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Changes in Compositional Parameters of Tubers of Potato (*Solanum tuberosum*) during Low-Temperature Storage and Their Relationship to Chip Processing Quality

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A four-year study of a number of compositional parameters of potato tubers during low-temperature storage was conducted to examine the compositional differences between cold-tolerant (low sugar-accumulating) and cold-sensitive (high sugar-accumulating) tubers in relation to potato chip processing quality. Compositional parameters analyzed included sucrose, reducing sugars, nitrogen, protein, ascorbic acid, and dry matter content. Pearson correlation analysis of the data illustrated that chip color was most closely correlated with reducing sugar concentration. Multiple regression analysis revealed that the relative contribution of each parameter to chip color varied greatly among the cultivars and selections evaluated and from season to season. This analysis demonstrates that the quantitative relationships between the measured compositional parameters and chip color were not sufficient to provide a general predictive index of chip color quality for tubers processed directly from low-temperature storage.

KEYWORDS: Ascorbic acid; chip color; low-temperature sweetening; nitrogen; potato; protein; reducing sugars

INTRODUCTION

Following exposure to low temperatures (i.e., <9−10 °C), tubers of potato (*Solanum tuberosum*) undergo a phenomenon known as low-temperature sweetening (LTS) (*1*−*3*). LTS is a widespread but not universally occurring phenomenon that occurs in various parts of many higher plants exposed to lower than optimum growth or storage temperatures (*2*). In stored potato tubers, LTS results in the accumulation of starch breakdown products, primarily sucrose and the reducing sugars glucose and fructose (*2*). The exact mechanism by which LTS occurs remains to be elucidated. Despite extensive research and numerous proposed mechanisms, there is still very little agreement with respect to the exact mechanism of LTS in potato tubers.

Sugar accumulation associated with LTS in potato tubers develops within a few days of exposure to cold (*3*−*5*). The cold-induced accumulation of high levels of reducing sugars from starch reserves is of concern to the potato-processing industry due to the participation of reducing sugars as substrates in the Maillard browning reaction during frying (*1*, *3*, *6*). High levels of reducing sugars result in the production of dark-colored chips that are unacceptable to the consumer due to their appearance and bitter taste. This deterioration in chip color quality may be reversed by reconditioning the cold-stored tubers at warmer storage temperatures (i.e., >10 °C) prior to processing, which results in a decrease in reducing sugar content as some of these sugars are converted back into starch (*7*). However, reconditioning does not always lower the concentration of reducing sugars to acceptable levels, and long-term LTS is considered to be irreversible (*3*). Therefore, to maintain low levels of sugars during long-term storage, processing potatoes are generally stored at temperatures around 9−10 °C and are treated with dormancy-prolonging chemicals to prevent sprouting.

In recent years, there has been great interest in the development of potato cultivars that can be processed into chips with acceptable color directly from low-temperature storage (e.g., 4 °C). Advantages to storing tubers at low temperature include natural control of sprout growth, minimization of physiological weight loss (i.e., H_2O and dry matter) due to decreased respiration, and reduction in losses associated with bacterial and fungal pathogens (*1*). The ability to store potato tubers at low temperature for long periods of time would alleviate environmental and consumer concerns regarding the use of chemicals for the prevention of sprouting and the control of storage pathogens. Despite the many advantages to low-temperature storage, the associated hexose accumulation in most cultivars is a major drawback, as this results in potato tubers that are unsuitable for processing.

The primary objective of this four-year study was to examine the differences in a series of compositional factors (i.e., reducing sugars, sucrose, solids/dry matter content, protein, total nitrogen, and ascorbic acid) between high sugar-accumulating, cold-sensitive cultivars and low sugar-accumulating, cold-tolerant

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selections stored at 4 °C and to evaluate the quantitative relationships between these compositional factors and potato chip processing quality (i.e., chip color).

MATERIALS AND METHODS

Plant Material. Mature *Solanum tuberosum* tubers of the cultivar Novachip and the cold-tolerant selection ND 860-2 were obtained from the University of Guelph Agricultural Research Station at Cambridge, ON, Canada, in the fall of 1997, 1998, and 1999. In the 2000 season, tubers of the cold-tolerant selections ND 860-2 (North Dakota), Wis 1355-1 (Wisconsin), and V 0056-1 (Alberta) were obtained from the Cambridge Research Station, tubers of the cultivar Monona were obtained from WD Potatoes (Beeton, ON, Canada), and Novachip tubers were obtained from Garth McEwen (New London, PE, Canada). The cultivars Novachip and Monona were chosen on the basis that both are very susceptible to LTS (V. Currie, personal communication). The cultivars and selections evaluated were not closely related, with the exception of ND 860-2 and V 0056-1 (the male parent of V 0056-1 is ND 860-2). All tubers were cured for 2 weeks at 15 °C and 90−95% relative humidity prior to 4 °C storage at 90−95% relative humidity at the University of Guelph Horticultural Cold Storage facility. The duration of each storage experiment was ∼10 weeks.

