Temperature Affects Postharvest Color Change of Apples

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ABSTRACT. Loss of green color (yellowing) in apples (*Malus × domestica* Borkh.) is due to chlorophyll breakdown, an enzyme-mediated reaction conforming to first-order kinetics. Nondestructive measurements of yellowing, using a tristimulus chromameter, were related to chlorophyll content for 'Cox's Orange Pippin' and 'Granny Smith' apples stored at temperatures of 0 to 35 °C. Yellowing determined by rate constant (k) of total chlorophyll and changes in hue angle, as a function of temperature, increased slowly from 0 to 5 °C, increased exponentially from 5 to 20 °C, reached a maximum from 20 to 24 °C, then declined at higher temperatures. Values of k and the rate of change of hue angle were characterized by a modified Arrhenius equation. 'Cox's Orange Pippin' apples harvested early had lower k and lower rates of hue angle change than late-harvested fruit. Values of k and hue angle change of 'Granny Smith' apples differed between years but not between harvests. The method used to characterize the relationship between yellowing and temperature may describe changes in other important quality attributes of apple fruit during storage and shelf life and help evaluate the efficacy of cool-chain handling and storage systems.

Fruit color is a major quality attribute of apples (Wills et al., 1989), affecting consumer perception of ripeness and eating quality (Lockshin and Rhodus, 1991). For a given cultivar, apples with a yellow background color are considered by consumers to be riper, softer, and sweeter than green fruit (Christensen, 1983). Chlorophyll content of apple skin is an important visual indicator of fruit maturity for growers and consumers. Many apple cultivars are harvested according to color, and many consumers prefer apples of a particular color; e.g., 'Golden Delicious' apples are yellow when fully ripe. Cultivars such as 'Cox's Orange Pippin' and 'Granny Smith' yellow as they ripen, and overripe fruit are characterized by their yellow background color. To characterize changes in color of apples under various storage environments, rapid and accurate methods of estimating color change are required. These methods must reflect physiological changes occurring in fruit skin and accurately mirror changes perceived by the human eye.

Many methods have been used to assess color and color change of horticultural produce (Knee, 1980; Knee et al., 1988; Mussini et al., 1985; Pai and Sastry, 1990; Rhodes and Woollorton, 1967; Stow, 1989; Watkins et al., 1991), but most are destructive and of little practical use outside a laboratory. The tristimulus chromameter measures color objectively, quickly, and nondestructively, expressing color as the L*, a*, b* system, which uses a pairing of red-green (a*) and blue-yellow (b*) colors that closely mimic those seen by the human eye.

Pigments responsible for apple color are chlorophyll (green), carotenoids, flavonoids (yellow), and anthocyanins (red). Red pigments change little once apples are harvested and placed into storage (Goldschmidt, 1980). Background color in apples changes from green to yellow during ripening through chlorophyll disap-

pearance, which makes yellow pigments visible (Gorski and Creasy, 1977; Hansen, 1956; Knee, 1972), and enhanced carotenoid biosynthesis (Gross and Ohad, 1983; Knee, 1980). Yellowing of apples is proportional to temperature; the higher the temperature the faster the yellowing (Pai and Sastry, 1990). Rate constants of change of color are not thought to be affected by prestorage conditions (Workman, 1963); for example, the rate of yellowing at 0 °C will be the same for fruit stored previously at 20 or 10 °C, even though the fruit from 20 °C initially will be more yellow than fruit from 10 °C.

Chlorophyll breakdown is considered to be an enzyme-mediated reaction (Hendry et al., 1987) conforming to first-order kinetics (Holden, 1961; Robertson and Swinburne, 1981) occurring at a rate dependent on temperature:

$$A_t = A_0 e^{-kt} \quad [1]$$

where A_t = chlorophyll concentration at time t ($\mu\text{mol}\cdot\text{m}^{-2}$); A_0 = initial chlorophyll concentration at time zero ($\mu\text{mol}\cdot\text{m}^{-2}$); k = rate constant (d^{-1}); t = time (d).

