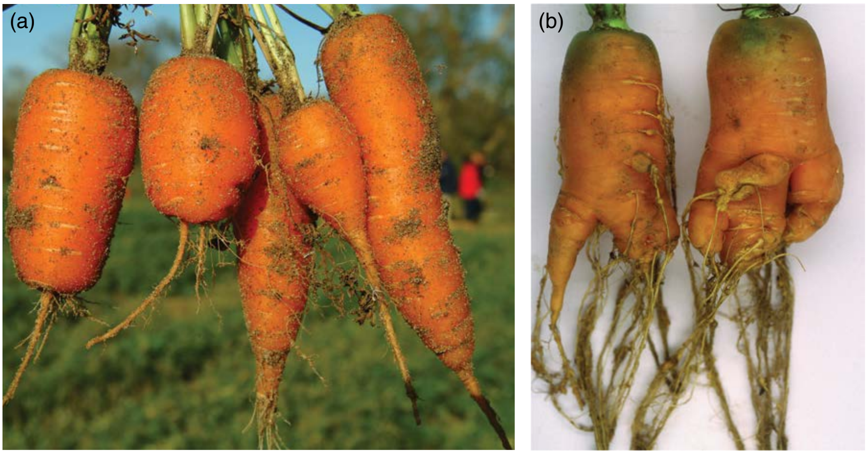

Fig. 11.1. Nematode symptoms: (a) cyst nematode, *Heterodera carotae*; and (b) root-knot nematodes, *Meloidogyne* spp. (Photos by F. Villeneuve.)

2010). There are opportunities to manipulate planting and harvest dates to avoid periods when the nematodes are most active and infective in soil (Roberts, 1987). Soil-applied nematicides can be effective. For cyst nematode an 8-year rotation is recommended in carrot-growing areas, or 10 years for severe infestations (Ellis and Hardman, 1992). According to AHDB (2016), options to manage the impact of free-living nematodes are limited, but approaches that could be considered include increasing the length of rotations, including poor hosts of free-living nematodes in the rotation, using soil testing (ideally with molecular diagnostics) to monitor populations, application of organic matter prior to planting and inclusion of cover crops in the rotation.

11.2 MOLLUSCS

Slugs occur in many countries but tend to be pests where there is a moist, temperate climate. Several species of slug are likely to cause damage; the most frequent in Europe are *Deroceras reticulatum* and *Arion hortensis*.

Slug life cycles differ in their length and reproduction may continue over a long period depending on when conditions are favourable for mating and egg laying. Field populations usually have a mixed age structure. Peaks of egg laying vary with year and location. Slugs are generally far more numerous in heavy, wet soils that are not cultivated frequently and many of the soil types used to grow carrots are less suitable habitats for slugs.

Generally economic damage is caused when slugs feed on the taproots making cavities and the plants may also show evidence of slime trails. The application of irrigation may exacerbate slug damage by making conditions more favourable for slug activity.

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Slug populations can be reduced using cultural approaches (soil management, weed management) and by increasing access to vertebrate predators (e.g. by ploughing). Chemical methods of control are limited and rely mainly on a small number of compounds. There can be issues with respect to contamination of water with molluscicides and integrated approaches are required to reduce contamination. Nematodes like *Phasmarhabditis hermaphrodita* are potential biological control agents for slugs.

11.3 INSECTS

11.3.1 Hemiptera

Aphids

Aphids are contaminants, affect plant growth, quality and yield if abundant and may transmit plant viruses. The willow-carrot aphid *Cavariella aegopodii* is probably the most damaging species and is distributed widely in temperate regions of the northern and southern hemispheres (Ellis and Hardman, 1992). However, more than 21 species of aphid can occur on carrot (Hullé *et al.*, 1999; Blackman and Eastop, 2006).

C. aegopodii overwinters mainly as eggs on willow trees (Dunn, 1965) and these generally hatch in February–March. Winged forms are produced later and migrate to carrot and other hosts (Ellis and Hardman, 1992). *C. aegopodii* may also overwinter as adult or immature stages on carrot crops and may produce colonies rapidly in spring (Ellis and Hardman, 1992). *Cavariella pastinacae* and *Cavariella theobaldi* infest carrot and parsnip and both overwinter on willow. Their life cycles are broadly similar to that of *C. aegopodii*. *Myzus persicae* has a very wide range of hosts including oilseed rape, potato, sugarbeet, vegetable brassicas and lettuce. In mild climates it overwinters as adult or immature stages on oilseed rape, vegetable brassicas and weed species, while in colder climates it overwinters as an egg on *Prunus* species. Alate aphids usually show a pronounced period of migration to new hosts starting in late spring–early summer. *Pemphigus phenax* feeds on the roots of cultivated and wild carrot in Northern Europe and Western Siberia (Blackman and Eastop, 2006). It has a sexual phase and overwinters on poplar. Parthenogenetic aphids may also overwinter on carrot crops.

C. aegopodii transmits several viruses to carrot. Large infestations of aphids may also reduce crop growth and subsequent yield (Ellis and Hardman, 1992). It is possible that *C. pastinacae*, *C. theobaldi* and *M. persicae* also transmit viruses to carrot (AHDB, 2015). The impact of *P. phenax* on yield and root quality is not well understood.

In Britain, aphids are captured in the network of suction traps operated by the Rothamsted Insect Survey and weekly reports are available. Commercial monitoring services using water traps are available in Britain. A forecast has

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been developed for *C. aegopodii* based on accumulated degree-days (R. Collier, 2010, unpublished results; Collier *et al.*, 2017). For *M. persicae*, the Rothamsted Insect Survey produces a forecast of the timing of the start of alate migration and the likely relative abundance of peach-potato aphids in the early summer, based on winter temperatures.

No reliable methods of cultural control of aphids in carrot crops have been established. Obviously crop covers will prevent alate aphids reaching the crop, but fleece or polythene covers may have been removed from the crop for agronomic reasons by the time aphids are present. No biological control methods have been used commercially, although infestations of *C. aegopodii* in Britain and France soon attract natural enemies (Brunel, 1981; R. Collier, 2009–2019, unpublished results). Some differences in varietal susceptibility to *C. aegopodii* have been observed (Dunn, 1970), but not exploited by breeders.

A number of insecticides with different modes of action have been used to reduce aphid infestations. Populations of *M. persicae* have shown resistance to organophosphate, carbamate, pyrethroid and neonicotinoid insecticides in various parts of the world (Bass *et al.*, 2014). In 2018, resistance in *C. aegopodii* to pyrethroid insecticides was identified in Britain (S. Foster, Harpenden, 2018, personal communication). There is further work to be done on the development of management strategies to minimize the transmission of virus.

Mirid bugs

Several species of mirid bug will feed on *Apiaceae* including *Lygus rugulipennis* (Ellis and Hardman, 1992). However, the main pest of carrot is *Orthops campestris*, which seems to be the same species as *Lygus campestris*. Van Turnhout and Van der Laan (1958), working in the Netherlands, reported that *L. campestris* overwinters in the adult stage and has at least two generations per year. Recent work in England on celery has confirmed the overall life cycle (AHDB, 2017).

Feeding by mirid bugs such as *Lygus* spp. and *Orthops* spp. can reduce the yield of seed crops. Approaches to monitoring and forecasting were investigated in England (AHDB, 2017). Adults and nymphs infesting Apiaceous weeds can be sampled by beating the foliage on to a tray or using sweep nets. Adults can be captured on the orange sticky traps used to monitor *Psila rosae*. As *O. campestris* is able to complete its life cycle on apiaceous weeds, management of such species in the vicinity of crops may reduce levels of infestation. Control could be achieved through the use of mesh covers. A number of insecticides have activity against adult *Orthops* spp. (AHDB, 2017).

Leaf hoppers and fulgores

The leaf hoppers (*Cicadellidae* family) and fulgores (*Cixiidae* family) do not cause much direct damage to apiaceous crops but they can transmit *Candidatus* Phytoplasma asteris (aster yellows disease, AYp), and also *Candidatus*

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Phytoplasma solani (stolbur disease) and *Spiroplasma citri*. More than 30 species are considered to transmit AYp. *Macrosteles quadrilineatus* is distributed widely in North America and is a serious pest of many plants because it can spread aster yellows disease.

AYp is persistently transmitted by the leaf hoppers and both nymphs and adults can acquire the pathogen (Frost *et al.*, 2013). Once infected, an individual aster leaf hopper can remain infective for the remainder of its life. *M. quadrilineatus* is polyphagous with more than 300 different hosts, many of which are susceptible to AYp infection. *M. quadrilineatus* can overwinter as adults in warm locations but in cooler locations they overwinter as eggs on overwintered cereal crops (Ellis and Hardman, 1992). In Canada, *M. quadrilineatus* feed on cereal crops first and adults subsequently migrate to carrot crops.

The direct damage caused by feeding is minor compared with the losses caused by aster yellows (Ellis and Hardman, 1992).

Management is based on monitoring by walking crops and using yellow sticky traps to determine when the first migrants arrive. The size of the population can be estimated using sweep nets and treatment thresholds are available (Delahaut, 1997).

Only a small percentage of *M. quadrilineatus* carry the aster yellows pathogen, and that percentage can change throughout the season. The aster yellows index (AYI) was developed as a risk assessment tool to enumerate the maximum allowable numbers of infectious *M. quadrilineatus* and indicate periods in the growing season when protection of a susceptible crop was most needed (Chapman, 1971, 1973). Molecular approaches to pathogen detection are now used to estimate the infection frequencies (Frost *et al.*, 2013). Removal of possible weed reservoirs and infected crop plants can reduce the spread of aster yellows although there will still be infective *M. quadrilineatus* transmitting the pathogen. It is also a good idea to avoid planting susceptible crops near untreated crops or weeds that *M. quadrilineatus* use for refuge. High stand density will further decrease the impact of aster yellows (Delahaut, 1997). Crop covers may be used to exclude *M. quadrilineatus*. No biological controls effectively reduce *M. quadrilineatus* populations. To effectively control *M. quadrilineatus*, insecticide applications should be timed to coincide with influxes. Because disease symptoms take a month to develop, treatment may be discontinued 30 days before harvest (Delahaut, 1997).

Psyllids

Different species of psyllids can develop on carrots, mainly *Trioza apicalis*, *Bactericera trigonica* and *Bactericera nigricornis*. The psyllid *T. apicalis* is a serious pest of carrot in Scandinavia, Finland and other parts of Northern and Central Europe, and occurs more widely in Eurasia from Britain to Mongolia (see references in Munyaneza *et al.*, 2010). *T. apicalis* has one generation per year and overwinters as an adult on coniferous trees (Kristoffersen and Anderbrant, 2007). In spring, *T. apicalis* migrates into carrot fields to feed and oviposit.

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Fig. 11.2. Larva of *Bactericera trigonica*. (Photo by F. Villeneuve.)

In Southern Europe and the southern Mediterranean region, the species observed in different apiaceous crops is *B. trigonica* (Fig. 11.2). Its biology is not well known. It can be present in carrot fields all year (Villeneuve *et al*., 2019) and a minimum of two generations can be observed. *B. nigricornis* can also be seen in carrot fields.

Damage occurs as soon as *T. apicalis* starts feeding on the carrot foliage and both adults and nymphs cause damage. Symptoms in affected plants include leaf curling, yellow and purple discoloration of leaves, stunted growth of shoots and roots, and proliferation of secondary roots (Munyaneza *et al*., 2010). Infestation of young plants may cause 100% yield loss (Markkula *et al*., 1976). However, carrot plants at 8–10 weeks of age can tolerate infestations at low levels (Seljåsen *et al*., 2013). *B. trigonica* seems to cause relatively little direct damage to carrot. Damage by *T. apicalis* can be associated with the bacterium *Candidatus* Liberibacter solanacearum (Munyaneza *et al*., 2010). Different haplotypes are described: haplotype C is associated with disease in carrots and transmitted by *T. apicalis*, haplotypes D and E are linked to *B. trigonica*.

Yellow sticky or water traps can be used to monitor adult *T. apicalis* or *B. trigonica* in the field. Insecticides can be used to control *T. apicalis* although it has been suggested that some insects show resistance to insecticides in southern Norway (Seljåsen *et al*., 2013). Repeated spraying can be required as migration into the crop continues for several weeks (Nehlin *et al*., 1994). Organic farmers protect their crop by covering them with insect nets or fleece. Feeding and oviposition by *T. apicalis* have been reduced by the application of fresh spruce and pine sawdust along the seedling rows in carrot fields. Turpentine and separate monoterpene hydrocarbons, mixed into old sawdust and/or placed in polyethylene tubes, were also effective (Nehlin *et al*., 1994). Research has been undertaken to investigate the potential of trap crops as a strategy for managing this pest (Nilsson and Rämert, 2017).

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11.3.2 Coleoptera

Carrot weevil

Carrot weevil (*Listronotus oregonensis*) is distributed widely in north temperate regions of North America (Ellis and Hardman, 1992) and overwinters as adults (Stevenson, 1976). In the spring, adults move into fields and start to feed. Eggs are laid in the petioles. The larvae feed on the roots. There may be up to three generations depending on temperature (Ellis and Hardman, 1992).

The most serious damage occurs from larval tunnelling in roots. The adults cause relatively little feeding damage. Carrot weevil populations can be monitored using traps (Fig. 11.3). All of the three monitoring methods compared in 1997 provided similar records of the seasonal pattern of adult activity (Stevenson and Barszcz, 1997). Damage can be reduced by careful choice of sowing dates (Stevenson, 1976) where late sowing reduced damage to a minimum. As *L. oregonensis* rarely fly, crop rotation in space and time can be effective (Ellis and Hardman, 1992). Integrated pest management recommendations in Ontario are based on thresholds using trap counts. Control with *Bacillus thuringiensis* (Saade *et al.*, 1996) and with nematodes (Miklasiewicz *et al.*, 2002) has been investigated. Insecticide treatments are available and can be effective in the absence of resistance.

Click beetle

Several species of click beetle (*Agriotes* spp.) can damage carrot and they have life cycles of different lengths. After several years of development, the larvae (wireworms) pupate and during late summer or early autumn, the adults complete their development and remain underground to overwinter. Adults then emerge between April and September the following year, depending on the species and geographic location. Damage caused by wireworms is generally

Fig. 11.3. Trap for carrot weevil, *Listronotus oregonensis*. (Photo by F. Villeneuve.)

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characterized by the formation of bites and tunnels at any point on the root. Inside there can be cavities with black and necrotic walls. Often wet rots develop.

11.3.3 Lepidoptera

Several species of Lepidoptera may damage carrot crops (Ellis and Hardman, 1992). Of these, the turnip moth (*Agrotis segetum*) is potentially the most damaging in temperate regions in Asia, Africa and Europe. In North America, *Autographa californica*, *Autographa falcifera*, *Agrotis exclamationis* and *Peridroma saucia* are chronic pests.

Female *A. segetum* lay eggs usually from the end of May in Britain. The young larvae spend most time in the soil, moving to feed on plant leaves (Esbjerg, 1988). Third instar larvae become subterranean. Survival of the first two larval instars is reduced in moist soil (Esbjerg *et al.*, 1986) and third instar larvae also suffer increased mortality if the soil is moist (Esbjerg, 1989). Using historical records, Mikkelsen and Esbjerg (1981) found a negative relationship between cutworm abundance in Denmark and low summer temperature and high levels of rainfall. A similar relationship between cutworm abundance and rainfall was shown using data collected in England and this was developed into a forecasting model (Bowden *et al.*, 1983).

There is a second generation of *A. segetum* towards the south of Britain, but this is not considered to be a threat to crops. In Britain, *A. segetum* overwinters in the soil as a fully developed larva and pupates when temperatures rise in the spring. In Southern Europe the main species are *Autographa gamma* and *Helicoverpa armigera*. More recently *Spodoptera exigua* and *Spodoptera littoralis* have been observed during hot summers.

The name 'cutworm' arises from the habit of the older larvae of feeding underground, damaging plant roots and stems, sometimes so badly that the plant collapses. In carrots, feeding by *A. segetum* and *H. armigera* larvae will destroy seedlings and young plants and in older crops the larvae will create cavities in the roots (Ellis and Hardman, 1992). The symptoms can be confused with slug damage.

Pheromone traps can be used to monitor numbers of male *A. segetum* and other pest species. The degree-day sum for the start of flight activity has been estimated as 340 degree-days above a base of 7°C from 1 January (R. Collier, 2010, unpublished data). In Britain, the cutworm model (Bowden *et al.*, 1983) has been available for a number of years and uses rainfall to predict larval survival.

Unhatched *A. segetum* eggs and the older, subterranean cutworms are largely invulnerable to insecticides. The application of irrigation is a very effective way of reducing infestations by cutworm larvae (Kay, 1980; Ellis and Hardman, 1992). Research has been undertaken on biological control of

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A. segetum with viruses (e.g. Wennmann *et al*., 2015) and with nematodes (Goudarzi *et al*., 2015). However, it is not clear whether products based on these control agents are available commercially. Crops planted into land previously covered with weeds are considered to be more susceptible to infestation (Ellis and Hardman, 1992).

11.3.4 Diptera

Carrot fly

Carrot fly (*Psila rosae*) (Fig. 11.4) is a pest of apiaceous crops (Collier and Finch, 2009). Approaches to management of *P. rosae* have been considered particularly in Europe (e.g. Collier, 2009), North America (e.g. Judd *et al*., 1985) and New Zealand (e.g. Sivasubramaniam *et al*., 1999).

In Europe, the number of generations ranges from one to two (Norway, Finland, Sweden) to two to three in countries further south (Collier, 2009). In most countries, there are more generations in the south than the north (Collier, 2009). However, in France there are three generations in the north and only two in the south. In the south of France, the two generations are separated by a period during the summer when carrot flies aestivate in the pupal stage (Villeneuve and Latour, 2017).

In Britain, first-generation adult carrot flies emerge from pupae from late April through to early June. The eggs are laid in the soil close to the base of a

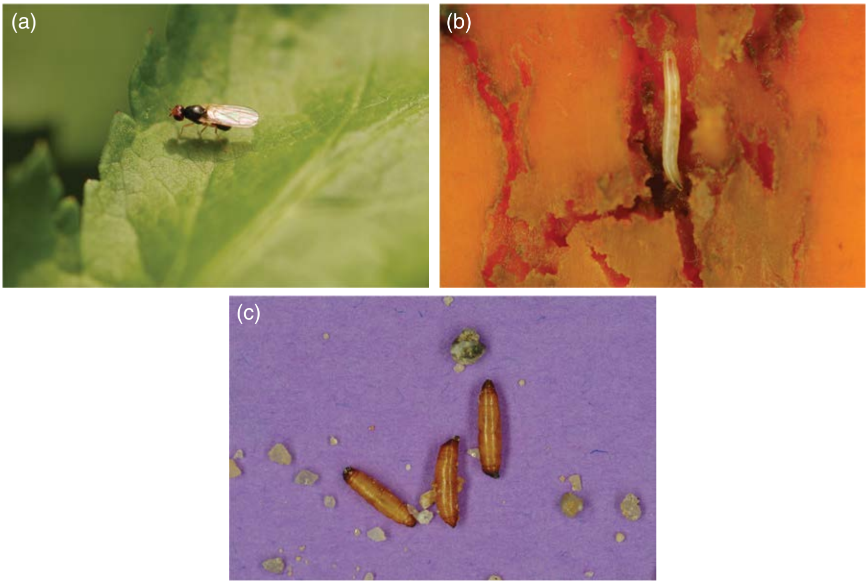

Fig. 11.4. Carrot fly: (a) adult; (b) larva; (c) pupae. (Photos by F. Villeneuve.)

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carrot plant and the newly hatched larvae move through the soil to the root system. At first the larvae feed on the lateral roots but then they tunnel into the taproot. When fully grown, the larvae pupate, and a second generation of flies emerges and lays eggs. Depending on weather conditions, the eggs laid at the beginning of the second generation may be able to develop into a third generation of adults which emerge in early autumn. Carrot flies may overwinter in the pupal stage or the larval stage, where they continue to feed on their host plant until they form pupae in the spring.

If *P. rosae* larvae attack carrot seedlings, then they are likely to kill them. Once the taproot has started to develop, damage is caused by the larvae tunnelling into the root to feed. In Britain and France, carrots are harvested from the field almost 12 months of the year and are overwintered under a layer of straw covered with polythene. In this instance, if crops have been infested it is possible for overwintering larvae to continue feeding during the winter, gradually increasing damage.

Adult carrot flies can be monitored using orange sticky traps (Collier and Finch, 1990; Collier, 2009). If traps are angled at 45° to the vertical, they become more selective for carrot flies which prefer to land on the lower surface of such traps (Finch and Collier, 1989).

Treatment thresholds have been used in a number of countries and are based on the numbers of carrot flies trapped per day or per week (Collier, 2009). In principle, for such a system to be effective, there must be a good relationship between the numbers of flies trapped and the amount of damage the crop would suffer if left untreated. However, in general, such relationships have not been established in any detail and indeed using thresholds can be difficult in some circumstances (Villeneuve *et al.*, 2007; Villeneuve and Latour, 2017). Trap placement to assess field populations accurately is critical since studies have shown that *P. rosae* numbers and subsequent damage are highest close to field margins and that fly numbers decrease quite rapidly over a short distance into the crop (Collier and Finch, 2009).

Approaches to predicting the timing of the various stages in the *P. rosae* life cycle have been developed in Britain (Phelps *et al.*, 1993) and Germany (SWAT model: Hommes and Gebelein, 1996). The SWAT model has been tested and used in several countries (e.g. France: Villeneuve and Latour, 2017). In addition, a degree-day model was developed in Sweden (Jonsson, 1992) to ensure that crops are harvested before *P. rosae* damage has developed on the taproots.

There was a research programme in the late 20th century in Britain to identify sources of host plant resistance. The breeding material was sold to commercial seed companies (Ellis, 1993). This led to carrot varieties such as Flyaway and Resistafly with partial levels of resistance, but these varieties are not grown commercially as they do not have the other characteristics required. There is scope to use partially resistant varieties as part of an integrated pest management strategy, for example with reduced doses of insecticide (Thompson *et al.*, 1994) or with methods of cultural control (Ellis *et al.*, 1987).

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Since adult carrot flies appear to move relatively short distances (Coaker and Hartley, 1988), there is the opportunity to develop management strategies based on the isolation of new crops from sources of *P. rosae*. Numbers can be kept low particularly if early and late crops are well-separated to break the sequence of host plants in the pest's life cycle. Research in Britain showed that relatively few carrot flies moved more than 1 km from a previously infested crop and that numbers declined steadily (and predictably) with increasing distance from the 'source' of *P. rosae* (Finch and Collier, 2004). Crops grown in exposed locations are likely to be less susceptible to infestation by *P. rosae* (Coaker and Hartley, 1988).

Susceptibility to attack varies with sowing date of the crop. In Britain, crops that emerge before mid-May are available to first-generation adults for egg laying (Ellis *et al.*, 1987; Collier and Finch, 2009). This may increase the level of second-generation damage, since adults emerging from the first generation are likely to remain in the vicinity of the crop. Timely harvesting of an entire crop can curtail the development of larval feeding damage. Alternatively, parts of the crop which are likely to become heavily damaged can be harvested early.

Woven fine-mesh netting or non-woven covers (fleeces) can be used to prevent adult carrot flies accessing a crop (Haseli and Konrad, 1988). The use of vertical fences (up to 2 m high) to prevent colonization by *P. rosae* has been investigated (Siekmann and Hommes, 2007; Collier and Finch, 2009). Although these reduced the size of *P. rosae* infestations, they did not exclude all flies. Studies have been made on management of *P. rosae* through intercropping (Rämert and Ekbom, 1996).

In recent years, insecticides have been applied either as seed treatments or foliar sprays (Collier, 2009; Collier and Finch, 2009). Spray treatments may be targeted against the adults or the larvae or both stages. Timing of treatments, particularly those which kill only the flies, (and thus need to be applied in a timely fashion to prevent them laying eggs), is critical, which is where forecasting systems are particularly useful (Collier and Finch, 2009; Villeneuve and Latour, 2017).

Leaf miners

Several Agromyzidae can cause damage to apiaceous crops. The most common species are, in order of importance: carrot miner; celery fly, which can be found on carrots; and *Liriomyza trifolii*. Caution should be exercised in the identification and taxonomy of these different species.

Female flies puncture the foliage with their ovipositor. They feed on the sap and then lay their eggs. The larvae mine the leaves with mines running towards the main vein and then down the petiole to the root. The biology of, damage caused by and approaches to managing *Napomyza carotae* are summarized in Ellis and Hardman (1992).

N. carotae has caused damage to carrot crops in several countries in Northern Europe (Hassan, 1971). Incidents of damage appear to have

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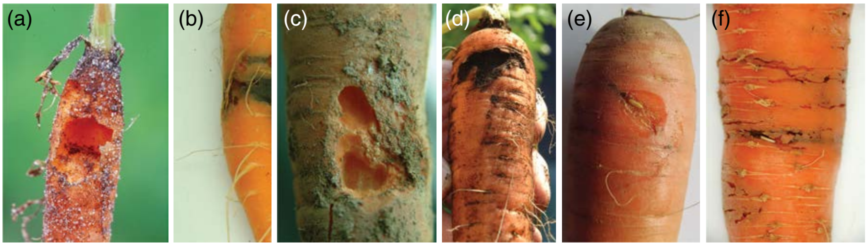

Fig. 11.5. Comparison of the different symptoms caused by different pests to carrot roots: (a) cutworm; (b) click beetle; (c) slug; (d) carrot weevil; (e) leaf miner; (f) carrot fly. (Photos by (a, b, c, d, f) F. Villeneuve; (e) V. Salou.)

increased more recently (Willhauck and Hommes, 2016), possibly because some of the more effective insecticide treatments are no longer available. The larvae usually damage the upper part of the root which deforms the root and allows the entry of bacterial rots. Damaged carrots deteriorate rapidly in store (Ellis and Hardman, 1992). Figure 11.5 compares the damage caused by different pest insects to carrot roots.

In principle the fly can be controlled with contact and systemic insecticides. Hassan (1971) developed a method to time applications based on the appearance of feeding marks caused by the female flies.

11.4 VERTEBRATE PESTS

Damage can also be caused by vertebrates. While birds do not cause particular problems in carrot crops, several species of mammal can cause damage through feeding and trampling in the case of larger species such as deer. Populations of these pests can be managed through shooting and other approaches to reducing numbers and in extreme cases it may be possible to fence crops to exclude them. Crop covers, such as those made of fine mesh netting and used to exclude pest insects, also have the benefit of excluding vertebrate pests.

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12

Carrot Diseases Resulting from Phytoplasmas and Viruses

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Among several bacteria-like organisms and virus-induced diseases observed in association with diseased plants in the carrot family (*Apiaceae*), those that consistently appear to be particularly harmful are referenced here.

12.1 ASTER YELLOWS PHYTOPLASMAS, *CANDIDATUS* PHYTOPLASMA ASTERIS

12.1.1 Disease symptoms and crops affected

Aster yellows phytoplasmas (AYp) are a group of phloem-limited, cell-wall-less bacteria associated with disease in herbaceous plants (Lee *et al*., 2004; Frost *et al*., 2013). Members of the AYp group have also been known to cause disease in both monocots and woody plants. The disease phenotype related to this pathogen depends on the plant host and the phytoplasma subgroup. AYp has been documented in more than 350 different plant species, encompassing 38 different families, and is commonly associated with agricultural crops including onion, lettuce, celery and carrots. Some plant species are asymptomatic, while a subset of plants can develop severe symptoms. Currently there are more than 100 classified diseases caused by AYp. General symptoms include witch's broom (proliferation of shoots), phyllody (retrograde development of flowers into leaves), virescence (flower organs remaining green), bolting, formation of shortened internodes and elongated petioles (Fig. 12.1).

12.1.2 Aetiological agent

The aetiology of aster yellows-related diseases consists of one taxon group of phytoplasma, *Candidatus* (*Ca.*) Phytoplasma asteris. However, within the species

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designation there are more than 15 different subgroups of the phytoplasma. The subgroup classification is based on phylogenetic differences between a conserved region of the 16S ribosomal RNA. The subgroup classification is based on an alphabetical designation (16SrI-A, 16SrI-B, 16SrI-C, etc.). It is important to note that a specific subgroup of AYp can cause multiple diseases in different plant species. For example, AYp 16SrI-A can cause aster yellows in carrot (*Daucus carota*), tomato big bud in *Solanum lycopersicum*, onion yellows in *Allium cepa*, and many more diseases.

12.1.3 Disease ecology and management

AYp is vectored by multiple insect species; however, members of the *Cicadellidae* family (leaf hoppers) are widely considered the primary insect vector. One such insect vector is the aster leaf hopper, *Macrosteles quadrilineatus*, which is the primary vector of AYp 16SrI-A and 16SrI-B, resulting in aster yellows disease (Figs 12.12 and 12.13). After an initial incubation period, the insect can

Fig. 12.1. Symptoms of aster yellows on carrot. (Photo by K.E. Frost.)

Fig. 12.2. Adult female *Macrosteles quadrilineatus* Forbes, the insect vector for *Candidatus* Phytoplasma asteris. (Photo by K.E. Frost.)

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Fig. 12.3. Third instar nymph of *Macrosteles quadrilineatus* Forbes, the insect vector for *Candidatus* Phytoplasma asteris. (Photo by K.E. Frost.)

persistently transmit the phytoplasma over the remainder of its life. The phytoplasma can replicate and circulate within the insect body and the phloem of infected plants. The movement of the insect vector has been associated with disease spread and should be the primary target for phytoplasma control. After the transmission of the AYp into the plant host, little can be done to salvage host quality and manage disease symptoms. It is also important to monitor for the influx of migratory insects. One tool used to determine the severity of disease pressure is the aster yellows index (AYI). Successive insecticide applications, based upon the exceedance of the computed AYI, are applied to agricultural crops to manage the insect vector.

12.2 BEET LEAF HOPPER-TRANSMITTED VIRESCENCE AGENT PHYTOPLASMA

12.2.1 Disease symptoms and crops affected

Beet leaf hopper-transmitted virescence agent (BLTVA) phytoplasma is a group of phloem-limited, cell-wall-less bacteria associated with disease in many commercial crops (Hiruki and Wang, 2004; Liefting *et al.*., 2004). Disease phenotypes related to this pathogen depend on the diseased plant species. The phytoplasma has been documented in more than 48 different plant species and is commonly associated with agricultural crops including potato, tomato, pepper and carrot. While infection with BLTVA can be asymptomatic in some plant species, the disease can lead to plant mortality in others. Symptoms range from aerial tubers in potato, seed sterility in radish to big bud disease in tomato. Further, BLTVA is associated with the virescence (greening of floral tissue) condition and phyllody (leaf-like petals and sepals). The phytoplasma can also cause a yellows condition in carrots, which is phenotypically similar to aster yellows disease (Fig. 12.4).

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Fig. 12.4. Symptoms of beet leaf hopper-transmitted virescence agent on carrot. (Photo by P.W. Simon.)

12.2.2 Aetiological agent

The aetiology of BLTVA-related disease consists of one taxon group of phytoplasma, *Candidatus* (*Ca.*) Phytoplasma trifolii. This specific agent is placed in group A of the clover proliferation phytoplasma species designation, and is usually designated as phytoplasma 16SrVI-A. The agent and associated diseases occur predominantly in the western USA; however, it has been found in pepper in Mexico.

12.2.3 Disease ecology and management

BLTVA is vectored by multiple insect species; however, members of the *Cicadellidae* family (leaf hoppers) are widely considered the primary insect vector. Within the *Cicadellidae* family, the beet leaf hopper, *Circulifer tenellus*, is generally considered the primary vector and the focus of most integrated pest management efforts. The control of BLTVA-related disease revolves around managing the insect vector. After the transmission of the agent into the plant host, little can be done to manage disease symptoms. Management practices must take into consideration movement and colonization of the insect vector using appropriate integrated pest management strategies.

12.3 *CARROT VIRUS Y*

12.3.1 Disease symptoms and crops affected

Carrot virus Y (CarVY) is a plant pathogenic virus that can seriously impact both the plant canopy (foliage) and the root of cultivated carrot, and results in significant losses in yield and root quality (Latham and Jones, 2003a; Latham

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et al., 2004; Jones *et al.*, 2005, 2006). Symptoms of the virus infection in the carrot canopy include chlorotic mottle, reddening and chlorosis of leaves, plant stunting and marginal leaf necrosis. The magnitude and severity of symptoms are often linked to carrot cultivar together with the developmental stage of the crop at the time of infection. Some cultivars will develop obvious symptoms, while others will express few symptoms that are often associated with later-stage infections. Below ground, severely affected plants can have roots which are very distorted or misshapen. Very often, infections occurring at later development stages can be confused with other aetiological agents, or nutritional deficiency. Carrot roots from plants that become infected during early stages of development are often stubby in appearance and can be distorted and possess knobs or swellings along the full length of the root. To date, the occurrence of CarVY has been limited to the carrot-producing regions of the Australian continent, but infections can sometimes reach epidemic levels, sufficient to bypass entire fields.

12.3.2 Aetiological agent

The disease symptoms previously described are the result of infections of CarVY, a plant pathogenic virus in the family *Potyviridae*. Virion shape (filamentous and flexous) and length (*c.*10 nm × 750 nm) are typical of potyviruses, and these can be identified in CarVY-infected carrot leaf and root extractions using electron microscopy. General *Potyvirus* monoclonal antibody is effective for the detection of CarVY, in addition to PCR protocols developed from leaf tissues. However, procedures for detection of CarVY in storage roots are not well developed.

12.3.3 Disease ecology and management

Field infections of CarVY appear to be limited to carrot, whereas laboratory challenge inoculations have established infections in a select few non-crop weed species. Primary sources of inoculum for spread to new carrot plantings are presumed to arise from infected 'volunteer' carrots in nearby or adjacent plantings. Proximity to production areas of continuous carrot has been identified as a significant risk factor for disease spread and pathogen persistence. The virus is spread by a combination of carrot-colonizing and non-colonizing aphid species in a non-persistent manner. Aphids rapidly acquire the virus when feeding on infected carrot plants and then quickly lose the capacity to transmit the virus after feeding on a healthy or non-host plant. The green peach aphid (*Myzus persicae*) is a very efficient vector. Effective control is achieved by lowering local sources of inoculum, limiting adjacent and continuous plantings of carrots, and the elimination of all volunteer carrots.

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12.4 CARROT THIN LEAF VIRUS

12.4.1 Disease symptoms and crops affected

Carrot thin leaf virus (CTLV) is regularly occurring viral pathogen of commercial carrot in the western USA, although the disease infrequently affects overall productivity and root quality (Howell and Mink, 1976, 1977; Falk *et al.*, 1991; Davis and Raid, 2002; Xu *et al.*, 2014). Yield reductions typically occur when CTLV co-occurs with other viral pathogens or foliar diseases. Symptom severity varies with the crop development stage at the time of infection (aphid transmission) as well as the carrot cultivar. Affected foliage possesses epinastic leaflets described as 'threadlike', resulting in a narrow and upright canopy. Leaves and leaflets can be chlorotic, with mild mottling and vein banding symptoms, especially when plants are infected at early development stages.

12.4.2 Aetiological agent

CTLV is a single-stranded (ss) RNA virus classified in the *Potyviridae*, with a viral genome containing approximately 9500 nucleotides. Virions are described as long, flexuous and rod-shaped, typical of other potyviruses, which measure approximately 11 nm × 736 nm. Infectious particles can be readily identified using transmission electron microscopy in vascular tissue of infected plants.

12.4.3 Disease ecology and management

In laboratory challenge inoculation assays, CTLV has been shown to infect several commercial crop species including anise, caraway, coriander, dill, parsley and parsnip, whereas natural infections occur principally in *D. carota* (commercial carrot cultivars). CTLV inoculum persists in adjacent, volunteer carrot and is acquired and transmitted to susceptible carrot in a non-persistent manner by carrot-colonizing (*Cavariella aegopodii*, *M. persicae*) species, although no non-colonizing aphid species have yet been confirmed as competent vectors. Elimination of local inoculum through sanitation of volunteers is an effective management approach. Effective rotation is another cultural control option to limit disease transmission to new plantings. Insecticide control during the current season of production is often not implemented due to the infrequent economic impact of CTLV observed in production fields.

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12.5 CELERY MOSAIC VIRUS

12.5.1 Disease symptoms and crops affected

Celery mosaic virus (CeMV) infects a number of umbelliferous crops, including carrot, celeriac, coriander, dill, parsley, parsnip and celery (Milbrath, 1948; Orsenigo and Zitter, 1971; Latham and Jones, 2003b; Xu *et al.*, 2011). The disease described as 'celery mosaic' is caused by systemic infections of the viral pathogen CeMV, originally described in 1938 in California as 'western celery mosaic'. Significant yield losses in susceptible crops have been reported in individual fields, with overt symptoms described as mild mottling within interveinal areas, vein clearing, plus narrowed, twisted and cupped leaves on mature foliage. Crops infected at earlier stages of development exhibit overall stunting, shortened petiole length and reduced canopy growth. Affected crops are often observed as groups of symptomatic plants in aggregate areas initially on field edges, progressing toward field centres in later stages of crop growth.

12.5.2 Aetiological agent

CeMV is included in the *Potyviridae* and is further classified by two distinct strains, a common strain and a strain named 'celery crinkle-leaf mosaic'. Virions are filamentous and flexuous rod-shaped, approximately 790 nm long. The genome consists of ssRNA containing an estimated 9999 bases, and virions are easily observed in cytoplasm of all plant tissues, along with pinwheel inclusion bodies.

12.5.3 Disease ecology and management

The virus is transmitted by at least 19 aphid species in a non-persistent manner. Nearby cultivated umbelliferous crops including celery, carrot, dill, parsley and parsnip, together with umbelliferous weeds that persist when cultivated hosts are absent, can all serve as sources of inoculum for subsequent spread. Critically important sources of inoculum are adjacent, infested fields that are stagger-planted over successive time periods, containing high levels of infections plus potentially viruliferous, aphid vectors. The virus is transmitted from infected source plants to susceptible crops by many aphid species following short probing events. Control is achieved by removal of local inoculum sources together with crop-free periods. The elimination of weed hosts has been proposed, but only if the major source of inoculum can be identified. Disease management through vector control is challenging due to the non-persistent nature of virus transmission, coupled with many non-colonizing aphid species known to acquire and inoculate the virus.

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13

Carrot Physiological Disorders and Crop Adaptation to Stress

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Several disorders mainly of abiotic origin can occur on carrots, causing problems of varying degrees for producers. They are often responses to lack or excess of essential crop nutrients, light, moisture or temperature. Other factors may be poor soil structure, poor aeration, soil compaction, high soil salinity, air pollution or from chemical pesticides. Symptoms of these abiotic factors often are difficult to diagnose. Additional identification may be needed because some disorders mimic symptoms caused by viruses or other pathogens.

