Production Environment and Nitrogen Fertility Affect Carrot Cracking

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Abstract. Carrot (Daucus carota L.) root cracking and breakage during harvest and handling operations result in serious losses. The environmental and management factors affecting carrot cracking and breakage susceptibility were investigated in a survey of fields and a series of trials conducted in California from 2000–02. Roots, leaves and soil were collected from a total of 31 commercial fields of ‘Sugar Snax’ carrot, and soil texture and plant and soil fertility status were determined. Soil moisture was monitored in 10 fields to determine whether irrigation management was correlated with root cracking susceptibility; in 4 of these fields roots were harvested both before 0800 hr and at 1300 hr on the same day to directly compare the effects of root water status on cracking. The effect of N fertilization on cracking and breakage was investigated in 5 field trials. The relative susceptibility of 10 cultivars to cracking and breakage was also compared. Cracking susceptibility was determined with an impact test, and breakage with a loading test. Roots were selected by size (18 to 24 mm diameter) and cooled to 5 °C before testing. The percentage of roots cracked in the impact test varied from 7% to 75% among survey fields. Initial root water potential was not correlated with cracking incidence. However, after hydrating roots to minimize differences in water potential among fields, cracking incidence was correlated with turgor potential (r = 0.41). Soil sand content and mean air temperature in the 30 days preceding harvest were also correlated with cracking (r = –0.48 and 0.36, respectively), suggesting that cracking susceptibility may be minimized in cool weather and in light-textured soil. Irrigation management in the final 30 days preceding harvest had no consistent effect on root cracking. Time of day of harvest had a small but significant effect, with roots harvested before 0800 hr being more crack-susceptible. N fertilization in excess of that required to maximize root yield significantly increased cracking susceptibility. Cultivars varied widely in cracking susceptibility, with less variation in tissue strength and stiffness. Removal of the periderm dramatically decreased susceptibility to both cracking and breakage.

Longitudinal cracking and transverse breakage of carrot roots result in significant losses to commercial growers worldwide. In California, root cracking is a particularly significant problem for carrots grown for cut-and-peel processing for fresh market. While it has been widely demonstrated that cultivars differ significantly in susceptibility to cracking and breakage (Cantwell et al., 1991; Hole et al., 1999; McGarry, 1993; Sorenson, 1997), cultivars possessing the requisite textural qualities for cut-and-peel use tend to be highly cracking-sensitive. Furthermore, for a given cultivar, the degree of cracking and breakage encountered varies widely among production fields. Identification of the factors governing cracking sensitivity may allow the development of field production, harvesting and handling practices that minimize root damage.

Physiological studies on carrot cracking have produced contradictory results. McGarry (1993, 1995) reported that failure force of parenchyma tissue was negatively correlated with both water potential and turgor potential. Similarly, Golacki (1993) found that resistance to impact loading increased as root water potential decreased. However, difference in cracking sensitivity among cultivars was unrelated to differences in water status (McGarry, 1993; Sorenson, 1997). Furthermore, Hole et al. (1999) found no consistent relationship between root cracking susceptibility and water status, either within or between cultivars. Agronomic and environmental factors have also been studied. Heavy N sidedressing (Bienz, 1965) and excessive soil drying between irrigations (Nortje and Henrico, 1986) increased cracking incidence. Increasing plant population reduced cracking (Bienz, 1965), probably by reducing mean root size; damage susceptibility increased as root size increased (Cantwell et al., 1991; Hole et al., 1999). Root temperature (Cantwell et al., 1991; Kokkoras, 1995) also has significant influence on carrot cracking or breaking. The objective of the present study was to investigate the influence of cultivar, field environment, soil fertility, and irrigation management on root cracking and breakage susceptibility during carrot harvest and handling.

Materials and Methods

Field survey. Several hundred roots plus 15 to 20 whole plants were hand harvested from each of 26 commercial fields of ‘Sugar Snax’ carrot in the Imperial and San Joaquin Valleys of California over the period 2000–02. These fields represented all seasons and a wide range of soil and environmental conditions. Composite samples of leaves and soil (top 0.3 m) were also collected. The roots and intact plants were placed in plastic bags to minimize water loss and transported on ice to the University of California, Davis (UCD), where they were cooled overnight at 5 °C. The following day the water potential of the roots was estimated by pressure chamber (model 610, PMS Instruments, Corvallis, Ore.) analysis of leaves excised from five different intact plants; moisture equilibrium between roots and leaves would be expected after the minimum of 12 h in the plastic bags (Fulton et al., 2001). Undamaged roots were then selected for cracking susceptibility testing.

