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Published in:
Postharvest Biology and Technology

DOI:
10.1016/j.postharvbio.2012.08.011

Publication date:
2013

Document version
Early version, also known as pre-print

Citation for published version (APA):
Proteomic changes and endophytic micromycota during storage of organically and conventionally grown carrots

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Article history:
Received 7 February 2012
Accepted 26 August 2012

Keywords:
Carrot proteome
Endophytic micromycota
Organic production
Cold storage

Abstract

The physiological state of carrot roots during extended cold-storage is decisive for high postharvest quality. We have investigated differences in the proteome and micromycota of organically and conventionally grown carrots during six months of storage. The levels of only 15 proteins changed in level during storage. Proteins involved in cold stress adaptation and cytoskeleton components changed; these changes in specific protein levels occurred mainly during the first month demonstrating adaptation to storage conditions and that the carrots were subsequently stable, indicating stable carrot quality. The changes observed were similar in the two cropping systems.

Using both biological isolation and a fungal PCR targeting the ITS region, we identified several endophytic species belonging to the Ascomycota. The most frequently encountered taxa were Tetrachadium, Leptodontidium, Nectriaceae and Phoma which are known to occur as root endophytes or as root-associated fungi. As for the proteomics data, no consistent statistically significant differences in micromycota were observed between the two cropping systems. We conclude that cropping system did not have an influence on the postharvest quality of the carrots during six months of cold storage.

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1. Introduction

The year-round availability of quality carrots is important for the consumer market; therefore continuing technical improvements to extend cold storage are an important developmental challenge for the carrot industry. However, during cold storage, carrot roots become stressed due to the environmental conditions (low temperature and drought); these stress conditions induce modification of the metabolism of the roots and favour the development of certain diseases (Lecam et al., 1993; Kastelein et al., 2007; Louarn et al., 2012). At the same time, there is an increasing interest among consumers for food safety, especially with respect to pesticide residues and potential human pathogens. Furthermore, there is a general increased concern about the state of the environment, especially in relation to environmental impact caused by the excessive use of inorganic fertilisers. Consumers are therefore turning increasingly to organic products as their production does not entail the use either of pesticides or mineral fertilisers (Woteki et al., 2001; Magnusson et al., 2003).

Relatively little is known about the physiological changes which occur during storage of root vegetables. Those demonstrated include changes in the occurrence of secondary metabolites, for instance, the isocoumarin, 3-methyl-6-methoxy-8-hydroxy-3,4-dihydroisocoumarin (6-MM) a phytoalexin (antimicrobial metabolite), which accumulates in carrots following pathogen infection and in response to treatment with various abiotic elicitors (Mercier et al., 1994; Jayaraj et al., 2009). Interestingly, the content of 6-MM from 1 month old stored carrots was significantly higher than after 4 and 6 months of storage (Louarn et al., 2012). Physiological changes due to cold stress (includes chilling (<20 °C) and freezing (<0 °C) temperatures) can also be observed at the protein level (Degand et al., 2009; Neilson et al., 2010). Several of these proteins e.g., dehydrin, heat-shock proteins (HSP) and anti-freeze proteins, are known to be involved in abiotic stress responses and have also been observed to accumulate following cold stress (Miernyk, 1997; Kawamura and Uemura, 2003; Griffith and Yaish, 2004; Renaut et al., 2004; Griffith et al., 2005).

Plant roots host a great variety of fungi; roots are not only susceptible to certain soil-borne pathogens, but can also be colonized by symbiotic mycorrhizae and endophytic micromycota.

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The spectrum of endophytic organisms present in a particular sample of roots will reflect the physiological state of the root and we assume that, if roots differ substantially in their physiological state, they will probably differ in their endophytic micromycota too. In carrot roots, several plant pathogen interactions have been studied (Kora et al., 2005; Kastelein et al., 2007; Louarn et al., 2012) as well as carrot mycorrhizal interactions (Dumas-Gaudot et al., 2004). Furthermore, Surette et al. (2003) investigated bacterial endophytes in carrots. However, no studies have been conducted on the endophytic micromycota of carrots roots. Endophytic fungi are asymptomatic for at least part of their life cycle but some can be latent pathogens or dormant saprophytes (that change lifestyle during host senescence, Promputtha et al., 2007; Yuan et al., 2010).