Chip Color Determination. A composite chip score for each cultivar or selection was determined from two replicates consisting of six potatoes each, which were abrasion-peeled and then sliced into 1 mm thick slices using a Hobart mechanical slicer (Hobart Corp., Troy, OH). The tuber slices were fried in vegetable shortening at 175 °C. Chips were considered to be cooked when the oil ceased bubbling. Samples were crushed into small (∼0.5 in.) pieces, and chip color was evaluated using an Agtron M30A colorimeter (Chism Machinery, Niagara Falls, ON, Canada) as an average of three separate measurements. Reference reflectance disks were used to calibrate the Agtron (Agtron score 0 = black, Agtron score 90 = white). Using this instrument, commercially acceptable chips are defined as those having an Agtron score of ≥50.

Sugar Analysis. Potato tuber concentrations of sucrose, and the reducing sugars fructose and glucose, were quantified on the basis of the HPLC technique of Wilson et al. (*8*). Two replicate determinations were performed for each sampling date. For each extraction, a 100 g sample of peeled and chopped potato, obtained from five tubers, was homogenized in 80 mL of methanol for 1.5 min at full speed in a Waring commercial laboratory blender. The homogenate was added to 5 g of activated carbon (50−200 mesh) and shaken for 20 min at room temperature on a benchtop orbital shaker (Lab-Line Instruments Inc., Melrose Park, IL). Samples were then stored for at least 1 h at 4 °C, followed by vacuum filtration through Whatman No.2 paper (Fisher Scientific, Whitby, ON, Canada). The filtrate was incubated at 35 °C for 16 h to precipitate proteins and then stored at 4 °C until analyzed by HPLC. Sample cleanup consisted of passing the sample through a Sep-Pak Alumina A cartridge (Waters Associates, Milford, MA), followed by filtration through a 0.45 μm Magna 13 mm nylon filter (Osmonics Inc., Minnetonka, MN).

The HPLC system consisted of a Beckman 110B solvent delivery module (Beckman Coulter Inc., Mississauga, ON, Canada) equipped with a Waters R401 differential refractometer (Waters Associates), a Jones Apex NH_2 column, 5 μm, 4.6 × 250 mm (Chromatographic Specialties, Brockville, ON, Canada), and an Alltech Adsorbosphere NH_2 guard column, 4.6 × 15 mm (Mandel Scientific, Guelph, ON, Canada). The mobile phase was 75:25 (v/v) acetonitrile/water run at 2.0 mL min^{-1} at room temperature. A standard curve was prepared using solutions containing 0.25−5.0 mg mL^{-1} of a 1:1:1 ratio of fructose/glucose/sucrose in 50:50 (v/v) methanol/water.

Dry Matter Determination. For each sampling date, a 10−20 g sample of peeled and thinly sliced (i.e., 1 mm) potato obtained from five tubers was dried at 110 °C for 48 h. The dry matter content was determined as the dry weight (DW) divided by the fresh weight (FW).

Protein Determinations. Protein concentrations were determined using the Bio-Rad protein assay (Bio-Rad Laboratories, Mississauga, ON, Canada), which is based on the Bradford dye binding assay (*9*). On each sampling date, two separate extractions were performed for each cultivar or selection. Each extraction consisted of a 10−20 g sample of peeled and chopped potato (obtained from five tubers), juiced using a Braun model MP50 juicer (Braun Canada Ltd., Mississauga, ON, Canada). A 50 μL volume of extract was added to 2.5 mL of the Coomassie blue dye reagent. Samples were incubated at room temperature for 15 min, and absorbance was measured at 595 nm. Bovine serum albumin (BSA) (Bio-Rad Laboratories) was used to generate the standard curve. The protein concentration of each sample was calculated as an average of three determinations.

