The influence of crop-load, delayed cooling and storage atmosphere on post-storage quality of ‘Honeycrisp’™ apples

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SUMMARY
The influence of crop-load, delayed cooling and storage environment on fruit quality and disorder, and on the incidence of rot was investigated on 7 year-old ‘Honeycrisp’ apple (Malus domestica Borkh.) trees on ‘Malling 26’ rootstocks at three different sites during 2003 and 2004. Fruit from non-thinned (control) trees, or trees thinned to three, six or nine fruit cm⁻² trunk cross-sectional area (TCSA) as possible, by subjecting newly-harvested fruit to a 7 d pre-storage warming period of 20°C, followed by CA storage at 2.5 kPa O₂, 1 – 1.5 kPa CO₂ at 3°C.

Since its release from the University of Minnesota in 1991 (Bedford, 2001), the apple (Malus domestica Borkh.) cultivar ‘Honeycrisp’ has become popular in the fresh markets of the north-eastern and mid-western USA and in eastern Canada. Its unique texture, flavour, crispness and long storage-life command premium prices for growers and may help revitalise the apple industry in those areas where this cultivar thrives. ‘Honeycrisp’ fruit have a tendency, however, to develop soft scald, as well as several other quality-related problems [e.g., bitter pit, watercore, low temperature breakdown (LTB), skin punctures and decay], which vary in severity with the particular growing region. If not checked, these problems threaten the long-term adoption of this potentially profitable cultivar (Evans, 2001; Greene and Weis, 2001; Schwallier, 2001; DeLong et al., 2004).

‘Honeycrisp’ trees produce heavy crop-loads and have a marked tendency towards biennial bearing in Nova Scotia and the northeastern USA (Embree and Nichols, 2005; Crassweller et al., 2005; Robinson and Watkins, 2003). Thus, proper crop-load management becomes critical for this cultivar to reduce cycles of alternate-year bearing, and for consistent annual production of high-value marketable fruit. Although in New York State, the optimal crop-load range for ‘Honeycrisp’ is four-to-five fruit cm⁻² trunk cross-sectional area (TCSA; Robinson and Watkins, 2003), it is not known if this crop-load can be applied in Nova Scotia to produce fruit of the highest market quality.

In Nova Scotia, soft scald (Figure 1) is the most frequently observed ‘Honeycrisp’ storage disorder, followed by LTB which is also known as “soggy breakdown” or “internal breakdown” (Figure 2). It is not uncommon to observe ≥ 30% incidence of these disorders after 3 – 6 months of storage (Prange et al., 2003; DeLong et al., 2004). Both of these conditions are exacerbated by low storage temperatures (i.e., < 2.5°C) (Watkins et al., 2004) or in fruit that are rapidly cooled after harvest (DeLong et al., 2004). Therefore, present ‘Honeycrisp’ storage protocols usually recommend a storage temperature of 3°C (Schwallier, 2001; Nichols et al., 2004; Watkins et al., 2004). In addition, several recent reports indicate that a short, delayed cooling (or warming) period of 10°C to 20°C for 7 d prior to controlled atmosphere (CA) or refrigerated air (RA) storage reduces the incidence of soft scald and LTB (Watkins and Nock, 2003; DeLong et al., 2004; Watkins et al., 2004). As ‘Honeycrisp’ apples are also prone to developing a high incidence of rot during storage (Greene and Weiss, 2001; DeLong et al., 2004), it is important to ascertain if a delayed cooling (DC) period...
prior to CA storage exacerbates the occurrence of rot. Moreover, it is not known if crop-load influences the effectiveness of DC on the expression of these disorders and the development of rotted fruit.

The objective of this study, therefore, was to examine the influence of crop-load and DC on fruit quality, disorder expression and the incidence of rot in 'Honeycrisp' apples following CA and RA storage.