The majority of endophytic populations are Ascomycetes (Gazis and Chaverri, 2010; Botella and Diez, 2011) as well as the majority of carrot root pathogens (Farrar et al., 2004; Kastelein et al., 2007; Louarn et al., 2012). Potential benefits of host–endophyte associations include increased resistance to herbivores, pathogens and abiotic stress (Kulda and Bacon, 2008; Porras-Alfaro and Bayman, 2011) and they can even, in some cases, be used as biological control agents. The root micromycota from plants grown in cold environments have been studied, thus the establishment of plant–fungal association in relatively extreme environments might help to understand the origins and the role of endophytes (Higgins et al., 2007; Rosa et al., 2010). Some endophytes, such as Curvularia protuberata in rice (Redman et al., 2011), are able to increase plant tolerance to cold stress. On the other hand, factors like soil pH, soil humidity, location and crop rotation (D’Amico et al., 2008), the use of fertilisers (Kernaghan et al., 2003) and predictably, the use of fungicides (Sieber and Grünig, 2006) can influence the diversity of the fungal endophytes communities, and especially nitrogen fertilisation might be one of the mechanisms by which agricultural management affects endophyte communities.

We have previously studied the response of organically and conventionally grown carrots at harvest and in response to pathogen attack during subsequent storage (Nawrocki et al., 2011; Louarn et al., 2012). Changes in specific defence-related metabolites including the accumulation of a phytoalexin (6MM) and proteins (PR-protein) were correlated to fungal infection. In contrast, the present study focuses on the differences between organic and conventional cropping systems and utilises physiologically independent assays to provide an objective evaluation as to whether there are indeed substantial differences in the way that organically and conventionally grown carrots develop during storage. Thus quantitative proteomics and sampling the endophytic Ascomycota of stored carrots provide two different assessments of the physiological state and, for the former, dynamics of the physiology of stored carrots. This study thus represents the first study of the endophytic Ascomycota in carrot roots. We show that, though there are some differences, the organically and conventionally cultivated carrots are substantially similar in quality, and that in essence the alterations in quality change concomitantly during storage.

2. Materials and methods

2.1. Plant material

The root experiment was started in the autumn of 2005 on a field grown organically since 1996, at Årslev, Denmark (10° 27’E 55° 18’N). The crops used in these rotations are representative of vegetables produced commercially in Denmark. The two cropping systems are described in detail in our previous study (Louarn et al., 2012; Thorup-Kristensen et al., 2012), and comprise a conventional system where synthetic fertilizers, pesticides, herbicides and fungicides were used according to normal practice and an organic system. The roots were harvested in October 2007 and 2008, samples were taken on harvest day and the carrots then placed in cold storage at 1 °C and >98% RH and roots were sampled one, four and six months after harvest. Sampling was achieved by cutting two 15 mm cylinders per carrot with a cork borer; this cylinder was cut longitudinally in two equal pieces, one was kept for proteomic and micromycota analysis and the other for secondary metabolite analysis (Louarn et al., 2012). Only the upper 10 mm of this cylinder was used for analysis. Each sample consisted of 12 parts from six carrots giving approximately 12 g of fresh tissue per sample for each three biological replicates. The samples were frozen directly in liquid nitrogen and then freeze-dried.

2.2. 2D gel electrophoresis and image analysis

For the proteomic analysis, freeze-dried root samples were used from the 2008 harvest. Gel electrophoresis and image analysis were performed as described by Nawrocki et al. (2001, 2011) with some modifications according to Louarn et al. (2012). Where necessary, manual corrections of the protein spot detection and matching across the gels were made. Thus a 1.5-fold up or down regulation (p < 0.05) of the protein spot volume was taken as the cut-off for further analysis, since a lower level of change is inferred to approach the technical limitations of the technique. The significance of the differences between averaged spot volumes between pair-wise comparisons in organic samples compared to conventional samples at each time point was tested using Student’s t-test, with p < 0.05. The same comparison and test was made between the samples at harvest time compared to samples stored 1 month, 4 months and 6 months for each cultivation systems. These two comparisons enable a comparison of the effect of cultivation system on the proteome changes and, independently, the effect of storage time on the proteome changes.