13.1 PHYSIOLOGICAL DISORDERS RELATED TO ROOT MORPHOLOGY

13.1.1 Root stubbing and root forking (also known as fanging or sprangling)

The apex of the root dies as soon as the root is a few centimetres long, thus apical dominance is suppressed. Either the main root can no longer elongate, resulting in very short roots called 'stubbing' (Fig. 13.1a), or we observe the proliferation of a variable number of roots giving forked carrots (Fig. 13.1b). The 'stubbing' carrots originate from many factors such as soil compaction, nematodes, *Pythium* or excess water. The development of forked carrots also has many causes, such as cold, attacks of pests and diseases (nematodes, fungi), excess water, excess manure or poor implantation (Table 13.1). The pathogens involved are mainly *Pythium* species such as *P. irregulare*, *P. ultimum* and *P. sylvaticum*, but also related *Rhizoctonia solani* anastomosis group 4. All these pathogens are common organisms in the soil; the root exudates emitted during

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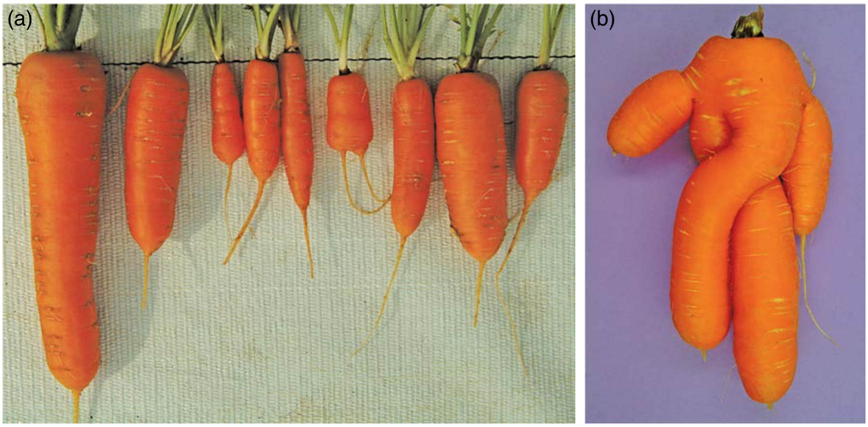

Fig. 13.1. (a) Very short carrot roots called 'stubbing'; (b) example of carrot forking. (Photos by F. Villeneuve.)

Table 13.1. The different factors that can induce forked carrots.

Abiotic factors	Biotic factors	
	Diseases	Pests
Frost	*Pythium* spp. (principally *P. irregulare* and *P. ultimum*)	Carrot fly (*Psila rosae*)
Growth stops	*Rhizoctonia solani* (principally AG4)	Cyst nematode (*Heterodera carotae*)
Herbicides		*Pratylenchus* spp.
Crop debris		Wireworms (*Agriotes* spp.)
Pebbles		Garden symphylan (*Scutigerella immaculata*)

germination cause the germination of spores which will attack the young roots and cause the death of the apex. The phenomenon often occurs very quickly, within 2 weeks of germination.

13.1.2 Root splitting/cracking/breakage

It is necessary to distinguish between carrots split in the field and those resulting from impacts during harvesting, washing and packaging operations (Fig. 13.2). Longitudinal cracking and transverse breakage of carrot roots result in significant losses for growers worldwide. The factors underlying this problem are very diverse: genotype (Cantwell *et al.*, 1991; McGarry, 1993;

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Fig. 13.2. Examples of carrot cracking/splitting: (a) occurring during field development; (b) occurring at harvest time. (Photos by F. Villeneuve.)

Hartz *et al*., 2005), amount of water contained in the root, low density, irregular irrigation, sandy soils, high leaf-to-root ratio, high growth, parasitic attack, fertilization and root temperature (Cantwell *et al*., 1991; Kokkoras, 1995). McGarry (1993, 1995) reported that failure force of parenchyma tissue was negatively correlated with both water potential and tugor potential, but there was no clear relationship between carrot variety and water status (McGarry, 1993). The periderm has less flexibility than the phloem parenchyma (Hartz *et al*., 2005). When the periderm fractures, the fracture readily propagates to parenchyma tissues. Excessive nitrogen fertilization above the required level results in increased cracking (Hartz *et al*., 2005).

13.1.3 Water spot

Water spot (similar to clay burn) is due to cell breakdown and the formation of longitudinal cracks with irregular contours. These cracks are very quickly invaded by secondary pathogens. 'Water spot' is related to a temporary anoxia caused by excess water, for example from a poorly conducted irrigation or a storm (Fig. 13.3).

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Fig. 13.3. Water spot symptoms, which are generally observed at the end of the culture when carrots are more sensitive. (Photo by F. Villeneuve.)

13.2 PHYSIOLOGICAL DISORDERS RELATED TO ROOT APPEARANCE

13.2.1 Surface browning

The phenolic browning of carrot, linked to an oxidation of polyphenols contained in the upper layers of cells, should not be confused with boron deficiency. Root colour changes can occur in field or after harvesting. Thus the incidence is variable and the number of possible causative factors is unclear and unresolved. Oxidative browning is usually caused by the enzyme polyphenol oxidase that, in the presence of oxygen, converts phenolic compounds into dark-coloured pigments (Dorrell and Chubey, 1972). The phenolic content of carrot roots ranges from 150 to 750 mg per kg and varies with cultivar, growing and storage conditions, and position of the tissue within the root. Most carrot phenolics are concentrated in cortical and vascular tissues (Chubey and Nylund, 1969, 1970). Carrot tissues seem to have distinct phenolic biosynthesis under wounding stress (Alegria *et al.*, 2016).

13.2.2 White or grey aspect of the periderm (bleaching, whitening)

The perception of carrot colour, in particular brightness and whitening, changes during carrot development. Monitoring by chromameter shows that luminance (L^*) fluctuates most along carrot development, with a downward trend that reflects a 'darkening' of the perception of the carrot colour (Fig. 13.4). Saturation

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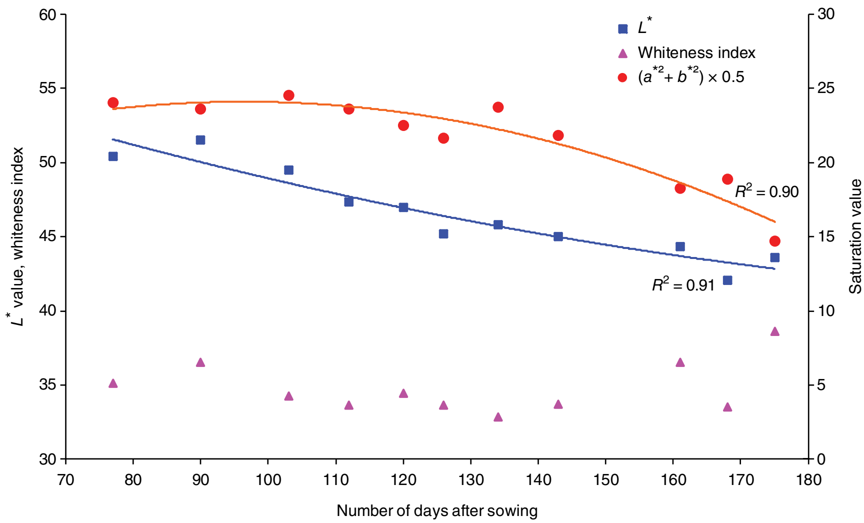

Fig. 13.4. Evolution of colour parameters (luminance, L^*; and saturation, $(a^{*2} + b^{*2}) \times 0.5$) and whiteness index during the development of Bolero variety (Vilmorin) sown on 19 June 1998. (From Villeneuve *et al.*, 2002.)

($(a^{*2} + b^{*2}) \times 0.5$, where a^* = from green (−) to red (+) and b^* = from blue (−) to yellow (+)) also tends to decrease. Estimated by the whiteness index proposed by Bolin and Huxsoll (1991), whitening is relatively stable, which shows that this phenomenon is not especially dependent on the growth stage of the carrot.

In addition to this 'normal' evolution, discolorations can occur at different times, such as after storage in a cold room, after too long a period on the shelf or after processing such as ready-to-use, cut-and-peel carrots or processing into sticks.

The mechanisms at the origin of the phenomenon have been studied for carrots when the time between washing and consumption is too long or following cold storage. Under these two situations with conditions drier than field ones, surface cells die (Den Outer, 1990; Tatsumi *et al.*, 1991) and periderm desquamation is observed (Fig. 13.5a). It is linked to general stress following grubbing-up. This stress seems all the more pronounced as the cultivation cycle is long. Whitening is very often associated with carrot freshness.

In the case of peeled, sliced, stick or baby carrots, the origin of the white blush phenomenon seems rather related to alteration in phenolic metabolism and may result in lignin deposition on the surface (Bolin and Huxsoll, 1991; Simões *et al.*, 2010).

In order to reduce these whitening phenomena, different solutions have been worked on, some of which are widely implemented. First, surface abrasion techniques are used to remove surface cell layers (polishers). This technique

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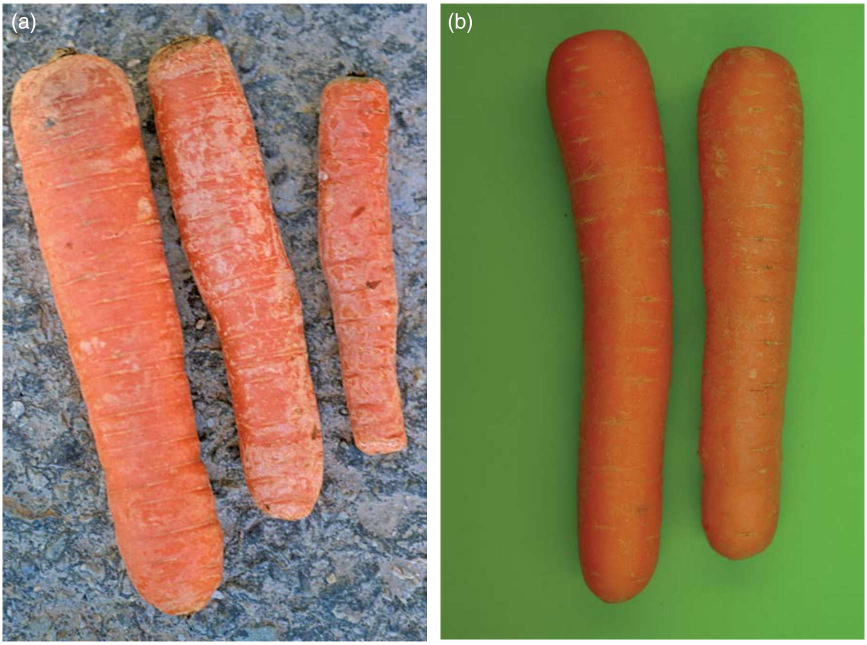

Fig. 13.5. Examples of whitening: (a) whitening generally observed after some months of cold storage; (b) impact of polishers on whitening (left, carrot with polisher; right, carrot without). (Photos by F. Villeneuve.)

works well for whitening observed during cold storage (Fig. 13.5b). However, after this operation it is necessary to keep the carrots in saturated humidity and at low temperature conditions. Various other techniques are used, such as the addition of calcium lactate solutions (Mei *et al.*, 2002; Rico *et al.*, 2007) and the use of microperforated films (Cliffe-Byrnes and O'Beirne, 2007) or edible coatings (Villafañe, 2017). These techniques can also extend the consumption period after processing.

13.2.3 Defects in uniformity of root colouring

The most common defect is a longitudinal band a few millimetres wide, due to a dysfunctioning of the secondary phloem with a growth difference between root secondary phloem and xylem (Kano, 1998). It occurs more often in low temperature conditions and therefore more frequently in early carrots, and there is a variety predisposition. Defects in colouring can also be observed at the base of the roots with white patches. This phenomenon is generally found in young carrots due to a deficit in carotenoid accumulation, and in older carrots stored in the field which have resumed growth.

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13.2.4 Off-colour of carrot crowns (green and reddish purple)

The above-ground root part takes on off-colours ranging from green to bronzed purple under the influence of sun or low temperatures. Both green and red-purple discolorations are considered market defects, although it is easily removed with minimal peeling. However, the greening can occur in internal carrot root tissues, or near cambium tissues between the xylem and phloem. This type of discoloration is highly dependent on variety and the absence is a breeding trait for new varieties.

13.3 PHYSIOLOGICAL DISORDERS RELATED TO PLANT DEVELOPMENT

13.3.1 Yellowing and reddening of foliage

Yellowing and reddening of the foliage are common expressions of dysfunctioning of plant metabolism. They can be attributed to pests and diseases (carrot fly, viruses, phytoplasmas, etc.) or occur due to nutrient deficiencies or blockages (Table 13.2). The most frequent deficiency symptoms depend on boron (Fig. 13.6) and magnesium. Low temperatures can also play a role in the development of these symptoms. For late crops, rapid yellowing of the foliage is often observed. This may be due to a magnesium deficiency.

13.3.2 Early bolting

Bolting is a natural phenomenon that occurs after floral induction by cold conditions. For carrot producers, early bolting during the first root development phase is not without consequences. All bolted roots show excessive hardness. The harvesting machine via the leaf pre-emergence system mobilizes two belts that grip the leaves. The leaves and petioles of an unbolted carrot are smaller in diameter than the flower stalk, which causes the unbolted carrots to slip, falling to the ground and not be collected.

In the case of early carrots from autumn or winter (from October to February in the northern hemisphere), cold requirements can be met and induce early bolting, despite the use of varieties not very sensitive to bolting (high cold requirements). The speed of elongation is all the more important in spring when two parameters are satisfied: plant development before the acquisition of cooling units and a significant amount of cold. Another possible cause is pollution of seed lots by wild carrots, the individuals resulting from these crosses are generally very sensitive to bolting. The work of Villeneuve and Latour

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Table 13.2. Symptoms related to nutrient deficiencies.

Origin of the deficiency	Most frequent symptoms
Nitrogen	Light green foliage then rapid yellowing of old leaves, reduced growth
Phosphorus	Leaves take on a reddish-purple hue from the early stages at the periphery of the leaves. Slower growth. Not to be confused with symptoms of virus attacks (young yellow leaves), or carrot fly attacks
Potassium	The leaves take on a reddish-brown colour, tend to roll up and wilt, and then dry out (starting with leaflets)
Calcium	Necrosis at the tips of the youngest leaves and vegetative bud. Structural degradation of petioles and the appearance of brownish areas. Brown discolorations can be observed in the core of the carrots. Not to be confused with the symptoms of *Carrot yellow leaf virus* (CYLV)
Magnesium	Chlorosis first marked on older leaves, evolving towards drying out
Sulfur	Generalized chlorosis. The veins are also light in colour. Frail appearance
Iron	Interveinal discoloration of the young leaves, while the veins remain green (except in extreme cases)
Copper	Discoloration of young leaves, dieback, lack of copper causes the root to fade
Zinc	Appears first on the youngest leaves, as marbled spots, interveinal chlorosis, stripes or streaks
Manganese	Interveinal yellowing of young leaves. Limited growth
Molybdenum	Similar to symptoms of nitrogen deficiency. Deficient plants lack vigour. Sometimes browning of leaves' perimeter
Boron	Leaves become orange and their growth is reduced. In the most severe cases, the vegetative bud can be damaged. At the root level, a dull brownish colour appears, making them difficult to market

Fig. 13.6. Effect of a boron deficiency on carrot colour (top two) in comparison with a control carrot (bottom). (Photo by F. Villeneuve.)

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(2017) has shown that in the seed-to-seed production system it is possible to have rapid drifts in the sensitivity of seed lots to early bolting. Finally, some phytoplasmas such as *Candidatus* Phytoplasma pruni have the consequence of inducing bolting.

13.3.3 Phytotoxicity

Some herbicides can cause symptoms of phytotoxicity in the form of whitening or reddening. In most cases, this has no impact on performance. On the other hand, some fungicides such as strobilurins will induce a greener foliage.

Fig. 13.7. Early bolting observed in a carrot field. (Photo by F. Villeneuve.)

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13.3.4 Weather-related injuries (frost, hail, heat, lightning, water and wind)

Frost damage can be observed on carrot foliage and root collar. Light frosts will cause the mortality of a few leaflets similarly to aerial fungi damage. These leaflets are very quickly colonized by secondary fungi such as *Alternaria alternata* or *Botrytis*. At the level of the collar, after a few days, small longitudinal cracks appear which quickly turn into rot when temperatures rise or during marketing (Fig. 13.8). When injuries are more severe, the inside of the root looks water-soaked, which darkens upon thawing (for more information see Chapter 7, this volume).

Hail events result in physical damage of leaves. Wounds caused by hail may pave the way for infection by a number of foliar pathogens.

13.4 MECHANISMS OF ADAPTATION TO STRESS

Plasticity to stress is important for biomass growth and yield stability. Abiotic stresses involve, in many plants, the abscisic acid (ABA), ethylene and alternative oxidase pathways, and activate modifications in primary and specialized metabolism. Most of the mechanisms are also found in carrot response to stress, even if a too-limited number of studies have been conducted so far on carrot to draw clear conclusions.

One of the base mechanisms seems to be cell reprogramming by *AOX* genes activated by high temperature or chilling conditions. These genes, mainly *DcAOX1* and *DcAOX2a*, are activated when the stress is applied, as measured by calorespirometry on carrot root meristem, but prior to the induction of response-specific genes (Campos *et al*., 2016).

Antioxidant-related compounds are involved in adaptation to stress. Reactive oxygen species (ROS) play a role as signalling molecules for primary and secondary metabolism induced by stresses. In the case of wound stress,

Fig. 13.8. Small transversal cracks, typical symptoms of frost in the field. (Photo by F. Villeneuve.)

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ROS and ethylene increase after the stress application (Jacobo-Velázquez *et al.*, 2015). However, ethylene and also jasmonic acid are involved indirectly by modulating ROS levels. Ascorbic acid (vitamin C) plays a role in carrot as in many plants by detoxifying free radicals. This antioxidant content increases in the edible part of carrot as a response to salt stress (Bano *et al.*, 2014). Other compounds such as glycine betaine, an osmoprotectant, are also accumulated rapidly in carrot under stress conditions. Conversely, salt stress leads to lipid peroxidation (Bano *et al.*, 2014). Peroxidases are expressed differentially depending on the root tissues, with the highest activity in epidermal tissues, compared with secondary xylem and phloem and moreover primary xylem (Lepeduš *et al.*, 2004). Logically, the epidermal region could be involved in the defence mechanism against stress conditions. However, no clear difference was observed by Perrin *et al.* (2017a) between phloem and xylem tissues in response to water stress.

Heat shock factors (HSFs) are crucial for plant thermotolerance. A first heat shock protein (Hsp17.7) was characterized in carrot by Malik *et al.* (1999). This protein increases in carrot cell cultures at high temperature (42°C) and might actually have a chaperone function. The manipulation of the expression of the corresponding gene leads to the increase or decrease of thermotolerance in carrot. The quite recent publication of the carrot genome has enabled the identification of numerous HSFs in carrot. Interestingly, the number of HSF transcription factors is related to plant evolution, as a possible result of carrot adaptation over time (Huang *et al.*, 2015). Several HSFs are up- or downregulated in response to heat or cold stress. Salt and drought stresses induce the upregulation of several HSF genes. HSFs represent therefore a complex regulatory network for plant resistance to stress.

Pathogenesis-related proteins are another family involved in response to biotic but also abiotic stresses. Thaumatin-like proteins (TLPs) are particularly involved in carrot response to drought stress. Activation of the *DcTLP* gene has been shown in different plant stages (Jung *et al.*, 2005). The underlying mechanism seems to be large and promising as this carrot TLP is not specific to the organ nor the developmental stage.

ABA is usually considered a stress hormone as it plays an essential role in stress signalling. However, its role in carrot response to stress is still largely unknown. Stress-response proteins such as TLP are ABA-independent for drought stress (Jung *et al.*, 2005), whereas Perrin *et al.* (2017b) noticed a significant increase of ABA in carrot roots after water restriction treatments.

Unsurprisingly, many studies highlight the effect of variety, with differences in the activation of genes or metabolism in response to stress.

13.5 VARIOUS EFFECTS OF MAIN STRESSES

Water stress is of increasing concern in some areas. A significant water restriction condition reduces leaf weight and root weight by 47–49% and 25–40%,

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respectively, at harvest (Perrin *et al.*, 2017b). Simultaneously, the root dry matter increases by 12–48%.

Carrot is considered a salt-sensitive crop. Root diameter of carrot increases under saline conditions but yield is reduced (Eraslan *et al.*, 2007). Several enzymatic metabolisms are affected by salt stress and salicylic acid seems to be effective to regulate accumulation of toxic ions but not in the long term. Foliar application of proline enhances plant growth, gas exchange and chlorophyll fluorescence activity, participates in ion balance (K^+ and Ca^{2+}) in root and shoot, and reduces Na^+ concentration in root (Qirat *et al.*, 2018). Carrot is known to accumulate heavy metals in the root, which can translate into stress at a certain level. Carrot response to cadmium stress has been studied *in vitro* (di Toppi *et al.*, 2012) with a biphasic response. In the first phase, cells tend to reduce cadmium movement in the root. Then cell hypertrophy and cell-to-cell separation events are observed which lead to progressive root collapse. However, no symptoms were observed on leaves.

Postharvest handling through transport and packing corresponds to a series of shocks on the product. Such mechanical stress increases ethylene production and carrot respiration, ethanol and 6-methoxymellein content, but reduces total terpenes and sugars content (Seljåsen *et al.*, 2001). Mechanical stress has a major consequence of reduced sensory quality, with higher bitter and earthy tastes and lower sweet score. Adapted practices reduce this effect nowadays but a digital device to monitor all mechanical stresses induced on carrot can help decrease impacts. Some varieties are more resistant than others.

Ozone and acid fog are air pollutants that damage plants. The impact is essentially at the leaf level, reducing the photosynthetic process. Even if not well documented on carrot, these air pollutants can have a significant effect on plant growth.

Most stresses are studied individually whereas carrots can be submitted to several stresses simultaneously in the field. A very few studies combine stresses on carrot: mechanical impedance and water stress on seedlings (Whalley *et al.*, 1999); saline and boron toxicity conditions on carrot growth (Eraslan *et al.*, 2007); and water stress and *Alternaria dauci* infection on biomass and quality (Perrin *et al.*, 2017b). If some kind of additional effects are observed, interactions between stresses are more difficult to investigate. In a cropping system approach and with erratic climate changes, the effect of stress combinations deserves more investigations to adapt cropping techniques and secure production.

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14

Carrot Root Quality

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Carrot is considered a healthy vegetable as it is rich in fibre and antioxidant-related compounds and with a low level of kilocalories. Some compounds are involved in both the nutritional and sensory quality. In most cases, carrot quality is highly dependent on the variety. However, environment conditions and growing practices influence carrot composition significantly. Whether for breeding for product quality or for producing carrots with high and stable quality, such influence needs to be better understood and taken into account.

14.1 DETERMINANTS OF CARROT QUALITY

Carrot is rich in various compounds having health benefits with, for some of them, a relationship with sensory evaluation (Fig. 14.1). Despite their importance, fibre, vitamins and minerals have received little attention compared with other compounds. As a general assessment, major factors affecting these compounds are, in decreasing order of importance: variety, environmental conditions and finally cropping practices, with varying levels of interaction between them.

14.2 INFLUENCE OF GROWING ENVIRONMENT

14.2.1 Area and year of production

It is recognized that growing location modulates the content of bioactive or sensory evaluation-related compounds, including carotenoids and polyacetylenes (Kidmose *et al.*, 2004). The year effect on falcarinol and falcarindiol levels, compounds involved in bitterness perception, appears to be much

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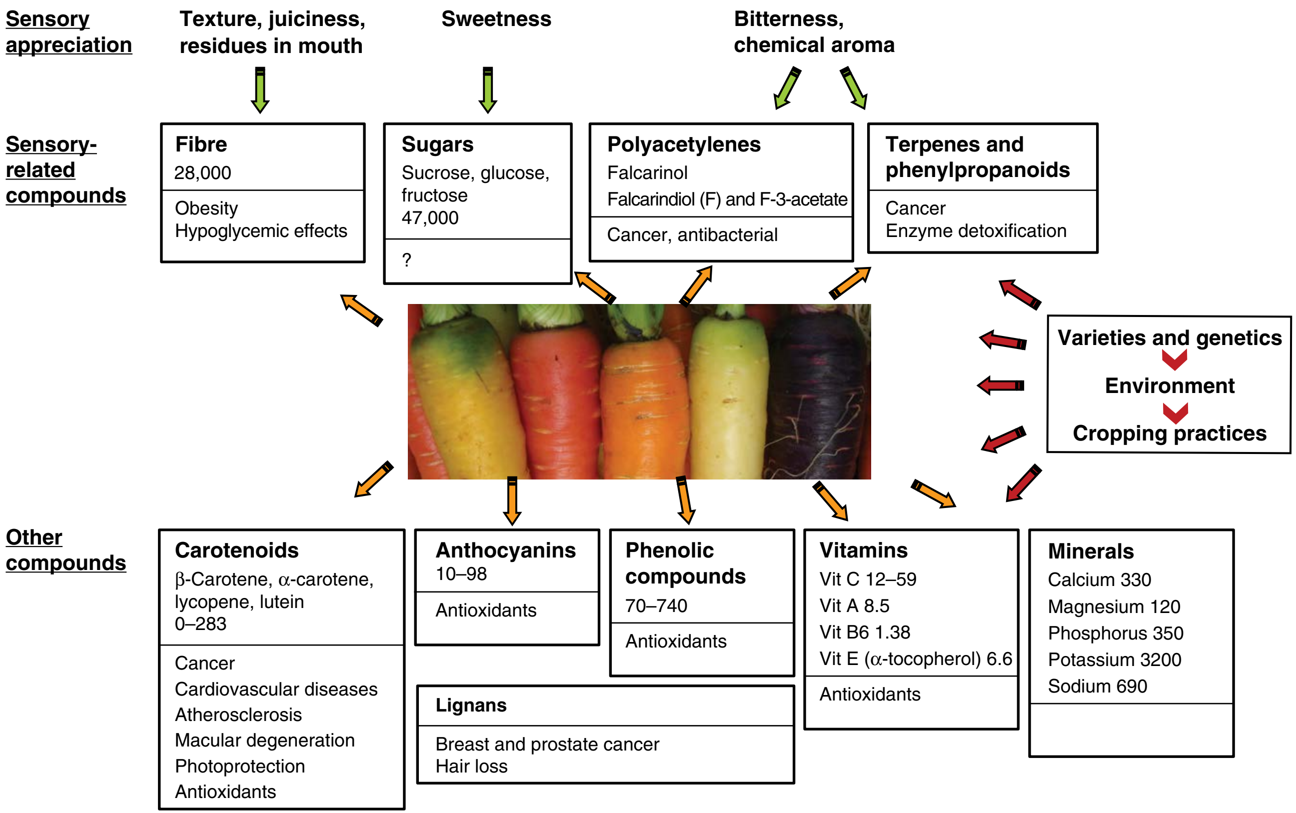

Fig. 14.1. Carrot nutritional, sensory and health matrix (numbers represent reference content or variation in content in mg/kg fresh weight from various sources).

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greater than the location effect (Kjellenberg *et al.*, 2010). However, the location effect (in relation to type of soil or climate conditions) is high on the sensory appreciation of carrot, especially for bitterness, tempered by a year effect (Navez *et al.*, 2017).

14.2.2 Sowing date and crop cycle

Carotenoid content is the quality trait most studied during carrot development. Carotenoid accumulation is continuous from 1.5 months after sowing, in parallel with root growth, then the level decreases after a certain stage of maturity, particularly for carrots stored in the field (Villeneuve and Leteinturier, 1992; Clotault *et al.*, 2008). The sowing period has an influence on carotenoid content of carrot roots: a period favourable to plant growth results in higher contents compared with a more penalizing growing period regarding global radiation and average daily temperature (Perrin *et al.*, 2016). Climatic conditions (global radiation and temperature) are major factors explaining differences between crop cycles (Bach *et al.*, 2015). Northolt *et al.* (2004) pointed out that the chemical compounds in the carrot root respond mainly to the amount of light and time of cultivation (stage) rather than the level of nitrogen. The highest sensory assessment was obtained for carrots grown with increased amount of light.

The levels of the three main polyacetylenes depending on the growing cycle length were monitored by Kjellenberg *et al.* (2010) in Sweden at 103 (very early), 117 (early), 131 (normal) and 146 (late) days after sowing. Falcarindiol levels were highest for the earliest harvest date, lowest with early harvest and then moderate with normal and late harvests. Falcarindiol-3-acetate levels followed the same trend but at much lower levels. However, the duration of the cycle did not have a significant effect on falcarinol content.

Regarding sugar content, Suojala (2000) indicated that the later the harvest, the higher the sugar content. However, this relationship is dependent on the year.

Overall, we can observe three patterns of compound evolution during carrot development, from 58 to 194 days after sowing (C. Aubert, 2013, unpublished results): a decrease (volatile compounds, phenylpropanoids, monoterpenes, glucose and fructose); an increase (sucrose); and a flat evolution but with varying amplitude depending on the compound (sesquiterpenes, acids such as malate and citrate). Vitamin C content decreases sharply 58 and 120 days after sowing and then is relatively stable until 194 days.

14.2.3 Influence of temperature

Temperatures during cultivation can influence the external and internal qualities of the carrot. Thus, firmness, soluble sugar and carotene contents

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are significantly influenced by low temperatures (15/5°C) while aromatic compounds β-pinene and caryophyllene are significantly influenced by higher temperatures (28/20°C) (Manosa, 2011). From a sensory point of view, carrots produced at higher temperatures (24/10 and 28/20°C) are described as bitter, sour, bland and chemical, while those produced at lower temperatures (15/5°C) correspond to sweet and carrot flavours. These results on the effect of temperature are confirmed by another study (Rosenfeld *et al.*, 2002): the best score for sweetness was obtained for carrots produced at low temperature, while the bitter perception, terpene and sugar contents increased with temperature. In that study, temperatures of 18 and 21°C led to higher levels of volatile terpenes which are correlated with a negative sensory appreciation and which actually mask the sweet taste despite the higher sugar content. Only terpinolene decreases with increasing temperature and would therefore not be involved in sensory perception.

Sakamoto and Suzuki (2015) studied the influence of temperature (20, 25, 29, 33°C) of the root zone on the growth and compound content of the root, based on a hydroponic culture system. High temperatures had a significant positive effect on the total polyphenol and soluble solid contents of roots but led to a decrease in water content. The root oxygen consumption increased with high temperatures, which also affected growth of the root and may reflect a stress-like response. However, no significant effects were observed for levels of total carotenoids, α-carotene, β-carotene and anthocyanin.

14.2.4 Soil nature

Although carrot cultivation is generally recommended on light, fresh, sandy to sandy-silty, deep, non-winging, well-draining soils favouring root morphological quality, more heavy and rich soils would allow a better sensory quality. For example, carrots grown on peat soil are scored higher for sweetness and lower for bitterness compared with those on sandy soil (Seljåsen *et al.*, 2012). However, soil type seems to have a lower effect than year and variety. Interactions exist which make it difficult to isolate the soil type influence.

Trace elements are quality compounds that are most often soil dependent. Jansson and Öborn (2000) showed that the nature of the soil had an effect on the cadmium content of carrot: the soil surface pH in relation to high organic matter content as well as the cadmium content of the soil are the best predictors of the presence of this element in carrot roots. More generally, there would be a negative correlation between the soil surface pH (0–25 cm) and the cadmium, nickel and zinc contents in carrots, similar to other crops. Acidification of cultivated soils would favour a decrease in selenium concentration but an increase in other trace elements.

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14.3 INFLUENCE OF GROWING PRACTICES

Cultivation techniques have a moderate effect on carrot quality compared with climate and variety (Seljåsen *et al.*, 2013). Fertilization and irrigation effects have received major attention, both on the quantitative aspect and application methods.

14.3.1 Soil preparation

Soil compaction can affect the absorption of mineral elements, but Pietola and Salo (2000) concluded that soil type and condition as well as climatic conditions have a much more significant influence than tillage on the potassium, phosphorus and magnesium contents of carrot roots.

Type of soil preparation may have an effect on carrot quality when comparing various preparations even if this effect is probably minor compared with the above ones. Evers *et al.* (1997) showed in Finland conditions that on flat soil configuration, carrots produced more glucose and fructose than those on ridges, when at high plant density. Carrots grown on narrow ridges (25 cm) produced more fibre and vitamin C than on broad ridges (75 cm). Finally, at low plant density, flat land and wide ridges produced more β-carotene. In a similar approach comparing flat land and ridges, no significant effect was observed on carrot dry matter content, while cultivation on ridges led to a reduction in root nitrogen content (Dyśko and Kaniszewski, 2007). Competition effect between plants and water availability depending on the type of ridge need to be investigated to understand the soil preparation influence.

14.3.2 Nitrogen fertilization

Carrot responds well to nitrogen fertilization with a well-known positive effect on yield but also on dry matter content (Haque *et al.*, 2014). Nitrogen input has a dramatic effect on main metabolism as shown by the impact on sucrose and carotenoid contents. Actually, the impact on sugar level seems contradictory depending on studies. With a moderate range of nitrogen input (from 0 to 60 kg/ha), Sandhu *et al.* (1988) showed a positive effect on soluble sugar content whereas others observed higher sucrose (Schaller and Schnitzler, 2000) or total sugars (Hogstad *et al.*, 1997) with lower nitrogen doses or no relationship (Gajewski *et al.*, 2010). There seems to be an optimum for nitrogen input regarding sugar content, maximized with 140 kg N/ha, but all varieties do not react the same (Hochmuth *et al.*, 1999).

Results are more consistent concerning the positive effect of nitrogen on carotenoid content (Freeman and Harris, 1951; Evers, 1989; Hochmuth *et al.*, 1999). The higher the better: the highest level of carotenoid was

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obtained with inputs of 160 kg N/ha (Hochmuth *et al.*, 1999) and 175 units of N in our own studies (Fig. 14.2). The effect is noticeable on β-carotene and total carotenoid contents but not on α-carotene. Contrary to sugars, the fertilization × variety interaction seems insignificant (Hochmuth *et al.*, 1999). The interaction with other fertilizer elements such as phosphorus can reduce the nitrogen effect (Evers, 1989). According to Leclerc *et al.* (1990), organic nitrogen fertilization results in a 12% gain in β-carotene content compared with mineral fertilization, while Bourn and Prescott (2002) did not find any difference.

Nitrogen has a negative impact on essential oil content (Schaller and Schnitzler, 2000) and overall flavour but decreases crunch perception

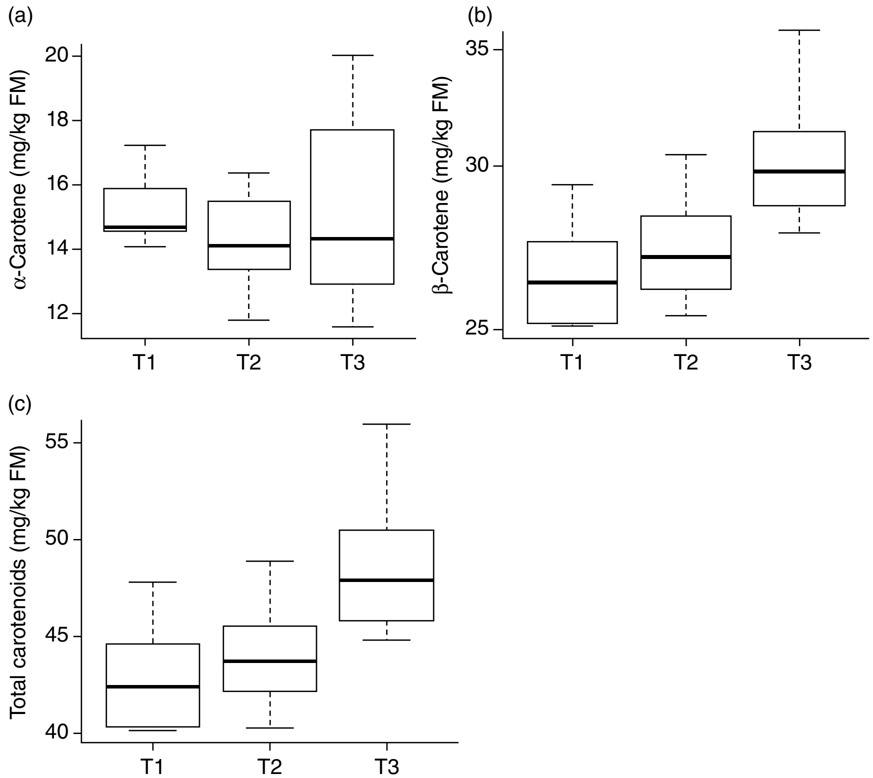

Fig. 14.2. Effect of nitrogen application on carotenoid content of carrot roots in mg/kg fresh matter (FM): (a) α-carotene; (b) β-carotene; and (c) total carotenoids. Box-and-whisker plots where the bottom and top edges of the box represent the first and third quartiles (interquartile range); the line within the box represents the median; and the bottom and top whiskers represent the minimum and maximum values. T1, nitrogen residues only, 19 units; T2, residues + 25 units at planting time + 3 × 35 units; T3, residues + 25 units at planting time + 3 × 50 units.

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(Hogstad *et al.*, 1997). Nitrogen input increases root nitrogen content with the highest content at 120 kg N/ha but it decreases over time when delaying the harvest date, and carrot juice colour would not be affected by nitrogen fertilization (Gajewski *et al.*, 2010).

Nitrogen supply represents a dilemma with its dual effect on environmental and human health. However, no study has addressed the issue in a completely systemic way, while other components of the cropping system may affect carrot response to nitrogen supply.

14.3.3 Other fertilizing elements

Potassium fertilization shows no effect on sugar and carotenoid contents, perhaps due to already sufficient soil levels (Freeman and Harris, 1951; Hochmuth *et al.*, 2006). The addition of boron and calcium is practised to improve the internal physical quality of carrot roots but comes at the expense of reductions in carotenoid and vitamin C contents (Singh *et al.*, 2012), suggesting that a balance needs to be found.

14.3.4 Influence of water supply

Several studies show that increased water supply reduces the carotene content, which may be due to a dilution effect (Ombódi *et al.*, 2014; Zeipiņa *et al.*, 2014). On the contrary, water stress seems to have no or a variable effect on carotenoid and sugar contents (Sørensen *et al.*, 1997; Perrin *et al.*, 2017).

The mode of water supply may have an effect: sprinkler irrigation achieved better yield but also higher carotenoid content compared with a drip system (Zeipiņa *et al.*, 2014), whereas sprinkler spacing did not affect root nitrogen content (Mitchell *et al.*, 2000).

14.3.5 Effect of cover crops

Eco-friendly practices are recommended such as cover crops or stubble crops. They have to be used carefully before implanting carrots as they can lead to root morphological defects if not sufficiently decomposed. However, this practice may have a positive effect on the crop quality, as the use of phacelia and spring vetch/field pea mixture led to an increase in dry matter, ascorbic acid and carotenoid contents but no effect on total sugar content (Kwiatkowski *et al.*, 2013). These same cover crops had a significant positive effect on the root content of macroelements (phosphorus, potassium, calcium, magnesium, sodium), nitrates and total phenolic compounds but no effect on nitrogen content (Kwiatkowski *et al.*, 2015).