MATERIALS AND METHODS

Orchard sites and thinning

Three separate 'Honeycrisp' grower sites were selected in 2003 and 2004 in the Annapolis Valley, Nova Scotia, Canada (45°03'00" N; 64°46'00" W). All trees were planted in 1996 on 'Malling 26' rootstocks and, at the time of establishment, were 1 year-old, feathered and had a minimum stem diameter of 1.6 cm. In May 2003

An example of soft scald on non-DC 'Honeycrisp' fruit following at least 3 months of RA storage. Symptoms are readily visible on the epidermis.

An example of low temperature breakdown (LTB) in the cortical tissue of a non-DC 'Honeycrisp' apple following at least 3 months of RA storage. Symptoms are visible only when the fruit are cut open.
and 2004, 16 trees per site were selected based on similar blossom cluster densities per TCSA. The latter was measured 30 cm above the graft union. Four crop-load treatments consisting of an untreated control and three, six or nine fruit cm\(^{-2}\) TCSA were then assigned at random to four trees per site. Blossom and fruitlet number counts were made on all trees at the three sites at three different stages of blossom or fruitlet development in 2003 and 2004: 1 week prior to full bloom (blossom density measurement), 20–25 days-after-full-bloom (DAFB), and 50 DAFB (coincident with the natural July drop). To achieve crop-load levels of three, six or nine fruits cm\(^{-2}\) TCSA, hand-thinning within fruit clusters was carried out immediately following natural fruitlet abscission at 50 DAFB.

**Harvest, delayed cooling and storage**

Fruits were harvested during the first week in October, in both years (125 DAFB), which coincided with the timing of commercial harvest. Sub-samples of 15 apples were then selected from each treatment tree at each site for storage evaluation. Half of the fruit were immediately cooled over 24 h to 3°C (Comm) and were then stored at 3°C in either RA or CA (2.5 kPa O\(_2\), 1.0–1.5 kPa CO\(_2\)) regimes, while the remaining fruit were held at 20°C for 6 d, followed by 1 d at 3°C (DC) then stored at 3°C in RA or CA storage. All fruit were held for 3 or 6 months in the RA or CA environments. In both storage regimes, apples were placed in top-loading 0.34 m\(^3\) cabinets and those in CA chambers were flushed with nitrogen until O\(_2\) levels of 2.5 kPa were obtained. The CA chambers were monitored and controlled by a David Bishop Instrument Oxystat\(^{\text{TM}}\) 2002 system (Bacharach Europe, Warwickshire, UK).

**Measurements on stored fruit**

Following 3 and 6 months of storage, respectively, 15 fruit were removed from each treatment combination. Ten apples were measured immediately after warming to 20°C and five were held for a shelf-life period of 7 d at 20°C. Fruit firmness (N) was measured on the red and green sides of individual apples with a fruit quality tester (Geo-Met Instruments, New Minas, NS, Canada), having the time-limit window set at > 0.1 and < 1.0 s (DeLong et al., 2000). Soluble solids content (SSC) and titratable acidity (TA) were measured on each 10-apple composite juice sample with a hand-held refractometer (Atago Co., Tokyo, Japan) and by titration of 2 ml apple juice with 0.1 M NaOH, respectively. Titratable acidity was expressed as mg equivalents of malic acid 100 ml\(^{-1}\) juice (DeEll and Prange, 1998). The incidence of bitter pit, soft scald, LTB and rotted fruit were assessed as percentages of all fruit in the 10-apple sample after removal from storage and in the 5-apple sample following the 7 d shelf-life treatment. Epidermal "greasiness" was evaluated on a four-point scale of 0–3, where 0 (= none), 1 (= slight), 2 (= moderate) and 3 (= severe and unmarketable).

**Experimental design and statistics**

The storage experiment was planned as a randomised complete block design with factorial combinations of the three treatments: crop-load (control, three, six or nine fruit cm\(^{-2}\) TCSA); pre-storage conditioning (Comm or RA); and storage (DC, Comm). Experimental design and statistics are described in Table I. The data were analysed using the Fisher’s LSD test and means were compared within each crop-load level for separate CA or RA storage data, as determined by the LSD test. Absence of a letter(s) implies non-significance. Each mean represents 24 measurements.

