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Yield, Quality Traits and Black Root Rot during Storage and Distribution of Carrots Grown in a *Chalara* Infested Field

P. Crespo[1)], W. Heller[2)], E. Hoehn[2)] and D. Baumgartner[2)]
([1)]Agroscope Changins-Wädenswil ACW, Research Center of Conthey, Conthey, Switzerland and [2)]Agroscope Changins-Wädenswil ACW, Wädenswil, Switzerland)

Summary

Carrot is one of the major vegetable crops produced and consumed in Switzerland. In the past years poor shelf life of carrots has led to frequent complaints from consumers and retailers. The most critical deficiency was the development of black root rot spot on carrots caused by *Chalara* species. Previous investigations showed that all the tested fields in the main carrot production regions of Switzerland were contaminated with *Chalara* sp. In Switzerland, carrots for long term storage are harvested in October and early November. They then are stored in wooden bins in refrigerated rooms for a period of up to seven months. It is recommended to use perforated plastic bin liners to minimize water losses of carrots. The effect of *Chalara* field contamination, cooling techniques, storage with or without polyethylene liners on overall yield of marketable carrots, quality traits and the occurrence of black root rot were investigated. Storage of carrots at temperatures between 0–4 °C prevented the development of *Chalara*. Excessive water losses resulted in wilting of carrots, and maintenance of high air humidity was critical during the entire storage. Hence, lining bins with perforated plastic foil is advisable in most storage rooms. In addition, replacing recycled water with fresh tap water during carrot washing and the maintenance of a closed cool chain below 8 °C after washing, packaging and in retail prevented the occurrence of black root rot and other decay. In conclusion, proper post-harvest processing, in particular optimal washing operations, can assure acceptable shelf life and high quality of carrots grown in *Chalara* infested fields.

Key words. temperature – relative humidity – mass loss – decay – washing – shelf life

Introduction

Carrot (*Daucus carota* L.) is among the most preferred and most consumed vegetable worldwide. Annual consumption in Switzerland and other European countries ranges between 7 and 10 kg per capita (Villeneuve and Leteinturier 1992; Carlsson-Kanyama 1998). This still falls short of recommendations promoted in healthy nutrition campaigns (e.g., Swiss „5 a day“, www.5amtag.ch). Improving carrot quality is critical for efforts to maintain or even further increase consumption.

Carrots are suitable for long-term storage (Nilsson 2000). Although the crop is grown from spring to fall in most central and northern regions of Europe and North America, the main harvest season for storage carrots lasts from September to November. Subsequently to the harvest, carrots are stored for up to six or seven months until end of April or early May. Quality and acceptance of carrots at the point of sale is affected by all the stages and steps of the supply chain from the field to the „fork“ including growing, harvesting, storage, washing, grading, packaging and distribution.

In recent years the black root rot caused by the fungi *Chalara elegans* Nag Raj & Kendrick (syn. *Thielaviopsis basicola* (Berk. & Br.) Ferraris) and *Chalara thielavioides* (Peyr.) Nag Raj & Kendrick (syn. *Chalaropsis thielavioides* Peyr.) has become a key problem for the Swiss carrot production (Heller 2000). The disease symptoms, grey-black lesions on the carrot surface, usually develop after storage during retailing when carrots are held at room temperature under moist condition (Weber and Tribe 2004). A survey of the distribution of *Chalara* species in soils of the main carrot production regions of Switzerland revealed that most of the fields were contaminated with *Chalara* (Kägi et al. 2006), and presumably most carrots and the adhering soil are infested. Nevertheless, differences in the decay of carrots at the point of sale were observed. This fact suggested that post-harvest factors played an important role in the appearance of the disease on carrots during their marketing and shelf life. Other

studies confirmed the influence of wounding, contamination of washing water with fungal spores and temperature on the incidence of black root rot at the point of sale (PUNJA and GAYE 1993; VILLENEUVE 2005; ESHEL et al. 2009), with percentage of carrots developing post-harvest rot upon incubation at 25 °C increasing after each step of the grading and packaging operation.

Fungal pathogens including *Chalara* and other species may elicit accumulation of antifungal compounds in carrots, such as 6-methoxymellein (6-MM, isocoumarin), polyacethylenes, chlorogenic acid and phenolics (PUNJA et al. 1992). In addition, abiotic stress during growth, harvesting, storage, grading, packing and processing can induce formation of these compounds (TALCOTT and HOWARD 1999; SELJASEN et al. 2001, 2004). If these compounds exceed certain levels they impart bitterness (SCHMIECH et al. 2008) and hence diminish eating quality and reduce acceptance of fresh and processed carrots (TALCOTT and HOWARD 1999). Sensory and consumer studies indicated that bitterness, as opposed to sweetness, correlated negatively with liking of carrots (HOEHN et al. 2003; VARMING et al. 2004). However, there are other quality defects including loss of crispness and wilting due to desiccation during storage. This can be prevented by maintaining a high humidity (e.g., using plastic bin-liners).