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14.3.6 Effect of growth stimulators

Kwiatkowski *et al.* (2013, 2015) have studied the effect of foliar applications of three growth promoters on carrot yield and quality. These substances had no significant effect on dry matter and carotenoid contents, but they did have a significant positive effect on contents of sugar, total phenolic compounds, ascorbic acid and some macroelements (magnesium, sodium). More generally, these substances increased total and commercial yield.

14.3.7 Other growing practices

Sandhu *et al.* (1988) compared different methods of weed control and their effect on carrot quality. They showed a clear positive effect of weeding on carotenoid and soluble sugar contents and sensory evaluation compared with the unweeded control. This can be easily explained by competitive phenomena. Herbicide product and stage of application may play a role, but herbicide dose does not seem to have significant effect on quality traits.

The effect of protection plastic films in early production would be interesting to measure, as well as the use of nets or protective sails used particularly against carrot fly in organic production. The plant microclimate modification could influence root quality through the possible presence or control of stresses.

14.4 COMPARISON OF CROPPING SYSTEMS

No consistent effects are found among studies when comparing organic and conventional cropping systems. Some studies show that organic systems result in lower levels of vitamin C and phenolic compounds, but higher contents in the protein, oil and mineral elements. In the absence of plant protection products, Bender and Ingver (2012) found higher content of vitamin C but no difference in sugar composition. However, these comparisons are delicate since many factors vary and may explain the effects, such as nitrogen availability. With an equivalent amount of nitrogen provided to the crop, lower amounts of nitrogen, manganese and copper but higher amounts of sulfur and boron were observed in organic conditions (Warman and Havard, 1997). However, effects were not consistent between years. Their results indicated a decrease in β-carotene content in organic agriculture, while other authors did not observe any differences (Bourn and Prescott, 2002).

Wrzodak *et al.* (2012) found sensory differences, but only for one year out of the two tested: root juiciness, hardness, sweetness and carrot taste were superior in organic carrots. The study by Paoletti *et al.* (2012) offers a more comprehensive system approach using a multivariate method. They observed no

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clear difference in quality between the two cropping systems, due to repeated effects within each system and season or year effects. More recently, Bach *et al.* (2015) confirmed in a three-year study that nutritional and sensory quality of organic and conventional carrots are equivalent; climatic conditions (global radiation and temperature) playing the major role. With a similar product quality, it can be assumed that organic carrots are produced in a more sustainable way.

14.5 EFFECT OF STRESSES ON QUALITY

Several types of stresses can have an impact on carrot root composition and therefore its nutritional or sensory quality (Table 14.1). Water, temperature and salt stresses are the most studied ones. Overall, stresses tend to increase bitterness-related compounds such as terpenes and 6-methoxymellein and have limited impact on sugar and carotenoid contents. Among nutritional compounds, vitamin C is the most negatively affected by stresses. Only the effects on levels of other compounds, rather than on those applied, are recorded in Table 14.1; but, as a general trend, the addition of a chemical compound as a stress leads to the increase of this compound in the carrot root, as is the case for sodium, boron, cadmium and zinc.

Anthocyanin content is a critical trait for purple carrots. Many studies have dissected the effects of stresses on anthocyanin content and the corresponding pathway, but only on cells in *in vitro* conditions.

However, as carrot is potentially subject to several stresses in the field, it is valuable to study the effect of combined stresses. For example, both boron and salt stress have a significant negative impact on ascorbic acid content in carrot root, the effect being slightly higher for boron (Eraslan *et al.*, 2007). However, the combined application of these stresses led to an intermediate level of ascorbic acid, not significantly different from the control. In a combined application of biotic (*Alternaria dauci* infection) and abiotic (water restriction) stresses, Perrin *et al.* (2017) showed that the combination resulted in a significant reduction in carotenoid and sugar contents, enhancing slightly the effect of the major stress (*A. dauci*).

14.6 MONITORING CARROT COMPOSITION

In most cases, the above knowledge is used to maintain the quality potential of a crop and to avoid a possible negative effect of a given technique. Postharvest, anoxia and ethylene are known to decrease the sensory quality of carrot but increase phenolic compounds. However, specific conditions or stresses could be used to monitor the nutritional or sensory quality of carrot. Only a few studies target field application, most are applied in postharvest conditions.

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Table 14.1. Effect of various stresses on carrot root composition and sensory perception.

Type of stress	Stress	Effect on carrot root content	Reference
Agronomic stress	Water	↑ sugars (FW)	Kovacs *et al*. (2007)
		= sugars, nitrate, vitamin C, β-carotene, dietary fibre (FW)	Sørensen *et al*. (1997)
		= carotenoid, sugar (DM)	Perrin *et al*. (2017)
		↓ polyacetylenes, falcarinol, falcarindiol and falcarindiol-3-monoacetate (FW)	Lund and White (1990)
	Salt	↑ nitrogen (DM)	De Pascale and Barbieri (2000)
		↓ ascorbic acid (FW)	Eraslan *et al*. (2007)
		= carotenoids (FW), antioxidant activity	
	Boron	↓ ascorbic acid (FW)	Eraslan *et al*. (2007)
		= carotenoids (FW), antioxidant activity	
Climatic stress	Cold	↑ sugars FW	Kovacs *et al*. (2007)
	High temperature, field	↑ terpenes, β-pinene and caryophyllene (FW)	Manosa (2011)
		↑ bitterness	Rosenfeld *et al*. (2002)
	High temperature, root zone	↑ phenols (FW) = carotenoids (FW)	Sakamoto and Suzuki (2015)
	Hail damage	↑ isocoumarin, 6-methoxymellein, organic acids and total phenolics (DM) = carotenoid or sugar (DM)	Talcott and Howard (1999)
		↓ sweet perception, ↑ bitterness	
Biotic stress	*Alternaria dauci* inoculation	↓ carotenoid, sugar (DM)	Perrin *et al*. (2017)

↑, increase; ↓, decrease; =, no effect; FW, content related to fresh weight; DM, content related to dry matter level.

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Through fertilization with specific compounds, carrot biofortification could be achieved. Fertilization with iodine and selenium decreases root nitrate content without affecting yield and total sugars and could be used to favour iodine and selenium uptake, enabling consumers to meet daily allowances (Smoleń *et al.*, 2016). A striking example is etephon foliar application during plant growth which increases anthocyanin content by 25% in purple carrot (Barba-Espín *et al.*, 2017), but it requires regulation approval for industry use.

Postharvest stresses alone or combined can be used to enhance specialized metabolism and design food products with increased content in metabolites: wounding stresses (cutting, shredding), postharvest water stress and hyperoxia storage can be used to increase dramatically the content of phenolic compounds and total antioxidant capacity. Reactive oxygen species play an essential role as signalling molecules in this process.

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15

Cold Storage of Carrots

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The long-term cold storage of carrots is easier than for some crops, because the carrot is a biennial plant that is grown as an annual. The plants store carbohydrates in the root and, when allowed to overwinter, go into a period of low metabolic activity to survive the unfavourable weather. The crop is harvested at the end of the first season of growth, when the storage root is the appropriate size for the intended market. Mature roots are best suited for long-term cold storage. A study in Finland found that mature roots harvested in late September or early October stored better than carrots that were harvested earlier in the growing season (Suojala, 2000). Sugar content and composition varied with year and growing season and were not an indicator of physiological maturity.

15.1 DIFFERENT APPROACHES TO LONG-TERM STORAGE OF CARROTS

Storage methods and the period between harvest and marketing vary among regions of the world (Lewis and Garrod, 1983). In regions with cool winters but where the soil does not freeze, mature carrots can be left in the ground with the tops covered with straw (Fig. 15.1). A layer of polyethylene film may be applied over the carrots before the straw is spread. In some production systems the carrots are covered with straw, polyethylene tarp and then more straw. The straw protects the foliage from frost damage and the ground and roots from freezing, if temperatures drop below 0°C. This is common practice in many parts of the UK, for instance. This method is less costly than refrigerated storage, but there are higher risks if the weather becomes very cold or if wet weather delays the harvest in the spring (Snowdon, 1992). In many regions of the world where carrots are kept in cold storage, roots can be stored in large piles in bulk bins, or

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Fig. 15.1. Carrot storage in the ground with tops covered by straw, Normandy France. (Photo by E. Geoffriau.)

in wooden or plastic (Fig. 15.2) pallet boxes, for up to 9 months (van den Berg and Lentz, 1966; Fraser and Chaput, 1998).

15.2 OPTIMUM STORAGE CONDITIONS

The recommended conditions for long-term storage of carrots are constant temperature of 0–1°C and 95–100% relative humidity (Salunkhe and Desai, 1984). Other researchers recommend saturated air (98–100% relative humidity) (van den Berg and Lentz, 1973). 'One of the worst things that can happen to carrots in storage is that they dry out' (Fraser and Chaput, 1998). A carrot will lose moisture as long as it is warmer than the surrounding air. Tests on other produce have shown that most of the moisture loss occurs within the first week of storage, and this is most likely the case for carrots also. Thus, rapid cooling and very high relative humidity are essential for successful cold storage (Fraser and Chaput, 1998). The goal is to achieve the highest relative humidity possible without free water condensing on the surface of the carrot root. Free water promotes the development of fungal diseases on carrots and can prevent normal respiration. The optimum temperatures are sometimes reported as 0–2 or 3°C. In practice, the temperature will vary in different

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Fig. 15.2. Carrots in plastic pallet boxes. (Photo by M.R. McDonald.)

sections of a cold storage and carrot roots can withstand temperatures slightly below 0°C without sustaining damage. Cold temperatures are very important, since there is twice as much metabolic activity at 5°C as at 0°C. The high humidity not only maintains quality by preventing moisture loss from the roots, but also reduces invasion by plant pathogenic fungi (Snowdon, 1992) as discussed below. Cold, saturated storage conditions also prevent the regrowth of the shoots and avoid the development of bitter compounds that are induced by ethylene. The bitter taste that develops in carrots that are exposed to ethylene (7–10 μl/l) is the result of 6-methoxymethellein and other phenolics (Kramer *et al*., 2012). Terpenes and polyacetylene volatiles are not strongly associated with ethylene-induced bitterness, but these compounds do contribute to baseline bitter flavours in carrots.

15.3 STORAGE FACILITIES

The most common facility for the long-term storage of carrot is the insulated and refrigerated storage shed that utilizes ventilated ambient air combined with refrigeration and fans for air circulation. High relative humidity is maintained with misters that provide a fine mist of water near the fans or in a plenum where the temperature and moisture are adjusted before the air enters the storage. Carrots are generally stored in side-slatted wooden pallet boxes or bins. These are usually about 122 cm × 122 cm × 91 cm high and hold about 570 kg of carrots. The bins have a two- or four-way forklift entry at the bottom, so they can be moved and stacked. The useable volume is about 1 m^3 (Fraser and Chaput, 1998). These bins are usually constructed from hardwoods, such

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as oak, and can last for several decades. They are easy to repair but do absorb moisture and are difficult to clean or sanitize. Some growers use plastic bins that are approximately the same size. These do not absorb water, are easier to wash and are lighter, so can be stacked higher. However, these are more expensive to purchase and more difficult to repair, so are not as widely used for long-term storage. Plastic bins may be lined with plastic and used for short-term storage or washed carrots.

Refrigeration units, vents for outside air and humidifiers are located near the top of these storages, as cold air falls. Careful placement of the bins is needed to ensure that the cold, humid air circulates through all of the carrots. They need to be stacked tightly together with the forklift openings in line and in the direction of the airflow from the refrigeration units. If air moves around, and not through the bins, then the temperature of the carrots in the centre of a bin will increase, reducing quality and predisposing the carrots to disease.

The other popular approach to storing carrots is in bulk piles. The carrots can be piled up to 4.9 m without physical damage to the carrots at the bottom of the pile (Fraser and Chaput, 1998). Bulk storage can be up to 40% more efficient in use of space, as there is no room taken up by the bins. The air is usually cooled and humidified in a plenum and then distributed throughout the storage by ventilation pipes (often metal culverts) located under the pile at intervals. In addition to utilizing space more efficiently, the bulk storages can be filled or emptied quickly using a bucket loader or water flume. The temperature and humidity are more evenly distributed within the pile with the plenum and under-pile distribution of air. The basic design of carrot storages has not changed much in decades, but there have been improvements in the engineering of controls and sensors to monitor the storages and alert growers to changes in temperature.

Carrots are usually washed (Fig. 15.3) prior to bulk storage in piles or in plastic pallet boxes, and usually stored unwashed in wooden pallet boxes, but this varies depending on individual grower practices. Washing the carrots has the advantage of removing any soil or foliage and it is easier to see decay and defects if the carrots are graded after washing and prior to storage. Washing can cause some damage to the periderm of the storage root, which provides points of entry for pathogens and may increase moisture loss. However, washing in cold water can provide some hydrocooling of the crop. Washed carrots are often treated with chlorine and/or a fungicide (where registered) to prevent decay in storage. Concentrations of chlorine between 50 and 100 ppm are recommended, but local guidelines and regulations may vary. The pH of the solution must be maintained between 6.5 and 7.0 for optimum effect. If the wash water is chlorinated, then it must be kept relatively clean as chlorine quickly binds to organic matter and becomes ineffective.

Two other systems that have been used for the long-term storage of carrots are the 'Filacell' system and 'jacketed' storages (Raghavan *et al.*, 1980).

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Fig. 15.3. Carrots being washed before entering the packing station. (Photo by E. Geoffriau.)

Both have been shown to provide excellent environmental conditions and reduce moisture loss in storage, but over time most commercial operations have decided that the extra cost is not justified for the storage of carrots. The Filacell storage remains in use for other types of perishable produce, such as leafy greens. In short, the Filacell storage provides saturated air at cold temperatures by moving air through chilled water into the storage room. Ice water is sprayed on filaments and as the water moves down, air is pushed upward and through the filaments before entering the storage room. Air exiting the storage is recirculated through the filaments. The Filacell storage system has been used successfully for storing carrots for research purposes, and carrots can be maintained in good condition for at least 10 or 11 months.

The ‘jacket’ or ‘jacketed’ storage was popular for a period of time in Canada. In this type of storage system, the cooling coils are located outside the storage room and cold air is circulated through a small enclosed space on all sides of the storage room. Thus, the cold air does not come into direct contact with the carrots. The relative humidity in the room is controlled separately. Jacketed storages are designed to allow direct circulation of air through the stored product for precooling. Schematic designs showing the specific components and direction of airflow are provided by Raghavan *et al.* (1980).

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There are some conflicting reports in the literature about the value of controlled atmosphere (CA) storage for carrots. A trial in Latvia reported highest quality carrots when they were stored in CA storage set at oxygen levels of 7–13% and carbon dioxide between 3 and 5% (Lepse *et al.*, 2014). However, other work on CA storage found that it contributed to higher decay (van den Berg and Lentz, 1966). The trial conditions vary considerably from report to report. In practice, there is very little commercial CA storage for long-term storage of mature carrot roots. A well-designed refrigerated storage can be as effective and more economical.

15.4 FACTORS TO IMPROVE STORAGE LIFE OF CARROTS

The first step in effective long-term cold storage of carrots is to minimize damage during harvest and to remove any broken or damaged carrots prior to storage. Removal of most of the soil and any foliage adhering to the roots is important. Carrots may be washed and then graded to removed damaged or otherwise unmarketable carrots before storage in bulk piles or plastic bins. Carrots that are stored in wooden pallet boxes are stored unwashed. The foliage is removed by rotating metal discs on the harvester and falls back on the field. The carrot roots may be moved over a 'dedirter' conveyor belt with rubber protrusions that rotate and jostle the carrots to remove excessive soil and any foliage adhering to the carrot roots. Some grading of damaged and unmarketable carrots is often done by someone standing on the harvest equipment during the harvest process. The unmarketable carrots are usually dropped back on the field. Growers often wait until soil temperatures are cool or cold, late in the autumn, prior to harvesting carrots, to have cold carrots going into storage. This reduces the energy needed to cool the carrots following storage, but is a balancing act. Frosting or freezing damages the foliage, which can make harvesting difficult. A strong freeze could damage the roots in the field and snow could interfere with the harvesting process.

15.5 FUNGAL PLANT PATHOGENS IN LONG-TERM STORAGE

The main losses in storage are caused by the loss of moisture and by decay caused by fungal plant pathogens. The most damaging pathogens are *Sclerotinia sclerotiorum* (Lib.) de Bary, the causal agent of white mould of carrots, which is also called Sclerotinia rot of carrot. Two other problem pathogens are *Mycocentrospora acerina* (Hartig) Deighton, which causes the disease 'liquorice rot', and *Botrytis cinerea* Pers. ex Fr., which causes grey mould on a wide variety of plants, including carrots in storage. Another pathogen which can infect carrots and spread in storage is *Rhizoctonia carotae* Rader (sexual stage *Athelia*

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arachnoidea (Berk.) Julich), the cause of crater rot (Lewis and Garrod, 1983; Snowdon, 1992). Infections by *R. carotae* were sometimes called 'cavity spot' in the literature, thus causing confusion with the disease, cavity spot, caused by *Pythium* species especially *P. violae* and *P. sulcatum*.

The steps to take immediately after harvest can depend on which carrot pathogens are prevalent in the crop or are expected to develop. Effective long-term storage of carrots usually depends on rapid cooling of the crop as it is placed in storage, in addition to the maintenance of constant cold temperatures over time. This is especially important for the suppression of *S. sclerotiorum*. The rate of cooling in storage is dependent upon three factors: the temperature of the carrots at harvest, the rate that the crop is loaded into the storage and the cooling efficiency of the storage (Pritchard *et al.*, 1992). These authors demonstrated that bulk carrots in piles in commercial refrigerated storages took 75 days to cool from 6°C, the temperature of the carrots when harvested and placed in the storage, to 1°C.

In situations where the major storage pathogen is *M. acerina*, a brief period of 'curing' the roots at warm temperatures and high relative humidity is recommended, to promote wound healing. Wound repair can be stimulated by exposure to warm (25°C) temperatures for a period of 12 h prior to cold storage (Garrod *et al.*, 1982). This treatment promotes lignification and suberization in the root and sometimes the formation of callus. Low storage temperatures reduce the rate of wound healing and suberization in carrot (Garrod *et al.*, 1982).

S. sclerotiorum is usually the most destructive disease of carrots in cold storage and losses have been reported of at least 30–50% in regions of Canada (Finlayson *et al.*, 1989). The disease is also called cottony soft rot. White cottony fungal threads (mycelium) form on the carrot roots and a soft watery rot develops underneath. Over time, hard black survival structures (sclerotia) form on the roots amid the white mould. The disease in stored crops is largely a consequence of infections that start in the field (Finlayson *et al.*, 1989). However, despite extensive research on the epidemiology of Sclerotinia rot in stored carrots, no method has been developed to predict disease development and yield loss during storage. No correlation has been found between disease incidence before and after harvest (Geary, 1978; Kora *et al.*, 2005). A high preharvest disease incidence does not consistently correlate with a high postharvest disease incidence, whereas a low preharvest disease incidence can result in high levels of postharvest infection. This may be due to host responses that prevent mycelium from leaf and petiole infections entering the root. Also, there can be latent infections in the crown (Finlayson *et al.*, 1989; Foster *et al.*, 2008) that will begin to grow and produce symptoms. Infection can occur quickly if infected foliage comes into contact with roots in storage, even at cold temperatures. Carrots may have some defence against infection of the crown by *S. sclerotiorum* while in the field but there was no defence reaction in storage and the disease progressed quickly from infected roots (Foster *et al.*, 2008). Once an infection by *S. sclerotiorum* begins to develop, the fungus produces heat and

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moisture which contribute to further growth. The fungal mycelium can grow from an infected carrot to adjacent healthy roots, creating a mass or 'nest' of infection (Fig. 15.4). One reason that growers prefer to store carrots in wooden pallet boxes is that this may contain an outbreak to a single box, whereas an entire storage room could be lost to *Sclerotinia* infection if the carrots were stored in a bulk storage. Pritchard *et al.* (1992) demonstrated that rapid cooling of carrots to 1°C within 6 h, as compared with 72 h, reduced the amount of *Sclerotinia* infection from about 80% of carrots diseased to about 20%. Higher disease after 15 weeks in storage was strongly correlated with a longer length of time to cool the carrots (Pritchard *et al.*, 1992).

Lesions caused by *M. acerina* (Hartig) Deighton and *B. cinerea* Pers. ex Fr. are dark and sunken, and mycelium and spores may develop under humid conditions. The lesions remain localized early in the storage period but begin to enlarge after 4 to 6 months at 2°C and cause severe rotting even at low temperatures (Lewis and Garrod, 1983). The fungus does not spread from root to root in storage. Lewis and Garrod (1983) suggest that the changes in a carrot root which make it more susceptible to progressive infection by this and other pathogens coincide with the phase in the biennial cycle of the plant when growth of new shoots develops and this change might be considered an indication of root senescence.

Infection of carrot roots by *B. cinerea* can result in dark, relatively small lesions with no mycelium or sporulation; or, in susceptible carrots and favourable conditions, the infection can progress to cause extensive rotting with white mycelium and the characteristic grey sporulation. The fungus can infect neighbouring roots and the air-borne spores can move throughout the storage and cause further infections on roots without an intact periderm.

Fig. 15.4. Sclerotinia rot of carrot spreading in a bulk storage. (Photo by M.R. McDonald.)

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The fungus can infect and rot carrots at temperatures as low as 0°C (Snowdon, 1992). The change from localized to progressive infection by *B. cinerea* has been attributed to a decline in the ability of carrot tissue to accumulate the phytoalexin, 6-methoxymellein (Goodliffe and Heale, 1978). An increase in the susceptibility of carrots to *B. cinerea* in storage has been associated with water loss of more than 5% (Tronsmo, 1989). This increase in susceptibility was also correlated with a decrease in the potential to accumulate 6-methoxymellein (Heale *et al.*, 1977).

Crater rot develops as white mycelium on infected carrot roots, which can appear somewhat similar to the symptoms of white mould. Small areas of white mycelium appear on the roots and sunken, soft lesions (craters) develop underneath. This fungus can also develop at temperatures close to freezing; high humidity and free water on the roots contribute to disease development (Snowdon, 1992).

Mould and other signs of fungi can sometimes be seen on wooden pallet boxes, and disinfection of the boxes and storages is recommended (Rubatzky *et al.*, 1999) but is not a very common grower practice. Growers sometimes alternate boxes between carrots and onions, and some believe that leaving them outside in the sun over the summer provides a certain amount of control of fungi. A study was conducted to determine if the fungi remaining on wooden pallet boxes represented a risk to carrots when the boxes were reused, and also to determine the ability of the fungal carrot pathogens to colonize the wood of the bins (Kora *et al.*, 2005). Wooden boxes from four commercial storages, with obvious fungal growth, were sampled. Ten different fungal species were recovered, but *B. cinerea* and *R. carotae* respectively made up only approximately 5 and 7% of the isolates that were recovered. *S. sclerotiorum* represented less than 2% of the fungal genera that were isolated. These three pathogens were able to cause lesions on washed, intact carrots under cold storage conditions (4 ± 1°C and 100% relative humidity). Disinfecting these large boxes can be difficult. It is important to remove soil and plant debris from boxes after use. Growers should avoid using visibly infested boxes for storage of carrots. Using these for onions may be a reasonable solution, since onions are stored at low relative humidity and dry onion bulbs are less susceptible to infection by these fungi.

15.6 OTHER FACTORS AFFECTING CARROT QUALITY IN STORAGE

Quality problems of carrots in long-term cold storage can develop under conditions of 'wet chilling storage' when carrots are stored at 0°C and the relative humidity is 90–92% (Den Outer, 1990). The outer layers of the storage root, the periderm or 'skin', lost brightness, probably as a result of a certain amount of desiccation. The author recommended spraying carrots with a vegetable oil

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emulsion or raising the temperature to 4 or 8°C to allow the roots to form a new layer of periderm cells to seal moisture in the root. This is a further indication that very high relative humidity is needed in cold storage to preserve the quality of the roots. A physiological condition of the surface known as 'silvering' may develop after several months in cold storage, even if conditions are optimal. This condition can be reversed if the carrots are rewashed or otherwise moistened prior to packaging (Snowdon, 1992).

15.7 METHODS TO IMPROVE STORAGE OF CARROTS

Non-ionizing ultraviolet (UV-C) radiation can effectively elicit the accumulation of the antifungal phytoalexin, 6-methoxymellein, in carrot roots and hence induce systemic resistance to subsequent infections by *S. sclerotiorum* (Mercier *et al.*, 1993). Treatment with UV-C radiation at a dose of 2.20×10^5 erg/cm^2 induced accumulation of 6-methoxymellein to maximal inhibitory levels (e.g. 60 μg/g) and reduced the growth of *S. sclerotiorum* on carrot slices incubated at 1 or 4°C. However, integration of ultraviolet treatments with other control strategies is recommended for a prolonged protective effect (Mercier *et al.*, 1993) and has never been adopted in commercial practice.

Ozone has demonstrated fungistatic effects on *S. sclerotiorum* and was proposed as an alternative disinfectant for stored carrots (Liew and Prange, 1994). Treatments with gaseous flow of ozone reduced the daily growth rate of *S. sclerotiorum* on inoculated carrots by about 50%. However, ozone concentrations of 60 μl/l in air caused significant physiological disruptions, including increased respiration rate, electrolyte leakage and discoloration of carrots. Therefore, an ozone supply of 15 μl/l for 8 h daily at 2°C was recommended as the optimum concentration to suppress disease without any negative effects on carrot quality. Since ozone has to contact the pathogen to have an effect, very good air movement within the storage and around each carrot is essential for efficacy. Some growers in Ontario, Canada, experimented with ozone generators in cold storages to try to get better control of carrot diseases. While working to improve the air circulation in the storages, the growers came to the conclusion that improving air circulation was just as effective as adding ozone to the atmosphere in the storage. Introducing adequate amounts of outside air to the storage on a regular basis was the key to optimum storage conditions. There were also some worker exposure concerns about entering and working in a storage with ozone in the air.

15.8 CONCLUSION

Carrots can be stored effectively for 6 to 8 months or longer in cold storage when they are cooled quickly and kept at constant temperature at or just

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above freezing and at very high relative humidity. Losses in long-term storage are generally the result of moisture loss and fungal infections. In general, advanced technologies for storage of horticultural crops, such as CA storage and ozone, are not needed or are not economically viable.

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16

Organic Carrot Production

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16.1 THE ORGANIC CARROT MARKET

Organic carrot production in the USA and Europe comprises a significant proportion of total carrots produced, reflecting the high demand of organic consumers for both fresh and processed carrot products. While organic carrot growers face many of the same challenges as their conventional counterparts, the limiting factors influencing yield and quality may differ as well as the allowable inputs and management practices. Thus, organic systems often warrant research and development specifically for the organic sector. Public research and extension programmes have expanded efforts in recent years to address organic production challenges, provide more information resources to growers and bolster market opportunities (Navazio, 2010; Seaman, 2016; Simon *et al*., 2017). Seed companies and a few public breeding programmes are also working to develop new varieties with traits that fulfil organic producers' needs and address the gap in supply of organically produced carrot seed (Simon *et al*., 2017; Herstatt, 2018).

The organic sector is one of the fastest-growing segments of agriculture with 125% growth over the last 10 years in Europe and the USA. Organic markets reached nearly US$50 billion in the USA as of 2017, and over €27 billion in Europe with over €81 billion globally as of 2015 according to the US-based Organic Trade Association (OTA) and the European-based Research Institute of Organic Agriculture (FIBL) and International Federation of Organic Agriculture Movements (IFOAM) (Willer and Lernoud, 2017; OTA, 2018). Fruits and vegetables comprise the largest market segment in the USA at US$16.5 billion in 2017 (OTA, 2018). In several European countries fruits and vegetables also account for about 20% of the national organic market and carrots are frequently a leading contributor to the organic vegetable segment (Willer and Lernoud, 2017; Herstatt, 2018).

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Organic consumers are commonly driven by the expectation that organically grown foods are more nutritious and grown with less environmental impact than conventionally produced foods (Reeve *et al.*, 2016). Organic eaters also prioritize nutrition, flavour and fresh eating qualities in vegetables, and carrots are widely known for these benefits (Lotter, 2003; European Food Information Council, 2013). Popularity for nutritional health benefits and ease of fresh raw consumption of carrots, particularly favourable for children, are key reasons why organic carrots hold a significant portion of the total carrot market. In recent years the organic market has also led the trend of novel carrot colours, including purple, yellow, red and white, and multicoloured, growing in popularity as 'rainbow carrots' among chefs and organic grocers (Fig. 16.1).

US organic carrot production reached US$88 million sales value in 2016, with over US$59 million from California alone. Sales of organic fresh market carrots including packaged 'baby' and cello types as well as bunched carrot products accounted for 67% of the market and 33% of sales came from organic processing carrots including canned and frozen market segments. According to the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), organic carrots contributed 11.7% of total carrot production acreage and 10.8% of sales in 2016, down from a peak of 14.7% total acreage and 10.7% sales in 2011, but much higher than the 5.8% of acres and 1.9% of sales in 2008 (USDA-NASS, 2009a,b, 2012a,b, 2015a,b, 2016a,b, 2017a,b) (Fig. 16.2). Organic carrot market and retail prices follow conventional trends over time, with a consistent margin of approximately twice the value for organic carrot (Luo, 2016). Thus, the reduction in percentage of acreage while holding close to 11% market value demonstrates the increase in yield per acre over recent years. These figures represent over 5% of total organic vegetable sales.

The organic carrot seed market is stimulated in the USA and Europe by the requirement that organic producers must plant organically grown seed if available. The USDA National Organic Program (NOP) regulation states that, 'The producer must use organically grown seeds ... except ... non-organically produced, untreated seeds and planting stock may be used to produce an

Fig. 16.1. (a, b) Novel coloured carrots are gaining popularity among organic consumers. (Photos by Organic Seed Alliance.)

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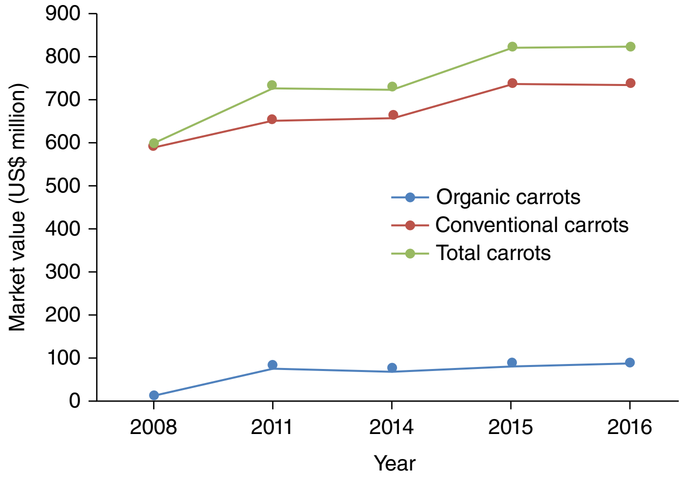

Fig. 16.2. Organic carrot market value compared with conventional and total carrot market in the USA. (From USDA-NASS, 2009a,b, 2012a,b, 2015a,b, 2016a,b, 2017a,b.)

organic crop when an equivalent organically produced variety is not commercially available' (NOP regulations §205.204).

European organic regulations include the same requirement; however, on a country-by-country basis it may be determined that sufficient quantity of organic seed is available in sufficient diversity of cultivars that the derogation for use of inorganic seed is not allowed (European Commission, 2018). The European system of variety testing and registry facilitates the determination of availability and suitability more readily than in the USA where a national testing system is not employed. Seed companies are striving to address the unique production challenges and market qualities of the organic sector and a diversity of organic carrot cultivars are commercially available in organic seed form in the USA and Europe.

Organic consumers prioritize flavour, nutrition and diversity in vegetables and carrot preferences in particular (Dawson *et al*., 2017; Simon *et al*., 2017). Breeding efforts to improve flavour, nutrition and novel colours are underway in both public and private programmes as the organic produce market and frozen products are expanding offerings of carrot types. There are few public programmes internationally working on organic carrot development. Most notably in the USA a project titled 'Carrot Improvement for Organic Agriculture' (CIOA), led by USDA plant breeder, Dr Phil Simon, launched in 2012 and is currently funded through 2020. The aim of this project is to improve the understanding of environmental influences on carrot performance under organic management, and to develop new cultivars for organic agriculture including improvements for key traits of nematode resistance, disease resistance, weed competitiveness and consumer qualities including flavour and nutrition. In Europe, the LiveSeed project is a European Union-funded initiative involving 16 countries with the goal of boosting organic seed and plant breeding efforts

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across Europe (European Union, 2017). In addition to efforts to address organic plant breeding needs as well as seed production and regulatory constraints, this initiative is analysing different seed value chains for organic carrot production including use of non-organic seed, organically produced seed, and seed bred for and produced in organic systems (Herstatt, 2018).

16.2 ORGANIC CARROT PRODUCTION

Organic production and handling are defined and regulated by the USDA NOP and the European Union as well as other governmental agencies internationally. Organic production is not only defined by the absence of prohibited substances, but as a system that is managed 'to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity' (USDA-NOP, 2002). Organic standards are also informed by IFOAM and described by IFOAM as adhering to the principles of health, ecology, fairness and care.

Carrot production challenges overlap between organic and conventional systems including major pests and disease, but the management practices and prioritization of cultivar traits often differ between the two systems. Public concerns and regulations on pesticide residue levels and accumulation of nitrogen and heavy metal content in carrots are also stimulating research on organic production methods, particularly given the significant carrot consumption by children and use in baby foods (Collier and Finch, 2009; Colquhoun *et al.*, 2018). Organic carrot producers rely on an integrated management approach with an emphasis on cultural methods including use of cover crops, organic amendments, crop rotations, mechanical weed management, site selection, timing of planting and selection of crop cultivar (Finckh *et al.*, 2015; Seaman, 2016). The environmental effects of organic management practices can significantly influence the presence and impacts of carrot pests and disease. Monitoring for pests and disease and avoiding introduction or spread of pathogen inoculum are critical in organic management. Exclusion or avoidance practices include planting clean seed free of bacterial, fungal and viral inoculum; selection of field sites to avoid soil-borne or weed hosts of inoculum sources; and ensuring inoculum is not introduced through equipment, inputs or irrigation water. Field management practices to avoid disease in carrot production include weed management, avoiding overhead irrigation, orienting fields to improve airflow and trimming the canopy when overly dense. In general, compared with conventional producers, organic producers avoid fallow periods, practise longer crop rotations and integrate a greater diversity of crops into their production system (Finckh *et al.*, 2015). These practices can aid in avoiding soil-borne pathogens, but also at times may contribute to their build-up if the pathogen has suitable alternate crop hosts including potential cover crop or weed species present in the rotation sequence. Soil nutrient management in

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organic carrot production commonly includes selection of field site and inputs of organic matter including compost applications or incorporation of cover crops to boost soil quality and optimize crop health. Increased organic matter inputs can also increase soil microbial diversity and enhance organisms that antagonize or compete with pathogens (Finckh *et al.*, 2015). While organic production does not allow chemical pesticides, there are several organic pesticides used as a last resort for insect and disease management. Organic pesticides may include a range of microbial agents, various copper compounds, and plant-derived ingredients and other naturally occurring substances. Organic pesticides must be listed in the organic regulations as approved materials or approved by the Organic Materials Review Institute (OMRI) as an approved commercial product. Most of the commercially available organic pesticides that are promoted for management of carrot diseases have not been evaluated in university research trials and the efficacy is not well documented (Seaman, 2016). Research on the efficacy of organically approved foliar treatments is underway in other crops with varied results, but some products demonstrate reduced disease levels (Egel *et al.*, 2019). As the scale of organic carrot production expands and the organic market grows, public and private research efforts and extension programmes are striving to address production challenges to meet the needs of growers and industry (Seaman, 2016; Simon *et al.*, 2017).

16.3 WEED MANAGEMENT

Carrot is notoriously slow to germinate and establish a crop canopy. For this reason, weed tolerance and weed control are key concerns in organic carrot production (Fig. 16.3). Weed management approaches emphasize cultural practices including cultivar choice as well as physical weed management through flaming, cultivation and hand weeding. The cost of weed management is a significant economic consideration in organic carrot production input and effects of weed competition can vary by cultivar (Peruzzi *et al.*, 2007; Seaman, 2016; Colquhoun *et al.*, 2017; Simon *et al.*, 2017).

Several physical control methods for weed management are commonly employed in organic carrot production including pre-plant or pre-emergence flaming or cultivation, between-row cultivations post establishment, and several rounds of hand hoeing. In Italy, Peruzzi *et al.* (2007) demonstrated a reduction in labour time and cost by using novel weed control methods that alter the standard row spacing and cultivation regimes in organic carrot production in the region. Researchers in the USA are similarly investigating various cultivation tools and efficacy of combining tools to improve the effectiveness of mechanical weed control (Hitchcock Tilton *et al.*, 2018b). Hitchcock Tilton *et al.* (2018a) found that applying a finger weeder and duo hilling discs at the first true leaf stage resulted in the greatest reduction in time required for hand weeding. The researchers also recognized that choice of cultivar impacted tolerance of

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Fig. 16.3. (a) Seedling vigour and (b) early crop establishment are critical in organic carrot production as weed management is a significant production challenge. (Photos by (a) S. Linehan, https://www.shawnlinehan.com; (b) Organic Seed Alliance.)

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the carrot crop to withstand mechanical cultivations, suggesting the potential to breed cultivars for traits that could improve effectiveness of mechanical means of control. In particular the partitioning of tissue to roots versus shoots improved tolerance to tools designed to uproot the weeds, such as the torsion weeder, while early shoot partitioning improved resistance to tools designed to bury weeds such as the finger weeder. The potential to breed for improved weed tolerance or weed competitiveness was also noted by Colquhoun *et al.* (2017, 2018), based on identification of differences in the ability of cultivars to suppress weeds through rapid emergence and early establishment of the crop canopy. Carrot shoot morphology is influenced by both genetic and environmental effects and a study is underway at University of Wisconsin–Madison to develop quantitative trait locus markers of shoot traits at various plant growth stages, with the goal of aiding marker-assisted selection for this trait in the future (Grahn *et al.*, 2018). There are very few organic herbicides employed by producers, but Canadian researchers found that banded applications of clove oil and citrus oil with between-row cultivation provided acceptable weed control and yields (Main *et al.*, 2013).

16.4 PEST MANAGEMENT

Pest control in organic production employs cultural management techniques such as field selection, crop rotation and choice of resistant varieties. Key pests in organic carrot production include carrot rust fly (*Psila rosae*), aphid species, lygus bugs (*Lygus hesperus*) and root-knot nematodes, most notably (*Meloidogyne javanica* and *Meloidogyne incognita*).