![Table I](image-url)

<table>
<thead>
<tr>
<th>Crop-load (fruit cm(^{-2}) TCSA)</th>
<th>Storage</th>
<th>Mass</th>
<th>Firmness</th>
<th>Colour</th>
<th>Soluble solids</th>
<th>Titratable acidity</th>
<th>Greasiness</th>
<th>Soft Scald</th>
<th>Breakdown</th>
<th>Rot</th>
<th>Incidence of Disorders</th>
<th>Incidence of Disorders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control CA</td>
<td>DC</td>
<td>105 D</td>
<td>70.5 A</td>
<td>73.6 A</td>
<td>69.6 C</td>
<td>0.12</td>
<td>1.11</td>
<td>2.22</td>
<td>4.18</td>
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<td>3 RA</td>
<td>DC</td>
<td>104 D</td>
<td>70.4 A</td>
<td>73.6 A</td>
<td>69.6 C</td>
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<tr>
<td>6 RA</td>
<td>DC</td>
<td>103 D</td>
<td>70.2 A</td>
<td>73.6 A</td>
<td>69.6 C</td>
<td>0.14</td>
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<td>2.22</td>
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<tr>
<td>9 RA</td>
<td>DC</td>
<td>102 D</td>
<td>70.0 A</td>
<td>73.6 A</td>
<td>69.6 C</td>
<td>0.14</td>
<td>1.11</td>
<td>2.22</td>
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DC); and storage regime (RA or CA), with each treatment combination being replicated six times [three growers year⁻¹ (= 3 experimental replicates year⁻¹) × 2 years]. All 3- and 6-month removal data were combined in the analyses. The two pre-storage conditioning treatments were compared at each level of crop-load and storage regime by the Fisher’s LSD test at the 10% level, while crop-load levels were compared within each pre-storage conditioning treatment by the Waller Duncan k-ratio t-test, where a k value of 50 approximates to the LSD 10% level. All statistical tests were performed using the SAS PROC GLM procedure (SAS Institute, 1994). Unless stated otherwise, only results significant at the 10% level are discussed.

RESULTS AND DISCUSSION

Crop-load

The post-storage data indicated that crop-load significantly affected fruit quality. As the number of fruit cm⁻² TCSA increased, fruit mass, firmness, colour, SSC and TA decreased regardless of the storage environment (CA or RA), or the pre-storage treatment (DC or Comm) (Table I). Fruit “greasiness”, however, was not consistently altered by either crop-load or pre-storage treatment. In general, the highest and lowest values of fruit mass, firmness, colour, SSC and TA occurred at the three fruit cm⁻² TCSA and control levels, respectively. These findings are similar to data presented by Robinson and Watkins (2003) from a ‘Honeycrisp’ trial in New York State, from which they concluded that optimal post-harvest fruit quality occurred at four-to-five fruit cm⁻² TCSA, a crop-load window slightly higher than the optimum of three fruit cm⁻² TCSA observed in this study. Marketplace quality criteria for ‘Honeycrisp’ apples include highly coloured, large fruit ranging from 200–250 g (Nichols et al., 2004; Robinson and Watkins, 2003) which were best met in this study at the three fruit cm⁻² TCSA level (Table I; Figure 3). Although total tree yield is compromised at this degree of thinning, growers will sacrifice gross yield in order to meet consumer demand for the lucrative niche that ‘Honeycrisp’ occupies in the fresh fruit market.