Protein spots whose intensity differed significantly were excised from the gels and digested with trypsin, and the proteins were identified using a 4800 Plus MALDI TOF-TOF Analyser (Applied Biosystems, MDS SCIEX) as in Louarn et al. (2012).

2.3. Micromycota

2.3.1. PCR identification

Freeze-dried samples of roots stored for one month, from the conventional and organic cropping system harvested in 2007 and 2008, were included. Roots cold-stored for one month were sampled in triplicate from the organic and conventional cropping systems both in 2007 and 2008. For DNA extraction, samples of freeze-dried carrot material were ground in liquid nitrogen and 20 mg was used for DNA isolated using the Nucleon Phytopure kit (Amer sham Biosciences, Buckinghamshire, UK) following the manufacturer’s instructions, except that 15 mg polyvinylpolypirrolidone (Sigma) was added to the lysis buffer. The total reaction volume of the PCR reaction was 20 μL and contained 1× Taq polymerase buffer including 1.5 mM MgCl2, 0.2 mM of each dNTP, 0.5 μM each of the primers FITS-Fw1: GCTTGTTCCAGGCGCTATT and FITS-R1: TCTACCTGATYCGAGGTCAA (Fig. 1), 2 U Taq DNA polymerase (Ampli gone, Copenhagen, DK) and 40–80 ng root DNA. The PCR was performed using a Mastercycler personal (Eppendorf). An initial denaturation at 95 °C for 3 min was followed by 36 cycles of denaturation at 94 °C for 20 s, annealing at 63 °C for 20 s, and extension for 20 s. The PCR was completed with a final extension step at 72 °C for 7 min. The PCR products were visualised on a 1.5% agarose gel. Following the manufacturer’s instructions, the PCR products were cloned into the pGEM T-easy vector (Promega, Madison, USA) and transformed into DH5α competent Escherichia coli cells (Invitrogen, Madison, USA). From each root sample in 2007 and 2008, respectively, 30 colonies and 25
colonies were picked. Colony PCR with the vector primers T7 and Sp6 was performed as described by Sundelin et al. (2009). The PCR products were separated on an agarose gel and clones with band size of approximately 200 bp were sequenced using the sequencing service of StarSeq, Mainz, Germany. Sequences were queried against GenBank and identified in a BLAST search with the National Centre for Biotechnology Information (NCBI). Each sequence was identified to the lowest taxonomic rank common to the top blast hits. Only clone sequences represented at least twice in 2007 and/or 2008 were considered as identified taxa; those occurring only once were assigned to the phylum Ascomycota.

### 3.1. Proteomics

The coverage of the proteome is approximately 1200 spots. The intensity of 10 spots increased and 5 decreased in response to cold storage (p < 0.05 and fold change > 1.5) in all the three replicates and both the organic and conventional root (Table 1 and Fig. 2). No significant differences were observed between organic and conventional roots.
Table 1
The effects of cold storage on the proteome of organically and conventionally cultivated carrots. Analysis of 2D-PAGE gels for proteins exhibiting more than 1.5 fold alteration in relative intensity following storage.

