Effects of Preharvest Weather Conditions on Firmness of ‘McIntosh’ Apples at Harvest Time

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Abstract. Apple fruit firmness is one of the main attributes indicating fruit quality at harvest. It is affected by numerous factors during the entire growing season. The effects of weather conditions during apple development are often mentioned as a result of their impact on attributes linked to fruit firmness: fruit size, calcium concentration, water content, etc. In this study, the effects of weather conditions on ‘McIntosh’ apple (*Malus × domestica* Borkh. cv. McIntosh) firmness at harvest time were analyzed. Fruit were harvested at nine sites in Quebec and Ontario over 15 years (1996–2011). For each case, weather parameters were analyzed from full bloom until harvest, either in monthly subperiods from May until September or in terms of days from full bloom (DFB) until harvest. Regression results highlighted the negative effect of lower air temperature conditions from 31 to 60 DFB, higher air temperature conditions and precipitations from 61 to 90 DFB, and higher temperature conditions from 91 DFB until harvest on ‘McIntosh’ apple firmness level at harvest. Precipitation from 61 to 90 DFB alone explained 39% of ‘McIntosh’ apple firmness variation at harvest time. The prediction of apple firmness at harvest time could be helpful for producers to adjust their marketing and storage strategies according to apple quality level.

Firmness is the main attribute that gives an indication of fruit texture and it is often used by producers to evaluate harvest date (Trillot and Tillard, 2002). This quality index can be influenced by many preharvest factors such as season, orchard location, nutrition, and exposure to sunlight, which are independent of the fruit maturity level (DeEll et al., 2001). Apple cultivar, rootstock, thinning timing, and the use of compounds that alter partitioning of photosynthates have been shown to have an impact on the levels of firmness measured at harvest (Harker et al., 1997; Johnson, 1994). Fruit calcium concentration also seems to be involved in the maintenance of membrane integrity linked to firmness loss rate (Conway and Sams, 1987; Marmo et al., 1985).

Fruit size and maturity at harvest influence the storage behavior of apples, including their rate of firmness loss (Saure, 1996; Tromp, 1997). In fact, fruit size is highly related to cell size and number with larger fruit containing less but larger cells per unit of volume than smaller fruit (Blanpied et al., 1978). Knowledge of interactions between cell water relations and resulting turgor and tensile properties of cell walls could lead to a better understanding of physiological basis of cell strength, which is an indicator of apple firmness.

Many studies on the distinction between apple quality levels at harvest highlighted the important influence of weather conditions during fruit development (Calderón Zavala et al., 2004; Chapon and Westercamp, 1996; Smock, 1953). Depending on the development stage, weather conditions may have multiple effects on final firmness that has been reported to increase and reach desired levels earlier when the apples are exposed to higher temperatures during the first 6 weeks of fruit growth (Warrington et al., 1999). Higher air temperature conditions after fruit set, when the maturation process begins, has also been highlighted as a factor leading to decreased firmness levels at harvest (Calderón Zavala et al., 2004; Kondo and Takahashi, 1987; Tromp, 1997; Warrington et al., 1999). Low photosynthetic photon flux, characteristic of shading, has been negatively related to apple

firmness at harvest (Corelli Grappadelli, 2003). Water tends to condense when exposed to lower temperatures, reducing turgor pressure in apples and slowing the maturation process. Lower air temperature conditions at harvest would thereby influence fruit firmness by varying water status of apples and delaying harvest time (Johnston et al., 2002). A study on the effects of weather conditions on apples in Quebec (‘McIntosh’, ‘Cortland’, ‘Spartan’, and ‘Empire’) highlighted the negative effect of high relative humidity during the entire growing season and the positive effect of long periods without rain during the period of 46 d after fruit set until harvest on firmness at harvest time (G. Bourgeois, unpublished data).

The overall objective of this study was to explain the variations in ‘McIntosh’ firmness values at harvest over multiple years and sites in Quebec and Ontario, Canada. The purpose of this approach was first to highlight the periods of apple development sensitive to specific weather conditions in reducing firmness levels at harvest. Second, characterization of these preharvest weather conditions in specific parameters was done to determine their direct or indirect effects on apple firmness. For future studies, the results of these analyses could permit the development of a spatiotemporal forecasting model based on preharvest weather conditions. Predictions of texture levels, both at harvest and after removal from storage, could provide a helpful tool to apple producers in their marketing strategies.

Materials and Methods

Experimental sites and years of harvest. Firmness data were obtained from ‘McIntosh’ apples (*Malus × domestica* Borkh. cv. McIntosh) harvested in nine sites, five in Quebec (Saint-Paul d’Abbotsford, Franklin, Frelighsburg, Oka, and Mont Saint-Grégoire) and four in Ontario [Cobourg, Georgian Bay, Simcoe (Orchard 1), and Simcoe (Orchard 2)], over 15 years, from 1996 to 2011. Fruit firmness was evaluated by two measures on opposite sides of each apple. The peel was removed before the analysis using the electronic Effegi handheld penetrometer (Facchini, Alfonsine, Italy) from 1996 to 2005 and the Fruit Texture Analyzer fitted with an 11-mm tip (GÜSS, Strand, South Africa) from 2006 to 2011.