In enzyme-mediated processes where a substrate is consumed, rate depends on substrate concentration. As substrate concentration declines so does the reaction rate; therefore rate constant (k), which is the proportional rate of change in substrate being consumed by the enzyme-mediated process, is used to quantify the rate of reaction (Eq. [1]).

A theoretical model combining the Arrhenius equation with the Boltzmann enzyme-distribution function has been proposed to describe temperature effects on the values of k in biological systems (Johnson and Thornley, 1985). This modified Arrhenius equation (Eq. [2]) describes rate of loss or increase in a physiological attribute at different temperatures:

$$k = K_a e^{-E_a/RT} / 1 + e^{\Delta S/R} e^{-\Delta H/RT} \quad [2]$$

where k = rate constant; K_a = maximum possible rate constant; E_a = activation energy ($\text{J}\cdot\text{kg}^{-1}\cdot\text{mol}^{-1}$); R = gas constant ($8.314 \text{ J}\cdot\text{kg}^{-1}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$); T = temperature (K); ΔS = increment of entropy ($\text{J}\cdot\text{kg}^{-1}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$); and ΔH = increment of enthalpy ($\text{J}\cdot\text{kg}^{-1}\cdot\text{mol}^{-1}$).

Equation [2] indicates that k rises exponentially from zero as temperature increases, reaching a maximum at an optimum temperature for the process, above which k declines. The modified Arrhenius equation has been used to describe the relationship between k and temperature for diverse systems such as growth

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rates of bacteria, leaf growth, and shoot dry mass changes in spring wheat (Feng et al., 1990; Johnson and Thornley, 1985). Progress is occurring in the development of models characterizing color change in a number of horticultural products including tomato (Tijssens and Evelo, 1994), where k was an integral component of the model describing green to red color change.

Understanding the relationship between apple yellowing and storage temperature would give apple marketers and handlers the ability to predict how changes to handling, storage, and transport systems may affect fruit color. Such a system could be used in apple industries where there is a major interest in describing fruit quality after storage and transport to distant markets. Nondestructive measurement of fruit color during postharvest life would allow indirect measurement of pigment changes during ripening. To be certain that such an approach has merit, the relationship between pigment concentration and nondestructive measurement required characterization. To examine this, hue angle and lightness were related to chlorophyll content for identical areas of apple skin of two apple cultivars maintained at different temperatures during ripening.

Materials and Methods

'Cox's Orange Pippin' (COP) and 'Granny Smith' (GS) apples, average mass 0.148 kg, were harvested early (8 Feb. 1989, 18 Feb. 1990, and 20 Feb. 1990 for COP and 1 Apr. 1989, 10 Apr. 1990, and 16 Apr. 1990 for GS) and late (22 Feb. 1989 and 6 Mar. 1990 for COP and 18 Apr. 1989, 6 May 1990, and 9 May 1990 for GS) during the commercial harvest period for export fruit, from six (COP) and four (GS) orchards in Hawkes Bay, New Zealand. Apples were transported to Palmerston North within 24 h of harvest, where they were weighed and placed into unsealed polyethylene bags perforated with six 10-mm-diameter holes. Ten bags of fruit from each harvest (five bags per orchard), each containing seven fruit, were used for temperature treatments. Bags of fruit were placed at (in °C) 0 ± 1 , 5 ± 0.5 , 10 ± 0.5 , 15 ± 0.5 , 20 ± 0.5 , 25 ± 0.5 , 30 ± 0.5 , and 35 ± 1 . Maximum delay between harvest and placement into storage was 2 d at prevailing temperatures (15 to 16 °C). The experiment was repeated in a second year.