This study focused on the impact of the conditions typically found in Swiss storagehouses on yield and quality of carrots after storage as well as on the development of *Chalara* disease symptoms. Key parameters investigated were temperature during storage and the impact of plastic bin-liners commonly used for carrot storage. All carrots used in this study originated from the same, *Chalara* infested field. This approach enabled association of not only general quality traits and yield losses but also losses due to this disease with the respective storage conditions. The focus on *Chalara* was further supplemented by monitoring the development of disease symptoms during shelf life and with laboratory experiments assessing the influence of the storage on the predisposition of previously disease-free carrots to post-storage infection with *Chalara*, as is frequently occurring during washing, as well as the influence of post-storage temperatures on disease symptom development.

Materials and Methods

Storage trials

Plant material. Carrots of the cultivar 'Bolero' were grown adhering to Swiss standard agricultural practise (VSGP/UMS 2007). The field selected for this trial was proven to be infested with *Chalara* sp. For this a total of 76 soil samples regularly distributed on the 1.8 ha field were collected and tested with the carrot stick assay as described by KÄGI et al. (2006). All carrots used for the storage trial were harvested at full mature stage (Oct. 26, 2006) from a heavy and homogeneously contaminated part of this field. Carrots were harvested mechanically into standard wooden bins ($120 \times 80 \times 115$ cm; load capacity approx. 480 kg). Half of the bins had been fitted with a perforated polyethylene liner (thickness 0.3 mm, 50 wholes m^{-1}) prior to filling. Humidity and temperature recording units (HOTDOG DH2, Elpro, Buchs, Switzerland) were placed approximately in the centre of each bin during its filling. Temperature was monitored in hourly intervals during the entire five months of storage.

Storage. Immediately after harvest, the bins were transported to six storehouses in different regions of Switzerland. Transportation time varied from 2–48 h and carrots were kept uncooled during transport. Each storehouse received three bins with plastic liner and three bins without plastic liners, respectively. Some of the store operators completely closed the plastic liners by knotting while others left an opening of 10–15 cm in the cover. The size of the cold rooms varied considerably (Table 1). All store rooms were equipped with humidifying systems consisting of jet spray humidifiers with time-controlled operation. In addition all rooms were fitted with time-controlled ventilators to insert outside air into the store rooms. Aeration was to ensure that carbon dioxide levels in the store rooms remained lower than 0.3–1 %. Store operators were asked to maintain recommended storage conditions for carrots (temperature 0–1 °C, RH 92 % or more) (SUSLOW et al. 2009).

Washing and sorting . After five months of storage, the carrots were collected from the six storehouses and washed and sorted. A washing drum of industrial size (Ultramatic Typ408, Winterthur, Switzerland: length 250 cm, diameter 80 cm, 10 rpm) equipped with a water spraying system was employed. In order to avoid cross contamination between the lots, only water of drinking water standard was used. After exiting the drum onto a conveyer belt, the carrots were sorted manually according to Swiss grades (SWISSCOFEL 2004). The content of each bin was washed and sorted separately. The fractions of marketable carrots, wilted as well as limp carrots and culls were weighed separately. The soil fraction was calculated based on the difference of the mass of carrots before washing and overall mass of washed carrots (e.g., marketable, wilted and culls). Water loss was calculated based on the net mass of carrots entering storage and net mass of carrots after storage. The soundness and appearance of carrots was judged, including the incidence of black root rot and decay due to other fungal activities as well as sprouting and occurrence of cracks. Sensory evaluations were made using 4–5 samples, each consisting of 5–6 carrots drawn from each bin, by 4–5 panellists. Evaluations considered rating scales for crispness (i.e., crisp, slightly crisp, not crisp/limp), sweetness (i.e., sweet, slightly sweet, not sweet/insipid), bitterness (i.e., bitter, slightly bitter, not bitter) and overall eating quality (i.e., good, sufficient, poor).

Table 1. Technical data of store rooms, half-cooling times and average storage temperatures.

Store house	Room volume (m^3)	Maximal capacity (t)	Mantel area (walls, ceiling and floor) ($m^2\ t^{-1}$)	Delta T (K)	Evaporator surface ($m^2\ t^{-1}$ / $m^2\ m^{-3}$)	Half cooling time (h) with / without PL	Average temperature after 14 d of storage (°C) with / without PL	Liner
A	521	143	2.95	6.5	1.7* / 0.5*	47 / 8	2.7 / 1.5	open
B	681	200	2.90	6.0	1.2 / 0.4	51 / 8	2.2 / 1.2	closed
C	4000	1100	1.18	8.0	1.2 / 0.3	30 / 13	2.6 / 1.9	closed
D	2881	700	0.74	1.4	1.3 / 0.3	36 / 11	0.9 / 0.4	open
E	1800	450	0.51	4.0	0.5 / 0.1	61 / 29	2.0 / 0.7	closed
F	5625	1200	0.84	5.0	0.8 / 0.2	40 / 21	1.8 / 0.8	open

PL: Plastic liner; *: Estimated value

Shelf life test . Washed, marketable carrots (2 kg) were packed into perforated polyethylene bags and left at 21.0 ± 0.5 °C during 8 d. After this interval incidence of black root rot spots due to *Chalara* sp. was appraised and decay (percentage of carrots showing symptoms of decay other than due to *Chalara*) was determined. In addition the prevalent *Chalara* species was determined by means of a binocular.