Weather data were obtained from the National Land and Water Information Service (Agriculture and Agri-Food Canada, 2007) and the weather apple network in Quebec (Bourgeois et al., 2008). Weather parameters available for analyses include: minimum, maximum, and mean daily air temperatures (°C) and daily precipitation (mm). Weather condition parameters were aggregated for each month from May to September, which represents the period of full bloom until harvest time. Temperature conditions were expressed in number of days for each month when mean air temperature was below 5 to 30 °C by steps of 5 °C. Precipitation conditions were expressed in number of days when

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cumulated precipitation was higher than the following values: 0.5 to 3.5 mm by steps of 0.5 mm, 5.0, and 6.0 mm.

To consider the weather condition effect on specific phenological development stages for each site and year of harvest, predicted growth stages of the 'McIntosh' apple were generated using a bioclimatic model for apple development (Bourgeois et al., 2013). The Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) phenological scale developed for the pome fruit in 1994 was used to describe the principal and secondary growth stages (Meier et al., 2001). Principal growth stages include bud development, vegetative growth, reproductive growth, development, and ripening of fruits, up to the senescence of the commercial product, allowing easy linkage between environmental data and particular developmental stages.

For each site and year of harvest, predicted phenological data were divided in number of DFB considering that BBCH stage 65 is the full bloom estimated date and BBCH stage 80 is the estimated harvest time based on apple diameter measurement. Subdivision of the DBF was established as the following: 0 to 30 DFB, 31 to 60 DFB, 61 to 90 DFB, and 91 DFB until harvest.

Principal component analysis (PCA) using the XLSTAT software (Addinsoft, Paris, France) was used to detect correlations between weather parameters, in terms of DBF, and firmness at harvest. The REG procedure and the STEPWISE selection method of SAS Version 9.2 (SAS Institute, Inc., Cary, NC) were used to analyze the effect of all the fruit quality attributes and weather conditions on firmness at harvest. Stepwise regression identified separately the variables that explained a significant portion of the variation in firmness levels at harvest. Regression results were then used to predict firmness levels at harvest and comparisons between accuracy levels of each model were assessed using statistical methods such as root mean square error (RMSE), forecasting efficiency (EF), and mean error (E) (Yang et al., 2000). The best prediction will have RMSE close to zero, EF close to one, and E close to zero. For each model, the percentage of well estimated (± 2.2 N of the observed firmness), over-, and underestimated cases of firmness were also calculated. This threshold represents the accuracy of the penetrometers used to measure the firmness level at harvest.

Results and Discussion

Observed firmness. Firmness data obtained from 'McIntosh' apples harvested in nine regions over 15 years varied from 52.9 to 79.6 N with a mean of 67.7 ± 6.3 N. The three highest firmness values observed at harvest were Franklin in 1999 (75.2 N), Mont Saint-Grégoire in 2001 (77.4 N), and Simcoe in 2005 (79.6 N), whereas the three lowest values recorded in this study were Simcoe in 2006 and 2009 (52.9 N and 59.6 N, respectively) and Saint-Paul d'Abbotsford in 2010 (57.4 N).

Comparison of annual firmness levels at harvest in 'McIntosh' apples shows a slow decrease since the 1990s for Ontario and Quebec regions (Fig. 1). However, studies still have to be conducted on multiple comparisons between apple productions before and after the 1990s to detect the main factor explaining this decrease. Simple modifications in orchard management practices, apple tree loads per orchard, cropland, handling techniques, or fruit quality indices used to detect maturity levels might imply modifications of firmness levels at harvest (Harker et al., 1997). It has been suggested that the deterioration in textural properties of apples may be linked with development of more intensive growing systems within the orchard and greater standards for apple caliber, which lowers the overall firmness values at harvest (Harker et al., 1997). In England, this downward trend in apple firmness has been shown on 'Cox's Orange Pippin' apples, where between 1966 and 1984, firmness after storage has declined by more than 10 N despite improvement in controlled-atmosphere regimes over the years (Horscroft, 1989). The interpretation of such data remains problematic as a result of variations in methods for measuring firmness and fruit size, storage technologies, and length of storage period as the fruit industry becomes more sophisticated (Horscroft, 1989).

Mean predicted dates and corresponding BBCH stages for each subperiod of fruit growth (expressed as DFB) for all sites and years of harvest included in this study are shown in Table 1. By relating dates to fruit development, monthly analyses results and phenologically based weather parameters could be interpreted together.

Predicted dates corresponding to each subperiod of DFB varied slightly between the cases corresponding to the lowest and the highest recorded firmness values at harvest. Overall estimated number of days elapsed since 1 Jan. for each BBCH stage, the earlier occurrences of the first four phenological

stages for cases when firmness levels at harvest are lower might have an impact on this fruit quality parameter. This variation is less noticeable for the BBCH stage 80.

Principal component analyses. The first PCAs were conducted on the effect of all monthly weather parameters on firmness level at harvest. A matrix of correlation highlighted parameters with significant negative effects, including the number of days with mean daily temperature below 20 °C in September, below 25 °C in June, and the number of days with daily cumulated precipitation above 6.0 mm in August ($r = -0.39$, -0.49 , and -0.40 , respectively) and positive effects on firmness levels at harvest, including the number of days when mean daily temperature was above 25 °C in June ($r = 0.49$).