In contrast to its marked effect on fruit mass, firmness, colour, SSC and TA, crop-load had little consistent influence on the incidence of soft scald, LTB and rot, although some differences were noted (Table I). In general, the best control of soft scald occurred when trees were thinned to three fruit cm⁻² TCSA. Although CA-stored, DC fruit at the three fruit cm⁻² TCSA level showed more soft scald than at other crop-load levels, the low incidence (< 1%) of this disorder is not commercially important. Robinson and Watkins (2003) found that soft scald expression in ‘Honeycrisp’ apples was not related to crop-load, while “soggy breakdown” (same as LTB) was greater at higher crop-loads. In the present study, regression analysis indicated that soft scald was not related, while LTB was negatively-related, to crop-load for CA-stored Comm fruit only (data not shown). While crop-load appeared to have at least a marginal effect on the incidence of storage disorders, other largely unknown environmental and cellular factors must exert a stronger influence towards predisposing this cultivar to the development of internal disorders. The identification of those compounds that are either up-regulated or metabolically concentrated in the cortex and epidermal regions of susceptible ‘Honeycrisp’ fruit would be a useful first step towards understanding the biochemical connection between the presence of the precursor(s) and manifestation of these disorders.

In addition, crop-load had no effect on the incidence of rot in CA apples, while its influence on rot in RA fruit was inconsistent. Interestingly, the smaller RA control fruit tended to develop less rot than those from the three (DC) or nine (Comm) fruit cm⁻² TCSA trees (Table I). A possible explanation is that the smaller, control apples (Figure 3) were less likely to stem puncture neighbouring fruit during harvest and handling, resulting in fewer entry points for rot-inducing pathogens such as Penicillium expansum (Rosenberger, 2003). ‘Honeycrisp’ is known to have tender skin and stiff stems, that make it particularly susceptible to stem-puncturing. As decay during storage is a major concern for this cultivar, harvest recommendations currently include careful

![Sample of 24 ‘Honeycrisp’ apples from each level of thinning treatment (control, three, six or nine fruit cm⁻² TCSA), graded immediately following harvest and prior to storage. Average fruit masses for the control, 9, 6 and 3 cm⁻² TCSA treatments were 99, 129, 168 and 214 g, respectively.](image-url)
Delayed cooling

In contrast to the effects of crop-load, the 7 d pre-storage DC treatment had little influence on fruit quality measurements, although it did reduce acidity in CA-stored apples thinned to six fruit cm\(^{-2}\) TCSA as well as in the non-thinned controls (Table I). The DC-related reductions in firmness and colour for CA-stored fruit from the control and nine fruit cm\(^{-2}\) TCSA trees, respectively, were small and not physiologically meaningful. Watkins et al. (2004) and Watkins and Nock (2003) also found that a 7 d-warming period prior to cold storage had little influence on post-storage firmness, SSC and TA levels in ‘Honeycrisp’ fruit. Although DC-treated, CA-stored fruit were more greasy than Comm apples at the nine fruit cm\(^{-2}\) TCSA as well as in the non-thinned controls (Table I). The DC-related reductions in firmness and colour for CA-stored fruit from the control and nine fruit cm\(^{-2}\) TCSA trees, respectively, were small and not physiologically meaningful. Watkins et al. (2004) and Watkins and Nock (2003) also found that a 7 d-warming period prior to cold storage had little influence on post-storage firmness, SSC and TA levels in ‘Honeycrisp’ fruit. Although DC-treated, CA-stored fruit were more greasy than Comm apples at the nine fruit cm\(^{-2}\) TCSA level (Table I), the difference was not commercially significant.