At regular intervals, skin color of a 10-fruit sample from each temperature was measured with a portable chromameter (DP100; Minolta Camera Co. Ltd., Osaka, Japan) equipped with a 10-mm-diameter aperture on the measuring head. Fruit chromaticity was measured in Commission Internationale de l'Éclairage Yxy units and converted to L^* , a^* , and b^* color space coordinates (Francis, 1952). The meter was calibrated at illuminant condition C (6774K) before use with a white standard ($Y = 87.5$, $x = 0.315$, $y = 0.308$) in 1989 and a green standard ($Y = 29.9$, $x = 0.273$, $y = 0.369$) in 1990 with viewing geometry d/0. At each sampling time, background green color of each fruit was measured twice around the fruit's equator. Care was taken to avoid blushed or marked areas of skin. The measured positions were marked so they could be used for chlorophyll extraction. The a^* and b^* values were converted to hue angle and chroma (McGuire, 1992).

Chlorophyll from marked positions on the same 10 fruit was extracted and measured as follows: two 10-mm-diameter skin disks, ≈ 1 mm thick, were cut from each apple, placed into a 16-mL tube containing 3 mL of cold Analaar grade *N,N*-dimethylformamide (DMF) (Moran, 1982; Moran and Porath, 1980), and covered with tinfoil before being placed at 0 ± 1 °C. After 96 h, the contents of each test tube were decanted into a 10-mm glass cuvette. Absorbance readings were made at 710, 665, and 647 nm using a spectrophotometer (U2000; Hitachi Ltd., Tokyo, Japan). Absorbance at 710 nm, used to quantify solution turbidity, was then

subtracted from absorbance at 665 nm (chlorophyll a) and 647 nm (chlorophyll b). Concentrations of chlorophyll a and b were calculated using the differential equations of Arnon (1949) corrected for DMF (Porra et al., 1989).

Chlorophyll concentrations from fruit at each sample time were averaged and used to calculate the rate constant, k , by linear regression, after $\log_e$ transformation, using the SAS statistical package (SAS, Cary, N.C.) according to Eq. [1]. Rates of change in hue angle and lightness were calculated as the slope of linear regressions with time using the SAS statistical package. The SAS procedure NLIN, with the Marquardt search method (Feng et al., 1990), using values of k and rates of change estimated above, was used to optimize parameters K_a , E_a/R , $\Delta S/R$, and $\Delta H/R$ of Eq. [2]. Comparisons of chlorophyll concentration with hue angle and lightness and differences in average values of k and rates of change of hue and lightness between cultivars and years were determined by analysis of variance using the GLM procedure of SAS and Duncan's multiple range test.

Results and Discussion

CHLOROPHYLL LOSS AND COLOR CHANGE. In general, total chlorophyll concentration in apple skin, from both cultivars at all harvests and from all orchards, decreased exponentially with time, with rate of loss being faster at higher temperatures (Fig. 1). This pattern is the same as reported previously for chlorophyll loss in pear skin (Laval-Martin, 1969). The rate constant (k) at specific

Fig. 1. Total chlorophyll concentration for 'Cox's Orange Pippin' apples from one orchard and one harvest maintained at 0 to 35 °C.

Fig. 2. Lightness and hue angle for 'Cox's Orange Pippin' apples maintained at 5 °C (●), 10 °C (□) and 25 °C (▲) after harvest. (a) Lightness: for 5 °C, intercept = 71.60%, slope = 0.01% per day, $r^2 = 13\%$, NS; for 10 °C, intercept = 72.36%, slope = 0.12% per day, $r^2 = 86\%$, $P < 0.05$; for 25 °C, intercept = 67.28%, slope = 0.43% per day, $r^2 = 96\%$, $P < 0.001$. (b) Hue angle: for 5 °C, intercept = 112.21 h°, slope = -0.143 h°/d, $r^2 = 88\%$, $P < 0.01$; for 10 °C, intercept = 110.69 h°, slope = -0.229 h°/d, $r^2 = 94\%$, $P < 0.001$; for 25 °C, intercept = 110.63 h°, slope = -0.582 h°/d, $r^2 = 99\%$, $P < 0.001$.

temperatures was derived from the slope of the $\log_e$ -transformed data regression line for each temperature studied. Therefore, k provides a unique means of expressing the rate of change of chlorophyll for a given temperature over time as a single value and permits easy comparison of treatment effects.