Analyses of carrots: dry matter, total soluble solids and 6-methoxymellein

Dry matter, total soluble solids (TSS) and concentration of 6-methoxymellein (6-MM) were determined before and after storage. Three samples per bin were analyzed. Each weighed between 1.5 and 2 kg and comprised of 15 to 18 marketable carrots. For each analysis the entire sample was cut in slices (2 mm thick) with a domestic slicer and the slices were carefully mixed. The determination of the dry matter and the TSS was carried out according to the standard methods of the Swiss handbook of food analysis (Slmb 2005). Carrot juice was obtained using a domestic juicer (Green Star, GS1000, St.Gallen, Switzerland). The TSS were determined in the carrot juice by means of an electronic refractometer (Atago PR-32, Japan) and expressed as °Brix.

To determine the content of 6-MM, frozen carrot discs were ground with a domestic mill (Moulinette D58, Moulinex, Opfikon, Switzerland) and extracted following the modified method of Seljasen et al. (2000). The automatic solvent extractor ASE2000 (Dionex, Solothurn, Switzerland) was used to extract the 6-MM from the carrot powder (5 g fresh matter) sequentially with 2x8 mL acetone followed by 8 mL methanol. The combined extracts were then dried with a rotary evaporator to near dryness and diluted to 20 mL with methanol. For HPLC analysis (Varian ProStar, Basel, Switzerland) the filtered solution (0.45 µm nylon filter, WICOM, Heppenheim, Germany) was injected on a column RP-18 (Nucleosil 100-5 C18, EC250/4, Macherey Nagel, Oensingen, Switzerland) and eluted with 1 mL min^{-1} 60 % methanol. Quantification of 6-MM was performed by evaluating the peak area at 268 nm with the external standard method.

Infection tests with Chalara

Carrots (*Daucus carota* L., 'Bolero' F1, Vilmorin) free of *Chalara* infections were obtained by growing them in seramis® (www.seramis.de) or in seramis®:soil mixtures (1:2 v/v) which had been previously pasteurized by heat treatment (80 °C, 5 min). The carrots were manually harvested, topped and immediately stored at 1 °C until use. The first experiments were conducted with freshly harvested carrots that had been stored at 1.0 ± 0.3 °C for a maximum of 4 d. A second experiment was conducted using carrots stored at 1.0 ± 0.3 °C for 6 months. Every carrot was wounded at two spots with a sharp cork borer of 8 mm diameter and to a depth of 2 mm. The wounds were inoculated with 10 µL of a conidial suspension (30×10^3 spores mL^{-1}) of *C. elegans* or *C. thielavioides* derived from 7–10 d old cultures grown on malt agar (Difco™, BD, Sparks, MD, USA). The carrots were then placed individually on moist filter paper in plastic boxes to ensure a high relative humidity (RH). The carrots were incubated at five temperatures (i.e., 1, 2, 4, 8 and 20 °C). Ten carrots were used for each treatment. Additionally, ten carrots were wounded as described but not inoculated and stored at 20 °C (control). The development of visible lesions was monitored daily during 60 d by measuring the expansion of the surface of lesions.

Statistical methods

All measurements were done in triplicate. The results were analyzed using Excel with XLSTAT (Addinsoft, Andernach, Germany), SPSS routines and the open source software package R. Significance of treatments was determined using Duncan's post hoc test for a probability of 95 %.

Results

Storage facilities and temperature course after harvest and during storage

Transportation time to the participating storehouses varied from 4–48 h. Since there was no cooling during transportation, a slight temperature increase of two degrees was observed in the bins without liners and of three degrees in the bins with liners (Fig. 1). The storehouses disposed of storage rooms differing in size as well as refrigeration systems (Table 1). Thus cooling rates during pull-down and also the average temperatures during the remaining storage time differed among the storehouses. For characterization of the cooling rates, the half cooling time was calculated based on the initial phases of the temperature curves (SARGENT et al. 1988). The half cooling times ranged between 8 h and 29 h for uncovered bins and between 30 h and 61 h for the bins with liners (Table 1). According to THOMPSON (2005), 3–4 half-cooling periods are considered to be equal to the total cooling time under commercial conditions. The temperatures at this stage deviated maximally 0.3 °C from the attained storage temperature. Thus it took 1.3–5.0 d to cool carrots to the storage temperature in bins without liners whereas 5–10 d were required to cool them in bins with liners. Furthermore, temperatures remained approximately one degree higher in the bins with plastic liners compared with the ones without (Fig. 1, Table 1). In addition, differences of storage temperatures were observed among the storage rooms, varying between 0.4 and 1.9 °C for bins without liners and 0.9 and 2.7 °C for bins with liners, respectively. However, leaving liners open (storehouses A, D and E) as compared to keeping liners closed (storehouses B, C and E) had only a minor effect on the course of temperature.