Nitrogen Determinations. Total nitrogen concentrations were determined using a LECO FP-228 nitrogen analyzer (LECO Corp., St. Joseph, MI). For each cultivar or selection, total nitrogen content was determined from two replicates of 0.1 g of lyophilized potato tissue from each sampling date. Total nitrogen concentrations were converted from dry weight percentages to units of milligrams per gram of FW.

Ascorbic Acid Determinations. Ascorbic acid concentrations were determined according to the method of Sapers et al. (*10*). On each sampling date, samples of 10−15 g of peeled and chopped potato (obtained from five tubers) from two separate extractions for each cultivar or selection were frozen in liquid nitrogen and stored at −85 °C. The extraction procedure consisted of vortexing 0.5 g of lyophilized tissue in 7.5 mL of a 2:1 (v/v) mixture of acetonitrile/0.05 M KH_2PO_4 (75:25) and 2.5% metaphosphoric acid. Samples were vortexed for 1 min and then microcentrifuged at 12800*g* for 3 min. The pH of the samples was adjusted to pH 6 using 80 μL of 2 N NaOH. Samples were then reduced by adding 120 μL of 2.5% (w/v) DTT in mobile phase and vortexed for 1 min. The reaction mixture was kept at room temperature for 30 min. Prior to injection, samples were filtered through C_{18} SPE cartridges (Chromatographic Specialties Inc., Brockville, ON, Canada) previously conditioned by flushing with the extraction solvent and then passed through a 0.45 μm Magna 13 mm nylon filter (Osmonics Inc.).

Separations were achieved by isocratic elution of a Jones Apex NH_2 column, 5 μm, 4.6 × 250 mm (Chromatographic Specialties), with acetonitrile/0.050 M KH_2PO_4 (75:25, v/v) at a flow rate of 1.5 mL min^{-1}. An Alltech Adsorbosphere NH_2 guard column, 4.6 × 15 mm (Mandel Scientific), was also used. The HPLC system consisted of a Rheodyne model 7125 injector with a 20 μL sample loop, a Beckman 110 B solvent delivery module, and a Varian 2050 variable wavelength detector (Varian Canada Inc., Mississauga, ON, Canada) operated at 254 nm. Sample injection volume was 20 μL. An ascorbic acid standard curve was prepared using solutions containing 10, 20, 50, 100, 150, and 200 μg mL^{-1} L-ascorbic acid (Sigma-Aldrich Ltd., Oakville, ON, Canada).

Statistical Analysis. Statistical analysis of the data was performed using SAS version 8.1 (SAS Institute Inc., Cary, NC). Duncan's multiple-range tests were performed to determine significant differences ($P \leq 0.05$) among treatment (i.e., cultivar or selection) means and significant differences ($P \leq 0.05$) among time points within each treatment. Stepwise elimination multiple regression and Pearson correlation analyses were also performed to evaluate the relationships between chip color and the various metabolic and compositional parameters measured in this study. For both of these analyses, the chosen level of significance was 0.05. The term significant is used to indicate differences for which $P \leq 0.05$.

RESULTS AND DISCUSSION

Chip Color. The results for chip color quality, as determined by Agtron color measurements, are presented in **Figure 1**. In the 1997 season, the cold-tolerant ND 860-2 tubers maintained a significantly lighter color relative to the cold-sensitive Novachip tubers over the duration of 4 °C storage, as indicated by the higher Agtron scores. Chip color quality declined rapidly in Novachip. Similar trends were observed in 1999; however, chip color scores for ND 860-2 declined more rapidly over the first few weeks of storage relative to 1997. In the 2000 season, chip color scores were again higher for ND 860−2 relative to Novachip over the duration of storage. The results for the second cold-sensitive cultivar (Monona) and the two additional cold-tolerant selections (V 0056-1 and Wis 1355-1) evaluated in the