Values of k were derived assuming that chlorophyll loss is best described by a declining exponential function. At 25 to 35 °C there was a slight delay before chlorophyll concentration started to decline (Fig. 1). This delay made it difficult to estimate chlorophyll concentration accurately at time 0 using the regression intercept, as k was defined by the curvilinear portion of the curve. Fitted estimates of chlorophyll calculated using k agreed reasonably with observed values (Fig. 1).

Lightness (L^* , brightness of the color) increased linearly with time (Fig. 2a). Yellowing in COP and GS apples is thought to result primarily from chlorophyll degradation and subsequent unmasking of yellow pigments (Gorski and Creasy, 1977; Hansen, 1956; Knee, 1972). The decrease in pigment concentration is represented by an increase in lightness (Fig. 3b). Lightness varied from $\approx 67\%$ to 80% in COP and from $\approx 58\%$ to 77% in GS apples (Fig. 3b). In general, lightness was higher for COP, these fruit having about half the chlorophyll of GS apples. There were no treatment effects on chroma (data not shown).

Hue angle changed linearly with time (Fig. 2b), similar to $\log_e$ -transformed chlorophyll concentration. Hue angle varied from ≈ 93 to 113 h° in COP and from ≈ 103 to 120 h° for GS apples (Fig. 3a), reflecting the lower chlorophyll concentration in COP than GS apples. We believe the range of values for lightness or hue angle from COP and GS represent the upper and lower values, which might be expected from other apple cultivars. As variability of lightness data was greater than for hue angle and chlorophyll concentration, it is a less useful measurement to define rate of color change with temperature.

This relationship of hue angle to chlorophyll concentration was initially exponential (for COP), rising to a maximum (for GS) (Fig. 3a). As chlorophyll declined, smaller changes in chlorophyll concentration were reflected by larger changes in hue angle; this caused the nonlinear declining exponential function of chlorophyll loss to become linear when measured as hue angle. Because rate of change of hue angle measurements over time mirrors chlorophyll k values, it can be used to characterize the relationship of yellowing with temperature, greatly simplifying calculations necessary to estimate rate of color change.

Chlorophyll degradation was faster in COP than in GS apples. In COP apples chlorophyll a disappeared more rapidly (k values were 1.3 to 1.9 times greater) than chlorophyll b. In GS apples values of k for chlorophyll a and b were the same (Table 1).

Fig. 3. Color measured as (a) hue angle and (b) lightness in relation to total chlorophyll concentration in the identical area of skin for 'Cox's Orange Pippin' and 'Granny Smith' apples. Each point is the mean of 10 apples from each sampling.

Table 1. Mean k values for chlorophyll a, chlorophyll b, and total chlorophyll and rates of change of hue angle and lightness in skin of 'Cox's Orange Pippin' (COP) and 'Granny Smith' (GS) apples from early and late commercial harvests 1989 and 1990.

			Rate constant (k)				
			Chlorophyll (10 ⁻³ ·d ⁻¹)			Hue angle	Lightness
Cultivar	Year	Harvest	a	b	Total	(h°/d)	(%/d)
COP	1989	Early	54	28	46	0.356	0.207
		Late	76	46	63	0.343	0.221
	1990	Early	63	43	56	0.303	0.164
		Late	87	66	78	0.449	0.200
GS	1989	Early	16	18	17	0.161	0.142
		Late	18	19	18	0.158	0.123
	1990	Early	24	27	25	0.184	0.227
		Late	21	24	23	0.144	0.195
Significance							
COP		Harvest	NS	*	*	**	*
		Year	NS	NS	NS	NS	NS
GS		Harvest	NS	NS	NS	*	NS
		Year	NS	NS	NS	NS	**

NS, *, ** Nonsignificant or significant at $P < 0.05$ or 0.01 , respectively.