<table>
<thead>
<tr>
<th>Spot number</th>
<th>Fold changes in the conventional roots (in the organic roots)</th>
<th>Theoretical/observed MW (kDa)</th>
<th>Theoretical/observed pI</th>
<th>Accession number</th>
<th>Protein name</th>
<th>Organism</th>
<th>Biological process (molecular function)</th>
<th>Matched peptides</th>
<th>Sequence coverage (%)</th>
<th>Score</th>
<th>Sequence (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9 (1.7)</td>
<td>2.3 (2.1)</td>
<td>2.3 (2.2)</td>
<td>5.1/187</td>
<td>49/182</td>
<td>5.52/5.28</td>
<td>G2:78006188</td>
<td>Probable l-ascorbate peroxidase II</td>
<td>Oryza sativa ssp. japonica</td>
<td>Stress response (Hydrogen peroxide removal)</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>1.6 (3.5)</td>
<td>1.8 (1.9)</td>
<td>2.1 (2)</td>
<td>84.58/93.137/8</td>
<td>6.51/6.77</td>
<td>G2:8145050</td>
<td>Methionase synthase</td>
<td>Solanum tuberosum</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>4</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>2.1 (2.2)</td>
<td>2.5 (2.4)</td>
<td>2.5 (2.4)</td>
<td>84.58/93.138/1</td>
<td>6.51/6.659</td>
<td>G2:8145050</td>
<td>Methionase synthase</td>
<td>Solanum lycopersicum</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>5</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>1.7 (3.5)</td>
<td>2.1 (3.9)</td>
<td>2.4 (2.5)</td>
<td>84.82/84.459</td>
<td>6.27/6.58</td>
<td>G2:8145058</td>
<td>Methionase synthase</td>
<td>Alnus rhombifolia</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>4</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>1.5 (3.5)</td>
<td>1.7 (1.8)</td>
<td>1.7 (1.8)</td>
<td>84.82/84.528</td>
<td>6.27/6.41</td>
<td>G2:8145058</td>
<td>Methionase synthase</td>
<td>M. crystallinum</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>4</td>
<td>65</td>
</tr>
<tr>
<td>6</td>
<td>1.6 (3.7)</td>
<td>2 (1.9)</td>
<td>2 (1.9)</td>
<td>84.58/84.135</td>
<td>6.51/6.51</td>
<td>G2:8145059</td>
<td>Methionase synthase</td>
<td>Solanum lycopersicum</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>4</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>1.6 (3.7)</td>
<td>2 (1.9)</td>
<td>2 (1.9)</td>
<td>84.58/83.857</td>
<td>6.51/6.42</td>
<td>G2:8145059</td>
<td>Methionase synthase</td>
<td>Solanum lycopersicum</td>
<td>Amino acid biosynthesis (methyl transfer)</td>
<td>4</td>
<td>65</td>
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Table 1 (Continued)