Influence of storage on diminution of yield

In all cases, the relative amount of soil adhering to the carrots after harvest ranged from 6–8 % (Fig. 2) reducing the marketable portion of carrots per bin. Amounts up to 6–10 % are considered acceptable. A considerable variation in water loss of carrots was observed among the participating storehouses, ranging from even a slight gain (storehouse F) up to 16 % loss (storehouse B, bins without liners). With the exception of storehouse F, water losses were higher for the bins without liners than for those with liners. It was observed that water losses increased with the storage room's mantel area per tonne (including walls, ceiling and floor), respectively, decreased with the size of rooms (Fig. 3).

Extensive water loss exceeding 3–5 % resulted in visible wilting (Fig. 4). The threshold water loss of 4.7 % was determined based on maximizing the correlation coefficient R^2 for the regression line. The amount of wilted or

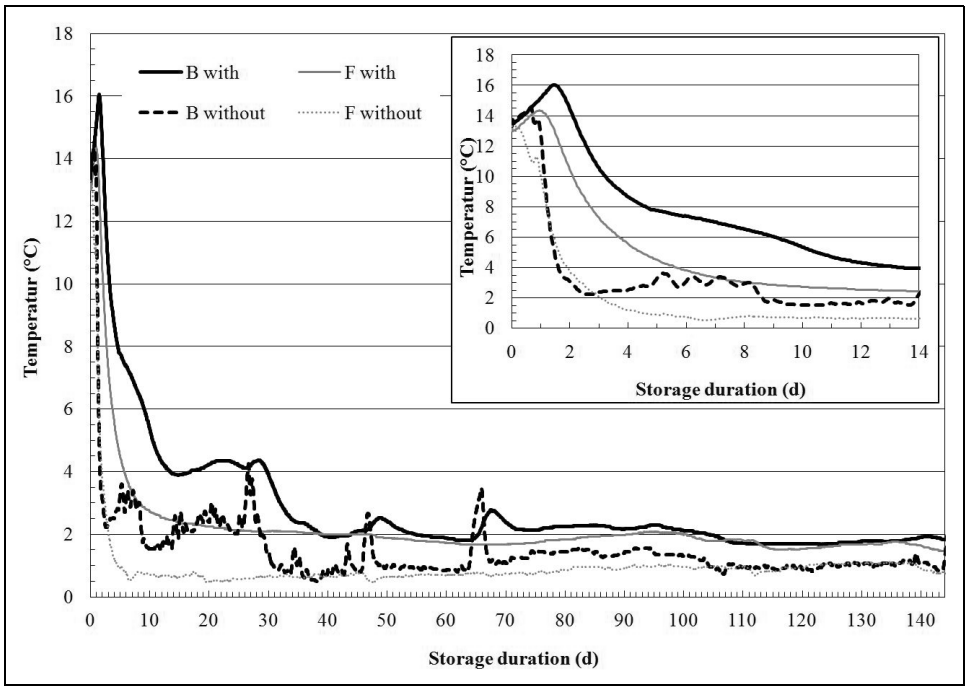


Fig. 1. Effect of polyethylene liners on the temperature course in the centre of bins filled with carrots stored in two different storehouses for the initial 14 days (insert) and the entire storage duration (means of 3 bins per treatment). The temperature courses of the other storehouses (A, C–E) are located in between the two examples (storehouse B and F).