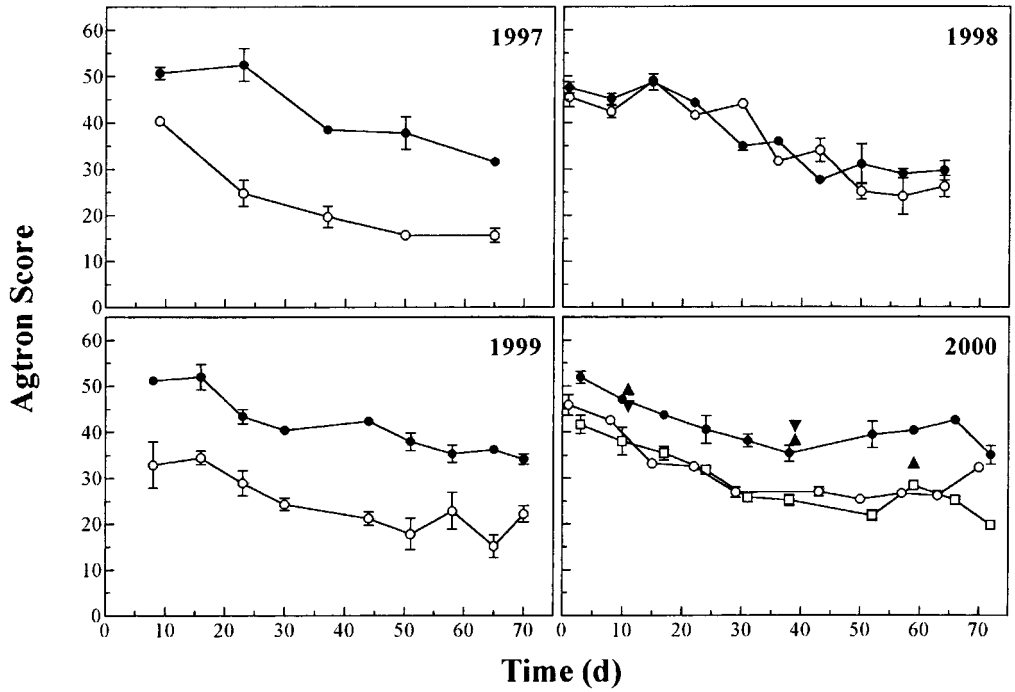

Figure 1. Chip color scores for potato tubers stored at 4 °C, 1997–2000 seasons: (●) ND 860-2; (○) Novachip; (□) Monona; (▼) V 0056-1; (▲) Wis 1355-1. The data are presented as the mean ± standard deviation of two replicates (three determinations per replicate).

2000 season were comparable to the respective results for Novachip and ND 860-2.

In the 1998 season, chip color quality was similar for ND 860-2 and Novachip over the duration of storage. Agtron scores for Novachip were higher than in any of the other three years of study, whereas chip color scores for ND 860-2 declined more rapidly and to a greater extent in 1998 than in 1997, 1999, or 2000. This may be attributed to the occurrence of moisture stress during the growing season. During the course of the 1998 storage experiment, it was observed that in many chip samples, a combination of light and dark chips was produced, and in a late season measurement, a single tuber was found to produce a mixture of light and dark chips. These observations are consistent with published results concerning the color of French fries produced from tubers subjected to moisture stress (i.e., sugar-end tubers) (*11*, *12*).

The chip color observations for the 1997, 1999, and 2000 seasons were consistent with expected results, as the cold-tolerant selections produced lighter chips relative to the cold-sensitive cultivars. In all years of this study, processing of the cold-tolerant tubers directly from 4 °C storage did not produce chips with industry-acceptable Agtron color scores (i.e., ≥50) for an extended period of time. Although this is important from an industry perspective, this does not diminish the comparison of the metabolic behavior in cold-tolerant and cold-sensitive tubers, nor does it compromise the study of the relationship between compositional changes during storage and chip color quality. Efforts to develop potato varieties with acceptable cold-chipping performance are ongoing, and the cold-tolerant selections evaluated in this study are representative of the attempts of North American breeding programs to develop cultivars with suitable cold tolerance. The notable difference in the chip color results for the 1998 season can be partially attributed to the perturbation of metabolism caused by the occurrence of water deficit stress during the growing season. The fact that chip color was not as negatively affected in Novachip tubers may be due to genotypic differences in the response to moisture stress (*12*, *13*).

Sugar Accumulation. Tissue reducing sugar accumulations (i.e., fructose + glucose) are presented in **Figure 2**. During the 1997, 1999, and 2000 storage seasons, accumulations of reducing sugars were significantly higher for Novachip relative to ND 860-2. The additional cold-tolerant selections screened during the 2000 season had reducing sugar concentrations at or just slightly below the levels observed for ND 860-2. The pattern of reducing sugar accumulation in Monona was almost identical to that of Novachip. In 1998, accumulations of reducing sugars in ND 860-2 tubers were greater than in any of the other three seasons of study, and levels were significantly higher relative to Novachip.