Another PCA included the number of days when daily cumulated precipitation was above 0.5 mm and the number of days when monthly mean air temperature was below 15 °C from May to September. For low air temperature, the months of May and June were divided into four weekly subperiods. No correlation was significant between any weather parameter and firmness levels at harvest despite aggregations to reduce the number of parameter included in the analysis. Therefore, the number of days when mean air temperature was below 15 °C was aggregated for July, August, and September, and the number of days when daily cumulated precipitation was above 0.5 mm was aggregated for July and August. Once again, no significant correlation was found between any weather parameter and firmness levels at harvest.

The same test was conducted on effects of weather parameters per phenological subperiod in DFB. Weather parameters calculated for each developmental subperiod included in the PCA were mean minimum air temperature (°C), number of days when mean air temperature was below 15 and 20 °C, and cumulated precipitation (mm). The matrix of correlation generated by this test highlighted

Fig. 1. 'McIntosh' apple firmness levels at harvest (N) as a function of years of harvest, for all sites and years of harvest included in this study, with a tendency curve plotted to the data.

a significant negative effect of the cumulated precipitation from 61 to 90 DFB ($r = -0.63$) and positive effects of mean minimum air temperature from 0 to 30 DFB and from 31 to 60 DFB ($r = 0.44$ and 0.42 , respectively) on 'McIntosh' firmness levels at harvest. PCA conducted with the same parameters according to DFB, although without the parameter of the number of days when mean air temperature was below 20 °C, highlighted the same three correlations as mentioned in the earlier PCA.

Regression analyses. Results from the following stepwise regression applied to weather conditions for each month of the apple development period, from 14 May to the end of September, on 'McIntosh' apple firmness levels at harvest. Three weather parameters over three different months explained $\approx 50\%$ of the firmness variation across environments included in this study (Table 2). The selected model for firmness level at harvest was:

$$\text{Firmness (N)} = 123.54 - (1.83 T < 25_{\text{June}}) - (1.29 \text{Prec} > 6.0_{\text{August}}) + (1.57 T < 15_{\text{August}}) \quad [1]$$

($R^2 = 0.48$; $P = 0.0023$) where $T < 25_{\text{June}}$ is the number of days when mean air temperature was below 25 °C in June, $\text{Prec} > 6.0_{\text{August}}$ is the number of days when cumulated precipitation was above 6.0 mm in August, and $T < 15_{\text{August}}$ is the number of days when mean air temperature was below 15 °C in August. Almost all parameters had negative relationships with firmness at harvest, implying lower firmness levels at harvest in years and sites with lower air temperature conditions in June (below 25 °C) and greater daily cumulated precipitation (over 6.0 mm) in August. The exception was for conditions during the month of August when lower air temperature

conditions (below 15 °C) had a positive relationship with firmness level at harvest. $T < 15_{\text{August}}$ and $\text{Prec} > 6.0_{\text{August}}$ varied between 0 to 5 and 1 to 8 d, respectively, accounting for 11% and 12% of the additional variation, respectively. As for $T < 25_{\text{June}}$, recorded values for all sites and years varied between 20 and 30 d and accounted for the highest variation (24%) of firmness at harvest.

The predicted values of firmness at harvest obtained with the regression equation [Eq. (1)] including only weather conditions during the growing season, in monthly values, were considered adequate with 52% of the predictions located in the threshold of ± 2.2 N of the observed firmness value at harvest (RMSE = 4.30, EF = 0.51, and E = 0.26). When plotted together, predicted and observed firmness data presented a higher underestimation for high observed values (between 60.9 and 77.4 N) than an overestimation of low observed values (between 52.9 and 69.4 N) (Fig. 2). Thirteen cases of intermediate firmness values (between 59.6 and 79.4 N) were well estimated using Eq. [1].

During the month of June, equivalent to the period of 20 to 40 DFB, as a mean of all sites and years included in this study (Table 1), 'McIntosh' apples are normally between fruit set (BBCH = 71) and 50% of final diameter achieved (BBCH = 75). At this period of fruit development, apple cell enlargement occurs at the highest rate, increasing the water and mineral needs of the fruit (Chapon and Westercamp, 1996). Lower air temperature conditions at this subperiod of development may reduce respiration rate (Blanke, 1995). Fruit cells require high amounts of energy to synthesize proteins, ethylene, and aromatic volatiles, and this energy is mainly provided by respiration. The resulting glucose is then used for further ripening in the presence of oxygen through glycolysis and the citric acid cycle, releasing carbon dioxide and

energy (Von Mollendorff, 1996). Nutrient uptake depends on respiration as well, diminishing under conditions of low soil temperature, and possibly also related to lower air temperature, implying lower uptake and partitioning of calcium. Lower growth rate and calcium content of apples both imply lower firmness level at harvest, explaining the highest variation of firmness level at harvest resulting from lower air temperature conditions during this period of the apple fruit growth. In fact, the highest firmness level at harvest, Simcoe in 2005 with 79.4 N, corresponded to the lowest number of days when mean air temperature was below 25 °C during the month of June with only 20 d. Mean value over all sites and years of harvest in this study was 29 d below 25 °C in June.