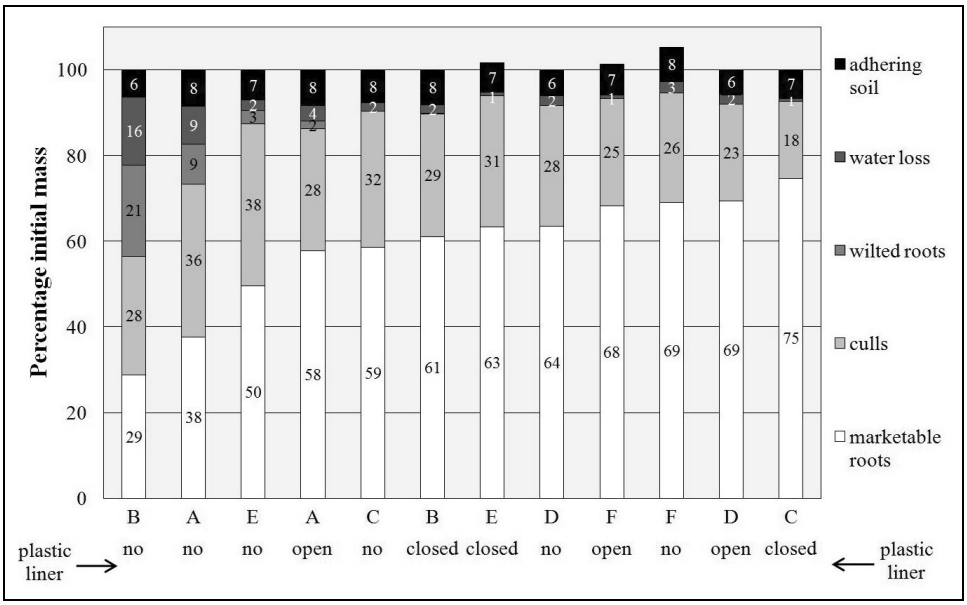


Fig. 2. Influence of storage of carrots for five month on water loss, amount of wilted roots, culls and marketable carrots with and without plastic liners, that were open (store houses A, D, F) or closed (store houses B, C, E).

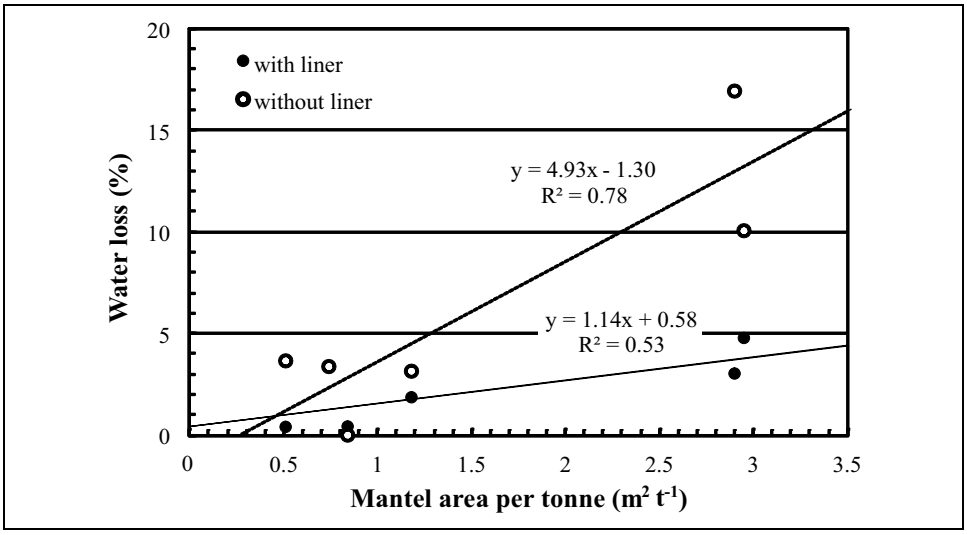


Fig. 3. Water loss of stored carrots depending on the storage room's mantel area („total area including walls + ceiling + floor per tonne of carrots") and liner use in bins.

limp carrots ranged from 0–21 % per bin. Wilting occurred exclusively in the outer layers of the bins.

The amount of culls varied among the lots stored in the different storehouses and depended on whether bin liners were used or not (Fig. 2). Culls included carrots which were not sound showing signs of decay (rejects) as well as carrots which did not concur with requirements pertaining to the Swiss grade standards in terms of size (diameter 25–50 mm), extent of „green shoulders" and uniformity of taper as well as broken roots. The amount of culls at harvest averaged 18–20 % and included mainly under or oversized carrots as well as broken roots. After storage the amount of culls varied between 18 and 38 %. Rejects after storage were mostly associated with various symptoms of decay. Brown or black spots were observed and were related to fungi of the species *Pythium*, *Fusarium* and *Stemphylium* on the basis of the observed lesions. This confirmed other studies concerning decay of carrots (Arsvoll 1971; Le Cam et al. 1993; Odebode and Unachukwu 1997; Seljasen et al. 2004). However, black root rot attributable to *Chalara* spp. was not found on the carrots immediately after storage during sorting (Table 2). Storage of carrots using liners reduced decay significantly ($P < 0.05$) presumably indicating that high amounts of water loss tended to promote decay. In particular, decay was absent in the cases where there was moisture, respectively free water adhering to the roots (storehouse F).

Finally, the yields of marketable carrots varied considerably depending on storehouse and use of plastic liners. Thus the fraction of marketable carrots stored in bins

