Determination of the optimal pre-storage delayed cooling regime to control disorders and maintain quality in ‘Honeycrisp’™ apples

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SUMMARY

Several pre-storage time (0, 1, 2, 4, and 6 d) and temperature (3.5º, 10º, 15º, 20º, 25º, and 30ºC) delayed cooling (DC) treatments were tested on harvested ‘Honeycrisp’™ apples to determine which combination was optimal for reducing soft scald and low temperature breakdown (LTB), while maintaining the highest fruit quality [i.e., firmness, minimal mass loss, titratable acidity (TA), soluble solids content (SSC), absence of rot, and minimal skin greasiness] after 4 months of refrigerated air (RA) storage. Fruit were harvested from three separate Annapolis Valley (Nova Scotia) orchard sites in 2006 and in 2007. Multiple linear regression and surface response curves showed that fruit firmness and SSC generally increased throughout the DC treatment, but were affected curvilinearly by temperature, reaching a maximum at approx. 15ºC, then declining. Loss of fruit mass was positively related to a (day × temperature2) interaction, indicating that it increased synergistically the longer and the warmer the DC treatment. Fruit acidity was affected only by temperature, with the highest TA values at approx. 15ºC, then declining at higher DC temperatures. Multiple logistic regression and surface responses demonstrated that the incidence of soft scald declined curvilinearly the longer and the warmer the DC treatment, while LTB declined curvilinearly with increasing DC temperature only. A positive (day × temperature2) interaction indicated that fruit greasiness increased non-linearly as the duration and temperature of DC increased. Collectively, these results show that both soft scald and LTB were suppressed or eliminated by a DC regime of 25ºC for 1 – 2 d, or 30ºC for 1 d, without incurring a major reduction in fruit quality.

The apple (Malus × domestica Borkh.) cultivar ‘Honeycrisp’™ has become popular in the fresh markets of North America. Its unique texture, flavour, crispness, and long storage-life command premium prices for growers, which is helping to revitalise the apple industry in those areas where it is grown. However, ‘Honeycrisp’™ fruit can develop soft scald, as well as several other quality-related storage problems [e.g., bitter pit, watercore, low temperature breakdown (LTB), skin punctures, and decay], which vary in severity in each growing region. These problems threaten the commercial viability of this profitable cultivar (Evans, 2001; Greene and Weis, 2001; Schwallier, 2001; DeLong et al., 2004).

In Nova Scotia, soft scald is the most frequently observed storage disorder of ‘Honeycrisp’™, followed by LTB, which is also known as soggy or internal breakdown (DeLong et al., 2004; 2006). It is not unusual to observe a ≥ 30% incidence of these disorders after several months of storage (Prange et al., 2003; DeLong et al., 2004). Both of these disorders are exacerbated by low storage temperatures (i.e., < 2.5ºC; Watkins et al., 2004) or by rapid cooling of fruit after harvest (DeLong et al., 2004). Therefore, current ‘Honeycrisp’™ storage protocols usually recommend a storage temperature of 3ºC or 3.5ºC (Schwallier, 2001; Nichols et al., 2004; Watkins et al., 2004). In addition, several recent reports indicate that a delay of 7 d at 10º – 20ºC 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; 2006; Watkins et al., 2004). Despite adoption of these delayed cooling (DC) regimes, some fruit still develop these disorders (DeLong and Prange, unpublished data). Therefore, there is a need to determine the optimal pre-storage DC combination of temperature and time that minimises the development of soft scald and LTB, without compromising other fruit quality characteristics. For ‘Honeycrisp’™, the most important quality attributes after storage are firmness, titratable acidity (TA), sugar content [i.e. soluble solids content (SSC)], and the extent of greasy and rotted fruit (Greene and Weis, 2001; DeLong et al., 2004).

The objective of this study was, therefore, to ascertain the pre-storage DC time and temperature combination that conferred the highest post-harvest quality in ‘Honeycrisp’™ apple fruit.

MATERIALS AND METHODS

Orchard sites and tree selection

Three separate ‘Honeycrisp’™ grower sites were selected in 2006, and in 2007, in the Annapolis Valley, Nova Scotia, Canada (45º03’00N, 64º46’00W). The orchard systems were established in 1996 and 2000 on Malling 26 and 7a rootstocks, respectively. One year-old
feathered trees were planted at a density of 1,000 – 1,500 trees ha⁻¹ and were trained as “spindle bush” or “vertical axis” forms.

Harvest, delayed cooling, and storage

Fruit were harvested on 25 September 2006, and on 24 September and on 2 and 3 October 2007, which coincided with the timing of commercial harvest. Apples from each site were then combined at random, prior to treatment application, in order to minimise the potential influence of trees on the variables measured. In each year, ten 30-apple samples (including the untreated control) of ‘Honeycrisp™’ fruit were placed in one of several time × temperature DC regimes within 6 h of harvest. The DC treatments consisted of 10º, 15º, or 20ºC for 2, 4, or 6 d (2006) and 20º, 25º, or 30ºC for 1, 2, or 4 d (2007). The untreated control for both years was immediate cold storage at 3.5ºC (no DC). Immediately following the various DC treatments, the loss of fruit mass was calculated, then all fruit were stored in RA at 3.5ºC for 4 months.