Several species of root-knot nematodes are a pest in both organic and conventional production systems. The most impactful species of concern are the endoparasitic nematodes *M. javanica* and *M. incognita*, which can cause severe root galling and loss of yield and product quality. These two species are of particular concern for growers in warm climates such as California, the leading state in carrot acreage in the USA (Simon *et al.*, 2017). Organic producers rely on field selection, crop rotations and soil management practices to boost soil health in order to minimize nematode impacts as the application of soil fumigants is not allowed in organic production. Prevention in organic systems is critical as once nematodes are established eradication is very difficult, which is attributed to the fact that eggs remain viable for a long period and there are many alternate crop hosts (Seaman, 2016). Growers monitor for economic threshold levels, which may vary by environment and field condition, and influence management decisions accordingly. Providing optimum crop timing, site selection, nutrition and soil quality is important as plants grown under optimum conditions tend to improve nematode tolerance (Seaman, 2016). Organic systems generally differ from conventional in a few ways that may influence the differences in nematode populations. For example, organic systems

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tend to include more rotations of leguminous cover crops, which can act as an alternate host, but also increase soil organic matter content potentially improving soil health. Organic systems also tend to include fewer fallow periods and less weed control, which can result in the presence of alternate hosts. Lastly organic production emphasizes enhancement of biological diversity of the soil microbial community as a measure to minimize pest and disease outbreaks, and, in the case of nematodes, the nematode community of free-living predatory nematodes can be an important aid in suppressing parasitic nematodes (Finckh *et al.*, 2015). Incorporation of organic matter, such as compost, has been shown to decrease the number of parasitic nematodes while increasing bacterial and fungal feeding nematodes (Wang *et al.*, 2008). Genetic mapping of multiple genes associated with resistance to major species of nematode is facilitating the use of marker-assisted selection in development of nematode-resistant cultivars. The recent release of nematode-resistant breeding lines for key species, *M. incognita* and *M. javanica*, holds promise to help address these pests in organic systems as well as reducing reliance on chemical soil fumigants in conventional production (Boiteux *et al.*, 2000; Simon *et al.*, 2000; Ali *et al.*, 2014; Parsons *et al.*, 2015).

Carrot rust fly can be a challenging pest to manage in organic systems without the use of chemical insecticides, commonly relied on in conventional production, but a number of management strategies show promise in organic systems. A review of the literature by Collier and Finch (2009) on carrot rust fly management in the UK identified several practices that when integrated together show promise in reducing rust fly impacts in organic systems. Partially resistant cultivars are reported and may aid in reducing impacts. Crop rotation is a primary factor to avoid build-up of overwintering rust fly pupae and larvae. As adult flies do not travel far, the spatial placement of fields to avoid susceptible crops also minimizes infestations. Manipulating sowing dates to avoid the first generation of adults in the spring and lifting roots before damage to roots is advanced by later generations can help reduce impacts. Covering crops with fine mesh to exclude adults is also practised, although costly, but the timing of cloth placement must avoid the first generation of adults and take into consideration other implications associated with management of weeds and disease.

16.5 DISEASE MANAGEMENT

Several diseases of carrot are common to organic and conventional production (Davis and Raid, 2002), but organic producers are limited in control options as plant protection chemicals and non-organic seed treatments are not allowed. Finckh *et al.* (2015) provide a valuable overview of general practices for organic systems and specific tactics for key carrot pathogens in their book, *Plant Diseases and Their Management in Organic Agriculture* (nematodes, pp. 99–100; general disease management, pp. 148–149; disease resistance breeding, p. 179;

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hot-water treatment recommendations, pp. 197–200; general vegetable disease control, pp. 311–317). Organic practices generally emphasize disease avoidance, as treatment options are limited. Cultural practices aim to increase the health of the crop while minimizing disease pressure, including crop rotations, soil-building practices, crop diversification, field site selection, timing of planting, irrigation management and use of resistant cultivars. Irrigation management is focused on avoidance of overhead irrigation to prevent spread of inoculum and limit leaf wetting and moisture conducive to the growth of many fungal and bacterial plant pathogens (Davis and Raid, 2002; Weber *et al.*, 2004). Care is also taken to ensure irrigation water is free from inoculum of pathogens.

Planting pathogen-free seed is the first step in avoiding introduction of pathogens (Davis and Raid, 2002). In organic carrot production, hot-water treatment is the most commonly employed treatment for mitigating seed-borne pathogens when detected on seed lots, although the efficacy varies by cultivar, pathogen type, pathogen load and quality of seed lot (Finckh *et al.*, 2015). Seed treatment recommendations are addressed further below in Section 16.7 on organic seed production. Research is also underway to develop alternative organic seed treatments and steam treatment protocols that show efficacy on some specific pathogens, although equipment is not widely available (Finckh *et al.*, 2015).

The same key diseases in non-organic systems are priorities for organic producers (Davis and Raid, 2002) and, in many cases, restrictions in pesticide use are stimulating research that benefits both organic and non-organic producers alike. Several leaf blights are among the most common diseases of carrot and necessitate careful prevention in organic production. Fungal leaf blights are caused by the seed-borne pathogens *Alternaria dauci* and *Alternaria radicina*. The bacterial leaf blight pathogen *Xanthomonas hortorum* pv. *carotae* is also a critical leaf blight to monitor in organic production. All of these pathogens can be seed-borne so seed testing is essential to prevent introduction (Du Toit *et al.*, 2017), but there are recommended regimes for hot-water treatment when the pathogens are detected on seed lots. Organic carrot producers in the USA ranked Alternaria leaf blight as a top production challenge and breeding priority (Simon *et al.*, 2017). Alternaria leaf blight is widespread throughout the USA and Europe, is most prevalent on older leaves, and occurs in regions with high humidity in mid- to late summer. Bacterial leaf blight also affects carrot foliage. Management is particularly critical in organic seed production as this disease is common in less humid seed production regions of the USA and can cause major reduction in seed yield and quality (Du Toit *et al.*, 2005). Recommended management strategies for the various leaf blights are similar across species. Partially resistant cultivars are available. Practising a crop rotation of 2–3 years is recommended along with incorporation of crop debris postharvest to avoid spread of inoculum. Avoidance and monitoring are the first steps in organic management, but there are organically approved pesticides

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registered. Research results on the efficacy of these pesticides are however variable. Active ingredients include various copper compounds, microbials and botanical products. Organic pesticides are not generally a reliable primary means of control of these pathogens (Seaman, 2016).

16.6 FERTILITY MANAGEMENT

Enhancement of soil quality is the key to organic vegetable production, but particularly critical in organic carrot production as root quality is negatively affected by production in depleted soils or soils lacking in adequate structure and aeration. While sandy soils are generally preferred in carrot production, in general choice of fields with adequate fertility is also important in organic production as nutrient inputs are not as easily applied as in non-organic production. Organic carrot producers commonly apply soil amendments of compost or manure along with rotations of cover crops to boost soil health and nutrient availability. Release of nutrients in an organic system is dependent on biological and environmental conditions and thus the timing of planting must be managed to coincide with release of nutrients available for crop growth. Nutrient availability, particularly of nitrogen, is often low in the spring under cool soil conditions, thus the timing of plantings must take account of the timing of release of nutrients. Soil testing is employed and applications of mineral phosphorus and various micronutrients, as well as various organically allowed bagged or liquid fertilizers with concentrations of macronutrients, are also utilized when needed to meet crop nutritional needs (Seaman, 2016).

16.7 ORGANIC CARROT SEED

As organic production continues to expand, organic agriculture still depends on non-organic seed and cultivars bred under conventional conditions for a large portion of production acreage (Hubbard and Zystro, 2016). According to the most recent (2016) State of Organic Seed report, organic farmers are using more organic seed than 5 years ago. Across all crops, organic farmers surveyed reported planting an average of 69% of their vegetable acreage to organic seed, up 14% since 2011. Carrot producers reported planting an average of 66% of their acreage to organic seed, representing a significant market opportunity for organic carrot seed suppliers (Fig. 16.4). The report also found that as the size of vegetable operations increases, the percentage of acreage planted to organic seed decreases. Seed companies selling organic seed also cite the lack of adoption of organic seed sources by larger producers, as well as legislation allowing derogations for use of non-organic seed as barriers to the growth of the organic seed sector (Herstatt, 2018). Organic farmers surveyed did report greater satisfaction with organic seed in 2016 compared with 2011, responding that

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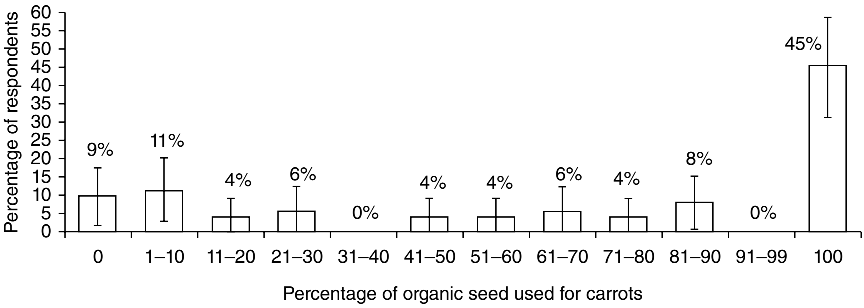

Fig. 16.4. Percentage of organic seed used for carrot production in 2014, with 95% confidence intervals represented by vertical bars. Among survey respondents, overall 66% of their carrot acreage was planted with organic seed. (From Hubbard and Zystro, 2016.)

quality issues were on par with conventional (non-organic) seed. They also recognized the importance of organic seed in the integrity of organic foods and 60% of farmers responding were already saving seed for their own on-farm use and/or for commercial sale (Hubbard and Zystro, 2016). The market for organic seed sources is clearly a significant interest of the seed industry as evidenced by the American Seed Trade Association (ASTA) convening an organic seed working group.

Organic seed production of carrot can be challenging as pests and diseases of the seed production phase can significantly affect yield and seed quality and the use of chemical pesticides routinely utilized in non-organic seed production is not allowed.

Conventional breeding programmes tend to focus on disease resistances in the vegetative phase of production rather than the reproductive phase, and thus often rely on pesticides to control pathogens in seed production. Hybrid seed production is particularly challenging as inbred lines can be less robust and disease resistances need to be integrated into both parent lines for reliable seed multiplication.

Lygus bug can be a significant insect pest in carrot seed production in major carrot-seed-growing regions of the western USA (Carlson, 1954). The insects utilize their stylets to suck the embryo out of developing seed while causing physical damage; a threshold of one insect per seed head can cause 50% reduction in seed yield (Carlson, 1954). Organic control has not received research as pesticide applications of seed crops are the norm in non-organic production and it is not a major pest of the vegetative phase of carrot production. Impacts of lygus bug on carrot seed have long been documented, and evidence of differences in cultivar resistance is noted, but as resistance has not been a breeding priority there are no known resistant varieties commercially available (Carlson, 1954; Scott, 1970; Stein and Nothnagel, 1995).

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Table 16.1. Hot-water treatment recommendations for common seed-borne foliar pathogens of carrot.

Seed-borne pathogen	Recommendations	Reference
Alternaria dauci, *Alternaria radicina*	50–53°C/10–30 min	Davis and Raid (2002)
Xanthomonas hortorum pv. *carotae*	52°C/25 min	Strandberg and White (1989); Grondeau and Samson (1994); Du Toit *et al*. (2017)

Management of seed-borne pathogens in organic carrot seed production is critical to ensure good seed quality and to avoid spread of inoculum (Davis and Raid, 2002). Multiple foliar leaf blights are seed-borne, including the fungal pathogens *A. dauci* and *A. radicina*. The Dutch organic breeding programme, Bioconnect, developed laboratory testing methods for identification of resistance to *A. radicina* and *Rhizoctonia carotae*, and assessed resistance in a collection of cultivated varieties and more exotic material (Voorrips *et al*., 2006). Testing for and management of the bacterial leaf blight pathogen, *X. hortorum* pv. *carotae*, is also important as this disease can be of significant impact in arid climates, including major carrot-seed-producing regions of the western USA (Du Toit *et al*., 2005). Hot-water treatment is the most commonly applied organic seed treatment for these pathogens, and recommendations for temperature and duration regimes are published in the literature (Table 16.1).

16.8 BREEDING CARROTS FOR ORGANIC SYSTEMS

Organic production methods were the standard in agriculture prior to World War I and the advent of synthetic fertilizers and pesticides (Lotter, 2003). From this perspective it can be said that all major food crops, including carrot, were domesticated under low-input ‘organic’ environments. Modern organic plant breeding similarly aims to improve cultivars’ adaptation to the environment under organic management conditions with low external inputs (Lammerts van Bueren and Myers, 2012). Efforts to breed and grow seed in and for organic systems initiated in Europe in the 1950s by biodynamic farmers striving to co-evolve their cultivars with their farming system and in the 1970s with the growth of the organic farmers striving to preserve crop biodiversity in the USA. A broader effort to expand breeding for the organic sector emerged in the early 1990s in response to growth in genetic engineering and increased consolidation in the seed industry. Since that time organic plant breeding has risen as a focused area of science and industry with broader goals of addressing organic market needs, employing breeding methods that reflect the organic sector’s values and developing cultivars with traits that support superior performance

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under organic conditions. There are now public programmes in the USA and European Union that support organic breeding initiatives (Hubbard and Zystro, 2016; European Union, 2017). Since 2009 the European Association for Research on Plant Breeding (EUCARPIA) includes a section for 'Organic and Low-Input Agriculture' (Lammerts van Bueren and Myers, 2012).

Organic producers still rely on many crop cultivars, including carrots, developed in and for conventional farming systems (Hubbard and Zystro, 2016). While many production challenges and breeding needs are similar between organic and conventional systems, differences in allowable management tools exist and the factors limiting crop growth may differ. The ranking of importance of crop traits may therefore differ between the two systems, raising the opportunity to improve crop performance specifically for organic systems (Lammerts van Bueren and Myers, 2012). Conventional systems have greater means to modify and control the cropping environment through input of synthetic fertilizers and crop protection chemicals whereas organic systems rely more on environmental adaptation of the crop cultivar (Lammerts van Bueren and Myers, 2012).

Surveys of organic producers were conducted as part of the Organic Seed Alliance's State of Organic Seed project, in 2010 and 2014, to identify the most important crops and traits to breed for organic systems (Hubbard and Zystro, 2016). In both years, organic carrot growers ranked breeding for weed competition and flavour as top priorities. Other recent reports assessing organic plant breeding priorities in the USA also surveyed organic producers and other stakeholders, and identified flavour, weed competitiveness, *Alternaria* resistance, cavity spot resistance and nematode resistance as top breeding priorities in carrots (Brouwer and Colley, 2016; Hultengren *et al.*, 2016; Dawson *et al.*, 2017; Simon *et al.*, 2017).

Breeding priorities aim to address key production challenges in organic systems. Nutrient-use efficiency is an important trait and breeding opportunity, particularly regarding nitrogen availability, as organic soil management relies on nutrient cycling to provide crop nutrition and thus nitrogen is often a limiting growth factor particularly under cool spring conditions (Thorup-Kristensen, 2006; Thorup-Kristensen *et al.*, 2012; Messmer *et al.*, 2012). Organic producers rely on mechanical cultivation and other cultural methods for weed management and, as such, crop vigour, weed competitiveness and weed tolerance are important cultivar traits in organic production. Without the use of synthetic crop protection chemicals, organic producers also rely on cultivar resistance to manage critical pest and disease issues.

To address these challenges there is clear potential to breed more robust crops for organic carrot production systems, but the number of public and private carrot breeders with interests in serving the organic sector is limited. The previously mentioned CIOA project is breeding carrots for improved weed competitiveness, disease resistance and market qualities, as well as researching plant–microbial interactions that may lead to future efforts to breed for

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improved nutrient-use efficiency and induced systemic resistance. One of the key project objectives is to release advanced germplasm and new cultivars to the organic seed industry. In the private sector the Dutch seed company, Bejo, is the leading company in organic carrot breeding efforts, with breeding programmes delivering several hybrid organic varieties. In addition to Bejo's carrot programme, a few biodynamic companies in Europe and organic companies in the USA are developing open-pollinated carrot cultivars for organic systems, notably Bingenheim in Germany, Sativa in Switzerland and Johnny's Selected Seeds in the USA. Other than these companies, a number of small, diversified organic seed companies in the USA and Europe contribute to the organic carrot seed supply, primarily producing and selling open-pollinated varieties (www.organicseedfinder.org).

Research and technology in organic agriculture and plant breeding are rapidly expanding fields. While public and private efforts are underway to support the most pressing organic carrot production challenges, there is also promising research expanding our knowledge of the complex biological dynamics of agricultural systems. Recent advances hold promise for the future potential of organic carrot breeding and production. One such project is the work of soil biologist, Dr Lori Hoagland, a researcher in the CIOA project. Hoagland's programme is exploring the association of carrots with the diverse assemblage of microbes living on the surface and within plant tissues, commonly referred to as the 'microbiome' (Hoagland, 2015). In particular Hoagland's team has identified higher levels of isolates of beneficial microbial endophytes in organic systems compared with conventional. These endophytes hold the potential to enhance early seedling growth and suppress key pathogens, indicating that soil management plays an important role in crop performance (Abdelrazek *et al.*, 2018). In a comparison of diverse genotypes, they found genotype plays a smaller, though significant role in shaping these beneficial endophyte communities, indicating the potential to breed for improved associations. New genomic tools to optimize the recovery and amplification of the plant microbes in carrots were created which should aid in future breeding efforts. In addition, the team determined that endophytes are vertically transmitted to offspring via seed, which could have important implications in seed production and handling (Abdelrazek, 2018). These findings shed light on the potential for future breeding and horticultural management efforts to optimize organic carrot production.

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17

Carrot Organoleptic Quality and Consumer Expectations

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Organoleptic quality is one of the aspects of a product's quality characteristics. For all products, sanitary quality is a prerequisite. For carrots, as is the case for many products, marketing quality, based on appearance, shape, colour and freshness, is the main criterion throughout the distribution channel. However, consumers judge a product's quality chiefly on its taste, and gustatory quality is decisive for a repeat purchase. Consumers are increasingly demanding and have high expectations regarding organoleptic as well as nutritional quality.

17.1 CHARACTERIZING ORGANOLEPTIC QUALITY

17.1.1 Contribution of sensory analysis

The sensory system reacts to sensory stimuli according to three dimensions:

- the qualitative perception, which transcribes the characteristics (e.g. this carrot is sweet; this carrot is bitter);
- the quantitative perception, which conveys the perception intensity (e.g. this carrot is not very sweet to very sweet); and
- the hedonic reaction, which is the sensation associated with like or dislike.

This results in two methodological approaches. On the one hand, the evaluation of organoleptic attributes makes it possible to give a quantified and objective description of a product (sensory profile). On the other hand, the hedonic approach studies the consumer's acceptance or preference during product tasting.

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The sensory characteristics of products have traditionally been assessed using descriptive analysis with trained assessors (Stone *et al*., 2012). However, several other alternative methods for sensory characterization have been developed recently (Ares and Varela, 2014).

17.1.2 Sensory profiles based on quantitative descriptive analysis

In quantitative descriptive analysis (QDA method), a group of assessors, trained to analyse a given product, attribute a score for intensity to the various products according to a list of descriptors. During training a set of descriptive terms is developed, which involves a definition and a procedure for each descriptor and evaluation of the references. Kreutzmann *et al*. (2007) and Cottet *et al*. (2012) describe the methodology to train a sensory panel on carrots. The panel and individual assessor performances must be monitored (ISO Standard 8586, 2014). The effect of product, assessor, replication and also the effect of their interaction have to be investigated (Depledt and SSHA, 2009).

17.1.3 Carrot sampling

Carrot roots have heterogeneous characteristics. Sweet taste is more concentrated in the middle and lower (tip) part of the carrot. The phloem is generally sweeter than the xylem (Rosenfeld, 2003). A bitter taste is more often detected in the upper part (crown) and more strongly connected to the phloem than the xylem (Rosenfeld, 2003; Czepa and Hoffmann, 2004). Consequently, the way the carrots are prepared has an influence on sensory perception and different modes of presentation are described in the literature. In all cases, the carrots are peeled, the upper and lower extremities are removed, and a middle segment is kept for sensory analysis. Then the roots are grated (Cottet *et al*., 2012; Paoletti *et al*., 2012), or cut into sticks (Araya *et al*., 2009), cubes (Varming *et al*., 2004) or slices (Kreutzmann *et al*., 2007; Szymczak *et al*., 2007). After preparation, all the carrots from the sample are mixed together, in order to take account of the possible heterogeneity of the roots. Sample preparation should be carried out as close to the tasting as possible. Depending on the study, the containers may be closed in order to allow analysis of the odours. For certain studies, the product is served under red light, in order to neutralize differences in colour between samples. Most of the time, the carrots are tasted raw; nevertheless, Cottet *et al*. (2012) compared the impact of cooking on the sensory characteristics and Araya *et al*. (2009) compared different modes of preparation, such as pressure processing and cooking.

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17.1.4 Sensory attributes most suitable to describe carrot

Descriptors can be classified into groups describing appearance, texture, odour/aroma, taste, aftertaste and flavour of the product. The description can cover all of the carrot characteristics or certain specific descriptors for a particular study (Table 17.1).

Throughout the different studies, the main discriminating attributes are sugar, flavour, bitterness and turpentine flavour.

Appearance

Appearance descriptors, evaluated at the start of the tasting, may concern colour shade, colour strength, whiteness, the difference between internal and external colour, and also brightness. Although the above information makes it possible to detect differences between products, it does not add to the information obtained by physical measurements. Care must be taken not to let appearance influence the characterization of in-mouth descriptors.

Texture

Texture attributes are very dependent on the way the product is presented (whole, sliced or grated). The most important attribute is juiciness. Crunchy is used for whole root evaluation. Firmness is also often found in the literature for grated carrot and concerns the degree of force needed to chew the roots (Szymczak *et al.*, 2007; Araya *et al.*, 2009; Cottet *et al.*, 2013).

Taste

Taste corresponds to sensations perceived by the taste organ when stimulated by certain soluble substances. The basic tastes are acid, bitter, salty and sweet. ISO Standard 5492 (2009) specifies that ‘the term “taste” shall not be used to designate the combination of gustatory, olfactory and trigeminal sensations which are designated by the term “flavour”. If, in informal language, this term is used in this sense, it should always be associated with a qualifying term (e.g.: nutty taste, green taste)’.

Table 17.1. Main sensory attributes of carrots according to the literature.

Type	Attributes
Appearance	Colour
Texture	Crispness, juiciness, firmness
Taste	Sweetness, bitterness
Aftertaste	Burning aftertaste
Odour	Odour intensity, green odour, terpene odour
Flavour	Overall flavour, carrot flavour, terpene flavour (turpentine or chemical flavour), harshness, pungency, soapiness, green flavour, nutty flavour

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The in-mouth perception of raw carrot is complex: a balance between sweetness and bitterness, which are the main criteria for the organoleptic quality of carrot (Cottet *et al.*; 2013; Navez *et al.*, 2017). The perception of sweetness is determined by the relationship between sugar and bitterness (Rosenfeld *et al.*, 1998a, 2002; Kreutzmann *et al.*, 2008a,b). It has no direct correlation with the total sugar content.

Sugars evolve during the carrot's life cycle, with reducing sugars decreasing and sucrose increasing. Likewise, bitterness, which is the result of several types of compound, remains complex to analyse. The first molecule that is supposed to play a part in the bitterness of carrots is 6-methoxymellein (Kreutzmann *et al.*, 2008a,c).

Flavour

The ISO Standard 5492 (2009) defines aroma as an odour with a pleasant connotation (English sense) and flavour as a complex combination of the olfactory, gustatory and trigeminal sensations perceived during tasting. The flavour may be influenced by tactile, thermal, painful and/or kinesthesic effects.

Depending on the study, the descriptors for 'flavour' may be reduced to 'overall flavour' and 'terpene flavour'.

Harshness is used to describe a burning sensation, turpentine-like flavour, and strong or pungent sensations (Simon *et al.*, 1980; Seljåsen *et al.*, 2001a,b). Polyacetylenes (falcarindiol) and terpenes (monoterpenoids and sesquiterpenoids) are thought to contribute to harshness (Simon *et al.*, 1980; Rosenfeld *et al.*, 2002). Falcarindiol has also been found to be closely linked with bitterness. It is the most abundant polyacetylene in raw carrots, mainly present in the peel (Czepa and Hofmann, 2004). Terpenes are connected with both the typical carrot taste and harsh flavours.

Bitterness, terpene flavour and harshness are linked and the distinction between these descriptors is difficult. A burning aftertaste in relation with terpene is also used by some panels (Rosenfeld *et al.*, 1999; Suojala, 2000). The other attributes observed in the various studies are 'soapinesss' as a flavour, 'earthy flavour', 'silage aroma' and 'hay aroma'. Also, in relation with storage, ethanol odours or off-flavours are described.

17.2 FACTORS IMPACTING SENSORY QUALITY

17.2.1 Sensory variability in relation with genotype

Genetic characteristics are among the main factors affecting carrot sensory profiles and specific decisive chemical compounds can be identified (Simon, 1985; Seljåsen *et al.*, 2013; Navez *et al.*, 2015). However, their level of expression depends on growing conditions.

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In Fukuda *et al.* (2013), the sensory and volatile profiles of 14 carrot varieties from different types, such as Kuroda, Flakkee, Imperator and Nantes, were determined to develop a map of eating quality characteristics of carrots. It appears that the aroma attribute intensity and volatile contents of the Kuroda type were lower than in other carrot types.

The development of a sensory map of carrots gives information on sensory dissimilarities or similarities between genotypes (Kreutzmann *et al.*, 2007). This type of sensory map is illustrated in the following example from the work by Navez *et al.* (2017), where a large number of cultivars produced at two different locations in France were evaluated. The principal component analysis (PCA) carried out on the average data of a panel, nine attributes on 48 carrot batches (Fig. 17.1), highlights the complexity of carrot taste. On the first axis, the attribute 'sweet' is opposed to the attributes 'bitter', 'pungent', 'chemical flavour' and 'overall flavour'. The second PCA axis, however, represents mainly texture attributes: 'juiciness' is opposed to 'residues in mouth'. Colour brightness is also identified on the second dimension; this attribute is significantly but weakly positively associated with 'juiciness' and negatively with 'overall flavour'.

The different carrot batches are scattered throughout the sensory space (Fig. 17.1). The local types, especially those grown in the north-west location, are mainly placed in the left part of the space, correlated with sugar. These types are also distinguished by a strong firmness, related to the PCA3 axis (not represented).

Four groups were identified by hierarchical clustering (Fig. 17.2). The first group is characterized by high scores for pungency, bitterness and chemical attributes. N_Maestro_SW can be highlighted among recent cultivars. The second group has a high perception of sweetness and juiciness; N_Maestro_W and Dordogne belong to this group. This illustrates the wide variability of Maestro. The third group is characterized by average score in sweetness, overall aroma and pungency, bitterness and chemical flavour perceptions. Laguna, Elégance are typical of this group. The fourth group is strongly characterized by low scores for flavour attributes, especially bitterness, chemical aroma and also pungency, with rather high sweetness. Major and Saint-Valéry are typical of this group.

17.2.2 Sensory variability in relation with the environment

The literature reports many different environmental factors impacting the sensory quality of carrots. The ones most commonly found in the literature are growing location, temperature, light, fertilization and soil. However, there is an interaction between cultivars and growing conditions in determining sensory characteristics, whose expression may also depend on optimal harvest stage.

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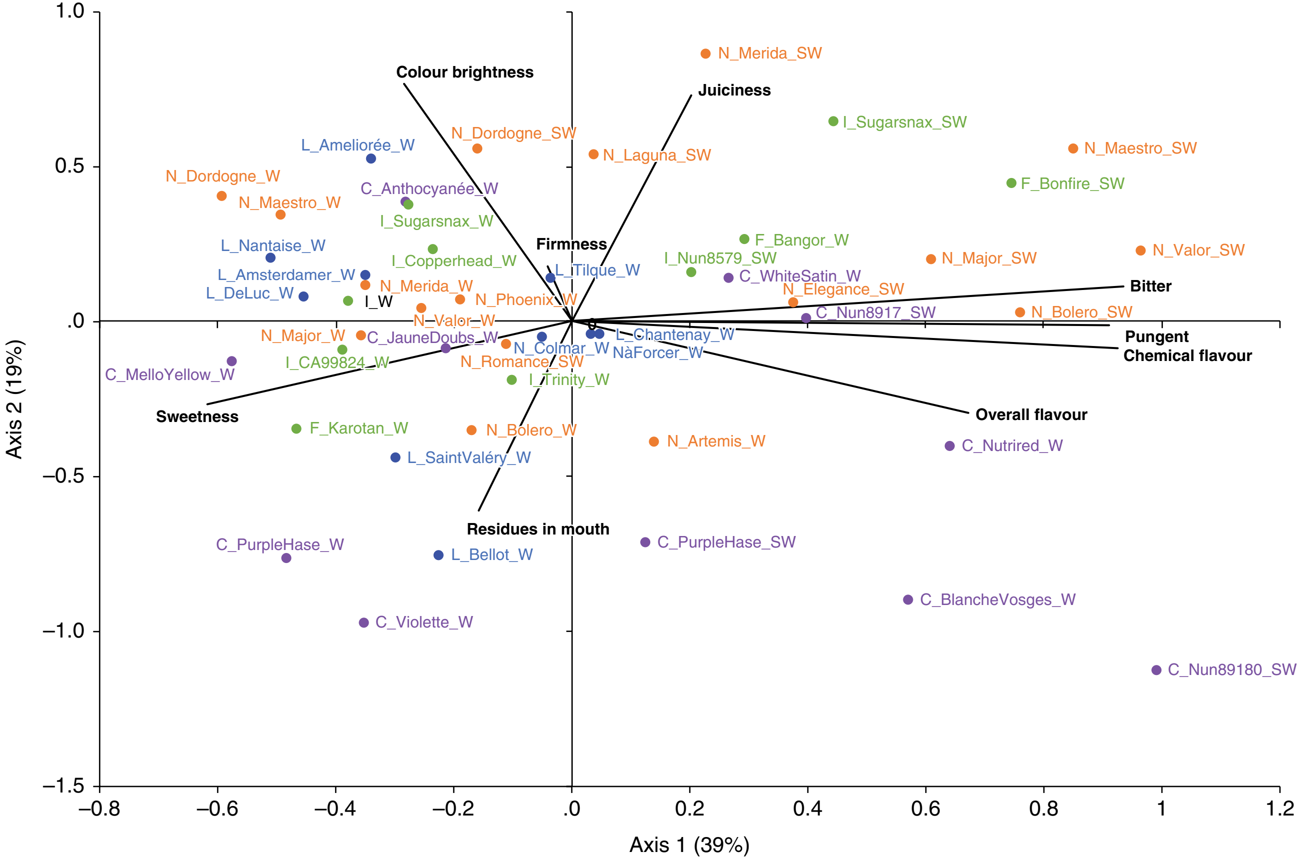

Fig. 17.1. Principal component analysis of sensory profile data (2010), 48 samples (cultivar × location) and nine attributes (axis 1 + axis 2 = 58%). Carrot types: N, Nantes; F, Flakkee; L, Local; I, Imperator; C, coloured. Growing locations: SW, south-west France; W, north-west France. (Adapted from Navez *et al.*, 2017.)

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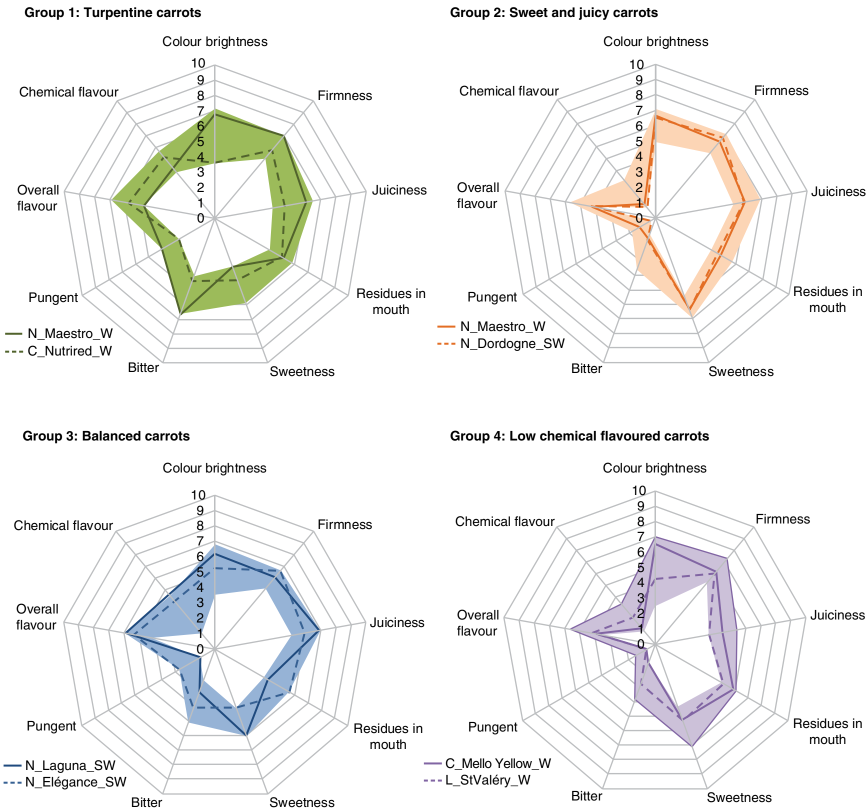

Fig. 17.2. Sensory profiles of the four groups individuated by means of hierarchical cluster analysis within the 48 batches considered in 2010; shaded area is surface of maximum and minimum value for each attribute of the group, with related representative cultivars. (Adapted from Navez *et al.*, 2017.)

Martens *et al.* (1985) showed that the principal factors of variation in chemical and sensory quality are the growing season and the growing location before the genetic factors. Varming *et al.* (2004) also explained that the growing location has a greater effect than the variety on the perception of fruity, sweet and carrot aftertaste. Rosenfeld and co-workers (Rosenfeld and Samuelsen, 1998; Rosenfeld *et al.*, 1998b,c, 1999) highlighted that the effect of temperature had a greater impact than genotype. The influence of location is mainly an effect of climate (Rosenfeld, 2003), heat being more important than soil type for sensory and chemical properties of carrots (Rosenfeld and Samuelsen, 1998; Rosenfeld *et al.*, 2002).

Seljåsen *et al.* (2013) concluded that variety and year (mainly temperature) effects could overshadow the effect of soil type and fertilization on sensory attributes. Kleemann and Florkowski (2003) related that factors influencing

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undesirable characters, such as bitter taste and turpentine-like taste, include genetics, growing conditions, diseases and insects, postharvest handling and storage atmosphere. The interactions between the effects related to the plant material and the growing location are highlighted by Navez *et al.* (2017), where two varieties, cultivated in the north-west and south-west of France, vary in a different way according to the genotype and the place of production. For one variety, the profiles are similar in both locations, while for the other, carrots are significantly sweeter and have lower chemical flavour when harvested in the north-west.

17.2.3 Sensory variability in relation to the growing system: conventional versus organic

The effect of the conventional versus organic farming system has been assessed by some studies, but the findings are contradictory. Haglund *et al.* (1998) showed that year, growing system and variety had an impact on sensory quality. Nevertheless, conventional carrots scored higher for carrot taste, while organic carrots scored higher for bitter taste. In a study carried out by Wrzodak *et al.* (2012), the organic carrot had superior value for juiciness, hard texture of the root, sweet taste and carrot taste but this was very dependent on the year. Paoletti *et al.* (2012) demonstrated that it is difficult to distinguish qualitative differences between conventional and organic products. Bach *et al.* (2015) showed over three years that the nutritional and sensory qualities of organic and conventional carrots are equivalent.

17.2.4 Impact of Postharvest Conditions on Sensory Quality

Regarding postharvest aspects and storage, the main influence is on texture criteria rather than on sweetness, even if bitterness can be affected by storage conditions. According to Suojala (2000), the most affected sensory parameters are firmness and crispness. These two attributes of texture decrease during storage, but the evolution appears slow in the case of storage at 0 ± 1°C with hygrometry levels ranging from 80 to 95%. A controlled atmosphere is conducive to better preservation of juiciness, firmness and crispness compared with conventional atmosphere storage. The content of soluble compounds (°Brix) decreases during storage but not significantly and without affecting the perception of sweetness (Crespo *et al.*, 2007). Postharvest stress leads to an increase in isocoumarin in roots, a compound related to bitterness (Seljåsen *et al.*, 2001a). Bitter taste scores increase when carrots are exposed to ethylene (Seljåsen *et al.*, 2001b). Ethylene induces synthesis of compounds which are linked to the chemical evolution of polyphenols, and this would in turn cause bitterness of the carrots. This is confirmed by Kramer *et al.* (2012) who showed

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that the presence of 1-methylcyclopropene, an ethylene antagonist molecule, leads to a decrease in the bitterness of treated carrots before storage.

17.3 CONSUMER EXPECTATIONS

17.3.1 Measurements of consumer preferences

As defined by the ISO Standard 11136 (2014), consumer studies (or hedonic tests) are intended to measure the level of appreciation and sensory preferences of consumers. This method aims to collect the affective responses related to the consumption of the product. The hedonic approach is carried out with a panel of 'naïve' consumers who are consumers of carrots. For fruits and vegetables, it is advisable to have a minimum of 100 consumers in order to take account of the intrinsic variability of the samples, which is difficult to control (Cottet *et al.*, 2013). In the case of carrots, the product is usually prepared in the same way as for descriptive analysis, making sure a homogeneous sample is presented. The tests are performed in the laboratory in boxes where the environmental conditions are controlled. The spontaneity of the consumers' answers is essential. It is better to have a minimum of questions posed clearly about the product, in order to preserve this spontaneity. In addition, the set of products presented for consumer evaluation must be clearly described beforehand. It will characterize the product space (sensory map) which is decisive in the interpretation of hedonic test results. Simon (1985) emphasized this point in a study of descriptors and their prediction.

Few hedonic tests on carrots are mentioned in the literature. The studies carried out are set up by teams working on genetics who wish to know the acceptability of a genotype or of a different colour (yellow, white, purple).

17.3.2 Preference mapping

The external preference mapping of consumers combines the results from the descriptive sensory analysis (objective description given by a trained panel) with those from hedonic tests (naïve consumer satisfaction score) (Depledt and SSHA 2009).

This method makes it possible to relate the preferences expressed by consumers to certain physicochemical or sensory characteristics of the products. This approach provides a reliable basis for adapting or creating products that meet consumer expectations. The first step is to map the products according to their characteristics (sensory map). The second step is to model the ratings assigned to the products for each consumer (or group of consumers), using the characteristics of the products as explanatory variables. The result is a preference map, representing consumers on the sensory map. Thanks to this method,

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the clearly preferred or clearly rejected product groups can be highlighted. It is thus possible for each product group to define the descriptors responsible for the preferences, in other words expected by the consumers, or on the contrary, the attributes responsible for the rejection of the products.

17.3.3 Drivers of preference

The different research and studies have highlighted that the highest level of consumer satisfaction was achieved with flavoursome, juicy and sweet carrots. The main rejected characteristics were too much bitterness and too intense chemical flavour (turpentine), which were usually accompanied by a lack of sugar. Sweet and harsh flavour account for most of the variation in overall liking.

Liking of carrot is generally correlated to the perception of sweetness, but this is not predicted by sugar content (Simon *et al.*, 1980; Varming *et al.*, 2004).

In Varming *et al.* (2004), six orange cultivars of carrots stored for 3 months were proposed to 112 consumers. Three questions, concerning overall liking, sweetness and bitterness, were asked. Liking and sweetness were correlated positively to sweet taste, fruity taste and carrot aftertaste, whereas earthy taste was correlated negatively.