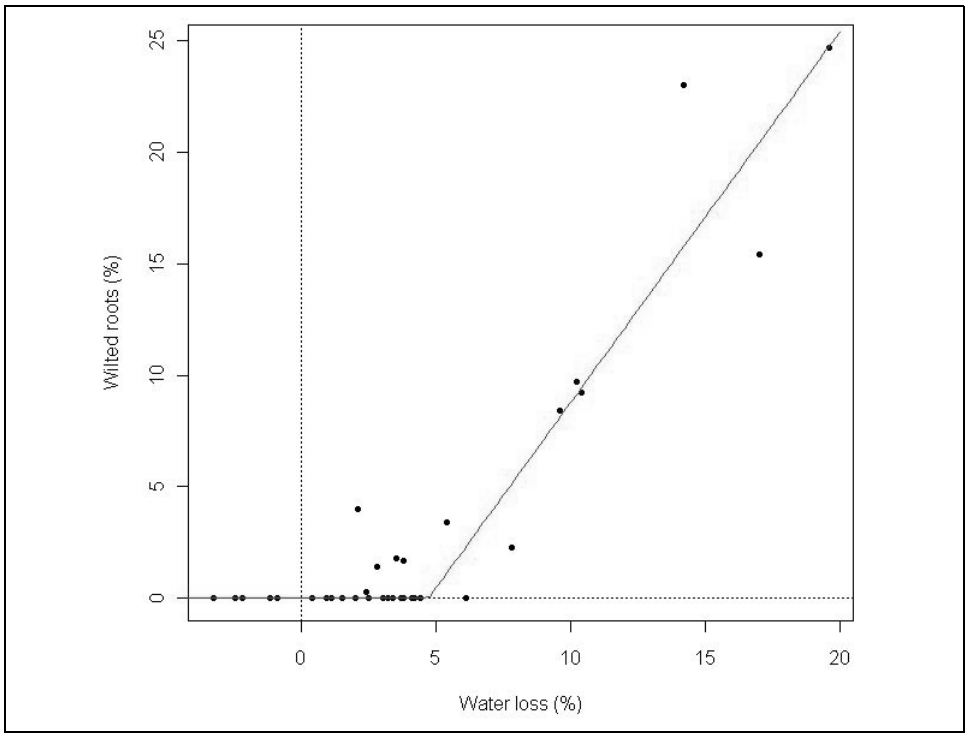


Fig. 4. Percentage of wilted carrots depending on water loss per bin. Regression line and threshold water loss are based on optimization of the correlation coefficient R^2.

Table 2. Eating quality and soundness of carrots after storage as well as decay and infestation with *Chalara* after shelf life.

Storage / Liner	After storage						After shelf life	
	Texture	Sweetness	Bitterness	Overall	Before sorting	Black root rot	Decay (%)	*Chalara*
A / with	crisp	sweet	not bitter	good	wilted, limp roots	–	0.0	+
A / without	crisp	sweet	not bitter	sufficient	black spots, wilted, limp roots	–	0.0	–
B / with	crisp	not sweet	bitter	insufficient	sprouting	–	4.1	–
B / without	crisp	not sweet	bitter	insufficient	black spots, wilted rubbery roots	–	5.3	–
C / with	crisp	sweet	not bitter	good	few black spots	–	0.0	–
C / without	crisp	sweet	not bitter	good	black spots (*Stemphylium*)	–	5.8	+
D / with	crisp	sweet	not bitter	good	sound, cracks	–	4.6	–
D / without	crisp	sweet	not bitter	good	black spots	–	0.7	++
E / with	crisp	sweet	not bitter	good	moist	–	1.4	+
E / without	crisp	insipid	slightly bitter	sufficient	dry (soil)	–	2.0	+
F / with	crisp	sweet	not bitter	good	moist, cracks	–	38.9	–
F / without	crisp	sweet	not bitter	good	moist, frequent cracks	–	11.5	–

without liners averaged 50.5 % and varied between 28.0 and 68.0 %, while it averaged 65.3% ranging from 58.0–74.0% in bins with liners.

Post-storage shelf life

Keeping marketable carrots after sorting at ambient temperature (21.0 ± 0.3 °C) during 8 d in perforated polyethylene bags lead in most cases to decay associated with fungi other than *Chalara* species (Table 2). The samples from storehouses A and C remained free from decay. Most decay was observed on carrots from storehouse F. *Chalara* species were detected on samples from storehouses A, C, D, and E (Table 2). No infestation was found on carrots from the storehouses B and F. Use of liners seemed to have no impact on the *Chalara* infection.

Quality traits: dry matter, total soluble solids and 6-methoxymellein content

The mean dry matter content of marketable carrots increased from 9.5 ± 0.6 % at harvest to 9.9 ± 0.1 % after storage (Table 3). A trend to slightly higher dry matter content of carrots derived from bins without liners was indicated. The TSS of marketable carrots ranged from 8.2–8.8 °Brix. With the exception of the carrots stored in bins with liners in storehouse B, no significant decrease of TSS was noted during storage. Regarding 6-MM, significant higher values were found in carrots stored in storehouse B in comparison to carrots stored in the other storehouses, with carrots stored without plastic liners showing a 60 % higher content of 6-MM than carrots stored with liners.

Infection test

At 2 °C fresh carrots inoculated with *C. thielavioides* showed first lesions after 33 d, whereas stored carrots remained free of lesions for more than 60 d (Table 4). At 4 °C both fresh and stored carrots inoculated with spores of *C. thielavioides* showed lesions while the carrots inoculated with *C. elegans* remained free of any symptoms at temperatures below 4 °C. At 8 °C lesions became visible after 10–20 d and at 20 °C lesions developed after 2 d. Stored carrots seemed slightly less susceptible to *C. thielavioides* than the fresh harvested ones.