Root water potential varied considerably among fields, so to more clearly distinguish the effects of root water status an attempt was made to standardize the water potential of roots from 18 of the fields. Detached roots, and the roots of intact plants, were immersed in water at 5 °C until leaf water potential averaged between –0.3 and –0.1 MPa. These hydrated roots were then subjected to cracking testing.

Leaf and whole root samples from all fields were oven-dried at 65 °C, then ground. N concentration was quantified by a combustion technique (Pella, 1990), P, K, Ca, Mg, Na, and B by plasma-atomic emission spectrometry (Meyer and Kelihker, 1992) following microwave acid digestion (Sah and Miller, 1992). The soil was air-dried and sieved to pass a 2-mm screen. Particle size analysis was performed by the method of Gee and Bauder (1982). Bi-carbonate extractable P (Olsen and Sommers, 1982) and ammonium acetate exchangeable cations (K, Ca, Mg, and Na, Thomas, 1982) were determined. Soil pH was determined on saturated paste extracts, and organic matter content was estimated by the Walkley-Black method (Nelson and Sommers, 1982).

Effect of N fertility. The effect of N fertility on carrot cracking susceptibility was investigated in five sprinkler-irrigated commercial fields of ‘Sugar Snax’ carrot. All trials were located in Kern County, California, in fields with <10 g kg⁻¹ organic matter. In each field 3 × 8 m plots received N fertilizer application in addition to that applied by the cooperating grower. Yield of roots and leaves, plant N status, and root cracking sensitivity of these plots were compared to matching plots receiving only the growers’ N application. The experimental design was a randomized block. The additional N, in urea form, was broadcast in one or two applications made 4 to 8 weeks preharvest. Cultural details are given in Table 1. Plants were hand-harvested from four randomly selected 1.0 × 1.0 m sections per plot and the mass of leaves and roots determined. Roots were bagged in plastic, transported to UCD, and cooled overnight at 5 °C before testing. Samples of both leaves and roots were oven-dried, ground, and analyzed for N concentration by the combustion method.

Effect of water status. To determine whether irrigation management over the final month of the season (the period during which the majority of root biomass developed) affected root cracking susceptibility, soil moisture tension was monitored in the grower N treatment of...
Pressure chamber analysis. An additional set of the bagged leaves were removed from the transported in plastic bags to UCD, and cooled long. Roots were hand harvested on 3 Dec., cultivar plots were one 1 m bed wide by 12 m main plot, cultivar the split plot. Individual the experimental design was a split plot within aluminized plastic bags to prevent transpira-

harvest individual leaves were enclosed in investigated by harvesting roots in the early

cracking and breakage of 10 commercial carrot cultivars was compared in a commercial field trial conducted near Bakersfield, Calif., in 2002. The cultivars selected had all been evaluated by the California industry and were considered to have suitable characteristics for the cut-and-peel market. The trial was planted 8 Aug. in a field of Wasco sandy loam (coarse-loamy, mixed, nonacid Thermic Typic Torriorthents, site 5, Table 1). To determine the effect of N fertility, cultivar response to two levels of N fertilization was compared. The N regimes were the grower’s N application (a seasonal total of 109 kg·ha⁻¹ N) and the grower program plus two applications of urea at 67 kg·ha⁻¹ N each, applied 17 Sept. and 24 Oct. The experimental design was a split plot within a randomized complete block, N rate was the main plot, cultivar the split plot. Individual cultivar plots were one 1 m bed wide by 12 m long. Roots were hand harvested on 3 Dec., transported in plastic bags to UCD, and cooled overnight at 5 °C.