<table>
<thead>
<tr>
<th>Spot number</th>
<th>Fold changes in the conventional roots (in the organic roots)</th>
<th>Theoretical/observed MW (kDa)</th>
<th>Theoretical/observed pI</th>
<th>Accession number</th>
<th>Protein name</th>
<th>Organism</th>
<th>Biological process (molecular function)</th>
<th>Matched peptides</th>
<th>Sequence coverage (%)</th>
<th>Score</th>
<th>Scorea</th>
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<tbody>
<tr>
<td>8</td>
<td>2.2 (2)</td>
<td>2.6 (2.5)</td>
<td>30261/29745</td>
<td>5.66/3.84</td>
<td>G2-366817</td>
<td>Vegetative storage protein</td>
<td>Arabidopsis thaliana</td>
<td>Storage</td>
<td>2</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.7 (1.9)</td>
<td>2.2 (2.2)</td>
<td>47972/47854</td>
<td>5.57/5.29</td>
<td>G2-901108</td>
<td>Fetolase</td>
<td>O. sativa</td>
<td>Glycolysis</td>
<td>3</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.6 (1.8)</td>
<td>1.9 (2)</td>
<td>13536/15136</td>
<td>5.0/5.60</td>
<td>G2-757005</td>
<td>Dehydrogenase</td>
<td>Daucus carota</td>
<td>Stress response</td>
<td>1</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.6 (1.5)</td>
<td>1.0 (1.5)</td>
<td>47173/41443</td>
<td>5.40/5.99</td>
<td>G2-170130</td>
<td>Actin</td>
<td>A. thaliane</td>
<td>Cytoskeleton (structural molecule activity)</td>
<td>5</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.9 (1.6)</td>
<td>2.2 (2.1)</td>
<td>15.54/15.258</td>
<td>6.30/5.54</td>
<td>G2-134907</td>
<td>Nucleoside diphosphate kinase 1</td>
<td>A. thaliane</td>
<td>Amino acid biosynthesis (role in synthesis of nucleoside triphosphates)</td>
<td>3</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1.5 (1.6)</td>
<td>1.8 (1.8)</td>
<td>50.73/49.821</td>
<td>4.8/4.74</td>
<td>G2-20707</td>
<td>Beta-tubulin</td>
<td>A. thaliane</td>
<td>Cytoskeleton (structural molecule activity)</td>
<td>3</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.8 (1.6)</td>
<td>2.3 (2.2)</td>
<td>49.823/49.752</td>
<td>5.19/5.62</td>
<td>G2-600443</td>
<td>Alpha-tubulin</td>
<td>D. carota</td>
<td>Cytoskeleton (structural molecule activity)</td>
<td>2</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2.5 (2.4)</td>
<td>2.7 (2.6)</td>
<td>53.02/50.854</td>
<td>6.5/7.89</td>
<td>G2-122239</td>
<td>Ribulose 5-phosphate carboxylase</td>
<td>O. carotae</td>
<td>Photosynthesis (photosynthesis)</td>
<td>2</td>
<td>4%</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Spot intensity decreasing</th>
<th>Spot number</th>
<th>Fold changes in the conventional roots (in the organic roots)</th>
<th>Theoretical/observed MW (kDa)</th>
<th>Theoretical/observed pI</th>
<th>Accession number</th>
<th>Protein name</th>
<th>Organism</th>
<th>Biological process (molecular function)</th>
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<td>2.2 (2.2)</td>
<td>47972/47854</td>
<td>5.57/5.29</td>
<td>G2-901108</td>
<td>Fetolase</td>
<td>O. sativa</td>
<td>Glycolysis</td>
<td>3</td>
<td>12%</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
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<td>1.9 (2)</td>
<td>13536/15136</td>
<td>5.0/5.60</td>
<td>G2-757005</td>
<td>Dehydrogenase</td>
<td>Daucus carota</td>
<td>Stress response</td>
<td>1</td>
<td>11%</td>
<td></td>
<td></td>
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<tr>
<td>11</td>
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<td>1.0 (1.5)</td>
<td>47173/41443</td>
<td>5.40/5.99</td>
<td>G2-170130</td>
<td>Actin</td>
<td>A. thaliane</td>
<td>Cytoskeleton (structural molecule activity)</td>
<td>5</td>
<td>14%</td>
<td></td>
<td></td>
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<td>12</td>
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<td>6.30/5.54</td>
<td>G2-134907</td>
<td>Nucleoside diphosphate kinase 1</td>
<td>A. thaliane</td>
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<td>3</td>
<td>17%</td>
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<td>Ribulose 5-phosphate carboxylase</td>
<td>O. carotae</td>
<td>Photosynthesis (photosynthesis)</td>
<td>2</td>
<td>4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Protein spot number as in Fig. 2.
b Protein accession number derive from either Swissprot or NCB database.
c Protein name derive from either Swissprot or NCB database.
d Biological process the proteins is involved in and molecular function derived from either Swissprot or NCB database.
e Ions mascot score for identified peptides by MSMS at p ≤ 0.05.
f Mox: oxidized methionine.
Only two of the 15 proteins identified matched directly to carrot protein sequences in the databases. Most of the proteins identified were at their predicted position in the gels (based on MW and pl) but some of the identified proteins are inferred to be degraded since their positions in the gels did not correspond to the theoretical pl or MW (Table 1 and Fig. 2). All spot identifications in Table 1 are based on two or more peptides except for spot 10 which is based on a single peptide: it is conceivable that this therefore represents contamination of the major spot from a protein in the background which is unaffected by cold storage. Among the 15 identified proteins, three of them are part of the cytoskeleton (spots 11, 13 and 14), and three others are involved in stress responses (spot 1, 10 and 12).