Measurements on stored fruit

After 4 months of RA storage, 30 fruit were removed from each DC treatment and warmed to 23ºC. Fruit firmness (N) was measured on the red and green sides of individual apples using a fruit quality tester (Geo-Met Instruments, New Minas, NS, Canada), having the time-limit window set at > 0.1 s and < 1.0 s (DeLong et al., 2000). The mass (g) of each fruit was measured on a digital balance (Sartorius, Göttingen, Germany). Soluble solids content (%) and TA were measured on each composite 30-apple 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 mass loss, SSC, and TA were measured on each continuous, dependent variable (Y; i.e., firmness, mass loss, SSC, and TA) by multiple linear stepwise regression on the combined 2006 and 2007 data. The stepwise procedure identified the significant independent variables (P ≤ 0.10), while non-significant effects were not included in the final regression equations. In some cases, significant independent (X) variables were dropped from the final regression model if their partial R² (coefficient of determination) values contributed < 5% to the overall model R². Multiple logistic stepwise regression (SAS Institute, 2004) was performed on those variables with binomial (i.e., 0, 1) responses (e.g., LTB, soft scald, greasiness, rot) to identify significant main and interaction effects, as stated above. Surface responses demonstrating the influence of days and temperature (i.e., linear, quadratic, and their interactions) were plotted as three-dimensional graphs using SigmaPlot graphical software (SigmaPlot Ver. 11; Systat Software, San Jose, CA, USA). For graphical presentation, the binomial data were transformed to ln (i.e., natural log) to smooth and demonstrate treatment effects more clearly. All statistical analyses were performed using the linear regression (Proc Reg) and logistic regression (Proc Logistic) procedures of the SAS Institute (2004) software.

RESULTS AND DISCUSSION

Fruit quality variables having a continuous, normal distribution [i.e., firmness (Figure 1A), mass loss (Figure 1B), SSC (Figure 1C), and TA (Figure 1D)], were influenced linearly and/or curvilinearly by days, temperature, or their interactions. For firmness (Figure 1A), SSC (Figure 1C), and TA (Figure 1D), negative curvilinear temperature effects occurred, indicating that these quality variables increased, plateaued, then decreased as DC temperatures increased. The highest values for these measurements occurred at approx. 15ºC. Firmness (Figure 1A) and SSC (Figure 1B) were also positively related to the duration of the DC treatments. Fruit mass loss (Figure 1B) was positively related to a (day × temperature²) interaction (accounting for most of the variation in the model) indicating that a synergistic influence on mass loss occurred the longer and the warmer the DC treatment (Figure 1B).

Studies reporting the influence of DC (usually one temperature for one time duration) on ‘Honeycrisp™’ fruit quality do not generally show changes in firmness, SSC, or TA (DeLong et al., 2004; Watkins et al., 2004; Watkins and Nock, 2003). However, in one recent study, TA dropped by 5 – 9% in DC apples compared with the control (DeLong et al., 2006). In this study, ‘Honeycrisp™’ TA declined by 14% to 25% when the highest levels at 15ºC were compared with corresponding values at 25ºC or 30ºC (Figure 1D; Table I). Thus, higher pre-storage DC temperatures conferred a greater reduction in TA levels after 4 months of RA storage.

The fruit mass loss data (Figure 1B; Table I) demonstrated that the duration of elevated pre-storage temperature can have a substantial effect on weight loss in the stored product. The goal of the DC technique is to expose fruit to the time and temperature regime which best controls disorders and maintains the highest quality, with minimal loss of mass. A 1.45% mass loss (e.g., 4 d at 30ºC) potentially translates into thousands of dollars lost in fruit tonnage. In this study, soft scald and LTB were eliminated with minimal loss of fruit mass by a DC regime of 1 d at 30ºC (Table I).