Cracking and breakage evaluation. To minimize the effects of carrot size (Cantwell et al., 1991; Hole et al., 1999) and temperature (Cantwell et al., 1991; Kokkoras, 1995) all measurements of susceptibility to cracking and breakage were conducted on roots with a crown diameter of 18-24 mm that had been cooled to 5 °C. An impact test was used to determine root cracking susceptibility. Undamaged roots (no cracks or breaks) from the survey fields, N tri-

als, and time of day comparisons were dropped from a height of 0.75 m onto an aluminum plate angled 30° from the horizontal. Roots from the cultivar evaluation were dropped from 1.0 m height to ensure some degree of cracking in all cultivars. The roots were dropped through a tube to ensure that the crown consistently struck the plate at the same angle (Cantwell et al., 1991). The percentage of roots cracked by the impact was recorded. Additionally, a cracking index was calculated to quantify the severity of the cracks developed. The index was calculated by the formula:

\[
\text{cracking index} = \frac{\text{no. roots with cracks} \times 5 \text{ cm} + 2}{\text{no. roots tested}} \times 100
\]

In cut-and-peel processing carrots are cut into about 5 cm segments, so cracks >5 cm would affect multiple segments. The cracking index, by weighting large cracks, provided a more accurate measure of economic loss than the percentage of cracked roots. Sixty roots per survey field were tested. For the N rate trials 30 roots per N treatment per block were tested, and 30 roots per cultivar per N treatment per block were tested in the cultivar evaluation. Cores of phloem parenchyma were excised from nine roots per field (survey fields) or three roots per treatment per block (N trials and cultivar evaluation) and frozen with liquid nitrogen. After thawing at room temperature these cores were crushed and the osmotic potential of the expressed sap measured by a vapor pressure osmometer (model 5100; Wescor Inc., Logan, Utah). Root turgor potential was calculated as water potential minus osmotic potential.

For the cultivar evaluation and the N trials conducted in 2002, the force required to cause transverse breakage of roots, and the deforma-

tion distance before breakage, was determined using a texture analyzer (model TA-XT2i; Texture Technologies Corp., Scarsdale, N.Y.). Carrots were placed on two support posts 65 mm apart. A blunt wedge was driven into the suspended root at a constant speed of 5 mm·s⁻¹ until breakage, with resistance force and de-

formation distance continuously recorded. Ten roots per N rate or cultivar per block were tested. From these data tensile stress at the point of failure (a measure of tissue strength) and modulus of elasticity (a measure of tissue stiffness) were calculated by the following formulae (adapted from Mohsenin, 1986):

\[
\text{Tensile stress} = \frac{(F \times L)}{\pi r^2} \times 2
\]

and

\[
\text{modulus of elasticity} = \frac{(F \times L)\times (48 D \times \pi r^4)}{4}
\]

where \(F\) = force (N) at failure, \(L\) = length (mm) between support posts, \(D\) = deformation (mm) before failure, \(r\) = radius (mm) of the carrot at the point of failure.

To document the influence of the periderm on cracking and breakage, roots from the 2002 N trials and the cultivar evaluation were peeled and subjected to both the impact and breakage tests. Fifteen roots per N treatment or cultivar per block were evaluated on the impact test. Only roots from the grower N plots were evaluated on the breakage test. Ten roots per subplot were tested.

Results

Across locations, N application in excess of that applied by the growers increased leaf biomass but did not increase root yield (Table 2). Excess N fertilization increased the root cracking percentage from 39% to 50%, and cracking index from 0.50 to 0.69. Cracking percentage of roots receiving the growers’ N regime varied among sites from 30% to 56%. Root strength and stiffness were unaffected by N treatment. Periderm removal by peeling had profound effects. Cracking was dramati-

cracking percentage from 39% to 50%, and

and modulus of elasticity (a measure of tissue

and cracking susceptibility. Periderm removal

between cultivars from 35% to 46%, and crack

index from 0.44 to 0.61 (data not shown); there was no N × cultivar interaction. At all trial locations the grower N application rate was conservative (59 to 137 kg·ha⁻¹ N, Table 1). Fertilization records obtained for 10 of the survey fields showed that mean seasonal N rate exceeded 190 kg·ha⁻¹, suggesting that the additional N treatment in the N trials represented seasonal N rates similar to that used in many commercial fields.

Cultivars varied in cracking susceptibility, ranging from 14% to 53% of roots cracked in the impact test (Table 3); the crack index ranged from 0.15 to 0.76. Cultivars also varied in root strength and stiffness, but there was no correlation between either of those measures and cracking susceptibility. Periderm removal virtually eliminated cracking. Peeled roots had both increased tissue strength, and increased flexibility. Across cultivars, there was no correlation between tissue strength or stiffness of intact roots and that of peeled roots.