### 3.2. Microcomyota

In the roots harvested in 2007, 143 different fungal isolates were identified as belonging to 22 taxa and 114 isolates identified to 21 taxa in the roots from 2008 (Table 2). The occurrence of each fungal taxa in the organic and conventional root were compared. In 2007, only Peyronellaea spp./Phoma spp. differed significantly in occurrence; this taxon occurred more often in the conventional roots than in the organic ones. No significant difference could be attributed to the cropping systems in 2008. Representatives from the nine most frequently occurring taxa were identified in both years (Fig. 2) and from most samples. This reproducibility supports the conclusion that these data are robust (see supplementary Tables 1 and 2). However, frequencies of occurrence in our samples varied considerably, e.g., 7% Geomyces was found in 2008 against 1% in 2007 and the same was seen for Davidiellaceae. On the other hand, many of the other groups like Tetracodium, DSE, Pleosporaceae, Nectriaceae and Didymellaceae were consistently represented with high frequencies in both years. Averaged over year and cropping system, Tetracodium, Leptotodonitdium, Nectriaceae and Didymellaceae were the most frequently isolated taxa, respectively, representing 31%, 14% and 10% of all isolates.

Culturable fungi were isolated from stored roots in 2009. Based on ITS 1-2 sequences, the following taxa were identified Tetracodium furcatum, Tetracodium maxilliforme, Leptodontidium sp., Ilyonectria radicicola, Phoma sp., Pyrenochaeta sp., Acremonium strictum. All the fungi identified from biological isolation were Ascomycetes.

### 4. Discussion

We have demonstrated in this study, using two completely independent methods to monitor physiological quality, that no substantial differences have arisen between organic and conventionally cultivated carrots during storage. At the protein level, three proteins that changed significantly during storage are involved in stress responses. The increase of ascorbate peroxidase (spot 1) correlated with its involvement in response to abiotic and biotic stress; this protein has been reported previously to accumulate following oxidative stress in roots due to cold treatment (Neilson et al., 2010). Interestingly, enhanced peroxidase activity might have an influence on bacterial as well as fungal endophyte populations. A dehydrin (spot 10) also accumulated and has been reported previously to be induced by drought,
salinity or/and low temperature (Close, 1996) and might stabilize cell membranes and protect other proteins from denaturation during dehydration (Aglagulova et al., 2003). Dehydrin accumulation has been shown in proteomic studies of cold stress in Arabidopsis (Kawamura and Uemura, 2003; Renaud et al., 2004). It might also play a role in conjunction with molecular chaperones, DNA binding and repair, or participate in the cytoskeleton (Rahman et al., 2011). Tubulins (alpha and beta) are the major constituents of microtubules. Both alpha- and beta- tubulin levels (spots 13 and 14) decreased during cold storage. The reduced abundance of tubulins correlates with the appearance of cold-stable microtubules which is linked with low temperature stress (Abdrakhmanova et al., 2003). Actin 7 (spot11), another cytoskeleton component decreased during storage. The cytoskeletal proteins assemble into polymers that play an important role in the cell structure and are determinant of the cell shape; during cold adaptation, a reorganisation of these polymers is necessary to preserve the cell integrity. The presence of RuBisCo (spot 15) in roots is surprising, because this is a non-photosynthetic organ but it has previously been reported in roots (Suzuki et al., 2005; Louarn et al., 2012). A CO₂-binding role for RuBisCo has been demonstrated in developing Brassica napus embryos (Schwender et al., 2004). RuBisCo might have a similar function in roots with respect to the expression of decarboxylating enzymes of the Krebs cycle (Mooney et al., 2006). A decrease of RuBisCo could indicate a slowing down of the energy metabolism. Vegetative storage protein (spot 8) levels increased and suggests an adaptation of the roots in order to store energy for the next year; carrot is a biannual crop plant and can thus withstand a period of cold/freezing temperatures over winter.