Chlorophyll a and b had different k values in consecutive years, with k for COP and GS apples being 20% and 30% higher, respectively, in 1990 than in 1989. Changes in chlorophyll a and b concentrations in the skin from year to year may affect total chlorophyll k (which is calculated by averaging the k values of chlorophyll a and b). Average total chlorophyll k for COP was 3 times greater than for GS (Table 1). Such a difference could possibly be a result of a faster rate of ripening for COP compared with GS fruit, as COP has a respiration rate about twice that of GS (Dadzie, 1992). Chlorophyllase activity is thought to increase just before the climacteric and is consequently related to respiration (Looney and Patterson, 1967; Rhodes and Woollorton, 1967). The lag in the start of chlorophyll degradation following harvest (Fig. 1) may be related to the climacteric, as fruit that have entered the climacteric have no lag (Workman, 1963). It is possible that k could be used to predict the ripening rate of fruit after harvest. High k values would indicate rapid ripening, while low values would indicate slow ripening.

Chlorophyll k and lightness change for COP were higher in late than early harvested fruit (Table 1). Initial values of total chlorophyll, hue angle, and lightness for the early harvest were $35.97 \mu\text{mol} \cdot \text{m}^{-2}$, $109.7 h^{\circ}$, and 69.1% , respectively, while corresponding values for late harvested fruit were $29.20 \mu\text{mol} \cdot \text{m}^{-2}$, $108.5 h^{\circ}$, and 60.9% . Early harvested COP apples yellowed more slowly than

late-harvested fruit because of higher initial chlorophyll concentrations and lower chlorophyll k values. For GS apples, there were no differences in k value, rate of hue angle, and lightness change (Table 1) and initial total chlorophyll concentration (93.44 and $86.20 \mu\text{mol} \cdot \text{m}^{-2}$), hue angle (117.4 and $117.5 h^{\circ}$), and lightness (60.9% and 60.6%) between harvests.

Although initial total chlorophyll concentration and initial hue angle did not differ between orchards for each cultivar, a considerable range in values were measured (24 to $39 \mu\text{mol} \cdot \text{m}^{-2}$ and 76 to $96 \mu\text{mol} \cdot \text{m}^{-2}$ for initial chlorophyll and 106 to $112 h^{\circ}$ and 116 to $119 h^{\circ}$ for initial hue angle for COP and GS, respectively). This suggests that an accurate description of postharvest color change would probably require derivation of parameters for each cultivar, orchard, season, and preharvest factor. These would account for any inherent differences due to location, microclimate, cultural practices, harvest date (Olsen and Schomer, 1971), and tree factors such as crop load, mineral content, fruit position on the tree, and fruit shading (Fallahi et al., 1997).

MODIFIED ARRHENIUS EQUATION. Both cultivars had the same pattern of response to temperature for values of k, which varied in magnitude rather than shape among fruit from different orchards, harvests, and years. For COP apples, k for total chlorophyll increased 11-fold from 0°C to a peak at 24.0°C , above which k declined (Fig. 4a). For GS apples, k for total chlorophyll increased

Table 2. Parameter values for Eq. [2] of total chlorophyll (k) and rate of hue angle change (h°/d) for 'Cox's Orange Pippin' (COP) and 'Granny Smith' (GS) apples.

		Parameter				r^2 (%)	P
Cultivar		K_a (d^{-1})	E_a/R (K^{-1})	$\Delta S/R$	$\Delta H/R$ (K^{-1})		
Chlorophyll (k)							
COP	Value	1.80×10^{23}	-16083.84	68.84	20039.05	91.0	<0.001
	SE	1.72×10^{24}	2717.79	6.46	1780.00		
GS	Value	2.50×10^{13}	-9923.28	91.30	27113.60	76.2	<0.001
	SE	1.78×10^{14}	2027.20	16.52	5055.48		
Hue angle (h°/d)							
COP	Value	1.76×10^{10}	-7055.07	67.55	20389.39	84.2	<0.001
	SE	6.32×10^{10}	1019.00	11.00	3401.00		
GS	Value	5.82×10^{13}	-9520.91	58.53	17182.03	70.2	<0.001
	SE	6.33×10^{14}	3041.39	8.97	2829.88

Fig. 4. Rate constant for total chlorophyll (a) and rate of hue angle change (b) in the skin of 'Cox's Orange Pippin' and 'Granny Smith' apples with temperature. The fitted curves were derived using the modified Arrhenius function (Eq. [2]) with parameters from Table 2.