After these analyses, stepwise regressions were conducted on weather parameters considering phenological development of apples as a number of DFB. Four weather parameters over three different subperiods of fruit development significantly explained firmness variation on 'McIntosh' apples. The selected model for firmness levels at harvest was:

$$\text{Firmness (N)} = 156.66 - (0.74 T < 20_{31-60}) - (0.08 \text{Prec}_{61-90}) - (2.65 T_{\text{min}_{61-90}}) - (2.21 T_{\text{min}_{91-H}}) \quad [2]$$

($R^2 = 0.76$; $P \leq 0.0001$) where $T < 20_{31-60}$ is the number of days when mean air temperature was below 20 °C from 31 to 60 DFB, Prec_{61-90} is the cumulated precipitation from 61 to 90 DFB, $T_{\text{min}_{61-90}}$ is the mean minimum air temperature from 61 to 90 DFB, and $T_{\text{min}_{91-H}}$ is the mean minimum air temperature from 91 DFB until harvest. All parameters had negative relationships with firmness level at harvest, implying lowest firmness in years and sites with lower air temperature conditions (below 20 °C) between 31 to 60 DFB, higher air temperature and cumulated daily precipitation conditions between 61 to 90 DFB, and higher air temperature between 91 DFB and harvest. $T < 20_{31-60}$ varied between 2 and 25 d and accounted for 11% of firmness level variation at harvest. At this period of apple development, from mid-June to mid-July, as a mean over all sites and years of harvest in this study (Table 1), 'McIntosh' apples are normally between fruit diameter of ≈ 40 mm (BBCH = 74) and 70% of final diameter (BBCH = 77). Apple cells enlarge at a high rate between 31 and 60 DFB, implying an increase in water and mineral demands of the fruit (Chapon and Westercamp, 1996). At this period of apple development, respiration is already at almost its minimal value and low air temperature conditions during this period might decrease respiration levels even more, provoking premature ethylene production and hastening the climacteric rise (Chapon and Westercamp, 1996; Westwood, 1993).

Fruits absorb calcium only during a short period after full bloom, rarely more than 6

Table 1. Subperiods of days from full bloom with corresponding BBCH stages and dates as a mean for all sites and years of harvest for 'McIntosh' apples included in this study.

Days from full bloom (DFB)	Mean date	Mean BBCH stage ^a	Description of BBCH stage ^a
0	17 May	65	Full bloom
30	16 June	73	Second fruit fall; fruit size above 20 and below 40 mm
60	16 July	77	Fruit $\approx 70\%$ final size
90	16 Aug.	79	Fruit $\approx 90\%$ final size
Harvest	8 Sept.	80	Fruit at 100% final size; harvest

^aBBCH scale from Meier et al. (2001).

BBCH = Biologische Bundesantalt, Bundessortenamt, and Chemische Industry.

Table 2. Multiple linear regression [Eq. (1)] of the weather conditions effect on 'McIntosh' apple firmness level at harvest for certain month during the fruit development (from 14 May until end of September) for all sites and years of harvest observed in this study.

Variable	Month	Parameter estimate	Partial R^2
Intercept	—	123.54***	—
Number of days when mean air temperature is below 25 °C	June	-1.83**	0.24**
Number of days when cumulated precipitation is above 6.0 mm	August	-1.29*	0.12*
Number of days when mean air temperature is below 15 °C	August	1.57*	0.11*

*, **, *** Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Fig. 2. 'McIntosh' apple firmness at harvest predicted with Eqs. [1] and [3] as a function of observed values for each site and years of harvest with their corresponding linear functions and the 1:1 ratio line.

weeks, then depending on fruit growth, calcium is diluted in the apple (Faust, 1986). The period of 31 to 60 DFB overlaps with this maximal calcium absorption, which may be altered by low air temperature conditions as well. Firmness has been linked to higher air temperature conditions during the first 6 weeks of fruit growth (Warrington et al., 1999). Calcium has many roles in cell integrity, influencing cell wall mechanical properties and adhesion between cells, both influencing turgor by their indirect effect on membrane permeability, osmotic gradient across plasma membrane, and cell wall movement (expansion and contraction) (Harker et al., 1997). Calcium deficiency has been linked to increase in membrane permeability as well as to increased senescence breakdown incidence during storage (Bramlage et al., 1979; Saure, 1996). Soil moisture excess encourages vegetative growth, large fruit size, and, if extreme, it may even affect time of fruit maturation (Bramlage, 1993). High soil moisture conditions are either the result of high irrigation or intense rainfall. However, precipitation events are closely related with low light intensities and low air temperatures, which make it difficult to separate the direct and indirect effects of each weather parameter on apple quality retention (Bramlage, 1993). It is possible that lower air temperature conditions between 31 and 60 DFB affect negatively apple firmness at harvest by increasing its final caliber, diluting even more the calcium concentrations absorbed by the apple (Faust, 1986).