In Szymczak *et al.* (2007), eight cultivars of different colour carrots were proposed to 65 volunteers who evaluated their liking for colour, flavour and overall liking. For colour, the orange-coloured cultivars scored higher. For flavour, the yellow cultivar (Mello Yellow) had a lower score than the others, and flavour liking was strongly positively correlated to juiciness and crunchiness. For the overall liking, coloured carrots, especially Mello Yellow, had a lower score than the orange ones. Szymczak *et al.* (2007) and Brückner *et al.* (1998) highlighted the importance of texture, particularly juiciness and crunchiness, in carrot preferences.

In a French study, consumer tests were performed on ten batches in three locations (Cottet *et al.*, 2013; Navez *et al.*, 2017). A total of 299 consumers were recruited according to the following characteristics: carrot consumers, older than 18 years, balanced age and gender, and more than 60% were economically active people. Raw grated carrot samples were presented using a Latin square design to avoid effects of order and position. For each batch, consumers gave a score of general appreciation on a scale from 0 ('I don't like it at all') to 10 ('I like it very much'). They also answered an open questionnaire about what they liked or disliked and were asked to fill in a questionnaire about usage and attitude in order to explain their preferences.

Based on preference mapping (Fig.17.3), the preferred products corresponded to a carrot that is both juicy, sweet and has flavour. For Phoenix, characterized by these attributes, 70% of consumers evaluated it above the average score. On the other hand, Bonfire and Amsterdamer were appreciated less,

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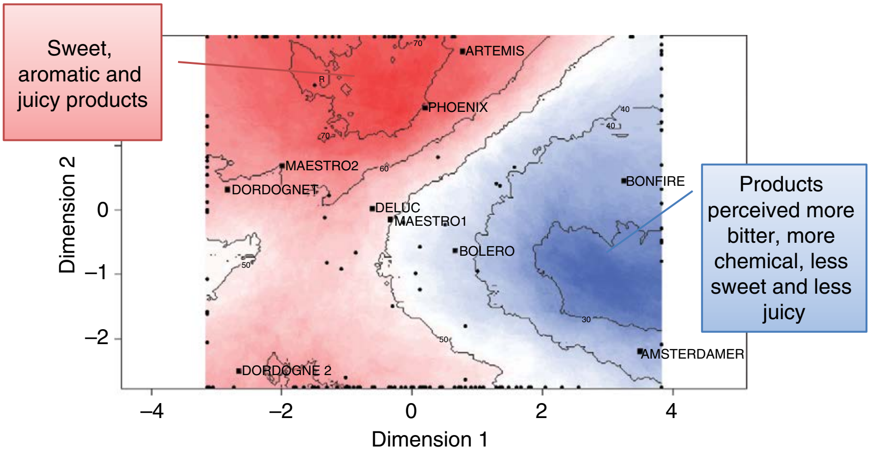

Fig. 17.3. External preference mapping; in blue, areas of rejection; in red, areas of preference. The black lines represent the percentages of satisfied consumers. (Adapted from Cottet *et al.*, 2013; Navez *et al.*, 2017.)

with more bitterness and chemical flavour and less sweetness. Only 30% of consumers gave a score above average for these batches. Consumers did not appreciate bitter products that have a turpentine flavour which is not counterbalanced by a high level of sugar. The batch of carrots Maestro1 was in an intermediate zone of appreciation, while its general appreciation average score was the lowest. This is explained by consumer segmentation: a few people were satisfied while others rated it very low.

17.3.4 Consumer segmentation based on their preferences

Nowadays, the industry is not looking for an ideal product that satisfies the expectations of all consumers but is conducting studies to satisfy the well-identified expectations of consumer targets.

When classifying consumer groups based on their preferences, three groups of French consumers with similar behaviour were identified (Navez *et al.*, 2015).

1. Consumers for a basic product: 33% of the panel expressed a preference for a juicy, sweet and aromatic carrot. They eat grated carrot but were not interested in a product identified for a specific use or of a better quality.
2. Carrot connoisseur: 19% of the panel clearly identified products exhibiting more flavour and sweetness and claimed to be interested in a very high-quality product.
3. The satisfied ones: 48% were satisfied with the quality of carrots and these consumers assigned good scores to all the tested products. Moreover, they were potentially interested in labelling for a specific use (grating, cooking, etc.).

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Consumer behaviour and preferences are determined by many factors that are not only related to sensory characteristics. To better understand consumer behaviour, it is necessary to integrate other aspects of the product such as the nutritional composition, price (study of willingness to pay) and market studies, and of course relate them to the agronomic aspects influencing the criteria of sensory quality (genetics, growing conditions, product origin or postharvest conditions) and their interactions.

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18

Ajowan

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Ajowan (*Trachyspermum ammi* (L.) Sprague ex Turrill, syn. *T. copticum* (L.) Link and *Carum copticum* Benth. and Hook. f. ex Hiern), as a member of the *Apiaceae* family, is an essential oil, an annual and a medicinally valuable herbaceous and seed spice plant which grows in arid and semi-arid regions of the world. All parts of the herb have a very strong thyme-like smell. This smell comes from the main constituents deposited in ajowan seeds which have a high yield of essential oil, such as *p*-cymene, γ-terpinene, thymol and carvacrol (Malhotra and Vashishtha, 2005; Soltani Howyzeh *et al.*, 2018c).

18.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Ajowan is a valuable medicinal herb which is widely distributed and cultivated in central Europe, India, Iran, Iraq, Afghanistan, Pakistan and Egypt. Ajowan is thought to originate from India and eastern areas of Iran, but some consider that the Middle East (especially Egypt) was the origin of this plant before spreading to the Mediterranean region and south-west Asian countries. The major producer of ajowan seed in the world is India, which exports this medicinal seed to about 46 countries. The main importing countries are Pakistan, Saudi Arabia, the USA and the United Arab Emirates (Malhotra and Vijay, 2004). In India, the area under ajowan crop cultivation was 25,850 ha (during 2010/11) with a production of 22,180 tonnes (Tomar and Malik, 2014). Ajowan has many diverse common names in different languages; for example, in English, they include bishop's weed, carom and Ethiopian cumin. A list showing the synonyms of ajowan's scientific name is available (http://mansfeld.ipk-gatersleben.de/, accessed 6 February 2020).

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18.2 PLANT DEVELOPMENT AND COMPOSITION

Ajowan is an aromatic, branched annual herb with a striated stem and much-branched, compound umbels and white flowers (Fig. 18.1), which grows up to 90 cm in height. Fruits are small, oval-shaped, compressed, about 2 mm long and 17 mm wide, with five ridges and six vittae in each mericarp, greyish brown in colour (Fig. 18.2). Ajowan seeds are usually confused with lovage seeds (Ramchander and Middha, 2017). The flowers are self-fertile but ajowan is a cross-pollinated crop and cross-pollination occurs through insects (Malhotra and Vijay, 2004; Sadat Noori *et al.*, 2017). Days to flowering in ajowan is 61–81 days with an average of 72 days. The number of umbels in a plant varies from 18 to 91, and each one can have ten to 18 umbellets

Fig. 18.1. Ajowan plant. (Photo by M. Soltani Howyzeh.)

Fig. 18.2. Ajowan seeds. (Photo by M. Soltani Howyzeh.)

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(Fig. 18.3) (Sadati *et al*., 2016). Ajowan is a long daylength plant and blooms from July to September each year (Sadat-Noori *et al*., 2018).

Ajowan has a somatic chromosome number of $2n = 18$; but in a cytogenetic study, chromosome number in two ajowan ecotypes increased from 18 in diploid samples ($2n = 18$) to 36 in tetraploid samples ($2n = 36$), with an increased thymol content from 52.9 to 70.0%, respectively (Sadat Noori *et al*., 2017).

The constituents of ajowan seeds include carbohydrates (24–39 g per 100 g seeds), fat (16–18 g per 100 g seeds), protein (15–17 g per 100 g seeds), fibre (12–20 g per 100 g seeds), tannins, glycosides, moisture (7–9 g per 100 g seeds), saponins, flavone, and mineral matter (7–7.5 g per 100 g seeds) containing calcium, phosphorus, iron, cobalt, copper, iodine, manganese, thiamine, riboflavin and nicotinic acid (Bairwa *et al*., 2012).

Ajowan is classified as a moderately salt-tolerant plant regarding the fact that it can maintain high K^+/Na^+ and Ca^{2+}/Na^+ ratios in shoots in water and soil salinity. High salt levels (120 mmol/l) can cause about 27 and 50% reduction in shoot dry biomass and seed yield of ajowan, respectively (Ashraf and Orooj, 2006). Additionally, it is a moderately drought-tolerant species and it can possess wide climatic adaptability. Scientific research showed that this plant significantly increases its free proline and glycine betaine content up to twofold in drought stress conditions (Rohamare *et al*., 2014).

The chemical composition of ajowan essential oil (Fig. 18.4) reported in different studies shows that the main constituents are thymol, γ-terpinene and *p*-cymene (Mirzahosseini *et al*., 2017; Soltani Howyzeh *et al*., 2018b). The essential oil concentration of ajowan inflorescence changes based on the developmental stage of the inflorescence. During the fruit ripening stages (Fig. 18.5), the thymol and *p*-cymene percentages increase but the γ-terpinene percentage decreases. There is a negative correlation between γ-terpinene, *p*-cymene and thymol. The anthesis stage is an important turning point for the percentage of the major constituents of the volatile oil composition of ajowan inflorescence (Soltani Howyzeh *et al*., 2018a).

Fig. 18.3. Ajowan inflorescence. (Photo by M. Soltani Howyzeh.)

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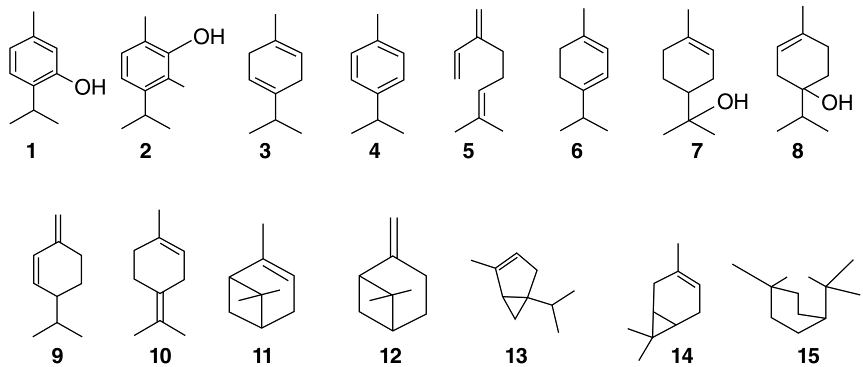

Fig. 18.4. Essential oil components of ajowan: **1**, thymol; **2**, carvacrol; **3**, γ-terpinene; **4**, *p*-cymene; **5**, myrcene; **6**, α-terpinene; **7**, α-terpineol; **8**, terpinene-4-ol; **9**, β-phellandrene; **10**, terpinolene; **11**, α-pinene; **12**, β-pinene; **13**, α-thujene; **14**, δ-3-carene; **15**, 1,8-cineole. (Data from Soltani Howyzeh *et al.*, 2018b,c; drawing by M. Soltani Howyzeh.)

18.3 CROPPING SYSTEM

Ajowan can be cultivated widely as an autumn- or winter-season crop in the plains and as a summer crop in the hills (Fig. 18.6). A warm and long frost-free growing season is essential for its production. Also, seed development needs warm weather. Ajowan crop grows on any soil type: loamy to sandy loam (Malhotra and Vashishtha, 2005). Seed germination (Fig. 18.7) percentages among different ajowan populations vary from low rate (11%) to a high rate (95.5%). Low germination percentage can be caused by seed dormancy (Sadati *et al.*, 2016). Preferable temperature requirement for ajowan seed germination is 18–20°C and the time taken for seed germination is 10–12 days. The seeds can be drilled in rows, 45 cm apart, with 20–30 cm plant-to-plant spacing in each row. The average seed rate is 4 kg/ha (Malhotra and Vashishtha, 2005).

Both organic (10–15 t/ha) and chemical (N–P–K) manures are recommended for ajowan crop (Malhotra and Vijay, 2004). Depending on the weather conditions and soil type, ajowan crop needs a total of five or six irrigations during the growing season. The harvesting is usually from August to October in cold-season cultivation and from February to May in summer-season cultivation. Inflorescence production terminates when the seeds start maturing and become greyish brown in colour (Fig. 18.5). The whole matured plant or only the dried inflorescences are harvested to obtain seeds. Seed yield is 300–700 kg/ha under a rain-fed cropping condition and 1100–2200 kg/ha under the irrigated system. Powdery mildew and collar root rot are the main diseases of ajowan crop and use of mancozeb (0.2% w/v) and wettable sulfur (0.2% w/v) spraying can control the pathogens. Insect damage is not economically important for crop production (Malhotra and Vijay, 2004). Various harvesting

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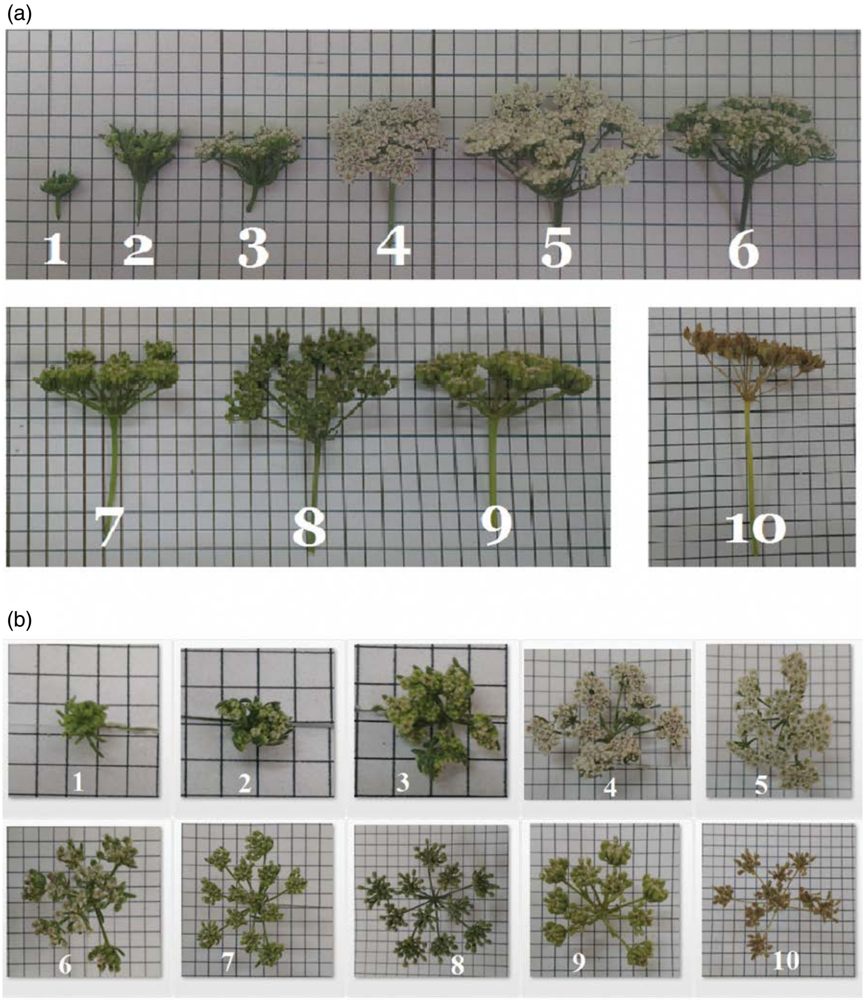

Fig. 18.5. Ajowan inflorescence ripening stages: (a) side view; (b) top view. Numbers show the inflorescence stages in tandem. (From Soltani Howyzeh *et al.*, 2018a; photos by M. Soltani Howyzeh.)

times of ajowan inflorescence can cause important changes in the essential oil concentration and composition (Soltani Howyzeh *et al.*, 2018a).

18.4 POSTHARVEST

After harvesting and before threshing, the ajowan crop is first laid in a thin layer on a clean dry threshing floor for 1 or 2 days. Next the seeds are cleaned by a screening mill and separated by a gravity separator from other plant parts

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Fig. 18.6. Ajowan farm in Ahvaz (31°02′N, 48°06′E), Khuzestan province, Iran. (Photo by M. Soltani Howyzeh.)

Fig. 18.7. Seed germination of ajowan in transplanting trays in the greenhouse of the College of Abouraihan, University of Tehran, Pakdasht, Tehran, Iran. (Photo by M. Soltani Howyzeh.)

and then dried. Drying the seeds in the sun reduces the oil content of the separated seeds. Well-dried seeds, with 7–10% weight moisture, are cleaned and graded by sieving and then stored in bags in a cool dry place. The dried seeds are ground using a mill to make fine ajowan powder. To minimize flavour loss, it is recommended to use a precooling technique utilizing liquid nitrogen for quick freezing (Malhotra and Vijay, 2004). The essential oils found in ajowan can be extracted by solvent extraction, supercritical fluid extraction, cold pressing and microwave extraction (Tomar and Malik, 2014).

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18.5 PRODUCT VALORIZATION

Ajowan is much valued for its different pharmacological properties such as carminative, stomachic, sedative, antibacterial, antifungal, anti-inflammatory, antispasmodic, antivirus, antihypertensive, hypolipidaemic, diuretic, antitussive and anthelmintic effects. Ajowan oil and its components are widely used in toothpaste, cough syrup, pharmaceuticals and food flavourings (Bairwa *et al.*, 2012). Ajowan seeds have a characteristic aromatic odour and the taste is sweetly aromatic. They smell approximately like thyme due to their high thymol content; however, they are more aromatic and less subtle in taste, as well as being somewhat bitter and pungent. Even a small number of seeds tends to overcome the flavour of a dish (Ramchander and Middha, 2017).

Nowadays, research on different aspects of ajowan plant and its various potentialities that can affect the pharmaceutical and food processing industries has increased, especially regarding molecular and genetic control of secondary metabolite content. The transcriptome analysis of ajowan enabled discovery of the genes responsible for secondary metabolite production (Amiripoor *et al.*, 2018; Soltani Howyzeh *et al.*, 2018b; Amiripour *et al.*, 2019) and recent research showed that the aerial part of transgenic plants with *TPS2* transgene of ajowan had greater thymol content compared with non-transgenic plants (Nomani *et al.*, 2019). Genetic engineering has also been applied to enhance drought and salinity tolerance in ajowan (Niazian *et al.*, 2019). For improving seed yield and essential oil yield of ajowan, the advanced computational method of artificial neural networks has been used, in addition to conventional statistical methods (Niazian *et al.*, 2018a,b). Thus, it is possible for researchers to use secondary metabolite pathway engineering alongside conventional breeding to increase seed yield and thymol content in this medicinal plant.

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Angelica

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19.1 BIOLOGY

Angelica (*Angelica archangelica* L.) is a herbaceous species belonging to the *Apiaceae* family that can reach up to 1–2 m in height when in bloom. Mainly in the second year of vegetation angelica produces a rosette of leaves divided into toothed leaflets. In the third year, the plant stops its vegetative development and emits a ridged hollow stem that carries opposite and pinnate leaves (Fig. 19.1). The petiole is fleshy and hollow, with an embracing sheath. The stem terminates with large hemispherical umbels measuring about 30 cm in diameter, composed of between 20 and 30 rays. The fruit, a diachene with four developed wings, is often between 5 and 7 mm in length. Several varieties are reported in different countries including France, selected for the production of fruits and roots and the quality of their essential oil (iteipmai, 2009).

19.2 USES

Multiple uses exist for various parts of the plant including the seed, the leaf, the petiole, the stem and the root. Among the food uses, the petioles and young stems are used for confectionery (candied angelica sticks). The fruits are a raw material for the beverage industry as is the essential oil of the fruits and roots, often giving rise to the production of typically strong, green liquors (e.g. Eaux des Carmes, Benedictine, Chartreuse, Vermouth). The essential oil derived from the seeds is also used in perfumery.

In medicinal use, the seeds and roots are traditionally used in the symptomatic treatment of digestive disorders such as epigastric bloating, slow digestion, eructation and flatulence, and as adjunctive treatment of the pain component

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Fig. 19.1. Angelica plants. (Photo by iteipmai.)

of functional disorders. The leaves can also be used for medicinal purposes. The root is described in the European Pharmacopoeia, 9th edition (monograph 01/2013: 1857 corr. 10.04.20) and it must contain not less than 2.0 ml of essential oil per kilogram, calculated with reference to the dried drug (Hornok, 1993; Agence du médicament, 1998; Wichtl, 2004; Bimbraw, 2006).

19.3 CROP MANAGEMENT STRATEGIES

Angelica requires light, fresh soils rich in organic matter. Heavy and hydromorphous soils are generally avoided as they make root removal difficult.

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Although angelica can be planted in a nursery followed by transplanting, the most advantageous method for growers is direct seeding.

In the case of planting, nursery sowing is often carried out after seed collection in August–September under cover or in spring in March–April. About 540 g of seed on about 70 m^2 of open-air nursery allows planting one hectare. Sowing in 96-well plates is also possible from one to three seeds per well, depending on the percentage of germination of the seed. One gram of angelica seeds contains around 180 to 200 seeds (mericarps). The germination rate is about 70 to 80% at the time of harvest, and decreases rapidly after 4 to 5 months. It is therefore preferable to keep the previously dehydrated seed in the freezer at –18°C. In the case of planting, densities of about 35,000 to 45,000 plants/ha, corresponding to an inter-row distance of 0.65 to 0.70 m and a distance between the plants of 0.35 to 0.40 m, are utilized with higher densities favouring the root yield.

Direct seeding is possible either in August with recently harvested seed or the following spring in March–April. Between 1 and 2 kg of good-quality seeds (about 70% germination) and 10 and 15 kg of older seeds are needed to plant one hectare with a grain or vegetable seed drill. The sowing depth is 0.5 to 1 cm and the emergence time, in good conditions, is about 4 to 6 weeks. It is important to keep the soil moist for a good emergence.

In terms of fertilization, it is advisable to maintain the soil fertility level high and to add organic matter during planting, if possible. Between 40 and 60 units of nitrogen are recommended at planting and between 60 to 90 units should be applied the following spring. Furthermore, 100 to 120 units of P_2O_5 and K_2O are recommended either during sowing or planting, followed by up to 150 units of P_2O_5 in the case of root production (iteipmai, 2009).

19.4 DISEASES AND PESTS

Few parasites seem to affect angelica, however some cases have been identified (Fritzsche *et al.*, 2007; Agridea, 2011; Ellis, 2017a,b):

- rust caused by *Puccinia angelicae* can cause damage to the stems and leaves;
- mildew caused by *Plasmopara angelicae* attacks the stems and leaves (Ellis, 2017a);
- Fusarium wilt can occur around the base of the stem of the plant; and
- a stem canker caused by *Rhizoctonia solani* can also damage the base of the stem.

In terms of pests (Fritzsche *et al.*, 2007; Agridea, 2011):

- in hot weather, on the lower part of the leaves, mites are sometimes observed and can lead to a drying out of the plant; and
- aphids can also parasitize the plant, which can cause malformations, especially on flower stalks.

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In France, plant protection products are approved to fight against certain diseases and certain pests. Maintenance of the crop is possible chemically with plant protection products registered at different stages of the crop: post-planted, post-emergent and on the installed culture of angelica.

In non-chemical weeding, several false seedbeds should be favoured before planting. After sowing, it is possible to carry out a thermal weeding before the emergence of angelica. Use of a harrow, properly adjusted after several tests, in the field, on young weeds (two leaves), in the four- to six-leaf stage of angelica or after the plant recovery in the case of a plantation, is possible. In the inter-row, weeding, star hoe, finger hoe, etc. can be used on young or more developed weeds (iteipmai, 2009).

19.5 HARVEST

For leaf production, harvesting is done using a self-loading mower at the rosette stage of the plant, from April to September, usually only one cut in year 2. Care should be taken during all steps that include direct skin contact with the plant, as exposure to sunlight following contact with angelica may induce photodermia (burning of the skin at the point of contact with the plant) because of the furanocoumarins contained in angelica. After harvesting, leaves are subsequently dried at a temperature of 40°C, the density of the fresh product is about 200 kg/m^3. The leaf yield is about 10 to 20 t/ha for fresh matter and 3 to 4 t/ha for dry matter.

For the production of roots, the harvest will take place in the autumn of year 2 in October or just after the fruit harvest, in July of year 3. Following the harvest, roots are washed, mechanically cut into sections to promote drying and then dried at a temperature of about 40°C. For an autumn harvest, the root yield is about 10 t/ha for fresh matter and 3.5 t/ha for dry matter. For a harvest of the roots just after the harvest of the fruits, the yield is about 10 t/ha for fresh matter and about 2.7 t/ha for dry matter. The essential oil content of dry roots harvested after fruit harvest varies from 0.2 to 0.5% of dry weight and the essential oil content of dry roots collected in autumn ranges from 0.3 to 0.4% of dry weight.

The fruit harvest is often carried out with the help of a combine harvester, in year 3, when the fruits of the central umbel of the plant change from green to yellow in mid-June. Harvesting fruit and then roots can be of economic interest. If the harvested fruits have too much moisture, natural or artificial drying may be necessary. The product will then be sieved to remove impurities. For a planting density of 40,000 plants/ha, the fruit yield ranges from 2 to 2.5 t/ha. The essential oil content of fruits ranges from 1.4 to 1.6% of dry weight (iteipmai, 2009).

The root contains an essential oil consisting mainly of monoterpenes, such as α-pinene, δ-3-carene and β-phellandrene, together with small amounts of

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sesquiterpenes. The macrolides 15-pentadecanolide and 13-tridecanolide are also found and are essential odour components. The root also contains many coumarins (e.g. osthenol, osthol, bergapten, xanthotoxin, angelicin, archangelicine) which are partially entrained in the essential oil (Bauer *et al*., 2001; ESCOP, 2009). The fruit contains an essential oil rich in monoterpenes (α- and β-phellandrene, α-pinene and *p*-cymene) and sesquiterpenes, like α-humulene. β-Phellandrene is the compound the most found in this essential oil (Wolski *et al*., 2003).

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Arracacha

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Arracacha (*Arracacia xanthorrhiza* Bancr.) is an interesting but little-known crop cultivated in South America at sites with altitudes between 1500 and 3000 m above sea level. Interestingly, while numerous old-world domesticated species of the *Apiaceae* family are generally propagated by sexual seeds, arracacha is asexually propagated. Arracacha is an excellent alternative for small and medium producers, especially family farmers, due to its considerable demand for labour, mainly in preparing and planting the seedlings and harvesting the roots. It assumes great socio-economic importance in regions where it is cultivated, generally reaching high market value. In addition, it has the characteristics of low input use and low production cost. Arracacha has a captive and growing market, usually associated with more elaborate cuisine and even high gastronomy. It also enjoys a reputation as a healthy product and a source of highly digestible carbohydrates, besides a good number of vitamins.

20.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Arracacha was domesticated centuries ago, possibly even before the potato (Hermann, 1997). It was cultivated by the Quechuas, Aymaras and other Andean peoples. It is found from Venezuela to Bolivia, with a higher concentration of wild forms in southern Colombia, Ecuador and northern Peru (Herman, 1997; Knudsen, 2003). Two wild types of *A. xanthorrhiza*, both with tuberous roots, are present in the domestication area, a perennial and a monocarpic type (Knudsen, 2003). Arracacha domestication started from the wild perennial form, which was probably selected for its ability to be asexually propagated (Morillo and Second, 2016).

Arracacha was introduced into Brazil at the beginning of the 20th century as a gift from Colombia on a commercial mission. At first, it was planted in

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the mountainous region of Rio de Janeiro State, from where it spread to other mountainous regions of the south-east and southern regions. Arracacha is cultivated in areas with altitude between 700 and 1500 m and mild climate all year, and today Brazil is the leading producer country, contributing 48% of world production. Colombia and Venezuela are the second and third producers followed by Peru, Bolivia and Ecuador. Arracacha is also cultivated on a smaller scale in north-west Argentina, Costa Rica, Puerto Rico, Dominican Republic and Haiti. There are also isolated reports of the crop in Sri Lanka and Mozambique. Attempts to introduce it into Europe and the USA were unsuccessful. It seems that world production has not changed over the years; for example, in the countries with the highest production, dos Santos and do Carmo (1998) highlighted 10,000 ha for Brazil and Vasquez *et al.* (2003) 8000 ha for Colombia. Curious to mention that Brazil had more than 20,000 ha and Colombia about 16,000 ha per year a few years ago, but the area has reduced due to climatic instabilities possibly associated with climate change (heat and drought in the summer in the south-east region of Brazil, with the consequent increase of pest and diseases, and excessive cold in the winter).

20.2 PLANT DEVELOPMENT

Arracacha is a perennial and herbaceous plant that forms clumps. The stem is cylindrical and rough and composed of a strain, commonly called a 'rootstock', from the upper part of which come shoots or propagules (between ten to 100, depending on the variety, environmental conditions and nutrition). The leaves are pinnatisect and the aerial part is commonly called the 'crown'.

From the lower part of the stem grow the tuberous roots, which constitute the main commercial part of the plant. They can be elongated, cylindrical or conical, with a colour ranging from white to deep yellow or deep purple, sometimes with orange or purple rings, depending on the clone. A plant may produce two to 20 commercial roots per plant, with size from 5 to 30 cm in length and 2 to 10 cm in diameter. The tuberous roots start to develop 70 to 90 days after planting and present two distinct phases. The longitudinal growth occurs up to the fourth to sixth month depending on the climate and variety. Thereafter, the radial growth occurs until harvest, done after the tenth month. Some early varieties may be harvested after the seventh month; if necessary, it is possible to extend the harvest until 18 months or even more.

Arracacha flowering in the Andean region is relatively rare, probably a result of the plant's adaptation to the constant mild temperatures and well-distributed water supply year-round. Curiously, when introducing arracacha in southern Brazil, where water deficit and hydric stress occur between winter and summer, the plant reacts by flowering and producing seeds. The inflorescence is composed of a set of umbels that are formed at different times. In

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some conditions, the plants flower and produce reasonable quantities of viable botanical seeds that have been used for breeding programmes. It is important to emphasize, however, that arracacha sexual propagation is not viable in commercial fields due to the heterozygosity (Morillo *et al.*, 2004), low vigour and low germination of the progeny (Knudsen, 2003).

The commercial propagation is vegetative, by transplants or propagules of the crown called *cormos* in Spanish. In Andean region, it is most common to propagate directly from vigorous selected mother plants at 9 or 10 months, leaving five to ten central shoots for the final development of the plant. In Brazil, the most frequent is the direct cutting of transplants immediately after the harvest of roots. In general, 1 to 3 cm of the reserve structure and 1 to 2 cm of petiole should be left.

Arracacha is a plant of continuous growth in conditions of a mild climate with good water supply during the whole year. When water deficit occurs due to a prolonged drought, a physiological disorder is observed consisting of a reduction in the development of the aerial part until the return of an adequate water supply, at which point a new development of the aerial part occurs due to the retranslocation of nutrients from the roots to the aerial part. In the Andean region it is common and viable to plant all year under constant climate conditions, whereas a single planting season is possible in regions with well-defined winter and summer. In southern Brazil, where frost is common from July to September, and in the south-east, where the summer is hot and the winter dry, the planting season is March to July. When planting in August–September, it is common for the plant to produce an early flower as a response to water deficit in the winter, damaging root production.

20.3 CROPPING SYSTEM

Manually, planting is usually done in narrow beds or ridges. The spacing varies from 70 to 100 cm between ridges and from 30 to 50 cm between plants on ridges, depending on the variety, management, location and planting season (Fig. 20.1). Thus, the plant density varies from 20,000 to 47,600 per hectare, considering spacing of 100 cm × 50 cm or 70 cm × 30 cm. There are different planting methods. Conventional planting is carried out directly in the field using transplants with a large reserve size of about 3 cm. However, it is common to observe irregular emergence and development, and therefore irregularity at harvest, in addition to a high percentage of field failures. Alternative practices are recommended to reduce losses: pre-rooting in beds (nurseries) or pre-sprouting in sand, sawdust (wood shavings) or water. Planting in areas with high declivity is very common, as cultivation predominates in mountainous regions because the plant does not tolerate soaked areas, making it unsuitable for lowland areas. Thus, another recommended practice is to orient the ridges in contour lines to mitigate erosive processes. There are

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Fig. 20.1. Arracacha field. (Photo by N. Madeira.)

conservationist systems without soil tillage and with permanent coverage with crops or cultural residues (straw), according to the principles of reduced tillage. This technique is widely used in the south of Brazil and brings numerous benefits such as decreased erosive processes, reduced use of water for irrigation or better water retention in non-irrigated crops, increased soil organic matter and soil biota, reduction of extreme temperatures, greater stability, and thermal and water comfort for plants.

Once the crop is established, the basic cultural practices are periodic weeding and maintenance of the ridges. In regions where there are long periods of drought, irrigation is necessary. In Brazil, for example, although southern region fields are not irrigated, about 70% of the crops are irrigated by sprinkling in the south-east region, which certainly brings greater production stability (Madeira and Souza, 2004). The main pests in arracacha are aphids (*Aphis* spp. and *Hyadaphis* spp.), mites (*Tetranychus* spp.), borer bug (*Conotrachelus cristatus*) and caterpillar (*Agrotis ipsilon*), among others. The main diseases are Sclerotinia wilt (*Sclerotinia sclerotiorum*) and bacterial root rot (*Pectobacterium* spp.). In addition, root-knot nematodes (*Meloidogyne* spp.) as well as free-living nematodes (*Pratylenchus* spp.) are present (Madeira *et al.*, 2017). The main measures to avoid or reduce the incidence of pests and diseases are the selection of transplants, chemical treatment, pre-rooting or pre-sprouting, the proper choice of planting area with good drainage and no

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history of diseases, crop rotation, a balanced nutrition and, when feasible and necessary, also an adequate irrigation.

The harvest is carried out manually after 10 to 12 months, but earlier varieties developed in Brazil can be harvested at 7 or 8 months. Plants are typically harvested with the aid of hoes or mattocks, the roots are separated and placed in boxes or bags. In some plateau areas in Brazil, a slide is passed under or aside the plants to facilitate harvest.

Regarding varieties, the Andean countries have a higher variability. In Brazil, the establishment of a breeding programme by the Brazilian Agricultural Research Corporation (EMBRAPA) released in 1998 the first registered cultivar of arracacha, Amarela de Senador Amaral (Bustamante *et al.*, 1997). In 2015, two new cultivars were obtained in a poly-cross field: BRS Rúbia 41 and BRS Catarina 64. These materials have high productivity (more than 40 t/ha), precocity (8 months) and yellow roots with superior visual appearance (Fig. 20.2).

In Ecuador, root production for commercial purposes is focused on the use of traditional 'white' varieties; meanwhile other types with potential organoleptic traits are not used and could even be lost in the next few years. The National Institute for Agricultural Research (INIAP for its initials in Spanish) has carried out research to characterize cultivated and wild germplasm, generating information that is valuable for promoting the incursion of arracacha genetic breeding projects. Using and developing molecular techniques (Morillo *et al.*, 2004), genetic characterization of arracacha germplasm has been done establishing the genetic relationships between cultivated and wild forms (Morillo *et al.*, 2017). On the other hand, molecular markers have also revealed a strong genetic structure among the cultivars (Morillo and Second, 2016). This finding is an important input to establish a programme of crosses

Fig. 20.2. Selected plants of arracacha from a Brazilian variety. (Photo by N. Madeira.)

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looking for recombinations with higher genetic variability and agronomic trait segregation. The use of wild germplasm should also be considered since these genetic resources could be a source of interesting traits such as drought or nematode resistance.

As Hermann (1997) pointed out, it is important to achieve more precocious cultivars, which should be done through breeding programmes. The induction of flowering in arracacha is not very clear yet. This prevents crossing between potential cultivars and achieving new cultivars. Arracacha is self-compatible and is also cross-pollinated, and it has been shown that flowering does not depend on age, since flowering has been observed from 5 months (Knudsen, 2003). It seems that the flowering and its induction depend on the characteristics of each cultivar (Knudsen *et al.*, 2001). Dehydration of the cormels seems the most effective method to achieve a greater number of flowers; however, Blas-Sevillano *et al.* (2006) did not find convincing results about the effectiveness of dehydration.

As mentioned above, the breeding programmes carried out so far have been done in Brazil (Hermann, 1997) and today there are several cultivars of high production. A notable characteristic of these cultivars is that the selection has been oriented to achieve a large amount of roots and little development of rootstock. Arracacha is well known for the wide differences in root yield among cultivars. It is quite likely that genetic factors controlling plant organ development as well as certain metabolic changes, such as alternative sink demand for assimilates, influence allocation of assimilates towards the roots; these are evidenced as differences in root yield values among cultivars. For example, in several Venezuelan cultivars, the roots represented approximately 65% of total weight after 242 days, whereas other cultivars scarcely reached 45% of the total weight. Despite the root growth increase after 242 days, this timing is apparently favourable to carry out the final harvest in precocious cultivars, since, after this interval, the percentage of roots diminishes indicating an increase in the allocation of assimilates towards other organs. Others are less precocious; thus, final harvest can be extended up to 307 days. From these data, it is apparent that there is a possibility to select and breed for early bulking cultivars that are harvestable with commercial roots at 8–9 months after planting. If this characteristic is combined with high instantaneous leaf photosynthetic rate, which is related to root yield as proposed by Jaimez *et al.* (2008), root yield at shorter growth period might be enhanced. Further research over years and locations is needed to test this hypothesis and to understand the physiological or metabolic mechanism that induces the assimilate distributions towards roots or rootstock. This could help to propose strategies of crop management.

20.4 POSTHARVEST

As arracacha roots are susceptible to rot and the skin is very soft, postharvest handling must be careful to reduce impacts. Compared with other tuberous

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roots, arracacha has a short shelf-life at room temperature. Arracacha roots can be efficiently stored under iced water at 5–6°C in open containers, changing the water once weekly, for more than 120 days. The presentation of arracacha for commercialization varies according to the market. The vast majority of arracacha is sold in bulk (Fig. 20.3). In more demanding markets such as São Paulo and Brasília, for example, it is common to offer small trays containing 0.5 kg with plastic wrap, which increases the shelf-life of the product.

20.5 PRODUCT VALORIZATION

In the Andean countries, more than 80% of root production is for fresh consumption. Arracacha starch has been used for several decades (Hermann, 1997), but demand is still low. The use of arracacha starch in the food and pharmaceutical industry is increasing. High content of amylopectin with low chains, low tendency of gelatinization and a high capacity of swelling in the starch of arracacha are important characteristics for the industry (Castanha *et al.*, 2018). Arracacha starch can be used as an excipient in the pharmaceutical industry to control the release of substances in hydrophilic matrices (Carrascal *et al.*, 2018). In addition, it has the potential to be used in biodegradable plastic materials (Medina *et al.*, 2012). Depending on the use of the starch, the demand for arracacha roots may increase.