Irrigation management over the final 30 d before harvest varied widely among the fields monitored, but had no consistent effect on

Table 1. Soil type, harvest date, and fertilizer rate of N field trials.

| Site       | Soil                     | Soil classification                  | Soil pH | Harvest date | Seasonal N rate (kg·ha⁻¹) |
|------------|--------------------------|--------------------------------------|---------|--------------|---------------------------|
| 1          | Cerini sandy loam        | Fine-loamy, mixed (calcareous), thermic Typic Torriorthents | 7.3     | 20 June 2000 | 123 235                   |
| 2          | Cerini sandy loam        | Fine-loamy, mixed (calcareous), thermic Typic Torriorthents | 7.4     | 20 June 2000 | 137 249                   |
| 3          | Milham sandy loam        | Fine-loamy, mixed, thermic Typic Haplargids | 7.1     | 12 June 2002 | 69 159                    |
| 4          | Panche loam              | Fine-loamy, mixed (calcareous), thermic Typic Torriorthents | 7.0     | 19 June 2002 | 59 149                    |
| 5          | Wasco sandy loam         | Coarse-loamy, mixed, nonacid, thermic Typic Torriorthents | 6.5     | 3 Dec. 2002   | 109 243                   |

a4 to 8 Mg·ha⁻¹ composted dairy manure also applied in these fields.

bCultivar trial site.
Table 2. Effect of N fertility on carrot yield, root cracking susceptibility, and resistance to breakage.

| Year | Site | N treatment     | Leaves | Roots | Intact | Peeled | Intact | Peeled | Intact | Peeled | Intact | Peeled | Fresh wt (Mg·ha⁻¹) | Percent cracked | Crack index | Tensile stress at failure (N·mm⁻²) | Modulus of elasticity (N·mm⁻²) |
|------|------|-----------------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|-----------------|----------------|------------|---------------------------------|----------------------|
| 2000 | 1    | Grower N        | 14.6   | 61.0  | 33     | 33     | 0.48   |        |        |        |        |        | 3 + (58 × MPa turgor)          |                | 4.01       | 3.75                         | 4.59                 |
|      | 2    | Additional N    | 15.4   | 58.2  | 42     | 42     | 0.72   |        |        |        |        |        | 3 + (58 × MPa turgor)          |                | 4.11       | 3.75                         | 4.59                 |
| 2002 | 3    | Grower N        | 10.4   | 40.7  | 30     | 30     | 0.37   | 0.07   | 3.07   | 3.75   | 4.59   | 3.01   | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |
|      | 4    | Additional N    | 8.7    | 49.3  | 37     | 37     | 0.40   |        |        |        |        |        | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |
| 2002 | 5    | Grower N        | 8.4    | 39.8  | 56     | 56     | 0.81   | 0.09   | 3.14   | 4.06   | 4.59   | 3.01   | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |
|      |      | Additional N    | 8.4    | 37.0  | 74     | 74     | 1.09   | 0.00   | 2.99   |        |        |        | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |
| Mean |      | Grower N        | 8.0    | 34.5  | 39     | 39     | 0.44   | 0.02   | 3.84   | 5.22   | 5.38   | 4.42   | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |
|      |      | Additional N    | 9.7    | 33.5  | 61     | 61     | 0.72   | 0.02   | 3.84   |        |        |        | 3 + (58 × MPa turgor)          |                | 4.11       | 4.41                         | 3.61                 |

*Peeled roots differed from intact roots across sites at p < 0.01. NS, **Nonsignificant or significant differences for grower N and additional N treatments across sites at p < 0.05 or 0.01, respectively.

Discussion

Prior research on carrot cracking and breakage focused on water relations (Golacki, 1993; Hole et al., 1999; McGarry, 1993, 1995; Sorensen, 1997) and structural characteristics of the phloem parenchyma (Hole et al., 1999; McGarry, 1995; Sorensen and Harker, 2000). Results of this study suggested that those may not be the predominate factors governing the degree of root damage observed in commercial fields during harvesting and handling. We found a 10-fold difference in root cracking susceptibility among commercial fields of the same cultivar, with only a minor portion of that variability attributable to root water status. McGarry (1993, 1995) reported that both water potential and turgor potential were negatively correlated with failure force of phloem parenchyma. Similarly, Golacki (1993) found that carrot resistance to impact loading decreased with increased moisture content (increasing water potential). However, in these studies carrots were apparently obtained from a single field source, so there were no confounding effects of production environment. In a series of experiments Hole et al. (1999) found no consistent relationship between root cracking susceptibility and water status, either within or between cultivars. Clearly, the stress induced within carrot roots by turgor potential influences root splitting (as demonstrated by the overall increase in cracking after hydration of roots from the survey fields, and the marginal decrease in cracking susceptibility observed in roots harvested at mid-day compared to early morning), but root water status explained only a minor portion of the field-to-field variability we observed.