Discussion

Despite the commercial importance of yield losses due to black root rot there were no reports on the influence of long term storage on the development of this disease on carrots grown in *Chalara* infested fields as investigated in this study. After 5 months storage in different commercial storehouses there was no incidence of black root rot disease noted on carrots immediately after removal from storage. Presumably storage at temperatures between 0 and 3 °C (Table 2) prevented development of *Chalara*. This was likewise indicated by infection tests in this study. Stored carrot roots were not more susceptible than fresh ones. However, incubation temperature decisively determined

Table 3. Influence of storage on dry matter, total soluble solids and 6-methoxymellein (6-MM) of carrots. Same letter within a column indicates non significant differences at P < 0.01 (Duncan-Test).

Storage	Plastic liner	Dry matter (%)	TSS (°Brix)	6-MM (mg kg^{-1})
Harvest		9.5 a	8.7 ab	0.4 c
A	without	9.9 a	8.8 a	1.6 c
	open	9.9 a	8.4 bc	3.2 c
B	without	10.0 a	8.8 a	139.0 a
	closed	9.1 a	8.2 c	84.7 b
C	without	10.2 a	8.7 ab	1.2 c
	closed	9.9 a	8.4 bc	1.7 c
D	without	10.5 a	8.7 ab	0.6 c
	open	10.4 a	8.5 abc	4.7 c
E	without	10.1 a	8.8 ab	3.8 c
	closed	9.2 a	8.5 abc	1.1 c
F	without	9.9 a	8.4 bc	0.6 c
	open	9.9 a	8.5 abc	1.2 c

Table 4. *Chalara* infection symptoms in function of incubation temperature. Number of days free of symptoms.

Chalara strainspecies	Age of carrots (days after harvest)	1 °C	2 °C	4 °C	8 °C	20 °C
C. elegans	4 („fresh“)	> 60	> 60	> 60	20	2
	180 („stored“)	> 60	> 60	> 60	10	2
C. thielavioides	4 („fresh“)	> 60	33	26	13	2
	180 („stored“)	> 60	> 60	38	18	3

growth of *C. elegans* and *C. thielavioides* on wounded and artificially inoculated carrots in the infection tests (Table 4). This confirmed findings of earlier studies (Punja et al. 1992; Punja and Gaye 1993).

However, the amount of marketable roots after storage varied considerably among participating storehouses. A key element represented the control of humidity in the store rooms and hence the related desiccation of roots. In spite of the fact that all store rooms were equipped with humidifying systems water losses amounted from none up to 16 %, a slight gain was even noted in storehouse F. Here, the carrots and also the adhering soil were moist or wet, in particular in the bins without plastic liners. This indicated and was confirmed by the operator that humidifying system was run more often and in longer cycles than in the other storehouses, resulting in intermittently wetting of carrots. The „high" water status of these carrots may explain the higher frequency of cracking (Van den Berg 1987; McGarry 1993) observed during washing (Table 2; observation before sorting) compared to the lots stored in the other storehouses. In the other storehouses mass losses of carrots during storage were supposedly mainly caused by transpiration. The rate of transpiration of a carrot root is recognized to be proportional to its surface area and the water vapour pressure deficit (WVPD) (Apeland and Baugerød 1971), which is determined by the temperature and RH between the product and the surrounding air (Van den Berg 1987). In addition it varies with air velocity and transpiration coefficient, which varies with cultivar and preharvest as well as postharvest factors (Shibairo et al. 1997, 1998b; Herppich et al. 1999). Carrots used in this study were all from the same field and of the same cultivar 'Bolero'. Thus differences in water loss were caused by fluctuations in relative humidity and temperature during storage. Based on data from Rooke and van den Berg (1985) it can be estimated that the moisture loss at temperatures between 0–2 °C and 99 % RH would have amounted to 8 % for a storage time of 150 d and at 98 % RH it would have exceeded 18 %. This indicated that the average RH in the store rooms attained levels ranging from 98–100 %. Humidity in cold rooms is determined by the temperature difference of room temperature and coil temperature of the evaporator (delta t), evaporator-coil surface area per tonne and the frequency and duration of cooling cycles. Frequency of the cooling cycles and consequently moisture loss are determined by heat of respiration and influx of heat from the outside into the cold rooms, which is proportional to mantel area per tonne. This confirmed findings of Van den Berg (1987) that heat leakage into a storage room markedly increased moisture loss. That moisture loss exceeding 4–8 % in carrots become apparent as wilting or limpness of the roots was indicated elsewhere (Van den Berg 1987), and was confirmed (Fig. 4) in this study.