8-fold from 0 $^{\circ}\text{C}$ to a peak at 20.4 $^{\circ}\text{C}$, above which k declined (Fig. 4a). This pattern of change with temperature is similar to the response curve for chlorophyllase activity in leaves of several plants (Holden, 1961) and illustrates the relationship between temperature and total chlorophyll k in COP and GS apples (Table 2). This is the first time temperature dependence of chlorophyll loss has been characterized in apples.

The asymptotic standard errors of the parameters of Eq. [2] indicate that the values for each parameter fall within the same range for both cultivars (Table 2), suggesting that the processes of chlorophyll loss and hue angle change are the same for each cultivar. The large standard error for K_a implies that this parameter is of little importance when fitting Eq. [2] to the values of k and hue angle change presented in this paper. To determine Eq. [2] parameters more accurately, additional measurements are needed at temperatures where the inflection points on the graph occur, i.e., 0 to 10 $^{\circ}\text{C}$ and 20 to 30 $^{\circ}\text{C}$. Changes of k in these regions had the greatest effect on the statistics of least square fitting (Feng et al., 1990).

Rates of hue angle change (Fig. 4b) had a similar pattern of response to temperature as did total chlorophyll k (Fig. 4a). For COP apples, rate of hue angle change increased 6-fold from 0 $^{\circ}\text{C}$ to a peak at 27.6 $^{\circ}\text{C}$, above which the rate of change declined. For GS apples, the rate of hue angle change increased 8-fold from 0 $^{\circ}\text{C}$ to a peak at 21.4 $^{\circ}\text{C}$, above which the rate of change declined. For COP apples, the modified Arrhenius curve for total chlorophyll k rose more quickly to a peak and declined more slowly thereafter than rates of hue angle change. This difference in curve shape may

be because hue angle measures all pigments in the apple skin, which may not have the same pattern of loss with temperature as chlorophyll. Despite this, the modified Arrhenius curve for rates of hue angle change was close to that of total chlorophyll k and could be used with confidence to predict color change with temperature. The aberrant value of hue angle change for GS apples at 35 $^{\circ}\text{C}$ was because the fruit developed severe internal browning, which affected chromameter measurements (data not shown).

The modified Arrhenius equation uses the current understanding of relationships between temperature and chemical reactions (the Arrhenius equation) and the nature of enzyme responses to temperature (the Boltzmann enzyme distribution function); it is based on commonly accepted physical and chemical theory (Johnson and Thornley, 1985). Parameters used in the modified Arrhenius equation represent characteristics of an enzyme system, such as activation energy (E_a). These parameters can be estimated for a variety of plant responses, e.g., apple cultivar differences in chlorophyll loss, and allow quantitative extrapolation of parameters from one study to another. The modified Arrhenius equation could also be used to characterize other temperature dependent processes, for example, to describe the relationship of ethylene production, respiration rate, or fruit firmness with temperature. Using k to describe chlorophyll loss could also help describe and interpret effects of other environmental factors affecting color in apples, such as oxygen, carbon dioxide, ethylene, and relative humidity effects. Such models may help postharvest handlers and marketers of apples to describe how cool-chain conditions will affect color and other important quality attributes.