The fungal communities of cold-stored carrot roots were identified by rDNA clone libraries that enabled us to identify 257 Ascomycetes isolates (clones) in the roots. The FITS PCR-primers used exhibit greatest affinity for detection of Ascomycetes and would not be expected to yield Basidiomycetes or Glomeromycetes due to mismatches at the primer binding sites (Fig. 1). Although the FITS reverse primer has a single mismatch at the 5’ end for several Ascomycete genera, it does not seem to affect the efficiency of the primers to amplify, e.g., Tetracladium and Leptodotidium. The robustness of the DNA based method was confirmed by the result of the biological isolation that yielded solely Ascomycete taxa, all bar one was also detected by the FITS primers. In general, ascomycetes also seem to constitute the majority of endophytic populations in roots of other species studied (Upson et al., 2009; Andrade-Linares et al., 2011). Concerning the absence of Glomeromycetes, these are known to be associated with carrots but most frequently with the fine roots which were not sampled in this study (Dumas-Gaudot et al., 2004). There was no significant effect of the cropping system on the micromycota community, only Peyronellae spp./Phoma spp. significantly differ (Table 2). In contrast Wilberforce et al. (2003) found that agricultural management practice affected communities of root-endophytic fungi in grasslands at different locations (Wilberforce et al., 2003). However, in our field experiment, the plots were situated at the same location.

The nine most frequently occurring taxa were identified in both years but the isolation frequencies of clones varied considerably between 2007 and 2008 (Fig. 2). These differences could be related to the relatively small sample size (257 clones), the varying climatic conditions or the use of different seed lots in the two years. The occurrence of several taxa only once, either in 2007 or in 2008, can be attributed to the same factors (Table 2). These pathogens can survive inside carrot roots (or carrot debris) in the field and might become inoculum sources that will infect a later crop. The taxon Leptotudindium orchidicola is frequent in both years and Cadophora spp., belong to the artificial group “dark septate endophytes” (DSE) which occur widely in association with plant roots in cold stressed habitats (Upson et al., 2009; Rosa et al., 2010) (Table 2). The DSE have received much attention since they can stimulate host growth and protect plants against various stress conditions, e.g., by secretion of secondary metabolites (Schulz et al., 2002; Porras-Alfaro and Bayman, 2011). Other taxa Geomycetes spp., and Davidiella spp. detected in the cold-stored carrots have also been identified as endophytes in roots of plant species adapted to cold conditions (Rosa et al., 2010) (Fig. 3).

Some of the identified taxa, e.g., Rhexocercosporidium carotae (Kastelein et al., 2007) and Fusarium spp., are known as carrot postharvest pathogens. However, they remained latent as no visible symptoms developed during the 6 months of cold storage (Table 2). This could be due to defence mechanisms like the accumulation of the antioxidative ascorbate peroxidase which can protect against necrotrophs (Table 1) induced either by the cold environment or by endophytic species.

The changes observed at the protein level indicate an adaptation of the roots to the cold storage conditions within the first month of storage after which the root proteome was stable for the remaining 5 months. Both organic and conventional roots were still marketable after 6 months of cold storage. The observed changes of the proteome could be associated with a cold adaptation of the carrots. We presumably did not isolate all the fungal endophytes taxa but with over 257 clones identified, representing

![Fig. 3. Proportion of fungal taxa recovered from DNA sequence analysis of cold stored carrots in 2007 and in 2008. DSE (dark septate fungal endophytes) contains Leptotudindium and Cadophora. Nectriaceae contains Fusarium, Gibberella and Byonectria. Pleosporaceae contains Bipolaris, Pyrenochaeta and Dendryphion. Davidiellaceae contains Davidiella and Cadosporium and, Didymellaceae contains Phoma and Peyronella.](image-url)
approximately 40 taxa from a total of 72 carrots, we believe these samples are representative of the micromycota. The fact that some pathogens were identified as symptomless endophytes might be due to activation of defence mechanisms induced either by the cold environment or certain endophytes. We conclude that cropping system did not have an influence on the postharvest quality of the carrots during six months of cold storage.

Acknowledgements

We thank Karin Olsen for her expert assistance during the sample collection and the micromycota experiments, and Andrea Maria Lorentzen for mass spectrometry support. This project was supported by an International Centre for Research in Organic Food Systems (ICROFS) grant “Organic cropping Systems for Vegetable production, - product Quality, Natural Regulation and Environmental effects (VEG-QURE 3304-FOJO-05-45-07)”.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.postharvbio.2012.08.011.

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