$T_{min_{61-90}}$ varied between 13.9 and 18.0 °C and accounted for 17% of 'McIntosh' firmness level variation at harvest. At this period of apple development, from mid-July to mid-August, as a mean over all sites and years included in this study, 'McIntosh' apples have normally achieved between 70% and 90% of their final caliber (Table 1). Apples are in cell expansion process, although fruit growth rate starts to decrease as apple maturation process sets in (Chapon and Westercamp, 1996). For

the same subperiod of apple development, cumulated precipitation ($Prec_{61-90}$), which varied between 10 and 150 mm, demonstrated a negative effect on firmness at harvest and accounted for the highest variation of 39% of firmness values recorded for all cases included in this study. Considering that these two weather parameters during this period of fruit development accounted for 56% of firmness variation together, we may consider this subperiod as the most sensitive to firmness variations observed at harvest. During this period, cell wall thickening and increase in attractive forces between the walls of adjacent cells remain important, as the primary wall integrity of individual cells in determining the overall physical properties of the fruit (Harker et al., 1997). Higher air temperature conditions and increased precipitation occurrences during this period might decrease firmness level at harvest by affecting cell wall integrity or the vacuolation process implied in the course of cellular expansion to maintain cell turgor (Harker et al., 1997; Warrington et al., 1999). Respiration rate decreases slowly during this period of fruit growth until a constant low value is maintained for the month before harvest (Fidler, 1973). Apples exposed to higher air temperature conditions start showing abnormal metabolism, resulting in loss of membrane integrity and structure with disruption of cellular organization and rapid deterioration of the produce (Wills et al., 1981). This might be the reason for decreased firmness at harvest linked to higher air temperature conditions during this period of fruit growth. Because 'Delicious' apples under a certain level of water stress showed lowered firmness loss rate, indicating an alteration in the physiological mechanism of fruit softening (Ebel et al., 1993), it is possible that the reverse effect could be observable as well. Increased precipitation during this period of fruit growth might imply a faster rate of firmness loss leading to lowered firmness at harvest.

$T_{min_{91-11}}$ varied from 11.6 to 15.2 °C and accounted for 9% of 'McIntosh' firmness level variation at harvest. Ninety-one DFB until harvest represents the last month before harvest, between mid-August and mid-September, where final fruit maturation processes occur such as soluble solid accumulation, slow fruit diameter increase, background fruit color change, and decrease in acidity (Devlin and Witham, 1983). Higher air temperature conditions during this period of the apple fruit development may lead to increase in respiration rate, which would result in premature ethylene production. Advanced maturity at harvest has been linked to reduced firmness level, which also influences fruit quality during storage (Chapon and Westercamp, 1996). Increased air temperatures, or its indirect relation with high solar radiation and low precipitation conditions, may also be involved with calcium deficiency as a result of reduced transportation of ions to and from cells (Westwood, 1993). This deficiency increases membrane permeability, thereby leading to water loss by evapotranspiration and reduced cell turgor (Saure, 1996).

By simulating the predicted values of firmness at harvest with the regression equation [Eq. (2)], including only weather conditions during the growing season in DFB values, the prediction was considered adequate with 48% of the predictions located in the threshold of ± 2.2 N of observed firmness values at harvest (RMSE = 3.04, EF = 0.75 and E = -0.47). The linear regression fitted to the predicted firmness values at harvest as a function of observed data revealed a more accurate slope (0.75), closer to the 1:1 ratio line, for predictions using Eq. [2] than predictions using Eq. [1]. Twelve cases of intermediate firmness values (between 52.9 and 73.4 N) were well estimated using Eq. [2]. Although this represents more over-estimated cases than for Eq. [1], with 32% instead of 16%, and less under-estimation than for Eq. [1], with 20% instead of 32%, Eq. [2] remains a better option for firmness prediction, because it shows higher accuracy than Eq. [1] based on RMSE and EF values. In addition, the R^2 value of the fitted regression for Eq. [2] (0.76) is much higher than the fitted regression in Eq. [1] (0.48), implying also a greater accuracy for predictions using phenological stages instead of monthly weather conditions.

In a perception of further development of a forecasting model for the prediction of 'McIntosh' apple firmness levels at harvest, weather parameters included in the stepwise analyses were standardized to obtain more consistent parameters of air temperature and precipitation conditions. Therefore, the parameters for the number of days when mean air temperature was higher than certain values were sorted out and replaced by simple parameters of mean values for minimum, mean, and maximum air temperatures for each subperiod of fruit development. Precipitation conditions were maintained as parameters of cumulated precipitation for each

subperiod of the growing season. Three subperiods of fruit development explained significant firmness levels variation on 'McIntosh' apples (Table 3). The selected model for firmness levels at harvest was:

$$\begin{aligned} \text{Firmness (N)} = & 83.94 + (2.82 \text{ Tmean}_{31-60}) \\ & - (0.08 \text{ Prec}_{61-90}) \\ & - (3.06 \text{ Tmin}_{61-90}) \\ & - (1.45 \text{ Tmin}_{91-H}) \quad [3] \end{aligned}$$

($R^2 = 0.74$; $P \leq 0.0001$) where Tmean_{31-60} is the mean air temperature from 31 to 60 DFB, Prec_{61-90} is the cumulated precipitation from 61 to 90 DFB, Tmin_{61-90} is the mean minimum air temperature from 61 to 90 DFB, and Tmin_{91-H} is the mean minimum air temperature from 91 DFB until harvest. The only difference between Eqs. [2] and [3] is the addition of the positive effect of mean air temperature parameter from 31 to 60 DFB on firmness at harvest, which replaced the negative effect of the number of days when mean air temperature was below 20 °C from 31 to 60 DFB ($\text{T} < 20_{31-60}$). These two effects represent the same trend for higher air temperature during this subperiod to increase firmness. Tmean_{31-60} varied between 17.6 and 23.8 °C for all sites and years included in this study and accounted for 12% of variation in firmness values at harvest. As for all other parameters, their effects were relatively the same as in Eq. [2], except that the parameter for mean minimum air temperature from 91 DFB until harvest was slightly nonsignificant ($P = 0.0959$) in Eq. [3].