Similarly, the strength and stiffness of phloem parenchyma tissue does not appear to be a major factor controlling susceptibility to damage during harvesting and handling. Comparing cultivars which ranged from 4% to 73% cracking incidence on an impact test, Hole et al. (1999) found that parenchymatensile strength, fracture toughness, and residual strain were unrelated to cracking incidence. We found differences among cultivars in susceptibility to cracking and breakage, but the lack of correlation between cracking incidence and root strength and stiffness, and the profound effect of periderm removal on all of these parameters, call into question the importance of parenchyma tissue strength. Indeed, the characteris-
Table 3. Effect of cultivar and periderm removal on root cracking susceptibility and resistance to breakage.

| Cultivar       | Year | Intact Cracked | Crack Index | Tensile Stress at Failure (N·mm⁻²) | Modulus of Elasticity (N·mm⁻²) |
|----------------|------|----------------|-------------|-----------------------------------|-------------------------------|
|                |      | Intact Peeled  |             | Intact Peeled                      | Intact Peeled                 |
| Prime Cut      | 53 a | 1              | 0.74 a      | 3.72 d                            | 5.41 abc                      |
| More Cuts      | 51 a | 1              | 0.76 a      | 5.05 a                            | 5.58 abc                      |
| Sugar Snax     | 50 a | 1              | 0.58 ab     | 3.84 cd                           | 5.22 bc                       |
| Top Cut        | 44 a | 0              | 0.55 ab     | 4.19 bcd                          | 6.05 a                        |
| Columbia       | 43 a | 0              | 0.65 ab     | 4.25 bc                           | 5.3 c                         |
| Caropak        | 42 a | 0              | 0.51 ab     | 4.10 bcd                          | 5.84 ab                       |
| Sweet Bites    | 36 a | 0              | 0.46 b      | 4.07 bcd                          | 5.40 ab                       |
| HM-02          | 35 a | 2              | 0.41 b      | 4.03 bcd                          | 5.27 bc                       |
| Tasty Peel     | 35 a | 1              | 0.44 b      | 4.14 bcd                          | 5.58 ab                       |
| Trinity        | 14 b | 1              | 0.15 c      | 4.36 b                            | 5.34 bc                       |
| Mean           | 40   | 1**            | 0.53        | 4.17                              | 5.48**                       |

<sup>a</sup>Mean of N treatments.

<sup>b</sup>Only grower N treatment tested.

<sup>c</sup>Significant differences for peeled roots vs. intact roots across cultivars at p < 0.01.

Table 4. Correlation of root cracking susceptibility and environmental variables; data from 31 fields.

| Parameter            | Range | Correlation (r) with % cracking<sup>a</sup> | Intact Cracked | Tensile Stress at Failure (N·mm⁻²) | Modulus of Elasticity (N·mm⁻²) |
|----------------------|-------|---------------------------------------------|----------------|-----------------------------------|-------------------------------|
| Mean air temp final 30 d (°C) | 27-7 | 0.36                                        |                |                                   |                               |
| Exchangeable Ca (cmol·kg⁻¹)      | 2.3-30.8 | 0.44                                       |                |                                   |                               |
| Exchangeable Mg (cmol·kg⁻¹)      | 0.2-8.3 | 0.52                                       |                |                                   |                               |
| Percent sand          | 23-91 | −0.48                                      |                |                                   |                               |
| Percent silt          | 5-53  | 0.45                                        |                |                                   |                               |
| Percent clay         | 4-24  | 0.47                                        |                |                                   |                               |

<sup>a</sup>All correlations significant at p < 0.05.

In summary, carrot root cracking susceptibility is a large extent governed by periderm strength, which in turn is affected by genetic and environmental factors. Practical methods of minimizing root cracking include cultivar selection, N fertility management and, perhaps, field selection based on soil texture.

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