In some countries, such as Bolivia and Peru, arracacha is a neglected food, often confined to more isolated communities with very little market insertion and low value. In others, as in Brazil, it is an ingredient highly valued in the market and in high gastronomy. The great majority of arracacha is sold *in natura*, with less than 5% of production processed.

Fig. 20.3. Arracacha conditioning. (Photo by E. Morillo.)

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The use of arracacha varies widely, according to the country of cultivation. In Colombia, the roots are cooked mainly in a traditional dish of Bogota called *ajiaco*, a soup with meat, potato and arracacha. In Bolivia, there is a traditional candy with grated arracacha. In Brazil, many dishes using arracacha, especially soups or creams, are most common in the winter. Arracacha is also used in salads; or fried in different shapes as thin slices ('chips') or sticks; or incorporated into dishes with meat, chicken or pork; or added as an ingredient in bread or pasta. The commercialization also differs, with arracacha often sold directly by producers in local markets. In Colombia and Brazil where there are larger markets for arracacha in big cities and supermarkets, the existence of middlemen is common. In Andean countries the root is commercialized without washing, but in Brazil the market demands that the roots are washed. There, small farmers use simple structures, but for higher productions there are packing houses specialized in washing and distributing arracacha.

There are interesting market differences in arracacha root types. In Brazil, for example, almost exclusively yellow roots are used, preferably of cylindrical shape and medium size (10 to 20 cm long and 3 to 6 cm in diameter). In Ecuador, the preference is for large, white roots. In Colombia, consumers prefer large, yellow roots. In Puerto Rico, it is curious that the consumed part of the plant is the corm rather than the roots. There are also reports of leaf consumption in Peru and Brazil.

20.6 PERSPECTIVES

As a very tasty, versatile and nutritious food, arracacha is appreciated in the countries where it is cultivated. This crop, however, requires more research and technological development. It is still an underutilized and neglected crop that presents great potential for market expansion even in the countries where it is already cultivated, as well as to develop opportunities to introduce arracacha to other countries.

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21

Caraway and Cumin

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Caraway and cumin are considered together because these two plants were confused for their similar smell and flavour profiles and subsequent uses. Such confusion appeared in the Middle East several centuries ago and is still extant. Caraway and cumin are in fact taxonomically very different species and must treated separately.

Differences between caraway and cumin fruits ('seeds') are:

- caraway fruits are ovoid-elongate, glabrous, dark brown between the yellow ribs;
- cumin fruits are narrowly ellipsoid to fusiform, the ribs scabrous to hairy, yellowish to greyish yellow (hair still remains noticeable after cleaning).

21.1 CARAWAY

Caraway (*Carum carvi* L.) is the type species of the genus *Carum* which includes about 30 species. Its generic limits were studied by phylogenetic analysis; the subsequent proposals of changes for its circumscription are given by Papini *et al*. (2007) and Zakharova *et al*. (2012).

The name 'caraway' comes from the Arabian 'karauya' (12th century). This initial name became 'carvi' (French and Italian), 'Kümmel' (German), 'alcaravea' and 'carvi' (Spanish), and 'Karwij' (Dutch). It is often named 'cumin' by mistake.

Two biotypes are extant: biennial (winter caraway) and annual (spring caraway).

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21.1.1 Importance of species and growing areas

The biennial form of this species is native in the meadows of Central Europe, the Alps, the Adriatic peninsula, the Caucasus, and also in the Rhine and Danube valleys, extending to Central Asia. The annual form is considered natural in the Middle East and eastern Mediterranean countries (Toxopeus and Lubberts, 1998) or probably originating from Egypt (Németh, 1998). Caraway is naturalized in North America, New Zealand and partly in South America. Winter caraway prefers mainly mountain climates but can also be found in humid coastal ones.

Caraway was used and cultivated in Europe longer than any other spice species, with samples dating from prehistoric times (Neolithic) found in pile dwellings. Seeds were also found in Tutankhamun's grave dating 1300 BCE (Teuscher *et al.*, 2005). Its cultivation is documented since the Middle Ages from northern Scandinavia to the south of Italy. It was traditionally grown in the Netherlands (where it started at the end of 18th century), in the countries of central Europe (Poland, Hungary, Czech Republic, Germany) and in Russia. Its cultivation is also reported from many other countries: Scandinavia, France, Spain, Egypt, India, Central Asia, Morocco, the USA and Canada.

21.1.2 Plant development

The root system is weakly branched, whitish or brownish. The stem is divaricately branched, glabrous, 30–60 cm high up to 90–150 cm (Fig. 21.1). The leaves are divided into lanceolate lobes. Fruits are 3–7 mm long, 1–2 mm thick, slightly curved, aromatic (Fig. 21.2).

The seedlings emerge usually after 2 weeks. Germination can be improved by soaking in water for a few days or cold treatment, cold stratification or adding gibberellins or cytokinin. The optimal time of sowing is October–November with daytime temperatures of 15–22°C and night-time temperatures of 7–13°C (optimal 15°C day/10°C night). The seeds must be sown not deeper than 1.5–2 cm, optimal 1 cm. The best time for sowing biennials is nevertheless in spring, whereas it is in autumn for annuals. Fertilization is needed with nitrogen during leaf development, with potassium during flower stalk growth, and with phosphorus and calcium during seed ripening (Putievsky, 1998).

The biennial types can be vernalized only when the taproot reaches at least the size of a pencil; the requirement is about 8 weeks of temperatures below 10°C. The annual types are induced to flower on long days of 10 h or more (Toxopeus and Lubberts, 1998); they lack a vernalization requirement, which corresponds to a rare homozygote mutation of biennial type that can be stabilized by selection.

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Fig. 21.1. Caraway plants in a garden. (Photo by J.-P. Reduron.)

The flowers are hermaphrodite to male, the hermaphrodite ones being protandrous, the pollen maturing 1–5 days before the pistils do. In annual caraway, the blooming of a flower lasts 7–15 days, 4–12 days of which have continuous nectar production. Nectar is hexose-rich (60/70% fructose, 27/27% glucose, 14/3% sucrose, respectively, for male/female phases) (Langenberger and Davis, 2002). Pollination is performed by wind and insects, thus promoting cross-fertilization.

21.1.3 Cropping system

Németh (1998) listed 23 cultivars of caraway but 13 were registered in the European Union plant variety database in 2019. The annual types are grown commercially in temperate zones of the Mediterranean, Africa, South America and Asia, whereas the biennial ones are cultivated in northern and central parts of Europe and North America (Putievsky, 1998).

Biennial biotypes indigenous in Europe have been known for a long time. The annual biotypes were cultivated only since the beginning of the 1970s; nowadays they highly predominate in cultivation because of the many complications for winter caraway cultivation.

The seed quality of biennial types is still considered to be better than that of the annual ones (size, aroma, colour, etc.). The development of annuals suitable for growing in northern areas is ongoing.

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Tetraploid populations are extant, but they face sterility disadvantage (Toxopeus and Lubberts, 1998).

Biennial caraway favours moderate temperatures while the annual one prefers high temperatures for good growth (Hälvä, 1998).

For caraway cultivation deep and warm soils rich in humus and nutrients are the most suitable: fen soils, loess, chernozem, limestone soils, not too heavy clays. Caraway grows well on neutral or slightly alkaline soils. Fertilization is necessary and can be done by manure, pre-cultivation of clover or lucerne, or green manure. Caraway is grown only from direct sowing (Fig. 21.1). The yields of fruit and essential oil (EO) are largely dependent on the availability of carbohydrate assimilates in the early stages of seed production: the plant requires a high light intensity and a high rate of photosynthesis in order to produce a good quality and great quantity of EO. Therefore, a low plant density in the cropping plot is required. The initial growth is slow. In Europe the harvest takes place from late June to mid-July (when the fruits have turned brown). A two-stage harvest is recommended. First, the plants should be harvested on a cloudy day or in the early morning, and the cut plants left in swathes or sheaves for a few days (up to 10 days): the fruit becomes finally formed and coloured. Second, after threshing and cleaning, the fruits must be re-dried down to 10–12% moisture content by weight (Wéglarz, 1998). For a good harvest quality, one must avoid damaging the EO ducts of the fruit.

The most serious pests are the gorse tip moth (*Agonopterix nervosa* = *Depressaria nervosa*) and caraway gall mite (*Aceria carvi*). Two aphids can also damage the plants: willow-carrot aphid (*Cavariella aegopodii*) and hawthorn-carrot aphid (= *Dysaphis crataegi*).

The weight of 1000 seeds is 2–7 g. The caraway yield reaches 1–3 t/ha. The seeds store well and are easy to transport. Packaging must be impermeable for aroma compounds.

21.1.4 Product valorization

Caraway is widely used as a condiment, drug and for industrial purposes. It is mainly cultivated for its properties coming from the chemical composition. The primary and secondary metabolites of caraway are given by Ruszkowska (1998); the EO is mainly composed of *S*(+)-carvone (50–80%) and *R*(+)-limonene (10–48%). The EO is excreted and stored in vittae (particular vesicles of the fruit). Light intensity is the most important environmental factor for EO content that enhances carvone content more than limonene. The caraway EO yield is 2–7% of weight steam-distilled from the seed.

Caraway has multiple uses:

- Culinary: in dishes with cabbage, sauerkraut, potatoes, pork, beef, goose, cheese fondue, raclette.

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Fig. 21.2. Caraway seeds, length 6 mm. (Photo by J.-P. Reduron.)

- Seasoning: in bread, 'cumin' Munster cheese, chilli con carne, curry, grilled sausage (Dachler, 1998).
- Bakery: mixed into the dough.
- Alcoholic beverages: in akvavit, kummel.
- Pharmacology: caraway has digestive, carminative, antiflatulent and galactagogue properties (Sadowska and Obidoska, 1998).
- Industry: as a sprout suppressant and control agent of fungal storage diseases, due to carvone content (Hartmans *et al.*, 1998); antioxidative and antibacterial effects; uses in cosmetics industry.
- Environment: caraway can be included in the mixes for bee pastures.

Adulterations with goutweed (*Aegopodium podagraria*) were noticed in the past.

In North European countries, caraway root is used as vegetable and cooked like carrots. The young leaves can be used like parsley.

21.2 CUMIN

Cumin (*Cuminum cyminum* L.) is the type species of the genus *Cuminum* which includes three species. The molecular diversity of cumin was investigated (16 genotypes) by Bhatt *et al.* (2017).

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Fig. 21.3. Cumin seeds, length 5 mm. (Photo by J.-P. Reduron.)

Local names of cumin are 'Roman caraway' (English), 'Kreuzkümmel' (German), 'jiiraka' (Sanskrit), 'jeera' or 'Safaid jeera' (Hindi) and 'kamoun' (Arabic).

In Iran, another species is cultivated (*Cuminum setiferum*), but on a smaller scale than *C. cyminum*.

21.2.1 Importance of species and growing areas

The origin of cumin is unknown; the two more probable places are the Nile valley and the Middle East. This plant has been grown for a very long time, being used by Egyptians for 5000 years; it is cited on a papyrus dating from 1550 BCE. Nowadays cumin is cultivated in many countries, most of them having a tropical or neotropical climate. The world's largest producer is India (main state Rajahstan), followed by Iran (main production area Khorasan). Among other countries one can find Morocco, Egypt, Lebanon, Turkey, Arab countries, Afghanistan, Pakistan, Indonesia, Central Asia, China, Spain, Denmark, Ukraine, Mexico and Argentina (Kafi *et al*., 2006).

Based on variation of wild types, cultivation and wide distribution of semi-wild races, the centre of diversification of cumin could be the Iranian plateau and Middle East (Kafi *et al*., 2006).

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A comparison of 50 genotypes of cumin was made in order to improve grain yield (Ghasemi *et al.*, 2017).

21.2.2 Plant development

Cumin is a glabrous and glaucous annual plant 5–50 cm high, with a highly branched stem and leaves divided into filiform long segments, distinctive from caraway. Fruits are narrowly ellipsoid, 3.5–6.5 mm long, aromatic (Fig. 21.3).

21.2.3 Cropping system

Cumin is sown from early February to early March in Iran, from mid-November to late December in India. The appropriate soils have a sandy-loam texture, are well drained, acid to alkaline and located in very sunny places. The seedbed preparation is important: the ploughed soil must give a firm and smooth bed according to the small seed size. The sowing must be done at a very low depth. Disinfection against fungal diseases is often useful. Optimum plant density is 120 plants/m^2, with a row distance of 40 cm. Cumin is grown in arid and semi-arid areas without or with limited irrigation, therefore the yield is highly dependent on rainfall (Alizadeh, 2006). Rotation with summer crops is recommended: sorghum, corn, soybean, millet and sesame (Mollafilabi, 2006).

The growth takes place during winter and spring. The nutrient requirement is low. The pollination is performed by wind, rarely by insects. One must prevent fungal attacks on the crop coming from *Fusarium oxysporum*, *Alternaria burnsii* and *Erysiphe polygoni*.

Cumin seed is usually harvested in January to February in India and from late May to late June in Iran (Mollafilabi, 2006). It is better to harvest the fruit before full ripeness (when they start to turn yellow), about 40 days after sowing (Teuscher *et al.*, 2005).

The maximum grain yield is 2000 kg/ha, but it is usually lower than 1000 kg/ha and down to 100–200 kg/ha.

21.2.4 Product valorization

The main organs used in cumin are fruits for their EO: they are a natural flavouring agent in the food industry (Kafi *et al.*, 2006). The main components of the EO are cuminaldehyde (19–35%), γ-terpinene (15–29%), β-pinene (10–22%) and *p*-cymene (8–12%). The chemical profiles vary according to diverse cultivation origins (Teuscher *et al.*, 2005). Cumin is a typical spice of South India, flavouring legumes, lentils and tandoori dishes. It seasons a lot of meals in Indian, Mexican, Iranian and Middle Eastern cooking. Cumin is used

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in many rice preparations and in several curries. It also spices many beverages, including aperitifs. It is used as natural antioxidant in biscuits.

The medicinal uses act against jaundice, dyspepsia and diarrhoea. Cumin is a stomachic, diuretic and stimulant. It shows antibacterial, antifungal and antiviral activities (Kafi *et al.*, 2006), and can be used in veterinary medicine. Because of its aromatic components, cumin is used in the cosmetics, perfumery and soap industries.

Beside the fruit, the dried leaves of cumin give valuable forage for cattle.

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22

Celeriac

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Celeriac, also referred to as 'root celery', is another example of a vegetable developed from the wild form by human selection of a particular organ, here the enlarged stem base, compared with the related 'stalk celery' with swollen petioles. Celeriac morphology and taste make it a very specific vegetable for growing areas and consumption.

22.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Celeriac, *Apium graveolens* var. *rapaceum* (Mill.) Gaudin, derives from the swamp ache. This wild plant, native to Europe and East Asia, is found from the Mediterranean basin to Norway. Since antiquity, the ache has been used as a condiment plant, a medicinal plant with depurative and diuretic virtues, but also as an award to athletic winners in Greek and Roman times and finally to decorate graves, the intense green foliage being the symbol of hope and rejuvenation.

By human selection, the swamp ache led at the end of the Renaissance to celery (*Apium graveolens* var. *dulce*) and celeriac (*A. graveolens* var. *rapaceum*), the vegetable forms. Sometimes assimilated to an old vegetable because of its unusual taste and unattractive appearance, celeriac has been submitted to varietal selection only very recently from the 17th century.

Celeriac is mainly eaten in Europe nowadays. The main world producers are the Netherlands, China and Germany. This is a low consumption vegetable with a decreasing trend. In France, consumption of fresh celeriac is about 500 g per person per year (Kantar World Panel, 2012). The consumption decreased by 15% between 2005 and 2014. Celeriac is mainly consumed raw in remoulade (grated with sauce seasoning), therefore a high proportion of the production is dedicated to processing.

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22.2 PLANT DEVELOPMENT

Celeriac is a biennial plant grown as an annual. The sexual reproduction of the species leads to the production of seeds during the second year in the natural cycle after vernalization by cold. As a result, a culture that is too early and/or unprotected can initiate undesired bolting (Fig. 22.1). Temperatures between 4 and 10°C for 10 to 14 days at the four- to five-leaf stage significantly favour celeriac bolting. Other factors seem to influence early bolting such as a lack of light, high temperature amplitudes and a weak plant, but these effects still need to be proved.

Celeriac cycle consists of three main phases, germination followed by vegetative development of the root and leaf system and finally the development of the swollen part. Reserves are accumulated mainly in the hypocotyl (lower part of the stem). The edible product is made of the enlarged stem basis, hypocotyl and taproot. Most of the edible part develops above the ground surface (Fig. 22.2). Roots are numerous and vigorous which is a constraint for harvest and product preparation. Celeriac product is mainly globe-like in shape, with external brown colour and internal white flesh. Favourable characteristics of celeriac presentation are a clean product, well-trimmed, firm, globe shape, 15–25 cm in diameter and 600 g to 1.4 kg depending on the use.

Fig. 22.1. Celeriac crop with early bolting plants. (Photo by E. Geoffriau.)

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Fig. 22.2. Celeriac plants in the field. (Photo by E. Geoffriau.)

22.3 VARIETY ADAPTATION

Traditional varieties, such as the famous Monarch, are still used by gardeners but professional growers use F1 hybrid varieties. The variety choice is made according to three main criteria. First, the variety needs to be adapted to the production location and the related climate. The climate needs to be temperate, since celeriac has a growth optimum between 18 and 25°C (risk of early bolting with temperatures lower than 10°C and growth is stopped when higher than 30°C). The plot should be exposed to full sun, the soil fresh and rich in organic matter, draining and with a pH between 6 and 7. Second, the variety must correspond to the commercial target and financial return. The main focus is on yield per unit area, root organization facilitating lifting at harvest, foliage quality with mechanical strength, leaf architecture and susceptibility to diseases. Differences between varieties are also observed for shape, texture, colour and oxidation after cutting, as well as for internal cavity development. Finally, each variety has a different aptitude for storage.

22.4 CROPPING SYSTEM

The cultivation cycle varies from 130 to 155 days according to variety earliness and takes place in summer in the northern hemisphere. There are three types of cultivation cycle depending on the objectives: early crop for early maturity, seasonal crop for yield and late storage crop for a longer marketing schedule. Typically, in France, early production under thermal cover corresponds to a transplanting period from mid-March to April and harvesting from June to October. The main cropping period corresponds to a May–June transplanting and a September–November harvest. Depending

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on the targeted harvest period, the variety, cropping system and planting material may change. Transplanting density varies from 40,000 to more than 60,000 plants/ha for field and early production, respectively. In field conditions, a distance of 70 cm between rows (and 30–35 cm on the row) facilitates mechanical operations and harvest. Product calibre depends on cultivation length and plant density.

22.4.1 Transplanting material

Celeriac crop is established using transplants only. Transplants are produced with sowing between February and April in the greenhouse for mini-clods, or in the open field for bare-root transplants. Mini-clod transplants are typically used at the beginning of the season or in difficult conditions of implantation. The plant is grown in a greenhouse for about a month, followed by foliage mowing at about 10 cm high and reduced temperature, which aims to harden the plant. The substrate constitutes an ephemeral reserve in water and nutrients which facilitates the recovery of the transplant and crop establishment.

22.4.2 Crop requirements

The average root depth of celeriac is 0.45 to 0.60 m (Christiansen *et al.*, 2006) which is important for efficient input management. Celeriac is very demanding in water, so the vast majority of celeriac crops are irrigated. Regular water intake significantly increases yield and marketable product (up to +35%) but does not change its nutritional composition (Kosterna *et al.*, 2012). Drip irrigation has a positive impact on yield (Kaniszewski *et al.*, 1999). Regular irrigation also prevents early bolting.

Celeriac is a demanding crop. At soil preparation, 25–50 t organic matter/ha, 70–100 kg P_2O_5/ha and 200–250 kg K_2O/ha are incorporated. Nitrogen (150–200 kg/ha) and a complement of K_2O are added during cultivation to support the taproot development. Fertilization with ammonium nitrate has a positive impact on yield but increases product nitrogen content and decreases dry weight content compared with organic nitrogen (Barczak *et al.*, 2007). Celeriac crop responds well to full doses of potassium and phosphorus, and low-acting fertilizers may improve fertilization efficiency (Niemiec *et al.*, 2015).

Boron and calcium deficiencies during cultivation cause internal cavities observed at harvest time, the main physiological disorder in celeriac. Fibrous product can be favoured. These deficiencies can be due to disequilibrium with potassium and calcium. A preventive input in boron as part of soil fertilization or by foliar application is recommended.

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22.4.3 Main diseases

Root celery is mainly susceptible to fungal diseases, similarly to stalk celery. The recurrent diseases are caused by early blight (*Cercospora apii*), late blight (*Septoria apiicola*) and *Sclerotinia sclerotiorum*. *Septoria* causes leaf blight while *Sclerotinia* causes rot of leaf bases (Fig. 22.3). Diseases are managed though plant spacing, keeping foliage dry by drip irrigation and with fungicide or bactericide specialties. *Celery mosaic virus* can impact leaves and is prevented by management of surrounding host plants.

22.4.4 Main pests

Celeriac is very attractive for the carrot fly (*Psila rosae*), the larvae of which will attack roots. Several species of aphids colonize celeriac, in particular green peach aphid (*Myzus persicae*). The lygus bug (*Lygus lineolaris*) causes damage on the leaves and petioles both at immature and mature stages. Slugs can cause damage especially on young plants. Celeriac is susceptible to several species of nematodes depending on the growing area: *Meloidogyne hapla*, *Pratylenchus penetrans* and *Pratylenchus bukowinensis*.

Pests are managed by careful detection, facilitating natural beneficials, pluriannual rotations and insecticide applications.

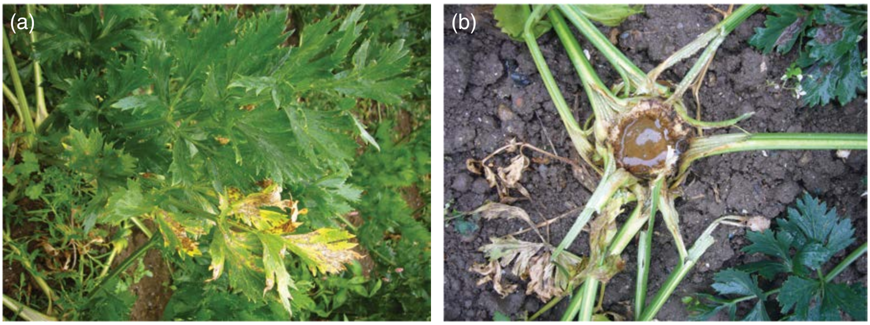

Fig. 22.3. Damage caused by (a) *Septoria* and (b) *Sclerotinia* on celeriac plants. (Photos by E. Geoffriau.)

22.4.5 Weed management

The generalized use of transplants helps weed management and a faster crop establishment. Hoeing or tilling is used to mechanically destroy young weeds and then herbicide application helps control weeds. Borowy (2004) has shown that intercropping with leeks can have a positive effect on weed

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management. However, it is not practised by large-scale growers as it is complicated to apply.

22.4.6 Harvest

Celeriac yield reaches 40 t/ha. Celeriac needs to be harvested before hard frosts. Tops of the plants are mowed to remove the remaining foliage and plants are lifted and ploughed out. Strong tops may also be used to lift the plants. The excess of attached soil is removed by washing with water. Celeriac requires significant preparation work to remove strong tops and numerous tangled roots (Fig. 22.4). This is done manually with the help of cutting discs, or mechanically in a rotating drum with an abrasive surface or cutting discs (Fig. 22.5). A more thorough washing is made after trimming.

22.5 STORAGE AND POSTHARVEST HANDLING

When cold stored, leaves and roots are removed, but washing is done before commercialization. Cooling down the product rapidly after harvest and trimming increases the storage shelf-life. Hydrocooling is used to decrease product temperature before storing in cold chambers.

Fig. 22.4. Strong roots (bottom row) need to be removed to obtain a globe-shaped product (top rows). (Photo by E. Geoffriau.)

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Fig. 22.5. Mechanical celeriac trimming. (Photo by E. Geoffriau.)

According to studies, celeriac can be stored for 3 to 8 months (Weichmann, 1977) at –1 to +4°C and relative humidity greater than 95%. A high relative humidity is crucial to avoid desiccation and weight loss. Controlled atmosphere does not seem to be efficient for storing celeriac, with low oxygen levels not reducing crop loss and high carbon dioxide levels increasing decay (Weichmann, 1977).

Waxing trimmed celeriac is possible but does not provide significant technical and financial benefits and may increase decay.

Celeriac nitrate content changes considerably during storage and evolution can be reduced by pre-storage washing treatments (Mirecki *et al.*, 2015).

22.6 COMMERCE

Celeriac production is predominantly European, averaging more than 426,000 tonnes over the period 2014–2016. The main producers are the Netherlands, Germany, Poland and France. In 2016, although Europe accounted for 62.6% of world exports, the main exporters were the Netherlands (20.4%), China (15.1%) and Italy (10.8%). On the other hand, Europe accounted for 59.5% of imports. The main players were Germany (14.3%), the UK (9.6%) and the USA (7.3%) (Tridge, 2019). The marketing of celeriac is carried out through three main ways of valorization. The majority of production goes to the agri-food industry, with processes of grating, slicing and dehydration,

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canning, freezing or cooking in soups or purées. The product requirements then focus on a minimum weight, level of whiteness and storage quality. The fresh market valorizes smaller products with superior aesthetic qualities. Finally, the pharmaceutical and medicinal industry extracts compounds such as mineral salts, terpenes and phthalides (Van Wassenhove *et al*., 1990; Alibaş, 2012; Lim, 2015).

Several limitations explain the consumption decrease. The pronounced taste and rough appearance assimilate it to an old vegetable. Moreover, celeriac is not an easy and quick vegetable to use as it systematically requires preparation before being consumed, even raw. The revival of its consumption will certainly need to go through a rejuvenation of its image and the development of ready-to-consume preparations. Finally, additional added value for growers will probably be through the valorization of the nutritional compounds.

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23

Celery

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23.1 IMPORTANCE OF SPECIES AND GROWING AREAS

There are 15 species of *Apium* in the world with most being found in the southern hemisphere. The only cultivated species is *A. graveolens*, which has three food crop varieties: stalk celery, *A. graveolens* var. *dulce*; smallage, *A. graveolens* var. *secalinum*; and celeriac, *A. graveolens* var. *rapaceum*. Celery is a biennial plant that is grown as an annual vegetable. Wild celery, *A. graveolens* var. *graveolens*, is adapted to wet locations and was found throughout marshy areas in Europe and western Asia. Stalk celery was first cultivated 850 BCE and was known to the Egyptians, Greeks and Romans. The wild plant has petioles that are hollow with a sharp aroma and was probably first used as a medicinal herb. It is not clear when selection for solid petioles started, but its use as a spice plant was first mentioned in 1623 and consumption as a vegetable was mentioned in 1686. Stalk celery is consumed primarily in North America and Europe. The stalks are consumed raw or cooked, but are also pickled, juiced, frozen, canned and dried. Celery seed is used as a condiment, spice and herbal medicine.

23.2 BOTANY

The edible portions of stalk celery are the leaf petioles which are long and fleshy. Mature plants have from seven to 15 large, upright petioles that occur on the outside of the plant surrounding smaller petioles inside, which surround the apical meristem (Fig. 23.1). The inner petioles receive less light and are more yellow and tender, forming the celery heart.

The petioles are long, broad, glabrous, crescentic in cross-section, with expanded sheathing and shingling bases. The tightly clustered petioles are attached to the flattened compressed stem. These fleshy petioles develop during the vegetative and first cycle of growth, during which time the stem remains

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Fig. 23.1. Celery plants just prior to harvest. Note the upright petioles form a head. The leaves will be trimmed for packing. (Photo by R. Smith.)

compressed as a fleshy crown (Hayward, 1938). The petioles consist mostly of large thin-walled parenchyma tissue and collenchyma strands associated with vascular bundles beneath the epidermis. Ribbing on the abaxial (convex) surface is prominent because of the proximity of collenchyma tissue whereas the adaxial (concave) surface is smooth. Vascular bundles and collenchyma strands cause celery petioles to be stringy (Fig. 23.2).

Leaf blades at the top of the petiole are glabrous and pinnate or bipinnately lobed with apical pinnae having three sessile leaflets. Leaflet shapes are somewhat rhomboid, or almost triangular with bases cuneate, apex acute and margins dentate or incised. Many celery cultivars have shiny dark green foliage, whereas self-blanching cultivars have light green or yellowish green leaves. Leaves of some celery cultivars have anthocyanin pigmentation.

Celery seed is a small flattened schizocarp and splits when mature into two single-seeded mericarps that often remain attached by a filament called a carpophore. Mericarps have five primary corky ribs, are mostly oval-shaped and are very small; about 2500 seeds weigh 1 g.

23.3 PLANT DEVELOPMENT

Celery seed germination and early seedling growth are slow and variable. The embryo is not fully developed when seeds mature and undergoes further

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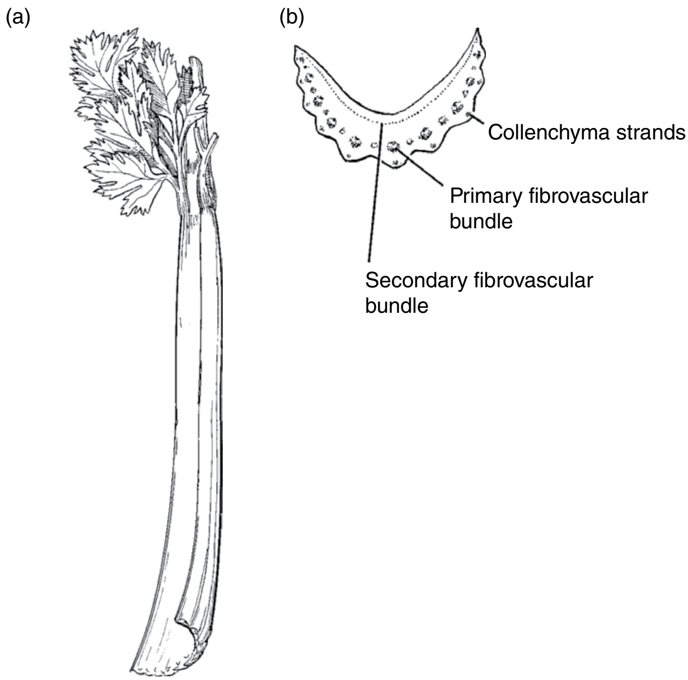

Fig. 23.2. (a) Celery petiole and (b) anatomy of celery petiole cross-section.

development during germination, resulting in delayed germination. Celery seed has postharvest dormancy that can cause erratic seed germination and variable seedling emergence. To overcome this dormancy, celery seed is often stored at 5–10°C for a year or more after harvest to allow germination inhibitors to decline naturally. Germination inhibitors in the seed can also be removed by leaching (Thomas *et al.*, 1975). Seeds are more heat sensitive when germinated in the dark, and periods of light and alternating periods of low temperatures help to alleviate periods of thermodormancy. Planting seeds shallowly facilitates exposure to light and helps germination. Priming is used to improve seed germination and seedling uniformity at higher temperatures. Primed seeds tend to have improved germination and uniformity but priming accelerates the ageing of the seed and reduces its longevity.

After seed germination, the growing seedling develops a strong spindle-shaped taproot and a rosette of erect petioles that form the stalk to be harvested after 90–110 days. The yield of stalk celery is maximized by the production of leaves with long and thick petioles. The rate of leaf production is temperature-dependent and both low and high temperatures cause reduced leaf formation (Roelofse *et al.*, 1990). Temperature also affects petiole development. High temperatures reduce the length of petioles. Daylength affects leaf production with less leaf production during long day conditions.

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Celery is a quantitative short–long day plant with a vernalization requirement to initiate reproduction. Celery bolting and flowering are dependent on the relationship of genotype and environmental conditions that include temperature, photoperiod, light quality and crop stress. Plants in the vegetative growth phase have an almost flat, relatively large-diameter apex of about 0.4–0.5 mm. As plants enter the reproductive phase, the apex becomes pointed as it rises and decreases in diameter. The major indication of bolting is the elongation of the inflorescence stalk which can be monitored by measuring changes in the diameter of the stem apex. Stem elongation occurs only in vernalized celery plants whose apices have differentiated into flower primordia (Pressman and Negbi, 1980). Celery plants will not bolt in the first year of growth if non-inductive temperatures persist. Chronological age is not a reliable indicator of plant responsiveness to vernalization induction. Rather it is the physiological age along with the appropriate temperature that determines the response to vernalization: physiological age varies among cultivars. Some cultivars are more easily induced to bolt than others, a distinction well known to celery growers. However, the duration of juvenility for some plants may extend until they have 17 leaves or more.

The occurrence of bolting along with high temperatures occasionally leads to the erroneous implication that high temperatures cause bolting, when in fact high temperatures simply accelerate and amplify the expression of the already-induced bolting. In general, vernalization temperatures of 5–10°C are efficient, although for some cultivars temperatures up to 14°C can be adequate for thermo-induction (Roelofse *et al.*, 1990). The duration of chilling temperatures is cumulative and full induction usually requires several weeks.

Sachs and Ryski (1980) reported that pre-devernalization of nursery-grown celery transplants by exposure to high temperatures (25–35°C) for short periods before transplanting into the field caused a significant delay in the rate of bolting. Lengthening that period of high temperature exposure further delayed the onset of bolting.

23.4 CROP PRODUCTION

Soil preparation for celery includes numerous tillage practices to prepare the soil: levelling to reduce wet spots in the field; deep ripping and chiselling down to 50–100 cm to reduce compacted layers in the soil and to facilitate root penetration and drainage; discing to incorporate prior crop residues and reduce clod size; and ring rolling to further reduce the clod size and smooth the soil (Takele *et al.*, 2012). Following primary tillage, 1 m wide beds are listed. Depending on the weather, the beds may be pre-irrigated to soften the soil and prepare them for passes with a lilliston cultivator to control weeds, reduce clod size and to prepare the beds for shaping. Beds are shaped with spike-tooth bed shapers or power mulchers. Shaped beds have a flat surface with soil in fine tilth. Raised

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beds improve drainage and soil aeration and facilitate irrigation practices, cultivation and other cultural operations. Raised beds in cooler climates can also contribute to increased soil temperatures, which can reduce time to maturity by a few days or more. Uniform flat field surfaces and/or uniformly shaped raised beds are critical for planting operations.

Celery is no longer seeded direct due to slow seed germination and low seeding vigour. The use of field-grown transplants is also rare due to difficulties growing the plants uniformly and economically. Celery stands are established using transplants produced in greenhouses. The benefits of transplanting include: earlier production; full populations of uniformly spaced plants; elimination of thinning and reductions in the amount of seed required; reductions in the number of days that the crop is in the field; reduced weed pressure; and more efficient use of inputs such as pesticides, fertilizer and irrigation water.

Transplant production has become a specialized industry. Facilities are typically film-, fibreglass- or glass-covered structures that have bench frames that hold transplant trays. Transplant trays are made of polystyrene or rigid plastic. Trays used by different companies vary considerably, but typically are approximately 35 cm × 70 cm containing 250 to >300 cells per tray. Cells are 4 to 8 cm^2 in surface area and 5 to 8 cm deep. The choice of which cell size to utilize is a compromise between the number and quality of plants produced. Superior plant quality is produced at lower densities, but at higher cost per unit area. The trays are filled with a potting mix that is typically a blend of peat moss, sand and perlite. The potting mix facilitates good water-holding capacity and drainage and is weed- and disease-free. Fertilizers are blended with the medium to facilitate early growth of the seedlings; low concentrations of nutrients are supplemented in the irrigation water during the production cycle to assure adequate crop nutrition during the transplant production cycle. In commercial nurseries, automated machines fill the trays with potting medium, plant the seed and top the cell with vermiculite. Coated seeds are used by the automated seeders to facilitate singulation of the seed into the cells of the tray. At optimum temperatures for germination, between 15 and 20°C, celery germinates in 7–12 days. Germination is slower at cooler temperatures and at ≥25°C due to thermodormancy. At temperatures >30°C, no germination occurs.

Plants are ready to transplant in about 7–9 weeks when the plants have three to six true leaves and can be pulled from the trays with sufficient roots to hold the plug together, so the potting mix does not fall away. If the plants grow too tall, they are trimmed with mechanical cutters to a height of 10–12 cm prior to transport to the field. Two or more light trimmings are preferred to one severe trimming. The trimming process helps hold back seedlings if planting is delayed. It also helps reduce leaf entanglement which facilitates handling of individual plants during the transplanting process.

Trays are placed on to shelves in special transport containers for delivery to the field. Trays are loaded on to shelves on mechanized transplanters. Workers remove the plants from the trays and place individual plants in the

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transplant mechanism. The most common transplanter uses a revolving carousel in which the plants are placed and carried around to where they drop down to the planter shoe that opens a slot in the soil for the plant and closes when the plant is placed in it. Sprinkler or drip irrigation is applied as quickly as possible after transplanting to set the transplants and keep them from drying out. Celery is commonly planted on beds that are 91–100 cm wide with two plant rows spaced 30–36 cm apart (Fig. 23.3), with in-row plant spacing of 18–23 cm apart (Daugovish *et al.*, 2006). Plant populations vary from 87,000 to 110,700 per hectare depending on the type of harvest product being produced. Blanched celery is either spaced wider to allow soil to be banked against plants to exclude light or planted closer to cause the plants to self-blanch.

Celery is a cool-season vegetable and is grown after the danger of severe frost has passed during the mild times of year, the optimal temperatures for production ranging from 16 to 21°C. Favourable temperatures determine the duration of the cropping period which can vary from 90 to 110 days after transplanting. Early plantings may experience freezing temperatures which can damage the crop; exposure to temperatures of 10°C stimulates the plants to produce a seed stalk, reducing crop marketability. Crop vigour is dependent on the use of adapted varieties and good growing practices; favourable environmental conditions allow seedlings to establish and develop vigorously. Celery

Fig. 23.3. Young celery transplants planted in two seed lines on a 1 m wide bed. (Photo by R. Smith.)

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is moderately sensitive to salinity and suffers yield loss when the electrical conductivity of saturated soil extract is greater than 1.8 dS/m. Irrigation and nutrient management are critical to producing high-quality celery that is free of defects.

23.5 NUTRITION/FERTILIZATION

A balance of macro- and micronutrients is required to produce high-quality celery. Celery has a relatively high demand for nitrogen, phosphorus and potassium. Total above-ground crop biomass at harvest contains 224–336 kg of nitrogen, 45–67 kg of phosphorus and 336–560 kg of potassium per hectare (Hartz, 2020). Careful fertilizer management is required to supply nutrients for optimal growth, but also to avoid supplying too much nitrate-N that can be lost to surface waters or by leaching beyond the rootzone, which can contaminate groundwater resources.