Tissue concentrations of sucrose (**Figure 3**) were higher and showed greater fluctuations relative to levels of reducing sugars in all four storage seasons. In the 1997, 1999, and 2000 seasons, sucrose levels increased rapidly over the first 10−12 days of storage for Novachip tubers and fluctuated over the remainder of the storage period. During each of these years, only slight increases in sucrose levels were observed for ND 860-2 tubers over the initial 10−12 days of storage. Subsequently, ND 860-2 sucrose levels remained relatively stable, with only subtle fluctuations over the balance of the storage period. In 2000, the cold-sensitive Monona tubers showed sucrose accumulation patterns similar to those of Novachip, whereas sucrose accumulation in the additional cold-tolerant selections screened was either slightly greater than (Wis 1355-1) or less than (V 0056-1) those observed in ND 860-2. During the 1998 season, sucrose content increased sharply in both Novachip and ND 860-2 tubers. Sucrose levels in Novachip were lower than in other seasons; however, levels in ND 860-2 were at least 25% higher (and up to 79% higher) relative to ND 860-2 tubers from the other three seasons of study. Similar to the other three years, 1998 sucrose levels were, on average, significantly higher for Novachip relative to ND 860-2.

The patterns of reducing sugar and sucrose accumulation observed during 1997, 1999, and 2000 are consistent with previous studies comparing the responses of cold-tolerant selections and cold-sensitive cultivars to low-temperature storage

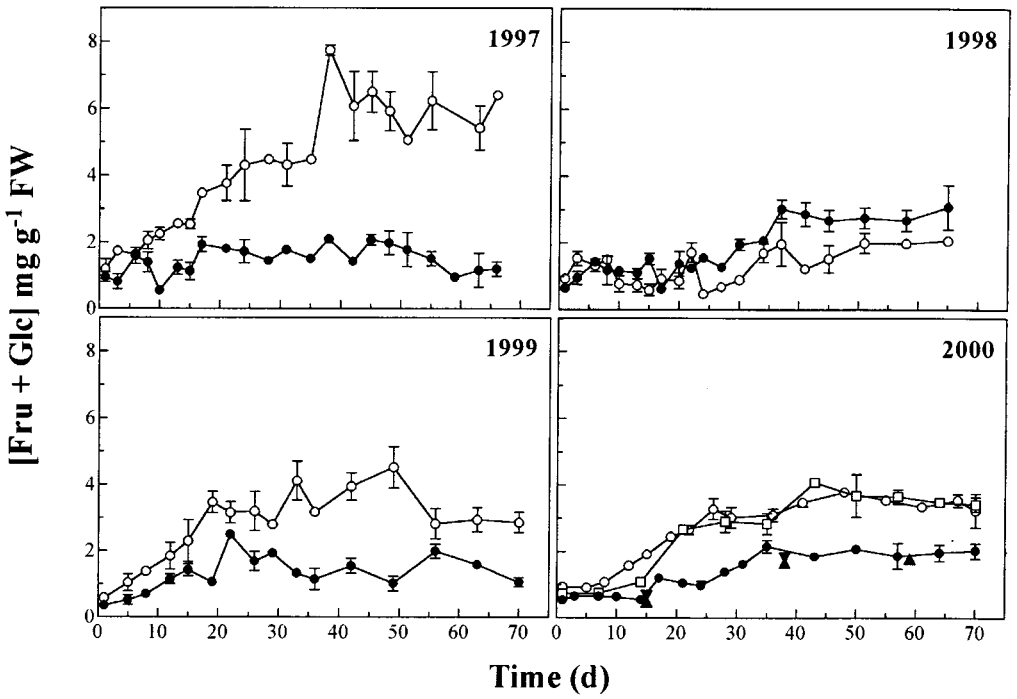

Figure 2. Reducing sugar concentrations (Fru + Glc) for potato tubers stored at 4 °C, 1997–2000 seasons: (●) ND 860-2; (○) Novachip; (□) Monona; (▼) V 0056-1; (▲) Wis 1355-1. The data are presented as the mean ± standard deviation of two replicates (one determination per replicate).