By simulating the predicted values of firmness with the regression equation including only weather conditions during the growing season, in DFB values, the prediction is considered adequate with 44% of the predictions that are located in the threshold of ± 2.2 N of the observed firmness value at harvest (RMSE = 3.17, EF = 0.73, and E = 0.40). Only 11 cases included in this study showed accurate predictions using Eq. [3], which is the lowest from all regression predictions, although the regression fitted with these data showed the slope closest to 1. However, in comparison with predictions from Eqs. [1] and [2], its R^2 value (0.74) is less important than for the relation illustrating predictions using Eq. [2].

When comparing Eq. [2] and Eq. [3], the second one would be more easily converted to a dynamic model for the purpose of forecasting firmness levels of 'McIntosh' apples at harvest. However, Eq. [3] contains a slightly nonsignificant parameter and a lower R^2 value than Eq. [2]. As for predictions of firmness values using both regressions, only one additional case was well predicted using Eq. [2] instead of Eq. [3]. Therefore, differences between both regressions are not very important, so Eq. [3] remains more appropriate for use for developing a forecasting model.

In previous regression results, the parameter of cumulated precipitation from 61 to 90

DFB remained the factor explaining most of the variation between firmness values for all sites and years included in this study with 39% of additional variation. When plotted with corresponding cumulated precipitation values from 61 to 90 DFB for each site and year, firmness values at harvest seem slightly separated in two aggregates (Fig. 3). In fact, a gap of cumulated precipitation values between 100 and 130 mm explains this division between both groups of firmness values, dividing high (64 N or greater) and low (less than 64 N) firmness values. The effect of precipitation conditions above ≈ 120 mm might induce a greater reduction of firmness observed in 'McIntosh' apples at harvest. This distinction is much easier to visualize when precipitation values are squared.

The next analysis was conducted on a quadratic precipitation parameter to evaluate its effect on firmness predictions. Three parameters over two subperiods of the apple growth season explained significant firmness variation in 'McIntosh' apples.

$$\begin{aligned} \text{Firmness (N)} = & 68.32 + (2.40 \text{ Tmean}_{31-60}) \\ & - (0.0005 (\text{Prec}_{61-90})^2) \\ & - (2.88 \text{ Tmin}_{61-90}) \quad [4] \end{aligned}$$

($R^2 = 0.73$; $P \leq 0.0001$) where Tmean_{31-60} is the mean air temperature from 31 to 60 DFB,

(Prec_{61-90})² is the squared value of cumulated precipitation from 61 to 90 DFB, and Tmin_{61-90} is the mean of minimum air temperature from 61 to 90 DFB. This regression varies mainly from Eq. [3] with an elimination of the negative effect of mean minimum air temperature from 91 DFB until harvest on firmness value. This parameter explained only 4% of firmness variation in Eq. [3]. Furthermore, the overall R^2 values between both regressions decreased by only 0.4% in Eq. [4]. With the quadratic parameter for precipitation from 61 to 90 DFB, the range of values was much higher varying from 100 to 22560 mm², which permits the distinction between trends of low and high precipitation effect.

By simulating the predicted values of firmness with the regression equation including only weather conditions during the growing season, in DFB values, the prediction is considered adequate with 64% of the predictions that are located in the threshold of ± 2.2 N of the observed firmness value at harvest (RMSE = 3.18, EF = 0.73, and E = -0.28). This regression overestimated fewer cases than Eqs. [2] and [3] with only 16% of overestimation compared with 32 and 24%, respectively. When plotted according to the observed firmness values for all sites and years included in this study, the regression fitted to this relation revealed a slope of 0.71, which is close to 1, although not as much as

Table 3. Multiple linear regression [Eq. (3)] of the weather conditions effect on 'McIntosh' apple firmness level at harvest with standardized weather parameters for periods of the fruit development, in days from full bloom (DFB), for all sites and years observed in this study.

Variable	Days from full bloom (DFB)	Parameter estimate	Partial R^2
Intercept	—	83.94***	—
Mean temperature (°C)	31-60	2.82***	0.12**
Cumulated precipitation (mm)	61-90	-0.08***	0.39***
Mean minimum temperature (°C)	61-90	-3.06**	0.09*
Mean minimum temperature (°C)	91-H	-1.45 ^{NS}	0.04 ^{NS}

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Fig. 3. 'McIntosh' apple firmness at harvest as a function of cumulated precipitation from 61 to 90 DFB for each site and year of harvest with a quadratic function applied to the plotted data and its corresponding equation and R^2 value. DFB = days from full bloom.

for predictions of firmness using Eq. [2] or [3]. As for the R^2 value for the regression fitted to the predicted values using Eq. [4] in function of observed firmness data, its value of 0.73 is also lower than for predictions with Eqs. [2] and [3].