The occurrence of soft scald, however, was markedly influenced by the 7 d pre-storage DC treatment, as shown by the DC-induced reduction in this disorder at each crop-load level in both CA- and RA-stored fruit (except for RA fruit from the three fruit cm\(^{-2}\) TCSA trees; Table I). DC-treatment also reduced the incidence of LTB at the three and six fruit cm\(^{-2}\) TCSA crop-loads for CA-stored ‘Honeycrisp’. DeLong et al. (2004), Watkins et al. (2004) and Watkins and Nock (2003) observed similar reductions in soft scald when ‘Honeycrisp’ fruit were subjected to a 7 d pre-storage warming period of 10°C or 20°C before storage. In the present study, the best control of soft scald occurred in DC-treated fruit that were CA-stored. Although the appearance of LTB in DC-treated fruit was low in both the CA and RA environments, its incidence was generally less severe than soft scald in the Comm fruit. Thus, the DC-related amelioration of LTB appeared to be less pronounced (Table I). At present, it is not known precisely how a pre-storage warming period reduces or eliminates the development of soft scald and LTB. DeLong et al. (2004) suggested that the 1.18 – 1.28% water-loss observed in ‘Honeycrisp’ fruit during a 7 d, 20°C pre-storage warming period may act as an evaporative carrier dissipating volatile compounds that have been associated with LTB [e.g., acetate esters (Wills, 1968)]. Watkins et al. (1995; 2000) stated that fruit-warming reduced the accumulation of toxic substances that occur at lower temperatures and increased the levels of unsaturated fatty acids and endogenous antioxidant compounds. The link between these observations and the specific biochemistry of soft scald and LTB remains to be established.

An early criticism of using a pre-storage DC (i.e., warming) period was that decay-inducing pathogens would start to proliferate prior to storage, resulting in a higher incidence of rot as the apples were eventually removed from the storage environment. However, compared with the Comm treatment, the incidence of rot did not increase in DC-treated fruit in this study, nor in the work reported by Wargo and Watkins (2004) and DeLong et al. (2004). In conventional storage practice, bins of fruit are cooled as quickly as possible to remove field heat and to rapidly establish the storage regime. In so doing, condensation on the skin surface is hard to avoid as warm, rapidly respiring, fruit enter a cold (e.g., 0°C – 3°C) holding room. It may be that the evaporative loss of water from fruit during the DC period (DeLong et al., 2004) actually provides some protection against the establishment of the pathogen due to the removal of free surface water. Thus, a pre-storage DC period of 7 d at 20°C before cooling did not appear to exacerbate the incidence of storage rot in ‘Honeycrisp’ apples (Table I).

Storage environment

Although the storage environment did not consistently alter fruit quality or the occurrence of disorders or rot, ‘Honeycrisp’ apples in CA-storage tended to be slightly more firm, more acidic, less greasy and develop less soft scald, regardless of the effects of the DC treatment (Table I). This may be attributed to a generalised lowering of senescence-related metabolism facilitated by the 2.5 kPa O\(_2\) CA environment, in contrast to the ambient 21 kPa O\(_2\) RA storage regime (Kader 1986; DeLong and Prange, 2003). Interestingly, the incidence of LTB was higher in CA-stored apples that received the Comm treatment compared to the corresponding fruit stored in RA (Table I), which was also observed by DeLong et al. (2004). It may be that the precursors (e.g., volatile compounds) required to develop LTB were metabolised more readily into non-toxic by-products in the RA environment with ambient O\(_2\) partial pressure, compared to fruit stored under low O\(_2\) CA conditions (e.g., 2.5 kPa CA would slow metabolism).

In conclusion, data from this study show that both crop-load and DC profoundly influence the overall quality of ‘Honeycrisp’ apples following long-term storage. Controlled atmosphere or RA storage environments, while having some effect, exert less influence on the post-storage condition of ‘Honeycrisp’ apples. The practical implications for growers and storage operators arising from this work are to thin ‘Honeycrisp’ trees as close to three fruit cm\(^{-2}\)TCSA as possible, subject the fruit to a 7 d pre-storage warming period of 20°C immediately after harvest, followed by CA storage (2.5 kPa O\(_2\); 1.0 – 1.5 kPa CO\(_2\)) at 3°C. This thinning, pre-storage and storage regime facilitates the production of large, highly-coloured fruit with minimal internal disorders, which will maximise economic returns and help secure the profitable ‘Honeycrisp’ niche market.

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Post-storage ‘Honeycrisp’ fruit quality