Required quantities of phosphorus and potassium fertilizer can be reliably determined by soil tests that are appropriate for local soils. Celery has a high demand for phosphorus and potassium, and it is important to supply adequate quantities of these nutrients to facilitate rapid growth. Over time in intensive vegetable production areas, soil phosphorus levels can increase due to the use of phosphorus fertilization rates that are higher than the amount of phosphorus removed with the harvested products, causing water quality concern if phosphorus is lost to surface waters. Phosphorus uptake is affected by soil temperature and pH. Less phosphorus is taken up at lower soil temperatures, which may justify higher rates early in the season when soils are cool. Soil pH also affects phosphorus availability. At pH <6.0, phosphorus is adsorbed on to aluminium or iron oxides. At higher pH, calcium carbonate fixes a higher percentage of applied phosphorus. In both situations, additional phosphorus fertilizer application may be necessary to assure that adequate phosphorus is available for optimal yields. Potassium uptake by celery is higher than any other nutrient. Potassium fertilizer practices need to assure that adequate amounts of potassium fertilizer are applied to the field to make up for crop removal. Approximately 50–65% of potassium taken up by celery (168–364 kg/ha) is removed in the harvested product, which underscores the need for replacing what is removed.

The crop cycle of celery varies from 90 to 110 days, and three or four applications of smaller quantities of fertilizer nitrogen are more efficient than two larger applications. The use of drip irrigation facilitates multiple fertigations over the crop cycle, even after the canopy closes, when fertilizer applications with tractor equipment cannot be made (Fig. 23.4). The quantity of nitrogen taken up by celery is a good starting point to base the season-long fertilizer applications. However, crop nitrogen-uptake requirements can at times be supplied from non-fertilizer sources such as residual soil nitrate-N, in-season

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Fig. 23.4. Mature celery plantings develop a full canopy that makes it difficult for tractors to enter the field to conduct fertilizer or pest management applications. (Photo by R. Smith.)

mineralization of nitrate from organic matter and nitrate-N in irrigation water. In-season soil nitrate testing can measure the pool of residual soil nitrate from various sources and guide fertilizer applications (Hartz *et al.*, 2000). Soil nitrate tests for planning should be run as close to the fertilizer event as possible to assure that the levels reflect the current soil nitrate levels. Soil samples from a composite of 15 to 20 soil cores collected from the top 30 cm of soil are generally adequate to provide a good measure of the nitrogen levels in the field. Samples can be analysed with a rapid testing technique or sent to a laboratory for analysis. Soil nitrate-N values of 20 mg/kg are equivalent to 83 kg N/ha, which is adequate to supply the nitrogen needs of the crop for 7 to 10 days. Soil sampling for nitrate can be repeated prior to subsequent fertilizer applications.

23.6 IRRIGATION

Celery is shallow-rooted and must be irrigated carefully to avoid water stress that can reduce the yield and quality, as well as leach nitrate from the rootzone of the crop and cause water quality impairments. The most common method to irrigate celery is to establish the plants by sprinkler irrigation for the first month following transplanting and then use surface-placed drip irrigation for the remainder of the season (Takele *et al.*, 2012). Some growers use drip irrigation

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throughout the entire season. Drip irrigation distributes water more uniformly in the field than sprinkler or furrow irrigation and facilitates fertigation of the crop. The use of drip irrigation can help reduce nitrate leaching from celery fields by allowing more frequent applications of smaller quantities of nitrogen fertilizer. Irrigation scheduling can be based on reference evapotranspiration data adjusted for the crop coefficient, which is closely related to the percentage of canopy cover (Daugovish *et al.*, 2006). Optimal celery yield and quality are achieved with irrigation water applications of 125% of crop evapotranspiration and maintaining soil moisture tension below 0.03 MPa. Good irrigation management is critical not only for maintaining high yields but also for avoiding quality issues such as pith (see below).

23.7 HARVEST

Mechanical harvest of celery is used for processing celery. Fresh market celery is mostly hand-harvested, but automated harvesters are increasingly being used. Celery fields are cut only once and fresh market celery is graded according to the number of heads per carton (24, 30, 36 and 48) that weigh 27.2 kg. Celery hearts (the centre of heads) are placed into polyethylene bags and packed into 12.7 kg cartons (Fig. 23.5). Cartons are delivered from the field to coolers and celery is cooled by hydrocooling, vacuum cooling or forced air cooling. Celery is pre-cooled to remove field heat from the product and then stored at 0–2°C with 98–100% relative humidity. At optimal storage conditions, celery should have good marketable storage for 5 to 7 weeks. Celery can absorb odours from other commodities and should not be stored near apples, carrots, onions or pears.

23.8 DISEASES

Celery is affected by diseases caused by bacteria, fungi and viruses that attack the foliage, stalks and roots. Diseases caused by bacteria and fungi include foliar diseases such as bacterial leaf spot (*Pseudomonas syringae* pv. *apii*), early blight (*Cercospora apii*) and late blight (*Septoria apiicola*). Diseases that cause lesions and rot on the stalks include pink rot (*Sclerotinia sclerotiorum*) and crater rot (*Thanatephorus cucumeris*). Aster yellows is a phytoplasma (a bacterium-like prokaryote) that causes yellowing and stunting, and distinctive twisting and curling of the petioles. Viruses that affect celery include *Celery mosaic virus* (CeMV) and *Cucumber mosaic virus* (CMV). Both viruses affect the leaves causing vein clearing and yellowing, as well as necrotic lesions on the stalks (Koike *et al.*, 2007). Disease issues on celery are managed by a combination of cultural practices such as keeping the foliage dry by the use of drip irrigation and the application of fungicides and bactericides. Viral diseases are managed by controlling host plants and vectors.

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Fig. 23.5. Trimmed celery heads being rinsed and packed into cello bags for packing into boxes. (Photo by R. Smith.)

23.9 INSECTS

Celery is attacked by several aphid species: green peach aphid (*Myzus persicae*), hawthorn-parsley aphid (*Dysaphis apiifolia*), cotton-melon aphid (*Aphis gossypii*), black bean aphid (*Aphis fabae*) and foxglove aphid (*Aulacorthum solani*). These insects form colonies on the leaves and petioles and can spread CeMV (Godfrey and Trumble, 2009). Several leaf miner species (*Liriomyza* spp.) attack celery; their larvae tunnel in leaf and petiole tissue. Lygus bugs (*Lygus hesperus*) feed on the stalks and growing points of celery, leaving reddish lesions on affected tissue. Beet armyworm (*Spodoptera exigua*) larvae can cause significant feeding damage on both the foliage and stalks of celery. Insects are managed by establishing habitat for beneficial insects and by the use of insecticide applications.

23.10 ABIOTIC DISORDERS

Symptoms of blackheart include necrosis of leaves in the heart of celery heads. It is caused by calcium deficiency of affected tissue brought on by a combination of

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factors such as rapid growth, uneven soil moisture and high nitrogen (Gubbels and Carolus, 1971). Blackheart can be managed by applying irrigations more frequently to avoid water stress. Petiole pith is caused by a collapse of parenchyma tissue. It is caused by dry soil conditions between irrigations during warm temperature conditions (Breschini and Hartz, 2002).

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24

Chervil

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INTRODUCTION

The term 'chervil' is found in the names of several plant species from *Apiaceae*, which is misleading, as they differ both in morphology and development, as well as in usefulness and importance as cultivated plants. Wild chervil (cow parsley) *Anthriscus sylvestris* (L.) Hoffm., bur chervil *Anthriscus caucalis* M. Bieb., and sweet chervil (sweet cicely or garden myrrh) *Myrrhis odorata* (L.) Scop. are rare as crops. However, chervil (garden or salad chervil, or French parsley) *Anthriscus cerefolium* (L.) Hoffm. and turnip-rooted chervil (tuberous, or bulbous, or parsnip chervil) *Chaerophyllum bulbosum* L. are cultivated plants in forms improved by breeding, considered as a herb and a vegetable, respectively (Vyas *et al.*, 2012).

24.1 IMPORTANCE AND HISTORY OF THE SPECIES

A. cerefolium (L.) Hoffm. is a plant known all over the world, used mainly as a seasoning in cookery. Its delicate leaves are the first ingredient of 'fines herbs', a blend popular in French cuisine. A mild aniseed flavour of chervil in the fresh state makes it particularly pleasant in salads and delicate dishes of dairy, eggs or poultry. As a condiment and garnish, herb and fruit are used as well. They also have some significance as curative raw materials used nowadays in folk medicine due to several activities: diuretic, diaphoretic, alleviating circulation disorders, enhancing lactation and expectorant (Milovanovic *et al.*, 2009).

The species is native to the Middle East, southern Russia and the Caucasus, and was known in cultivation in ancient Greece and Rome, both as a culinary herb and a medicine. Introduced probably by the Romans to European gardens

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(listed in the famous capitulary of St. Gall monastery from the 9th century AD), it has since spread as a crop across all continents. By 1647 it was grown in Brazil and a century later in North America. It is now cultivated around the Mediterranean region (France, Italy, Spain) and in Russia, the UK and the USA (California and New Mexico) (Charles, 2013).

24.2 PLANT DEVELOPMENT

Chervil is an annual plant, not frost-tender, hardy to zone 7 (UK), 6–9 (USA). Escaping from cultivation and domestication, in the wild it is found on damp and semi-shady habitats.

Chervil grows to a height of 0.3–0.7 m and width of 0.15–0.30 m. The spindle-shaped root is thin and white. The stem is round, hollow, finely grooved, hairy and branched. Compound leaves are two–three (four)-pinnately divided, deeply cut, green, resembling parsley's but thinner and paler. A few hairs appear on a mid-vein and margins of leaflets. Lower leaves have long petioles while upper ones are sessile with stem sheaths (Farooqi and Srinivasappa, 2012). Tiny, white flowers are gathered in compound umbels 2.5–5.0 cm across (Figs 24.1 and 24.2). Fruits (achenes) are oblong, up to 11 mm long, with a beak equal to one-third to one-half of their length; shiny and dark brown, nearly black, in colour. The whole plant, irrespective of development phase, possesses a distinct anise odour.

Chervil is propagated by seeds only. Although the germination of this species is said to be low and lasting up to 4 weeks (Liopa-Tsakalidi and Barouchas, 2011), with quality seeds, full emergence of about 90% of seeds is possible after 5–7 days at 22°C in the dark (own observations). Chervil grows quickly and its leaves are ready for harvesting after 6 to 8 weeks. In temperate regions, when sown in March–April, it is in flower in May–June and fruits ripen in June–July (Vyas *et al.*, 2012). Seed vernalization induces rapid bolting under long days. Hot weather together with water deficiency is also a reason for premature bolting. In intensive growing conditions (greenhouses) calcium and boron deficiency symptoms (tipburn, distortion and discoloration) are frequently observed (Kleemann, 2001).

Specific compounds comprise first of all the essential oil located in secretory ducts extending from the roots throughout all plant parts. Its content is about 0.2–0.5% by weight in the dried herb and leaves and 0.9% in the fruit. Methyl chavicol, methyl eugenol and 2-allyl-1,4-dimethoxybenzene are the main volatile constituents and their share depends on the stage of plant development. Other important active compounds are flavonoids (quercetin, apiin and luteolin), bitter substances and phytosterols. Chervil is also a rich source of vitamins C and B, carotenoids and minerals (Simándi *et al.*, 1996; Milovanovic *et al.*, 2009).

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Fig. 24.1. Chervil leaves and branching shoot. (Photo by E. Capecka.)

24.3 CULTIVATION

Chervil is a cool-season crop of short vegetation period, therefore in the open field it is usually grown in spring and autumn. In temperate climates, it can also be grown in summer but partial shade and constant proper moisture level in the soil are needed to avoid poor growth and rapid running to seed. Optimum growing conditions always consist of moist, well-drained, humus-rich, fertile soil of pH 6.5. Planting is started with direct sowing in rows about 30 cm apart. Distance between plants after thinning should be 8–10 cm. During plant growth, except for standard weeding, irrigation and fertilization, the practice of cutting flower stems before they bloom is recommended whenever leaves

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Fig. 24.2. Chervil plant at flowering stage. (Photo by E. Capecka.)

are the purpose of production. This results in stronger branching and denser foliage.

Leaves are ready to harvest 6–8 weeks from sowing. When the purpose of the crop is herb, plants are collected at the stage of beginning to full flowering. After collection of the first yield, plants give new growth and a second cut. When fruit is desired, it is allowed to mature on plants and then collected stems are thrashed in the field with special care taken to avoid crop losses due to scattering.

Chervil is also grown indoors where the production is geared towards obtaining fresh leaves, seedlings or microgreens to be available constantly at the market. Various growing techniques are applied, including the most innovative like vertical farming based on hydroponics and artificial light, with the focus on accelerating plant growth, multiple harvests and thus increasing economic efficiency. This way of obtaining fresh culinary herbs is common especially

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from autumn to spring. Followers of accelerated cropping systems believe that in terms of flavour, herbs from hydroponics are superior to those cultivated in soil (Giurgiu *et al.*, 2014). Growing and distributing chervil in pots reduces the problems with maintaining the quality in the trade.

The most harmful pests of chervil are aphids feeding on the undersides of leaves, leaf petioles and flowering stalks. They also contribute to viral diseases like *Anthriscus yellows virus* (AYV) or *Carrot red leaf virus* (CRLV) (Farooqi and Srinivasappa, 2012). Discolorations and stunting of plants may also be caused by phytoplasmas. Other diseases are damping-off (root rot) affecting mainly seedlings, and powdery mildew and downy mildew harmful especially to older plants. On stems and petioles of hydroponically cultured chervil, Plectosphaerella rot diseases were observed.

Two groups of chervil varieties are known: flat-leaved (plain) and curl-leaved (frisé). Such cultivars as Massa or Vertissimo of Brusseler Winter type have flat, dark green, smooth leaves. Their good vigour, increased cold tolerance and lower susceptibility to bolting make them suitable for autumn sowings. The curl-leaved chervil is characterized by a weaker growth, but a very attractive appearance of serrate, crisped leaves, suitable particularly for garnishing.

24.4 POSTHARVEST

As a perishable produce, cut chervil for the fresh market must be cooled down, protected against wilting and delivered quickly to recipients. Careful handling to minimize mechanical damage is required. Rigid clear plastic boxes for transport and storage are recommended. Optimum conditions during postharvest handling and storage are 0–5°C and 95–98% relative humidity that provides a shelf-life for fresh chervil of about 10–14 days. Controlled atmosphere, low light irradiation and mineral nutrient supply in storage allow for longer preservation of chervil visual quality (Fujiwara *et al.*, 1999).

When dried chervil is required, harvested foliage or herbage should be immediately dried at 35°C in the dark, then tightly packed in paper bags or glass containers and stored in cool, dry and dark conditions.

The threshed fruits require further dehydration in drying facilities. Packing and storage are as for the dried herb.

24.5 MAIN UTILIZATION AND QUALITY PRESERVATION

Chervil is used primarily as a culinary herb applied in the fresh state. Dried leaves and herb lose their characteristic aroma. They are also deprived of most vitamins. Loss of flavour and nutritional value also applies upon subjecting the delicate herb to high temperature when preparing meals. Fresh chervil sprigs

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should be cut and added at the last moment of cooking or used for cold dishes or as a garnish. It is possible to preserve chervil's subtle fresh flavour and anise-like aroma for longer by freezing or with the use of white wine vinegar and vegetable oils or butter (Farooqi and Srinivasappa, 2012).

Chervil herb after drying becomes grassy and as a seasoning is practically useless, nevertheless it has some importance as a gentle remedy recommended by folk medicine. Fruits, due to their greater essential oil content and enclosure in vittae located inside stronger tissues than in leaves, keep the aroma much better and are a valuable condiment which is prized by restaurant professionals, using chervil microgreens with fruit husks remaining attached to cotyledons.

24.6 CONCLUSION AND PERSPECTIVES

Chervil may be an important contributor of vitamins and minerals to the human diet. In addition, a considerable content of flavonoids in the herb increases its health-promoting value. Chervil extracts possess antioxidant and anti-lipoperoxidation activity proved in numerous *in vitro* tests. This indicates the possible preventive role in the pathogenesis of diseases caused by overproduction of free radicals. Chervil, next to other common herbs, was identified by the National Cancer Institute as possessing cancer-preventive properties (Craig, 1999). According to Milovanovic *et al.* (2009), *A. cerefolium* is a good source of phytosterols which present additional health benefits, especially for people with cardiovascular problems. To some extent, this confirms the legitimacy of traditional use of this plant as a therapeutic agent. Hence, this herb should be perceived not only as a flavouring supplement but also as a source of nutritional and functional food ingredients. The increasing awareness of this fact among consumers, dietitians and restaurateurs, along with the simplicity in chervil cultivation and the advanced techniques of packaging and quality maintenance, indicate the potential for widespread popularization of this plant crop.

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25

Coriander

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25.1 BIOLOGY

Coriandrum sativum is an annual species belonging to the *Apiaceae* family. It can reach 20–60 cm in height with an erect, slightly striated and branched stem (Fig. 25.1). The leaves vary in morphology depending on how they are positioned on the plant, with the basal leaves displaying a rounded contour that differs from the upper leaves that display branched pinnate segments and linear lobes. The flowers are carried in umbels formed of two to six unequal rays. Flowers are made up of unequal, triangular or lanceolate sepals, white petals often veined with dark pink, and purplish pink or yellow anthers. The ovoid fruit measures 2–6 mm, is agreeably aromatic, hard-walled, crossed by primitive ribs (Fig. 25.2). The plant is easy to identify by its double odour (leaves/fruit), its foliar gradient and its globular fruit (Reduron, 2007).

Morphologically, there is little variability between the different accessions available for this species. But, sometimes, two types are distinguished: one small-fruited type with fruits of 1.5–2 mm in diameter and which contain high essential oil content; and one larger-fruited type, which has a lower content of essential oil but that is preferred for spice use (Purseglove *et al*., 1981). Despite this, coriander has been the subject of various breeding programmes and today many varieties exist in the world, including in France, selected mainly on the production of leaves (Bimbraw, 2006; iteipmai, 2011).

25.2 USE

Coriander remains one of the most cultivated aromatic species in the world and several parts of the plant can be used, including the dried diakenes (defined by the European Pharmacopoeia, 9th edition, monograph 07/2014: 1304 corr 10.0),

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Fig. 25.1. Bolted plants of coriander. (Photo by iteipmai.)

Fig. 25.2. Coriander fruits. (Photo by iteipmai.)

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the fresh plant (known as Arabic parsley or Chinese parsley depending on the user kitchen) and the essential oil of the leaf or fruit. The fruits are used in the food industry for vinegar preparations, to flavour beer and in the manufacture of certain liqueurs. In herbal medicine, the drug is a stomachic, spasmolytic and carminative because of its essential oil and is used in the manufacture of many mixtures for infusion with various therapeutic indications, but also as a taste corrector. The essential oil is also used as an aroma in the tobacco and perfume industries (Wichtl, 2004; Reduron, 2007).

The standard ISO 2250:1996 specifies the requirements for coriander (*C. sativum* L.), in the whole and ground (powdered) forms. The standard ISO 3516:1997 is dedicated to the essential oil of coriander fruits (*C. sativum* L.). The essential oil is also described in the European Pharmacopoeia, 9th edition (monograph 07/2014: 1820).

The coriander leaf aroma is typical, due to its content of insaturated aldehydes with 8 to 14 carbon atoms. The leaf is rich in vitamins A, K and C (Ambrose *et al.*, 2016).

The main constituent of the leaf essential oil is linalool (see e.g. Lawrence, 2011). The composition of this essential oil is closely linked to the maturity of the fruit: essential oil yield and linalool content regularly increase from the first stage of maturity to the last one (Msaada *et al.*, 2007).

25.3 CROP MANAGEMENT STRATEGIES

Coriander is usually grown by directly sowing in the field, preferably in permeable soils (preferably limestone). Fields that were used to produce crops from the *Apiaceae* family (e.g. dill, green anise, fennel, parsley) should be avoided. For seed production, the plant is sown in the spring between March and April, whereas for leaf production, in a temperate zone, the crop is sown in summer, in July–August, to avoid a rapid flowering. In southern zones, coriander cultivars that are more tolerant to colder temperatures can be sown from the end of the summer until the first half of November and in January/February. Care must be taken to ensure that the surface of the soil is kept moist during the entire emergence period. Most often a pneumatic or mechanical precision seed drill or a conventional grain drill is used to sow the seeds at a depth of 1 to 2 cm. Seedlings can take about 15 days in good conditions to emerge. Sowing densities are adapted depending on the part of the plant that is to be harvested. For instance, in the case of seed production, the inter-row spacing is often set at 35 cm with seed rate of 15 kg/ha, whereas for leaf production the inter-row spacing is often close to 17.5 cm and 30 kg seed/ha will be required. One gram of coriander seeds contains about 130 seeds (mericarps). In the case of species of the *Apiaceae* family, seeds are often described as diakenes with mericarps, which are elements of the fruit that dissociate at maturity. Seed shelf-life is usually estimated at 2 to 4 years.

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In terms of fertilization, coriander is relatively demanding, notably in phosphorus. It is advised to use 50 units of nitrogen, 100 to 120 units of P_2O_5 and 60 to 100 units of K_2O per hectare.

The water requirements of the plant are estimated at 20–25 mm every 8 to 10 days for leaf production and around the time of fruiting for seed production (iteipmai, 2011).

25.4 DISEASES AND PESTS

Several diseases are caused by various pathogens on coriander including:

- Bacterial leaf spots caused by *Pseudomonas syringae* pv. *coriandricola*, transmitted by the seed and characterized by brown necrotic lesions on leaves and inflorescences which can result in wilt (Cerkauskas, 2009; Refshauge *et al.*, 2010; Gupta *et al.*, 2013).
- Stem gall disease caused by *Protomyces macrosporus*, present on stems and petioles, characterized by yellowing spots and an appearance of elongated or globular swelling. The corky surface reaching maturity causes cracks on the stem (Mishra and Pandey, 2017).
- Ramulariosis caused by *Ramularia coriandricola* which appears as necrotic circular spots on the leaves with a discoloured centre. *R. coriandricola* is less often recorded but is one of the most damaging coriander pathogens (Weiss, 2002).

Coriander is generally free from major insect pests. However, a number of pests can parasitize coriander such as the chalcid wasp (*Systole albipennis*) whose larvae damage the fruits, a leaf miner (*Liriomyza trifolii*), a defoliating moth (*Spodoptera litura*) and aphids like *Hyadaphis coriandri* (Weiss, 2002; Singh *et al.*, 2009; Kant *et al.*, 2013).

25.5 CROP PROTECTION

In France, plant protection products are approved to fight against certain diseases and certain pests. Chemical solutions are also available for weeding, with plant protection products registered at the different stages of the crop's development: post-planted, post-emergent and on the installed culture of coriander. In non-chemical weeding, false seed bedding is often used before sowing, followed by thermal weeding before the emergence of the coriander. The use of a harrow properly adjusted after several tests, in full fields, on young weeds (two leaves) in the four- to six-leaf stage of coriander, is also possible. In the inter-row, more sophisticated weeding methods such as hoeing (type Super Prefer) can be applied (iteipmai, 2011).

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25.6 HARVEST

Seed harvesting occurs, for a spring-sown crop, in July–August. Pre-wetting of 2 to 3 days is possible in good weather conditions. If the crop is too wet, drying may be necessary at a temperature of approximately 35°C. The seeds are subsequently sorted to rid them of their impurities.

In warmer conditions, the harvest of the leaves can take place in April and May of the year following the installation in the case of late sowing periods. In the case of a summer sowing period, the harvest can occur between September and early November of the same year. The first cut is carried out 45 to 60 days after sowing. Two harvests are possible for late summer sowing under good growing conditions (heat and humidity). In industrial culture, a loader-picking harvester or type spinach harvester is utilized. The cutting height is adjusted to avoid harvesting yellow leaves at the base of the plant.

In industrial production, to obtain a dehydrated product from the leaf, the harvested plant is cut so as to separate limbs and petioles. Then, washing with disinfected water and wringing of the product is performed before drying. To best preserve the aroma of the plant, the drying must be done in two phases: a first rapid phase at 100°C then a second phase at 50°C to finalize the dehydration. After drying, the product is calibrated to meet the specifications of the manufacturer.

In artisanal production, to obtain dry leaves, the dried product is beaten with a conventional thresher to separate the limbs from the petioles. The product obtained is either entire/whole leaf or fragmented. About 30 to 35% of the leaves are broken during this operation.

To obtain a frozen product from the leaf, the plant undergoes the same process as for dehydration except that drying is replaced by freezing.

Leaf yields per cut and per hectare are about 10 tonnes in fresh produce or 1.5 to 2 tonnes in dry weight. About 1.5 to 2 tonnes of fruit are obtained per hectare and the essential oil content varies from 0.12 to 0.17% by weight for fresh leaves and from 0.8 to 2% by weight for fruits (iteipmai, 2011).

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26

Dill

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Dill (*Anethum graveolens* L.) is cultivated worldwide as a fresh or dried herb and for essential oil. Indian dill, formerly classified as *Anethum sowa* Roxb. ex Fleming, is a botanical variety of *A. graveolens* that predominates in India and South-east Asia.

26.1 HISTORY, IMPORTANCE AND GROWING AREAS

Dill is believed to have originated in the eastern Mediterranean. In Egypt, dill was discovered in the tomb of Amenhotep II (reigned 1427–1401 BC), while in Ancient Greece dill-scented oil was burnt in homes and used to flavour wine. Hippocrates (*c.*460–*c.*370 BC) prepared a mouthwash from dill seeds in wine, and dill leaves were placed over the eyes to induce sleep. Roman gladiators ate dill with their meals and applied dill oil to invigorate themselves and bring good fortune. The physician Dioscorides (*c.*AD 40–90) recommended placing scorched dill seeds on wounds to assist healing.

Dill (named *anetum*) was among the herbs listed in *Capitulare de Villis*, a work decreed by Charlemagne (742/747–814), and in the Middle Ages it was used to protect against witchcraft, scent houses and displace unpleasant odours. Culpeper (1616–1654) mentioned dill in his *Complete Herbal* and recommended it to stop hiccups and reduce flatulence. By the 17th century, dill was cultivated throughout Europe and had been introduced to North America. In India and South-east Asia dill has been cultivated since ancient times (Le Strange, 1977).

Nowadays, dill is increasingly grown as a herb and to produce oil for the food and pharmaceutical industries, but because cultivation occurs mostly in small units, precise data on yields/areas are not available. The largest producers of dill seed are India, Pakistan, China and Russia, with principal consumers

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the USA, Japan and Germany. Hungary, the USA and Bulgaria are significant producers of dill oil.

26.2 ETYMOLOGY, MORPHOLOGY, CONSTITUENTS

The Latin name *Anethum graveolens* comes from the Greek ἄνητον or ἄνησον (indicating 'upright growth') and the Latin *graveolens* indicating 'strong odour'. Common names include dill (English and German), aneth (French), eneldo (Spanish), ukrop (Russian), shíluó (Chinese) and savaa (Hindi).

Dill is an erect, annual or biennial, freely branching plant (Fig. 26.1), 0.5–0.9 m in height during the vegetative stage, reaching 1.5 m at flowering. Stems are slender, glabrous and hollow, with sheathed, alternate leaves that divide three or four times to terminate in thread-like segments. The lower leaves may be 50 cm × 25 cm, but higher leaves are smaller. The hollow taproot can grow to 1–1.5 m. The inflorescence is a compound umbel (Fig. 26.2), normally 5–15 cm in diameter. Flowers are yellow, bisexual, actinomorphic and protandrous, stigmas becoming receptive after shedding the stamens and corolla. The fruit is a lens-shaped, brown schizocarp (2.5–5 mm × 2–4 mm), ridged longitudinally, with a white-brown margin; at maturity it divides into two mericarps (so-called 'seeds'). However, morphological traits vary considerably (Ninou *et al*., 2017).

Dill-weed (as the fresh herb is commonly called) contains 86% water, 7% carbohydrate, 3.5% protein, 1.1% lipid and 2% fibre by fresh weight. The major minerals and vitamins per 100 g of tissue are: calcium (208 mg), phosphorus (66 mg), magnesium (55mg), potassium (738 mg), iron (6.6 mg), sodium (61 mg),

Fig. 26.1. Vegetative growth of dill. (Photo by I.C. Karapanos.)

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Fig. 26.2. Dill umbel with seeds. (Photo by I.C. Karapanos.)

vitamin C (85 mg), niacin (1.57 mg), thiamine (0.06 mg), riboflavin (0.3 mg), pantothenic acid (0.4 mg) and vitamin A (7718 IU) (USDA-ARS, 2018).

Dill-weed oil, extracted from the leaves and stems, comprises α-phellandrene (30–65% v/v) and 3,9-oxy-*p*-menth-1-ene (dill ether) (15–20% v/v), with limonene, β-phellandrene and *p*-cymene in smaller amounts. Traces of another ten to 20 constituents have been identified (Charles *et al.*, 1995; Vera and Chane-Ming, 1998). Dill-weed oil totals 0.1–0.3% v/w of the green plant, but quantity and composition vary with extraction method, plant development, climatic conditions and cultivation practices (Callan *et al.*, 2007; Madhava Naidu *et al.*, 2016).

Dill-seed oil, extracted from seed-containing umbels, consists mainly of carvone (40–70% v/v) and limonene (15–30% v/v). A study of 35 cultivars identified three chemotypes: Type-1 contained myristicin and apiole, Type-2 contained apiole, but not myristicin, whereas Type-3 contained neither myristicin nor apiole (Badoc and Lamarti, 1991); however, other chemotypes occur. The yield of seed oil is 1.7–7.5% v/w, but varies (as does its composition) with extraction method, fruit maturity, cultivar and growing conditions. Oil is usually extracted by hydro- or steam distillation, or by organic solvents (e.g. hexane or pentane). The occurrence of carvone in dill-weed oil indicates that fruits/seeds were present at harvest; therefore, to obtain pure weed-oil, extraction should occur before flowering.

26.3 CROPPING SYSTEM

Dill grows best in well-drained, sandy-loam soils (pH 5.5–6.5) with a moderate organic/nutrient content (<4 dS/m). Soil should be well rotavated before

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sowing; shallow, hard or compacted soils are unsuitable because they restrict taproot development. Dill is moderately tolerant to salinity (≤8 dS/m) (Tsamaidi *et al*., 2017) and in India has been recommended for cultivation in areas where soil salinity occurs.

The optimum growth temperature is 18–25°C, when crop duration is 2.5–3 months. Propagation is by direct sowing of seed, but not by transplantation, which can damage the taproot. At 10–21°C seedlings emerge within 15 days. Common cultivars include Bouquet, Dukat, Hercules, Tetra, Mammoth and Vierling, although many unnamed landraces are also grown. For production of the fresh herb, dill may be sown successively throughout the year according to climate (absolute growth temperatures 4°C and 35°C) and market demand. For seed production spring sowings are preferable since flowering is promoted by daylength above 14 h and seeds mature under favourable conditions. The 1000-seed weight is 1.7–1.9 g and sowing rate is 3.5–6 kg/ha. Plants should not be exposed to strong winds, which cause lodging and impede harvest, especially in seed crops. High temperatures promote flowering and suppress vegetative growth.

Field application of farmyard manure (≤30 t/ha) or other suitable organic material is beneficial. Inorganic fertilizers are applied on the basis of soil analysis. Nitrogen application promotes vegetative growth, but in seed crops can delay flowering and reduce seed carvone content (Wander and Bouwmeester, 1998). Dill requires frequent irrigation because water deficiency severely restricts growth (Tsamaidi *et al*., 2017).

Weed control is important especially during early plant growth. Dill is susceptible to *Sclerotinia sclerotiorum*, which infects stems and leaves in the neck region, particularly in soils with excessive humidity. Other pathogens include Alternaria leaf blight (*Alternaria dauci*) and powdery mildew (*Erysiphe* spp.) of the foliage and umbels. Pests include wireworms and nematodes, which attack the roots, as well as psylla and aphids which infest the foliage. Control measures include crop rotation and/or soil sterilization and insect traps.

Harvesting of fresh dill starts once leaves have attained 30–40 cm in length. Leaves are collected by hand preferably in the early morning; they must not be exposed to direct sunlight or washed, as this reduces their aroma. In contrast, seed crops are best harvested in full daylight so that the seeds are dry. For maximum seed yields, crops are harvested by hand, but for large areas machine harvest is the norm, in which case the umbels (hence seeds) will be at different stages of maturity at harvest. Yields are 10–20 t/ha (dill-weed) and 0.7–1.3 t/ha (seed). For dill-weed oil, plants are machine-harvested when the seed stalks start to form. Oil yield from the foliage is *c*.55 kg/ha and from the seeds *c*.30 kg/ha.

Dill grown alongside Brassica species is reported to repel caterpillars and aphids from the latter; it can also be cultivated hydroponically.

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26.4 POSTHARVEST

There are no standard market requirements for fresh dill. Leaves are normally tied in bunches of 12–18 and enclosed in plastic to restrict water loss. Leaves should be fresh green, fragrant and uniform in size, with no signs of yellowing, decay or damage (Wright, 2016).

Because of its delicate nature, dill is susceptible to rapid water/weight loss. Dill should not be stored together with produce that releases ethylene as this will cause yellowing. Leaf respiration rates are 324 mg CO_2/kg per h at 20°C, decreasing to 103 mg CO_2/kg per h at 10°C and 22 mg CO_2/kg per h at 0°C; thus, after harvest, dill must be rapidly cooled and stored at 0–2°C and 95–100% relative humidity. Storage life is 7–14 days (Wright, 2016). Low temperature is the single most important factor for storage; overall, modified atmosphere and controlled atmosphere are not beneficial (Tsamaidi and Passam, 2015).

When dill herb is dried, especially in hot air, some aromatic components decrease or are lost. Therefore, alternative methods such as freeze-drying may be preferred. Dried dill-weed can be stored for 1–3 years under cool conditions in sealed containers, although potency will decrease with time. Freezing is unsuitable since it damages cell structure, causing a loss of consistency and aroma.

26.5 PRODUCT VALORIZATION

Fresh and dry dill-weed is used to flavour many industrially produced foods, including sauces, soups, butter, cheese, bread and vinegar. Dill juice is used to flavour other juices, ice creams and pickles, especially gherkins; whole or ground seeds are used to flavour meats, sauces, curries and pickles.

Dill oil is marketed as a paramedical product or food additive. It possesses antioxidative properties and is claimed to relieve anxiety, flatulence, blood pressure, hyperglycaemia and diabetes. The calming effect of dill seeds is attributed to myristicin, but in some individuals this may cause allergy. The presence of carvone and limonene in dill-seed oil makes this product potentially valuable in antimicrobial preparations. Moreover, dill-seed oil alone or blended with other oils has a strong insecticidal activity. Other uses of dill oil include the production of soap, cosmetics and perfumes (Jana and Shekhawat, 2010).

Increasing awareness of the health value of fresh herbs suggests that cultivation and consumption of dill are likely to rise in coming years, although apparent health benefits require confirmation through clinical trials. With increasing concern over the use of organic fungicides and insecticides, carvone-rich dill-seed oil could be exploited further for agrochemical production and organic agriculture. Breeding is required to select cultivars with desirable traits (e.g. high carvone) and with increasing production there will be a need for greater farm mechanization and improved oil extraction.

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27

Fennel

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27.1 BOTANY AND CLASSIFICATION

Fennel (*Foeniculum vulgare* Mill.), family *Apiaceae*, is commonly divided into two subspecies (USDA-ARS, 2019). Subsp. *vulgare* includes var. *azoricum* (Mill.) Thell., the vegetable Florence fennel, or bulb fennel; var. *dulce* (Mill.) Batt., the sweet fennel, the fruit of which is used as a spice and for essential oil extraction; and var. *vulgare*, the wild ancestor of the cultivated types, commonly referred to as bitter fennel. Subsp. *piperitum* (Ucria) Cout. is the wild fennel. 'Sweet' types are distinguished from 'bitter' ones by the composition of their anethole-rich essential oil. Subspp. *vulgare* and *piperitum* should be differentiated by their growth habit, respectively annual–biennial and perennial (Pignatti, 1982). However, annual wild forms are seldom observed in Italy, and transition forms between the two may occur.

Fennel has a robust and branched taproot, rather deep in natural populations, but shallower in cultivated vegetable crops, especially when established by transplant. Leaves are alternated; the petiole forms a sheath, moderately embracing the stem at the insertion point; basal leaf sheaths of horticultural forms develop abundant fleshy parenchyma, generating an above-ground, bulb-like structure, representing the edible part. Leaves are pinnatipartite, with capillary leaflets; leaf size and their division level decrease from the base to the top of the plant.

The flowering stems are partially hollow, or pithy, with a characteristic 'undulated' aspect, reaching over 2.5 m height in wild plants, but far less in cultivated seed crops.

The inflorescences are composite umbels, with 20–60 rays, bearing smaller umbels on top, in turn made of 20–40 rays, bearing one flower each. One plant can produce several tens of umbels of different order, according to environmental conditions, competition, etc., with a potential of several tens

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of thousands of fruits. Flowers are small, with null calix and early deciduous, bright yellow petals.

The ovary, typically for the family, has two carpels, giving rise to a schizocarpic fruit, made of two achenes initially longitudinally connected, then separating when dispersing.

27.2 IMPORTANCE AND GROWING AREAS

Fennel is an ancient agricultural crop; the multiple uses of non-bulbiferous forms as aromatic herb, medicinal and ritual plants have been amply documented (Rather *et al.*, 2016). The origin of the bulb-forming types, used as a vegetable, seems to date back to the 15th century, in the area of Florence. Forms with thickened basal leaf sheaths, spontaneously occurring in natural populations, have likely been fixed and improved by selection, generating the present horticultural forms, which use was mainly restricted to Italy until a few decades ago.

No world statistics report fennel production data separately for the different uses. Some reports also confuse seed with vegetable fennel, giving completely misleading data.

With respect to the vegetable Florence fennel, Italy maintains the leading position for growing areas, with over 20,000 ha and 500,000 tonnes in 2018, over 94% of which are located in the south of the country (Fig. 27.1). The Italian production accounts for about 85% of world production and is used for domestic consumption at about the same rate; a 70:30 ratio between internal and export production is reported for some major growing companies. Other

Fig. 27.1. Field crop of fennel in southern Italy. (Photo by Ortofrutta Caligari e Babbi SRL, Italy.)

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producing countries are France, Spain (increasing), the Netherlands and the USA. North Africa is also a growing area, but exclusively using local open-pollinated populations, for domestic consumption.

27.3 ADAPTATION, DEVELOPMENT AND BIOLOGY

Wild fennel is considered a west Mediterranean native, but it is presently spontaneous from the Canary Islands to west Asia and naturalized worldwide.

Wild fennel is typical of early-stage successions, tending to disappear with the evolution of the vegetation towards more complex communities, whereas its persistence is favoured by disturbance, like periodic cultivation practices, cuts, fires, overgrazing, etc. On the basis of the adapted Ellenberg ecological indices, wild fennel can be defined as a heliophilic, thermophilic, calcicole, moderately ruderal species. Outside its native area, wild fennel is considered an invasive species of primary importance for natural habitats (CABI, 2018).

The cultivated forms retain the main characteristics connected to this origin. Cultivated fennel is basically a cool-season crop, with base temperature for vegetative growth of 2–4°C and an optimum temperature of about 20°C. It has a low frost tolerance, however: while roots of wild plants can survive short periods of moderate frost, the vegetative parts are destroyed by short periods at a few degrees below 0°C. So, vegetable fennel is a crop for frost-free conditions.