The use of the number of DFB has proven to increase the accuracy of the effect of weather conditions on firmness level at harvest for 'McIntosh' apples. Predictions of BBCH stages linked to DFB values were used to evaluate the maturity stages of apples linked to these effects of weather conditions on firmness. However, this scale is based on fruit caliber after full bloom until harvest, which limits the ability to link them to maturation stages. Knowledge of the diameter values corresponding to each BBCH stage of the 'McIntosh' development could add concrete information for producers to relate more easily with which stages of apple growth are more sensitive to firmness loss as a result of highlighted weather conditions in this study. By including the combined effect of caliber and firmness measurements at harvest, the compromise between these two parameters could lead to a better understanding of weather condition effect on the volume of apple by distinguishing their effects on the number of cells and the volume per cell in an apple, representing cell division and cell expansion processes (Harker et al., 1997).

Also, according to Tong et al. (1999), lower winter air temperatures, below critical air temperature levels for apple trees, may damage the tree vascular system, affecting fruit maturity and ripening during the growing season. It would be interesting to analyze the effects of weather conditions outside fruit growth season as well to verify the indirect effect of winter conditions on fruit firmness at harvest. Acquiring information on thinning practices in orchards, timing and intensity, could differentiate cases of high variations in apple firmness levels between orchards. In fact, it was shown that thinning during the period of 5 to 15 d after bloom was identified as a critical time to influence fruit firmness through thinning on 'Cox's Orange Pippin' apples (Johnson, 1994). Because it is also known that calcium and phosphorus sprays and nitrogen fertilizer treatments influence final firmness at harvest, obtaining information on nutrient spraying practices could also help discriminate the cases when firmness was strongly influenced by these practices (Webster and Lidster, 1986).

Decrease in firmness observed since the last decade or so is either the result of increased intensity in apple production systems and fruit size standards for fresh fruit market or variations in weather conditions (Harker et al., 1997; Johnson, 1992; Tromp, 1997). The importance of preharvest weather condition effects on apple firmness at harvest is often mentioned in studies on apple quality at harvest, although information on their impact on fruit development is limited (Calderón Zavala et al., 2004; Green, 1963). This study

highlighted the combined negative impact of lower air temperature conditions after cellular division, higher air temperature conditions and precipitations during the end of cellular expansion process, and higher air temperature conditions preceding harvest time on 'McIntosh' apple firmness level at harvest. The parameter of precipitation conditions during cellular expansion explained by itself 39% of firmness variation with a higher impact on decreasing firmness when daily precipitation was higher than 120 mm. Using the regression including only standardized weather parameters, it would be interesting in future research to develop forecasting models for apple firmness using only weather conditions during the growing season. The ability to predict firmness indices before harvest could help producers in establishing appropriate marketing strategies. They could either invest in long-term storage in years of high firmness values at harvest or sell fruit on the fresh fruit market if firmness has already started to decrease. In another perspective, these predictions could also permit the determination of temporal and spatial conditions required to maintain higher apple firmness values at harvest.