For those disorders having binomial responses (i.e., 0, 1), logistic multiple regression analysis and surface responses demonstrated that the incidence of soft scald declined curvilinearly the longer and the warmer the DC treatment (Figure 1E), while LTB declined curvilinearly...
FIG. 1
Three-dimensional surface responses of temperature (ºC) (X1) and time (d) (X2) on Honeycrisp® apple following 4 months of refrigerated air storage. Panel A, firmness [firmness (N) = 71.57 + 0.75 (days) – 0.01 (temp)²]; Panel B, mass loss [mass loss (%) = –0.018 + 0.004 (days/ºtemp) + 0.0003 (days/ºtemp²)]; Panel C, soluble solids content [SSC (%)) = 12.35 + 0.11 (days) – 0.001 (temp)²]; Panel D, titratable acidity [TA (mg malic acid 100 ml⁻¹ juice) = 478.92 + 6.63 (temp) + 0.26 (temp)²]; Panel E, soft scald [soft scald = –1.15 + 0.133 (temp) – 0.009 (temp)² – 0.04 (days)²]; Panel F, low temperature breakdown [LTB = –2.82 + 0.20 (temp) – 0.01 (temp)²]; Panel G, greasiness [greasiness = –0.67 + 0.01 (days/ºtemp) + 0.0002 (days²/ºtemp²)]. Mass loss was measured after the DC treatment and prior to storage. Soft scald, LTB, and greasiness values (0, 1) were transformed by ln to smooth the surface responses (Panels E – G). The regression equations were calculated on non-transformed data.
only with increasing DC temperature (Figure 1F).

Interestingly, a positive (days × temperature) interaction influenced fruit greasiness (Figure 1G), indicating the presence of a synergistic curvilinear influence as the duration and temperature of the DC treatment increased. In general, fruit that manifested greasiness were largely in category 1 (‘slightly greasy’) and would be acceptable as fresh market apples. Interestingly, the DC treatment of 30ºC for 1 d or 2 d did not show an increased incidence of greasy fruit. At 30ºC for 4 d, however, nearly three-times more apples were greasy. Also, apples exposed to a DC regime of 20ºC for 6 d manifested greasiness on 50% of the fruit evaluated (Table I). Thus, the longer the duration of the DC exposure intervals (e.g., 30ºC for 1 d reduced the development of 'Honeycrisp' storage disorders, the optimal pre-storage time and temperature combination that eliminates soft scald and LTB was not discovered. Data from this study indicate that, for 'Honeycrisp' apples from Nova Scotia, 30ºC for 1 d can eliminate both soft scald and internal browning disorders. Surface response analyses (Figure 1E, F) also showed that these disorders were suppressed more strongly at higher rather than at lower DC temperatures and with shorter exposure intervals (e.g., 30ºC for 1 d reduced the disorders more than 15ºC for 6 d; Table I).

The cellular causes of soft scald and LTB are presently unknown. Local seasonal observations indicate that some fruit are pre-disposed to these disorders in the field, and express them during the first 2 to 3 months in storage, and thereafter (data not shown). The environmental and genetic factors that induce susceptibility and trigger the development of soft scald and LTB in tissues are also not known. How DC suppresses the development and expression of these disorders therefore remains elusive. It may be that the water loss associated with a period of DC acts as an evaporative carrier, dissipating volatile compounds which are associated with the disorder(s) (DeLong et al., 2004; Wills et al., 1968). Past work has shown that water loss from ‘McIntosh’ fruit is associated with a reduction in senescent breakdown and LTB (Blanpied, 1981), and a reduction in brown core (Lidster, 1990). In this study, the elimination of soft scald and LTB was associated with a loss in mass (presumably synonymous with water loss) of 0.4%, which was facilitated by a DC regime of 30ºC for 1 d (Table I). It is also known that fruit warming mitigates chilling-related browning disorders by reducing the concentration of toxic substances that can accumulate at lower temperatures (e.g., at 2º – 3ºC; Alwan and Watkins, 1999; Watkins et al. 1995). Thus, active respiratory processes occurring during the warming
period may catabolise the toxic substances that are required for disorder development.

Soft scald and LTB appear to be more problematic in ‘Honeycrisp’™ fruit the further East the growing region in North America. For example, New England and Nova Scotia generally have a higher incidence of the disorders than the Pacific northwest. Interestingly, western regions that delay-cool fruit to control soft scald and LTB, report success with lower temperatures of shorter duration (e.g., 1 – 2 d at 10°C) than those observed in this study and what has been observed in the past (DeLong et al., 2004; 2006; Watkins et al., 2004). It may be that, in cooler growing regions, the effect of environmental triggers on genetic expression predisposes fruit towards an accumulation of those metabolic precursors required for expression of the disorders. Or it may be that warmer temperatures simply facilitate degradation of the metabolic precursors that are fundamental for the disorder to appear during storage. Whatever the relationship between the growing environment and disorder development, it appears that regional differences have a large effect on the degree of incidence, and on whether soft scald and LTB are major post-harvest concerns in ‘Honeycrisp’™ fruit. Fortunately, pre-storage DC regimes appear to eliminate expression of these disorders.

CONCLUSIONS

This work shows that treating ‘Honeycrisp’™ apple fruit with a DC regime consisting of 25°C for 1 – 2 d, or 30°C for 1 d, strongly suppresses (or entirely eliminates) the occurrence of both soft scald and LTB, while causing the least loss of fruit mass. While the 25°C or 30°C treatments may cause some reduction in TA, the potential economic benefits of a period of DC far outweigh the reduction in acidity, or in any other fruit quality attribute measured in this study.

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