Fennel is a quantitative long-day plant for flowering. Photoperiod also affects thickening of the basal leaf sheaths ('bulb formation' hereafter): in this case, fennel behaves as a quantitative short-day plant, so bulb formation is enhanced by shorter days. Cultivated Florence fennel types are characterized by ample variability for these traits, determining their suitability for growing in different seasons and places. Fennel is also partially sensitive to vernalization: cold periods may shorten time to flowering but are not essential. Partial vernalization may have some impact on seed crops, either for spice or essential oil production or for propagation.

27.3.1 Main developmental stages

- Germination/emergence: this can take 8–30 days, as a function of temperature >4°C.
- Leaf production: initial growth is slow and generates leaves from the basal knots, in a number depending on earliness and inductive conditions for flowering.
- Bulb formation: this is the typical stage of the horticultural forms. It starts during leaf formation and is induced by short days; bulb formation on lateral sprouts is a commercial defect.

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The duration of the two preceding stages is highly variable, according to cultivar earliness and growing cycle.

27.3.2 Main physiological disorders of Florence fennel

- Bolting is the main problem for summer to early autumn crops, growing under long-day inductive conditions. Bolting resistance is a genetic characteristic. Bolting does not stop with harvest and negatively affects morphological and gustative characteristics.
- Formation of lateral sprouts, within the outer leaf sheaths of the bulb, is favoured by stress conditions, as determined by temperature (high or low), water and nitrogen, alternating with regrowth.
- Outer sheath cracking has various causes: the development of buds inside the sheaths, excess water/nitrogen or frost damage. In any case, it can be the starting point of secondary bacterial rotting.
- Pithiness/hollowness is partially genetically controlled and enhanced by water and heat stress. It can also occur postharvest, with prolonged storage periods.
- Greenish sheaths and yellowish bulbs are rather commercial defects than true-sense disorders; both are favoured by exposure to light of the edible parts. Green colour is determined by chlorophyll located at the top of the sheaths, close to petiole insertion; cream colour is connected to flavonoid synthesis and may affect the whole bulb. These characteristics are also genetically controlled, with modern varieties being less sensitive than old local populations; they are prevented by a well-developed foliage.

27.4 ADAPTED VARIETIES FOR YEAR-ROUND PRODUCTION

Although Florence fennel is still mainly an 'Italian' crop, its popularity and consumption have been increasing in many countries during the last three decades. As a consequence, fennel demand has changed from a seasonal Mediterranean product, mainly available from autumn to early spring, to a year-round request. This change required the availability of new genotypes, with special respect to their adaptability to a wide range of growing conditions, basically obtained by exploiting the variability of photoperiodic response and the related reaction of the plant to bulb formation and bolting.

The terms 'early' and 'late' varieties may be somewhat misleading in a crop that is planted virtually year-round. Their understanding must refer to the traditional growing cycles in Mediterranean Italy, where the so-called 'late' or 'medium-late' varieties were and still are planted from late summer to mid-autumn,

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to be harvested from December to May, with a growing cycle of 110–180 days. These varieties are considered as short-day for bulbing, since bulb formation is induced by decreasing daylength. Resistance to bolting is not a main issue, since the product is harvested in a season preceding stem elongation.

The so-called ‘early’ varieties are harvested before autumn; their main requisite is a low sensitivity to short days for bulbing, since bulb formation takes place during long-day periods. To obtain suitable varieties for late spring to early autumn harvest, resistance to bolting is fundamental, owing to a very high photoperiodic requirement for flower induction. ‘Very early’ varieties, for end-of-winter planting, may also combine short-day sensitivity to bulb formation, occurring still in the short-day regime, with resistance to bolting. Early varieties are presently also used for autumn production.

As a result of these combinations, the range of growing cycle duration is between 50–60 and 150–180 days, from planting (or emergence) to harvest.

Bulb size and shape are associated with earliness, with late varieties generally being heavier (up to 600–700 g) and rounder in shape. Round shape tends to be preferred anyway.

Other relevant varietal characteristics are: uniform bulb shape and growing cycle, white bulb, regular shape, smooth and brilliant surface, cold resistance, for winter productions, and resistance to major diseases.

Nowadays commercial production for advanced agricultural areas is almost exclusively obtained by new F1 hybrid varieties.

27.5 CROPPING SYSTEM

Vegetable fennel is quite adaptable to soil conditions, with the exception of water logged and acidic soils. Fennel is mostly grown in open air and greenhouse production is negligible. The preparation of a regular and smooth seedbed is fundamental to obtain a uniform crop.

Minimum suggested rotation time is 3 years, including similar crops like carrot or celery.

Fennel can be established by direct sowing, but transplanting represents the standard for about 85–90% of modern commercial production. Direct sowing followed by thinning is reserved for special situations of very accurate seedbed preparation; direct sown plants develop a deeper root system.

Final density ranges from 6–8 to 12–15 plants/m^2 for late and early varieties, respectively, and distance between rows is generally not less than 40 cm to allow post-planting operations.

A good fennel crop, yielding 50 tonnes of commercial product per hectare, uptakes about 300 kg N/ha, 60 kg P_2O_5/ha and 350 kg K_2O/ha, about 40, 30 and 40% of which, respectively, are removed with the harvested product. Fertilization must be tuned accordingly, also taking account of the basal soil fertility and preceding crop. Nitrogen is generally given in two or three

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distributions, according to cycle length: at pre-sowing or pre-transplant stage only for very early spring or summer crops, then at plant establishment and during subsequent operations for mechanical weed control. The old practice of covering the plant base with soil to guarantee white colour is no longer applied.

Weeds can be controlled manually in small-scale crops or mechanically, while the space between rows is still accessible. However, fennel is scarcely competitive against weeds during early growing stages, so chemical weed control is a favourite option in large-scale crops. The main problem is the scarcity of approved pre-emergence chemicals of proven efficacy and selectivity. To reduce the risk of damage, it is sometimes suggested to apply herbicides pre-transplant or just post-transplant, when fennel plants are still in the recovering phase, to overcome a possible herbicide stress.

Continuous and accurate irrigation, when needed, is fundamental to optimize yields and quality.

Harvest is done when the bulb has reached the commercial size and shape, depending on the variety. Late harvest increases yield but can be associated with physiological disorders. Early harvest can occur when market demand sustains higher prices, but yield is lower and bulbs can be more frequently subject to shape defects, less crunchy and more fibrous.

Although precise data are not available, the great majority of the commercial fennel grown in Italy is harvested manually, by well-trained crews of personnel. Outer sheaths may be removed and about 10 cm of petioles are left on the bulb. However, mechanical harvest is being introduced and supported by stakeholders whose farm structure and cropping systems are adequate for this relatively new technique (Fig. 27.2).

27.6 MAIN DISEASES

Fennel is considered moderately sensitive to diseases. With appropriate rotation, proper irrigation management and in summer cycles, it is reported that the crop can be often managed without the need for any direct control measures.

Critical diseases are those affecting the commercial products:

- Bacterial rotting by *Erwinia carotovora* affects the bulbs in very humid conditions and is often enhanced by bulb damage from other sources (frost, water excess, secondary growth, etc.).
- *Sclerotinia* spp. cause rot of basal sheaths, with the mycelium developing externally. Affected plants should be immediately removed from the field.
- *Cercospora* (*Ramularia* spp.) and *Phytophthora* spp. affect the leaves. *Phytophthora* is rather infrequent on fennel. Both develop preferentially in conditions of high air humidity and moderate temperature, more frequently in autumn cycles.

These diseases are preferentially controlled by means of copper-based products.

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Fig. 27.2. Mechanical harvest of bulb fennel. (Photo by Fellini Patrizio SRL, Italy.)

27.7 POSTHARVEST

Florence fennel for large-scale trade is generally processed on packing stations, the older way of on-field trimming being almost completely abandoned.

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After receiving the raw product, the main operations are the following:

- temporary storage at about 1–4°C, generally without humidity control;
- product cleaning by removal of residual roots, excess leaves and all damaged outer sheaths;
- first washing and sorting;
- transport by water, also acting as a further clean, to the final sorting line; and
- packing into boxes, final washing and possibly covering with film.

Storage can be done at 1–5°C with no humidity control, in the short term (7–10 days). Storage of 1–2 months is reported with 90–95% relative humidity and perforated polyethylene film. Fennel has a rather intense respiration and can tolerate an atmosphere with 10–15% CO_2 concentration for about 10 days (Capotorto, 2016).

27.8 MAIN USES

The main interests of the crop are the following:

- the bulbous structure, made of the fleshy basal leaf sheaths of the Florence types, is used as a vegetable, mainly consumed fresh (Fig. 27.3);
- the fruits are used as a spice and for essential oil extraction; and
- the vegetative parts and the florets are locally used as condiment ingredients (Fig. 27.4).

On average, the edible part of a Florence fennel bulb contains 6–7% dry matter by weight, of which 2.1–2.2% is fibre (90% from cell wall material, so insoluble fibre), 1.1–1.2% proteins, 1% soluble sugars and 0.12% vitamin C. The nutritional value of fennel is therefore low.

Florence fennel is a vegetable, mainly used raw for fresh consumption. It is appreciated for its crispy texture and sweet, aromatic taste and flavour. Fibrousness and excess aroma are considered defects, largely overcome by the use of modern varieties.

Fresh fennel can be consumed raw alone in ‘pinzimonio’ (dipped in olive oil and salt) or in diverse types of mixed salads, depending on culinary tradition. It is also popular with spread soft cheese. Industrially, it can be a component of vegetable mixes in brine or vinegar. Frozen fennel slices for catering is a recent product. Fennel can be also eaten cooked, according to different recipes. Pre-cooked fennel is sometimes available as a ready-to-eat product.

The whole plant contains essential oil, giving the characteristic aroma. Essential oil content may range from about 1–2.5% in leaves to 5–6% in florets and fruits, on a dry matter basis. High essential oil content in the bulb, favoured by hot and dry growing conditions, is considered a sensory defect.

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Fig. 27.3. Fennel bulbs in a box. (Photo by Ortofrutta Caligari e Babbi SRL, Italy.)

Fig. 27.4. Fennel fruits and florets on sale in a local market. (Photo by L.F. D'Antuono.)

The main component of commercial essential oil obtained from the fruits is reported to be *trans*-anethole, representing the valuable compound for the extraction industry. However, a large variability between populations and plant

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parts does exist. Some data indicate that in the wild population *trans*-anethole dominates in leaves and florets, whereas estragole tends to be more abundant in ripe fruits (Ferioli *et al*., 2017).

Fennel fruits are directly used as a spice in Indian and other Asian cuisines, as a component of spice blends of curry type and sauces. In Europe, fennel fruits are mainly used to season different foodstuffs, from bread to cured meat products. This latter use is very typical of Italy: in central Italy, a cured sausage takes its name 'finocchiona' from fennel, a high-quality finocchiona is however made using florets.

Fennel fruits have also been an important raw material for essential oil extraction, although they have recently been replaced by the less expensive star anise (*Illicium verum* Hook. f.) as the primary anethole source. Anethole is largely employed in a range of industries: food (sweets, beverages), perfume and pharmaceutical.

Fennel fruits are commercially offered and commonly employed to prepare infusions, mainly as an aid for digestion and to counter intestinal fermentation.

Fennel leaves and stalks are used as flavouring agents in the preparation of local meat and fish recipes, especially in central and southern Italy, but also in other countries. Very typical of Italy is the use of the dried florets, harvested at full bloom, as a priced spice (D'Antuono *et al*., 2017).

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28

Parsley

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28.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Parsley (*Petroselinum crispum* (Mill.) Fuss 1886 = *P.c.* (Mill.) A.W. Hill 1925) is a crop plant that has been used for more than 2500 years. At present, it is grown worldwide in temperate and subtropical climate zones. The origin of parsley is doubtful but most probably this species came from the eastern Mediterranean region or west Asia.

In the period of the ancient Greeks, parsley was used for sacred ceremonies and up to the end of the Middle Ages it was a distinguished medicinal plant. Nowadays, it is an important aromatic plant used fresh, dried or frozen as a culinary herb, with minor importance for medicinal use and as a fragrance in cosmetics and perfumes. Root parsley is used as a vegetable, but the present chapter focuses mainly on leaf parsley.

The use of parsley is common on all continents. For production of dehydrated parsley, green bunches and frozen products, Egypt is the most important producer worldwide, as well as Uzbekistan for production and export to Asia. About 5000 ha are specified in the European Union. Production of dehydrated parsley is important in Germany, France, the Netherlands and Poland. In Germany parsley is the most important condiment plant, cultivated on more than 1800 ha (Marthe, 2020).

Petroselinum crispum comprises considerable variability according to its long usage. Linné Sp. Pl. (1753) described it as *Apium petroselinum*, but it belongs currently to genus *Petroselinum* J. Hill, Brit. herb. (1756) 424 with the most used name being *Petroselinum crispum* (Mill.) Nym. ex A.W. Hill (Hanelt and Institute of Plant Genetics and Crop Plant Research, 2001). The used taxonomical classification within species is according to Danert (1959) with nomenclature changes. However, it needs to be noted that the use of ‘convar.’ was replaced by ‘cultivar-group’ in the 1995 International Code of Nomenclature for Cultivated Plants.

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The convar. *radicosum* (Alef.) Danert in Mansf. Verzeichnis (1959) 322 with eatable swollen taproots was detached from uneatable rooted forms belonging to convar. *crispum*. All populations of convar. *radicosum* are flat-leaved and belong to var. *tuberosum* (Bernh.) Crov (Fig. 28.1). Different leaf types exist among convar. *crispum*: accessions with crisped leaves attributed to var. *crispum* (Fig. 28.2a), flat-leaved to var. *vulgare* (Nois.) Danert (Fig. 28.2b) and var. *neapolitanum* Danert, also known as Neapolitan or Italian parsley, with fleshy and longer petioles.

28.2 PLANT DEVELOPMENT AND CROPPING SYSTEM

Parsley is a biennial species but can grow as a semi-perennial in warmer regions. Annual accessions also exist without requirement of vernalization. For production of parsley biennial varieties are used, which form in the first vegetation period the utilized rosette of leaves. After the first winter, the stalk of biennial parsley will shoot immediately.

Flowering plants reach 60 to 120 cm high. The five anthers start anthesis about 5 days before the two stigmas are receptive to pollen. Therefore, the protandry of parsley is about 5 days.

Fig. 28.1. Rooted parsley (*Petroselinum crispum* convar. *radicosum* var. *tuberosum*) with flat leaves. (Photo by International Seed Processing.)

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Fig. 28.2. Parsley (*Petroselinum crispum* convar. *crispum*): (a) var. *crispum* with crisped leaves; (b) var. *vulgare* with flat leaves. (Photos by F. Marthe.)

Parsley is grown in fields or greenhouses and plastic tunnels. It must be sown at the beginning of the vegetation period. The plants form a rosette of leaves and the first harvest takes place 10 to 12 weeks after sowing. According to weather conditions, harvest can occur every 21 to 30 days. For harvest, plants of the flat-leaved type should reach 20 to 25 cm high. Varieties of the crisped leaf type are not so tall. The cut should be 4 to 6 cm over the ground level (Hoppe *et al.*, 2013). Cutter loaders are used for harvest. Only for direct marketing of fresh bunches are parsley leaves harvested manually, to a smaller extent.

Parsley leaves tolerate temperatures down to –6 to –8°C. In the open field, roots will survive winter with temperatures down to –10°C. However, alternating frosts can lead to complete loss by rot. A crop rotation of 5 to 7 years is necessary. Previous crops of the *Apiaceae* family should be avoided, as well as pressure of weeds.

Following Bomme *et al.* (1993), the nutrient removal was measured for a yield of 60 t of leaf parsley (fresh weight) per hectare with 184 kg N/ha, 43 kg P_2O_5/ha, 306 kg K_2O/ha and 30 kg MgO/ha. Per 10 t yield fresh weight, a fertilizer application is recommended of 59 kg N/ha, 14 kg P_2O_5/ha, 102 kg K_2O/ha and 9 kg MgO/ha. Per hectare, 60–70 kg N are recommended in the beginning and then as a top dressing after each cut except the last one, when 25–40 kg N/ha are recommended.

Parsley growers in German regions of >700 mm precipitation per year use the following fertilizer application: according to soil tests, at the beginning 60 kg P_2O_5/ha, 200 kg K_2O/ha and additional 80 kg K_2O/ha as top dressing after the first cut. After emergence of the seedlings, 100 kg N/ha are applied and 60–80 kg N/ha after each cut except the last one (Hoppe *et al.*, 2013).

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Within the growing period from June to September the water demand is high: from 60 to 140 mm, depending on weather conditions and the number of cuts. The irrigation management is made of 20 mm applications. After cutting, the irrigation should follow the fertilizer application (Hoppe *et al.*, 2013).

Leaf-damaging fungi cause the economically most important diseases: Septoria blight (caused by *Septoria petroselini* (Lib.) Desm.), downy mildew (*Plasmopara petroselini* Săvul. & O. Săvul.), powdery mildew (*Erysiphe heraclei* DC. ex Saint-Aman) and Alternaria leaf blight (*Alternaria radicina* Meier, Drechsler & Eddy).

The seed-borne Septoria blight is one of the most important pathogens worldwide. It causes round or angular greyish brown lesions, which are clearly bordered by a darker brown margin to the surrounding tissue and have small or no chlorotic zones. Spores containing black pycnidia appear within lesions (Cerkauskas and Uyenaka, 1990; Marthe and Scholze, 1996; Meyer *et al.*, 2010).

Downy mildew, an important pathogen in the production of potted parsley, causes faint chlorotic spots on the upper surfaces of the leaves as first symptoms. On the corresponding lower surfaces, sporangiophores and white to greyish white mycelium develop (Crepel and Inghelbrecht, 2003).

Powdery mildew is an increasingly significant pathogen worldwide (Koike and Saenz, 1994; Scholze *et al.*, 1996; Marthe *et al.*, 2003). The identification is easy because of the mycelia growing on the leaf surface. Infected leaves show chlorosis and crinkling.

Alternaria leaf blight infestation causes important damage by leaf spots and damping-off of seedlings depending on annual weather conditions (Marthe *et al.*, 2003; Marthe and Scholze, 2006; Gärber *et al.*, 2007; Meyer *et al.*, 2010). Infestation starts from older leaves with brown coloured, small round lesions. The Alternaria lesions expand rapidly, usually from the margin of the leaf.

There are more pathogenic fungi damaging parsley such as *Sclerotinia sclerotiorum* (Lib.) de Bary causing Sclerotinia rot, Fusarium wilt (*Fusarium oxysporum* Schltdl.), Pythium root rot (*Pythium* spp.) and Rhizoctonia root rot (*Rhizoctonia solani* J.G. Kühn).

Viruses of economic impact on parsley are the widespread *Celery mosaic virus* (CeMV), the *Apium virus Y* (ApVY) and a virus complex probably from the *Carrot red leaf virus* (CtRLV), the parsley-specific *Carrot mottle virus* (CMoV) and the *Carrot mottle mimic virus* (CMoMV). In addition, the ApVY and the *Carrot yellow leaf virus* (CYLV) are possibly involved in this virus complex.

Bacteria can cause leave spots and macerations, especially by *Pseudomonas* spp.

28.3 POSTHARVEST AND PRODUCT VALORIZATION

Harvested leaves of parsley as well as taproots of rooted parsley are used fresh, dried or frozen as a culinary herb or vegetable. The shelf-life of fresh leaves is relatively short.

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Parsley contains antibiotic-acting secondary metabolites. Nevertheless, unhygienic contamination in the production process with bacteria harmful for consumers can occur but be solved by hygienic standards (Santos *et al.*, 2014). Fast drying postharvest processing, starting with temperature of 90°C and higher, and the pressurized CO_2 disinfestation process, has proven its reliability (Marthe, 2020).

Horizontal belt dryers are used for the drying of leaves, with air temperature decreasing from 90–120°C to 60°C. The process ends with 4 to 6% residual moisture content (Hoppe *et al.*, 2013). The ratio of fresh weight to dry weight is about 7:1 and 10:1 for leaves and roots, respectively. The roots are sliced in small pieces and dried at 40°C.

Parsley is rich in antioxidants especially vitamin C and the flavonoid luteolin, as well as vitamin A and folic acid (vitamin B_9). In fresh parsley leaves vitamin C can reach 0.12 to 0.4% of fresh weight (Scheunert and Theile, 1952). Parsley contains essential oil in the roots, leaves and fruits, with clear differences in amount and composition according to the plant tissue used. The essential oil content of parsley taproots is the lowest (0.1 to 0.3% of dry weight) compared with leaves (0.02 to 0.9%) and fruits (1.0 to 6.0%) (Hoppe *et al.*, 2013).

The essential oil, mostly from parsley fruits, is applied in the food industry and to a very limited extent as a fragrance in perfumes and for cosmetics.

The consumption of parsley has health-promoting impacts besides the seasoning action. Parsley has carminative, tonic and aperient effects, but it is mainly used for its diuretic properties (Warncke, 1994). It stimulates the appetite, has anti-inflammatory properties and has the ability to induce menstruation because it stimulates gentle contractions of the uterus. Traditionally, it has been used for flatulent dyspepsia, colic, cystitis, dysuria, bronchitic cough in the elderly, dysmenorrhoea, functional amenorrhoea, myalgia and specifically for flatulent dyspepsia with intestinal colic. For these reasons, parsley consumption should be increased. The considerable genetic variability should be used for increasing yield, health-protecting secondary metabolites and resistance to pathogens (Marthe *et al.*, 2013; Marthe, 2020). The evaluation of genebank accessions provides sources for breeding of improved parsley varieties.

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29

Parsnip

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Parsnip (*Pastinaca sativa* L.) is a root crop best suited for production in cool climates. It is grown for its characteristic white taproots (Fig. 29.1) which have several culinary uses: as a vegetable including roasting, as an ingredient in soups and stews, and also more recently in snack form as chips or crisps. While a relatively minor vegetable crop, it is of local horticultural significance in countries in northern and eastern Europe in particular.

29.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Parsnip has a long history of cultivation; documentation indicates it was grown as a crop by the Romans, although archaeological evidence is relatively rare (Zohary *et al.*, 2012). Writings of the period tended to group parsnip and carrot under the single term 'pastinaca'. It achieved significance as both a vegetable and fodder root crop during the Middle Ages in Europe prior to the introduction of the potato, and was introduced to the New World where it was cultivated by indigenous peoples as well as European colonists (Austin and Jarrett, 2012). As parsnip is suited to cooler environments, cultivation is limited to temperate regions and areas with an altitude above 900 m in subtropical and tropical regions. The main centres of production in Europe include the UK (Fig. 29.2), Hungary and France. In the UK, parsnip cultivation occupies around 3000 ha (Defra, 2018), producing 90,000 tonnes with a value of £30 million. It is also grown commercially in other countries including Canada, the USA, Australia, New Zealand and South Africa. In order to produce high-quality roots free from distortions or branching, it is necessary to cultivate parsnips in fine, stone-free soil such as sandy loams. This requirement, together with the need for cooler temperatures for optimum root quality, dictates where major production centres are located.

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Fig. 29.1. Parsnip roots at harvest. (Photo by A. Weekes, Elsoms Seeds.)

29.2 PLANT DEVELOPMENT

A member of the *Apiaceae* family, the botanical characteristics of the species have been described by Cain *et al*. (2010). *P. sativa* is a biennial species which forms a rosette of pinnate leaves during the first year of growth. A fleshy white to light brown taproot develops to function as a storage organ. Following vernalization the floral apical meristem develops in the second year, reaching a height of 150–200 cm. The flowers are yellow in colour and clustered into compound umbels of 10–20 cm diameter. The terminal (primary) umbel is comprised of staminate flowers at the centre surrounded by hermaphrodite flowers. Sepals are very small or absent. The schizocarps (fruits) split into two flat narrowly winged mericarps (seeds).

Due to the sequential nature of umbel production and maturation, seed from a given parsnip plant is often at a variety of stages of maturity. Timing of harvest for seed production systems is then key to maximizing maturity and availability of the seed crop while minimizing seed loss through shattering. Seed yield is impacted by plant density, harvest date and planting pattern (Gray *et al*., 1985).

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Fig. 29.2. Parsnip production field in the UK. (Photo A. Weekes, Elsoms Seeds.)

Like other members of the *Apiaceae*, parsnip produces a range of secondary plant metabolites. The whole plant has a characteristic aroma. Parsnip is known to produce furanocoumarins, a group of compounds with known toxicity and potential carcinogenicity. These compounds are also thought to trigger photosensitive dermatitis and contact dermatitis in sensitive individuals who come into contact with foliage (Aberer, 1992). In addition to its toxic/allergenic properties, wild parsnip (the same taxon: *P. sativa*) is recognized as a problematic invasive weed species of increasing concern in many areas (Averill and DiTommaso, 2007). Wild parsnip was not found to be genetically distinct from cultivated types, and generally high levels of genetic diversity were found in regions where *P. sativa* is considered invasive, suggestive of multiple introduction events and a close relationship between wild and cultivated types (Jogesh *et al.*, 2015).

29.3 CROPPING SYSTEM

Parsnips are best grown in free-draining, deep soil to avoid root deformities such as branching and forking. Dependent on variety and environment, parsnips can take 90–130 days to mature from sowing to harvest; a relatively long cropping cycle. In the UK seeds are directly drilled into pre-prepared 20 cm deep beds at a density of up to 500,000 seeds/ha for maincrop parsnips. As a deep-rooted crop, parsnip is often regarded as relatively drought-tolerant;

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however, irrigation may be beneficial to aid crop establishment or to reduce undesirable changes to skin quality caused by soil moisture stress (AFS, 2016). Fertilization recommendations are shown in Table 29.1. Market demand peaks in the winter months; and a layer of straw may be applied to enable storage of roots in the ground, lengthening the harvest window. Parsnips can be drilled from February to April to supply main and late cropping markets; late sown crops can be lifted in the spring of the following year. Early crops can be produced from seed sown the previous winter, a protective plastic film is used to improve the soil environment (AFS, 2016). Rotations should be planned to avoid build-up of pests and diseases which infect other apiaceous crops such as carrot and celery; in addition, other crops such as potatoes and sugarbeet can increase populations of pests such as free-living nematodes.

Parsnips suffer from many of the same pests and pathogens as carrot. Carrot root fly (*Psila rosae*) can be problematic in many regions; adult flies lay eggs into the developing roots of seedlings and young plants, which are then damaged by the developing larvae. Damage can range from total crop loss to reduced growth and marketable yield. Carrot fly is the target of the majority of insecticidal treatments to parsnip crops in the UK. Cultural control includes use of forecasting tools to time sowing, rotation and separation of early and maincrop fields (AFS, 2016). Other insect pests affecting parsnips include willow-carrot aphids (*Cavariella aegopodii*) and willow-parsnip aphids (*Cavariella theobaldi*) which not only can cause direct damage to young plants, but also are vectors for viruses such as *Parsnip yellow fleck virus*. Nematodes are also important crop pests of parsnip, causing characteristic types of root deformities such as galls and forking. Both root-knot nematodes (*Meloidogyne* spp.) and free-living nematodes (various taxa including *Pratylenchus* spp. and *Trichordorus* spp.) can cause root damage. Other pests include cutworms (soil-dwelling larvae of a number of moth species) and wireworms (larvae of various beetles from the family *Elateridae*).

Parsnips are affected by a range of fungal pathogens, which mainly cause cankers on the root – these impact the storability and marketability of the

Table 29.1. Fertilization recommendations (kg/ha) for parsnip based on soil nitrogen supply (SNS) and nutrient index of soil. (From AHDB, 2019.)

	SNS, P, K or Mg index						
	0	1	2	3	4	5	6
Nitrogen (N)	170	130	100	70	20	0[a]	0[a]
Phosphate (P_2O_5)	200	150	100	50	0	0	0
Potash (K_2O)	300	250	200 (2–)[b] 150 (2+)[b]	60	0	0	0
Magnesium (MgO)	150	100	0	0	0	0	0

[a]A small amount of nitrogen may be needed if soil nitrogen levels are low in the top 30 cm of soil.
[b]Recommendations depending on whether the soil is in the lower half (2–) or upper half (2+) of K index 2.

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crop. Black or brown canker presents generally as dark lesions and can be caused by a range of organisms including *Itersenilia*, *Phoma* and *Cylindrocarpon* (Channon, 1963; Channon and Thompson, 1981). *Mycocentrospora* can also cause root lesions. As with carrots, parsnips can also be affected by *Pythium* spp., the causal agent of cavity spot in carrot (Petkowski *et al*., 2013).

29.4 POSTHARVEST AND PRODUCT VALORIZATION

Root quality is improved by exposure to freezing temperatures, which cause breakdown of starch into sugars (Bufler and Horneburg, 2013). This can take place while the crop is in the ground, but storage at 0°C for 14 days has been shown to have a similar effect. Root quality can be maintained for several months in storage in a low-temperature, high-humidity environment (98–100% relative humidity) as roots are particularly susceptible to desiccation (DAFF, 2013). Postharvest browning can be a problem and appears to be related mainly to injury incurred during harvest or handling (Toivonen, 1992). Parsnips are generally consumed fresh or processed into a variety of end products such as pre-prepared meals. Inevitably different markets have different requirements. Parsnips destined for the retail market via supermarkets may have to meet stringent specifications in terms of size and appearance in order to be considered acceptable. The consequences of not meeting these specifications result in a loss of income for the grower and potentially a total write-off of the crop and the consequent problem of wastage.

Parsnip breeding has developed over the past decades; F1 hybrids are now available offering greater yield and uniformity compared with open-pollinated types. Breeding targets include root shape, skin and flesh colour (certain markets prefer white compared with cream coloured roots), as well as disease resistance. There is known variation among existing varieties for susceptibility to issues such as postharvest browning (Toivonen, 1992), resistance to canker-causing pathogens (Channon *et al*., 1970; Cerkauskas, 1986), as well as other traits considered important such as root shape, core size and propensity to bolt. Development of molecular and genomic tools in the apiaceous crop carrot can aid researchers seeking to understand the genetic basis of these and other phenotypic traits in parsnip and provide breeders with tools to expedite the exploitation of gene pool diversity.

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30

Tuberous-Rooted Chervil

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INTRODUCTION

Tuberous-rooted chervil, *Chaerophyllum bulbosum* L., has been collected in the wild and used as a food since antiquity. The crop was first described in Austria in 1601. After realizing success as a crop during the 19th and beginning of the 20th centuries, particularly in France and Germany, it was forgotten by growers until the beginning of the last decade. Today, thanks to genetic, physiological and technical progress, the crop is emerging again.

30.1 IMPORTANCE OF SPECIES AND GROWING AREAS

Tuberous-rooted chervil was introduced to Britain in 1726 as an ornamental and grown on a large scale for a time. Its introduction to France occurred in 1846 (Rozé, 1899) where it became a popular crop, particularly during the first half of the 20th century (Gibault, 1912; Bois, 1927). The crop was also described in Germany and the USA. Despite its excellent taste, the crop was gradually abandoned because of agriculture intensification after the Second World War. In the early 1980s it could be found growing as a crop only in a very few areas in France (Péron, 1989; Ayala Garay *et al.*, 2003). The almost complete disappearance of this crop was attributable to two difficulties in root production and storage. Due to its seed dormancy (Augé *et al.*, 1989), planting had to take place in November in order for germination to occur at the end of the following February or the beginning of March. Moreover, after harvesting in July, the root had to be stored for several months to reach an acceptable taste and aroma to be marketed from November to March. Breeding programmes

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by French scientists, initiated in 1985, developed new varieties with no seed dormancy, high germination rate (90%) and uniform root shape, and this contributed significantly to a renewed interest for this alternative crop in regions of France like the Loire Valley and the north of Brittany (Péron, 1990; Péron and Dubost, 1992; Péron and Briard, 2003). Even today the popularity of the crop continues to grow.

30.2 PLANT DEVELOPMENT

Tuberous-rooted chervil, *C. bulbosum* L., is a biennial species belonging to the *Apiaceae* family and is native to Central and South-east Europe. It is found growing spontaneously in Russia, Siberia, Austria, Germany, Italy and Romania. In France, dense native populations can be found in the Rhine and Mosel river basins that are the western limit for wild specimens. Propagation is ensured by seeds dispersed by rivers or birds. The high genetic diversity of wild as well as cultivated genotypes, based upon molecular markers, has been documented (Le Clerc *et al*., 2014), in accordance with the allogamous character of the plant (Reuther and Claßen-Bockhoff, 2013).

Three cultivars are registered: Altan, an old type variety with seed dormancy; and Véga and Doléane, two new varieties with low seed dormancy and high yield developed by breeding programmes of the Institut National d'Horticulture and registered in 2000 (Péron and Briard, 2003).

Tuberous-rooted chervil is first a small rosette of four to six leaves morphologically similar to those of carrot (Fig. 30.1). During the second year, a flowering stalk, up to 2.5 m tall, develops to give rise to seeds that are achenes (Fig. 30.2). The edible part of the plant arises from expansion of the hypocotyl and top of the primary root. This expansion phenomenon occurs as soon as the plantlet emerges from the soil (Fig. 30.3). Approximately 4 months after emergence, the storage root has a suberized epidermis, ochre to light brown colour, with globular, conical or elongated shape and white flesh at harvest maturity (Fig. 30.4).

With 37.6% of fresh weight being dry-matter content, storage roots of tuberous-rooted chervil have a relatively high content of dry matter compared with other root and tuber crops like potato, yam, malanga or sweet potato, and this is primarily composed of starch (76%) at harvest time. At that time the root is tasteless. Traditionally, storage under cave conditions (10–12°C, 75–80% relative humidity) for 4 to 5 months stimulates changes in the carbohydrate content required for roots to achieve optimal gastronomic product quality. The final product quality was characterized by Péron and Briard (2003) as carbohydrate reserves consisting of sucrose (15–20% of dry matter), starch (10–15%) and reducing sugars (2–3%) with chestnut-like aroma. Studies evaluating storage under varying temperature and relative humidity demonstrated that maturation could be reduced to only 2 months. Indeed, when storage roots are

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Fig. 30.1. Open field crop of tuberous-rooted chervil. (Photo by J. Granger.)

stored at 4°C and 98% relative humidity, induction of high β-amylase activity results in dramatically hydrolysed starch to initiate accumulation of sugars – mainly sucrose, glucose and fructose (Ayala Garay *et al*., 2003; Geoffriau *et al*., 2005).

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Fig. 30.2. Seeds of tuberous-rooted chervil. (Photo by J. Granger.)

30.3 CROPPING SYSTEM

Depending on which variety is grown, there are two contrasting production practices that differ in their sowing date and duration of cropping period:

- Varieties with long seed dormancy must be sown before the end of December to get seed stratification (application of damp cold for 8 to 9 weeks at 0–6°C during germination). Emergence occurs from February to March. The crop cycle can reach 7 months.
- Varieties with short seed dormancy, such as Doléane or Véga, are sown in February or March. Plantlet emergence occurs 4 weeks later. The crop cycle is 4 to 5 months.

30.3.1 Soil preparation

Tuberous-rooted chervil needs a deep sandy or sandy-loam soil. In order to prepare the seedbed optimally, the soil must be friable with a regular surface and a fine texture to ensure good contact between the soil and the seed. For this, two steps of bed preparation are required. The first one at about 15–20 cm deep, the second one for soil surface layers (7 cm).

30.3.2 Sowing

Direct seeding is performed on 1.2 m wide precision beds with a row spacing of 0.3 m. The optimum seed density per hectare is about 2 to 2.5 kg seeds (Fig. 30.1). Seeds are sown at a depth of 2–3 mm and lightly covered with a thin layer of sand. Sowing depth greater than 4 mm must be avoided.

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Fig. 30.3. Hypocotyl and upper part of primary root begin to accumulate reserves as soon as cotyledon stage. First true leaf appears at cotyledon side. (Photo by J. Granger.)

30.3.3 Irrigation

Soil moisture must be maintained during plant development and this often requires the use of irrigation equipment. Drought stress may cause lateral storage root production that depreciates the commercial quality of the product. Irrigation is terminated 1 month before harvesting time.

30.3.4 Fertilization

Best results are obtained by providing 14:7:17 slow-release N:P:K fertilizer in March and April. An additional supply is sometimes necessary at the end of May in sandy soils.

30.3.5 Pest and disease management

The foliage and especially the storage root of the plant can be damaged by diseases or pests; however, there is no pesticide registered for this crop.

During production, storage roots can be attacked by carrot fly (*Psila rosae*). Major damage can also be caused by rabbits and crows. On foliage, aphids, powdery mildew or *Alternaria dauci* are often observed. With regard to weeding, there is no herbicide registered. The use of soil disinfection limits the development of weeds and protects against soil pathogenic fungi and nematodes.

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Fig. 30.4. Tubers of cv. Doléane, the white buds are indicators of gastronomical maturity. (Photo by J. Granger.)

30.3.6 Harvest

The crop is harvested using a potato harvester in July or early August, after foliage completely disappears. Care must be taken in this operation in order to not damage the epidermis and to limit the susceptibility to fungal diseases. The marketable yield (storage root size between 30 and 50 mm) is about 15 to 20 t/ha.

30.3.7 Postharvest

During postharvest storage, significant damage from *Botrytis*, *Penicillium*, and especially from strains of *Fusarium oxysporum* and *Fusarium solani*, on storage roots cause dry rot from infections arising in the field or during harvest. Decreasing the relative humidity of storage conditions and removal of infected storage roots may limit their development.

30.4 PRODUCT QUALITY

The sweet tasty root of the tuberous-rooted chervil, reminiscent of both potato and chestnut, was considered to be of very high gastronomic quality by

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Péron (1989). From this subtly flavoured root, many gourmet restaurant chefs have created recipes not only for vegetable use but also for desserts. Because of the combination of high amounts of sucrose and starch simultaneously in the same organ, uncommon for a vegetable, Ayala Garay *et al*. (2003) recommended tuberous-rooted chervil for the human diet arguing that it is combining very rapidly-digestible sugars along with a more slowly-digestible one, resulting in long-term availability of energy. They also mentioned that *C. bulbosum* offers a good opportunity for industrial starch production if used at harvesting time.

30.5 CONCLUSIONS

Growers now have high-performing genetic material and postharvest storage conditions and cropping requirements have been precisely defined. Commercial seeds are available for Véga and Doléane cultivars. All this should pave the way for the development of this crop.

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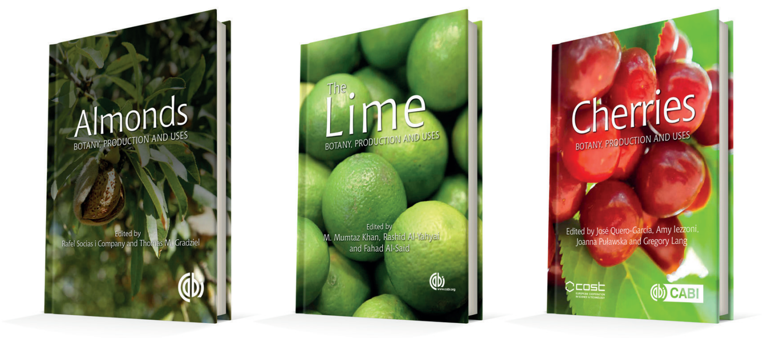

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