Literature Cited

- Agriculture and Agri-Food Canada. 2007. National land and water information service. Daily 10km gridded climate dataset; 1961–2003, Canada, Version 1.0 (CSV) Generated using ANUSPLIN. Version 4.3.
- Blanke, M.M. 1995. Regulation of respiration in apple, avocado and citrus orange fruit. *Acta Hort.* 398:139–146.
- Blanpied, G.D., W.J. Bramlage, D.H. Dewey, R.L. LaBelle, L.M. Massey, G.E. Mattus, W.C. Stiles, and A.E. Watada. 1978. A standardized method for collecting apple pressure test data. *Plant Sci.* 1:1–6.
- Bourgeois, G., D. Plouffe, N. Beaudry, D. Choquette, G. Chouinard, and S. Bellerose. 2013. Using the DJPheno software for model calibration and validation of apple phenological stages. *Proc. of the IXth Intl. Symp. on Modelling in Fruit Res. and Orchard Mgt.* *Acta Hort.* (in press).
- Bourgeois, G., D. Plouffe, G. Chouinard, N. Beaudry, D. Choquette, O. Carisse, and J. DeEll. 2008. The apple CIPRA network in Canada: Using real-time weather information to forecast apple phenology, insects, diseases and physiological disorders. *Acta Hort.* 803:29–34.
- Bramlage, W.J. 1993. Interactions of orchard factors and mineral nutrition on quality of pome fruit. *Acta Hort.* 326:15–28.
- Bramlage, W.J., M. Drake, and J.H. Baker. 1979. Changes in calcium level in apple cortex tissue shortly before harvest and during postharvest storage. *Commun. Soil Sci. Plant Anal.* 10: 417–426.
- Calderón Zavala, G., A.N. Lakso, and R.M. Piccioni. 2004. Temperature effects on fruit and shoot growth in the apple (*Malus domestica*) early in the season. XXVI Intl. Hort. Congr.: Key Processes in the Growth and Cropping of Deciduous Fruit and Nut Trees. *Acta Hort.* 636:447–453.
- Chapon, J.-F. and P. Westercamp. 1996. Entreposage frigorifique des pommes et des poires. Tome 2: 'Conduite de la conservation.' Centre technique interprofessionnel des fruits et légumes (Ctifl), Paris, France.
- Conway, W.S. and C.E. Sams. 1987. The effects of postharvest infiltration of calcium, magnesium, or strontium on decay, firmness, respiration, and ethylene production in apples. *J. Amer. Soc. Hort. Sci.* 112:300–303.
- Corelli Grappadelli, L. 2003. Light relations, p. 195–216. In: Ferree, D.C. and I. J. Warrington (eds.). *Apples; botany, production and uses.* CABI Publishing, Cambridge, MA.
- DeEll, J.R., S. Khanizadeh, F. Saad, and D.C. Ferree. 2001. Factors affecting apple fruit firmness—A review. *J. Amer. Pomol. Soc.* 55:8–27.
- Devlin, R.M. and F.H. Witham. 1983. *Plant physiology.* 4th Ed. Willard Grant Press, Boston, MA.
- Ebel, R.C., E.L. Proebsting, and M.E. Patterson. 1993. Regulated deficit irrigation may alter apple maturity, quality, and storage life. *Hort-Science* 28:141–143.
- Faust, M. 1986. Preharvest factors affecting storage quality of apples. The Deciduous Fruit Grower. Frigair 86 Conf., Pretoria, Gauteng.
- Fidler, J.C. 1973. Conditions of storage, p. 1–51. In: Fidler, J.C. (ed.). *The biology of apple and pear storage.* Cmwth. Agricultural Bur., UK.
- Green, G.C. 1963. The effect of weather and climate upon the keeping quality of fruit. Technical Note No. 53. Rept. of Working Group of the Commission for Agricultural Meteorol. World Meteorol. Organization, Geneva, Switzerland.
- Harker, F.R., R.J. Redgwell, I.C. Hallett, and S.H. Murray. 1997. Texture of fresh fruit. *Hort. Rev.* 20:121–224.
- Horscroft, J. 1989. Production factors influencing the textural qualities of apples. PhD thesis, Wye College, Univ. London, London, UK.
- Johnson, D.S. 1992. The effect of flower and fruit thinning on the firmness of 'Cox's Orange Pippin' apples at harvest and after storage. *J. Hort. Sci.* 67:95–101.
- Johnson, D.S. 1994. Influence of time of flower and fruit thinning on the firmness of 'Cox's Orange Pippin' apples at harvest and after storage. *J. Hort. Sci.* 69:197–203.
- Johnston, J.W., E.W. Hewett, and M. Hertog. 2002. Postharvest softening of apple (*Malus domestica*) fruit: A review. *New Zeal. J. Crop Hort.* 30:145–160.
- Kondo, S. and Y. Takahashi. 1987. Effects of high temperature in the nighttime and shading in the daytime on the early drop of apple fruit 'Starking Delicious'. *J. Jpn. Soc. Hort. Sci.* 56:142–150.
- Marmo, C.A., W.J. Bramlage, and S.A. Weis. 1985. Effects of fruit maturity, size, and mineral concentrations on predicting the storage life. *J. Amer. Soc. Hort. Sci.* 110:499–502.
- Meier, U., H. Bleiholder, E. Weber, C. Feller, M. Hess, H. Wicke, T. van den Boom, P.D. Lancashire, L. Buhr, H. Hack, R. Klose, and R. Stauss. 2001. Growth stages of mono- and dicotyledonous plants; BBCH monograph. 2nd ed. Federal Biological Res. Ctr. for Agr. and For.
- Saure, M.C. 1996. Reassessment of the role of calcium in development of bitter pit in apple. *Aust. J. Plant Physiol.* 23:237–243.
- Smock, R.M. 1953. Some effects of climate during the growing season on keeping quality of apples. *J. Amer. Soc. Hort. Sci.* 62:272–278.
- Tong, C., D. Krueger, Z. Vickers, D. Bedford, J. Luby, A. El-Shiekh, K. Schackel, and H. Ahmadi. 1999. Comparison of softening-related changes during storage of 'Honeycrisp' apple,

- its parents, and 'Delicious'. J. Amer. Soc. Hort. Sci. 124:407–415.
- Trillot, M. and S. Tillard. 2002. Le pommier. Monographie. Centre technique interprofessionnel des fruits et légumes (Ctifl). France.
- Tromp, J. 1997. Maturity of apple cv. Elstar as affected by temperature during a six-week period following bloom. J. Hort. Sci. 72:811–819.
- Von Mollendorff, L.J. 1996. Physiological changes in fruit during development and ripening, p. 33–38. In: Combrink, J.C. (ed.). Integrated management of post-harvest quality. INFRUITEC; An Inst. of the Agricultural Res. Council, Stellenbosch, Western Cape.
- Warrington, I.J., T.A. Fulton, E.A. Halligan, and H.N. De Silva. 1999. Apple fruit growth and maturity are affected by early season temperature. J. Amer. Soc. Hort. Sci. 124:468–477.
- Webster, D.H. and P.D. Lidster. 1986. Effects of phosphate sprays on McIntosh apple fruit and leaf composition, flesh firmness and susceptibility to low-temperature disorders. Can. J. Plant Sci. 66:617–626.
- Westwood, M.N. 1993. Temperate-zone pomology; Physiology and culture. 3rd Ed. Timber Press Inc., Portland, OR.
- Wills, R.H.H., T.H. Lee, D. Graham, W.B. McGlasson, and E.G. Hall. 1981. Physiology and biochemistry, p. 17–37. In: Postharvest: An introduction to the physiology and handling of fruit and vegetables. AVI Publishing Company Inc., Australia.
- Yang, J., D.J. Greenwood, D.L. Rowell, G.A. Wadsworth, and I.G. Burns. 2000. Statistical methods for evaluating a crop nitrogen simulation model, N_ABLE. Agr. Syst. 64:37–53.