ESTIMATING CHLOROPHYLL LOSS IN A SIMULATED APPLE COOL-CHAIN. Values of total chlorophyll k of COP apples and the modified Arrhenius equation can be used to predict rate of yellow-

Fig. 5. Total chlorophyll concentration of 'Cox's Orange Pippin' apples in a simulated idealized cool-chain compared with one where fruit had a 5-d delay at 20 $^{\circ}\text{C}$ before entering the same cool-chain. The idealized cool-chain consisted of picking, packing, and precooling to 3 $^{\circ}\text{C}$ within 24 h, 14 d at 3 $^{\circ}\text{C}$, loading onto a transport vessel, 28 d on ship at 3 $^{\circ}\text{C}$, 24 h unloading, then storage at a distribution center at 3 $^{\circ}\text{C}$ before shelf life at 20 $^{\circ}\text{C}$ in retail outlets. In this example, fruit were removed from 3 to 20 $^{\circ}\text{C}$ when they had an estimated shelf life of 7 d at 20 $^{\circ}\text{C}$. Fruit were considered unsaleable at a chlorophyll concentration of 5 $\mu\text{mol}\cdot\text{m}^{-2}$.

ing and potential storage and shelf life of fruit in different cool-chains. Color changes of fruit were simulated for an idealized cool-chain (fruit were harvested and cooled to 3 °C within 24 h) and for one that experienced a handling delay before precooling (Fig. 5). Total chlorophyll concentration of fruit was estimated using values of total chlorophyll *k* calculated using Eq. [2] and parameters presented in Fig. 4a. Initial chlorophyll values were assumed to be 45 $\mu\text{mol}\cdot\text{m}^{-2}$ ($\approx 112.5 \text{ h}^\circ$). Fruit were considered unsalable once a minimum total chlorophyll concentration of 5 $\mu\text{mol}\cdot\text{m}^{-2}$ (or a hue angle of $\approx 95 \text{ h}^\circ$) was reached (these values were obtained from Fig. 3a).

Shelf life (days at 20 °C) of COP apples in the idealized cool-chain after 44 d at 3 °C (the typical storage period for New Zealand apples exported to the United Kingdom before retail sale) was estimated to be 17.4 d; this was reduced to 13.3 d, a 23% reduction, in fruit with delayed cooling. In the idealized cool-chain, maximum storage life of fruit at 3 °C with no subsequent shelf life was ≈ 201 d compared with ≈ 154 d for fruit exposed to a 5-d delay at 20 °C before cooling. Assuming the need to have a shelf life of 7 d, storage life of fruit from the idealized cool-chain was ≈ 164 d, 57 d more than delayed-storage fruit (Fig. 5). This difference was about the same regardless of shelf life requirements (e.g., 4, 7, or 10 d) for fruit experiencing a 5-d delay before cooling because of the approximate parallel curves for chlorophyll decay. Every day of delay at 20 °C before precooling represents a subsequent loss of ≈ 9.5 d storage life at 3 °C, reflecting differences in values of *k* at these respective temperatures. This model highlights graphically the importance of field heat removal on rate of change of one important quality attribute of apples and reinforces the importance of maintaining temperature control throughout the cool-chain (Wills et al., 1989). This simulation shows that rapid cooling gives marketers more flexibility in distributing fruit from cool storage to retail outlets by indicating how long fruit can be in cool storage and yet have a predetermined shelf life. It is likely that *k* values, derived for other elements in the cool-chain, such as atmosphere composition, can be used to describe specific attributes of apple quality.

Establishment of this relationship between chlorophyll and hue angle makes it possible to calculate chlorophyll content using a chromameter and allows repeated nondestructive, indirect estimation of chlorophyll at the same position on the same fruit during storage. This should give greater accuracy of estimates of color change than using average measurements from several fruit. The rate constant of chlorophyll loss or hue angle change can be used to estimate yellowing in COP and GS apples over a wide range of temperatures during postharvest handling, provided variations in some parameters caused by preharvest factors are taken into account. Potential storage and shelf life can be estimated using this approach, and it also provides a tool to evaluate effectiveness of cool-chain handling systems.

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