There is evidence that carrots stored at less than 98 % RH are more prone to decay than at 98–100 % RH provided that temperature does not exceed 4–5 °C (Van den Berg 1987). There are even recommendations that they should be wetted intermittently as long as temperature is maintained below 4 °C (Shibairo et al. 1998a). However, after storage during shelf life when carrots were kept at 21 °C for 8 d decay and also development of black root rot was observed in some of the lots (Table 2). It may be speculated that the high incidence of decay of carrots stored in storehouse F was due to cracks and other wounds as these roots seemed more prone to injury and cracking during washing than the roots from the other storehouses. The low incidence of black root rot registered in this study in comparison to the observations in commerce may be related to the washing step. Recycling of water in the washing operation is common commercial practice but may result in infection in particular of wounded roots. Preliminary trials (data not shown) revealed that the use of fresh water for washing reduced the incidence of black root rot development substantially. It is documented that washing with tap water reduced microbial counts on carrots (Hassenberg et al. 2008). These authors demonstrated furthermore that washing with ozonated water boosted the effect of washing in terms of the inhibition of *Pectobacterium carotovorum* (bacterial soft rot) without affecting produce physiology. However exposure to ozone may lead to slightly elevated 6-MM levels in carrots (Song et al. 2003; Hildebrand et al. 2008).

The overall eating quality of the carrots used in this trial was with the exception of the carrots stored in storehouse B assessed as sufficient or good and roots were judged as sweet (Table 2). The TSS averaged 8.5 °Brix, exceeding the minimum level of 7.6 °Brix which was required for the 'Bolero' cultivar to get rated as sweet and as of acceptable eating quality (Höhn et al. 2003). Carrots from storehouse B were not sweet but bitter in taste and of poor overall eating quality. This presumably related to the 6-MM content. 6-MM was reported to suppress sweetness perception and to exert bitterness (Höhn et al. 2003). Sensory just noticeable levels of 6-MM ranged according to Talcott and Howard (1999) from 48–71 mg kg^{-1} in strained carrots and 94 mg kg^{-1} exerted bitter taste in spiked carrot puree. However, more recently a bitter taste detection threshold of 20 mg kg^{-1}in water was found for 6-MM (Czepa and Hofmann 2003). Calculation of the taste activity value (TAV) as the ratio of 6-MM concentration in carrots and its threshold concentration as proposed by Czepa and Hofmann (2004) yielded TAVs of 4–6.9. Such high values stipulated that 6-MM caused bitterness. In the carrots stored in the other storehouses 6-MM contents were at similar levels as reported for 'Bolero' elsewhere (Kreutzmann et al. 2008) and the calculated TVAs were less than one, thus no bitterness was to be expected. It has been demonstrated that carrot roots under stress conditions caused by fungal pathogens but also wounding and ethylene synthesize 6-MM. In particular exposure to ethylene during storage induces 6-MM formation and bitterness in carrots (Gordon and Kuc 1960; Sarkar and Phan 1979; Lafuente et al. 1996; Seljasen et al. 2000). We

observed that the fresh air intake for the storehouse B was located in the vicinity of the exhaust stack of a wood chip burning heating system. Thus it was most likely that the outside air used for aeration was polluted with traces of ethylene from the exhausts and induced 6-MM formation in the carrots. Barrefors and Petersson (1995) found that exhausts of wood burning may contain substantial levels of ethylene ranging between 10–20 ppm.

Conclusions

Our study showed that it was possible to produce carrots of acceptable quality and free of black root rot in fields contaminated with *Chalara* spp. Provided that harvest operations were handled in such a way that wounding of roots was minimal and storage temperature was maintained at 0–4 °C development of black root rot was prevented. The use of perforated bin liners effectuated reduced water losses and less decay in most of the store rooms. Abandonment of liners was only indicated in store rooms which ensured maintenance of a high humidity (99–100% RH) during the entire storage. Even intermittently wetting during storage seemed indicated since it prevented water loss without promoting decay. However, proper washing and low temperatures during market distribution and retailing were crucial to avoid black root rot at the point of sale. Inoculation tests indicated that maintaining a distribution temperature of 8 °C would be sufficient to avoid black root rot symptoms development during 10 d. In Switzerland, carrots are usually distributed to the consumer within 3–5 d after grading and packaging (data not shown). Apparition of black root rot symptoms and of decay until purchase would be avoidable at a distribution temperature of 8–10 °C, even if wounding and contamination occurred during the washing and grading process. Since carrots for the fresh market are usually sold in Switzerland on an unrefrigerated shelf at ambient temperatures (20–22 °C) freedom from black root rot and decay could not be assured during distribution lasting more than two days. This study showed that the washing step and the distribution chain entailed most risks for the occurrence of decay of carrot roots. Future work may show whether an optimized washing process with clean water improves carrot shelf life at ambient temperature.

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Addresses of authors: P. Crespo, Agroscope Changins-Wädenswil ACW, Research Center of Conthey, CH-1964 Conthey, Switzerland, and W. Heller, E. Hoehn, and D. Baumgartner (corresponding author), Agroscope Changins-Wädenswil ACW, Schloss 1, CH- 8820 Wädenswil, Switzerland, e-mail (corresponding author): daniel.baumgartner@acw.admin.ch.