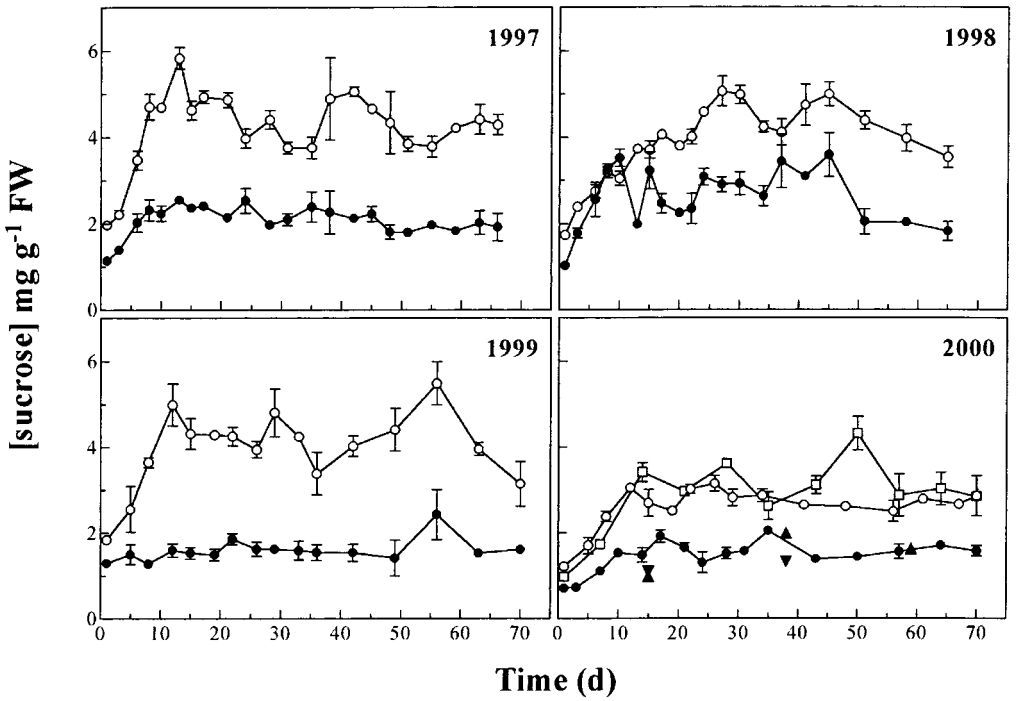

Figure 3. Sucrose concentrations for potato tubers stored at 4 °C, 1997–2000 seasons: (●) ND 860-2; (○) Novachip; (□) Monona; (▼) V 0056-1; (▲) Wis 1355-1. The data are presented as the mean ± standard deviation of two replicates (one determination per replicate).

(*3*, *14*, *15*). In 1998, the magnitudes of sugar accumulation for ND 860-2 and Novachip tubers were remarkably different from the three other years of the study, due to the suspected effects of moisture stress during the growing season. Relative to the 1997, 1999, and 2000 seasons, ND 860-2 tubers accumulated greater levels of reducing sugars and sucrose in 1998, whereas sugar accumulations were substantially lower in Novachip tubers, so much so that levels of reducing sugars were significantly lower than in ND 860-2 tubers. Moisture stress during tuber growth, particularly during the early stages of development, is associated with the occurrence of sugar-end tubers (*11*, *12*, *16*). In this study, tuber sugar concentrations were determined from whole tissue extracts rather than from longitudinal sections (i.e., basal, center, and apical regions). Although no direct evidence for the occurrence of sugar-end tubers in 1998 can be provided from the analysis of sugar accumulations, the 1998 observations of chip color provide support for the occurrence of sugar-end tubers caused by moisture stress.

There is general agreement that reducing sugars are the most influential factor in potato chip color development (*17*−*21*). As a result, the processing industry utilizes reducing sugar levels

Table 1. Mean Concentrations of Protein, Total Nitrogen, and Dry Matter Content in Potato Tubers Stored at 4 °C, 1997–2000 Seasons[a]

	dry matter, g of DW g^{-1} of FW	protein, mg g^{-1} of FW	total N, mg g^{-1} of FW
		1997	
ND 860-2	0.20 ± 0.01a (44)	4.81 ± 0.63a (44)	4.00 ± 0.31a (41)
Novachip	0.21 ± 0.01a (44)	4.97 ± 0.41a (44)	4.03 ± 0.47a (44)
		1998	
ND 860-2	0.20 ± 0.01b (40)	8.51 ± 0.78b (40)	4.68 ± 0.34b (38)
Novachip	0.23 ± 0.01a (40)	10.89 ± 0.87a (40)	5.22 ± 0.41a (38)
		1999	
ND 860-2	0.20 ± 0.00b (44)	7.94 ± 1.11a (32)	4.38 ± 0.32a (32)
Novachip	0.22 ± 0.01a (44)	7.56 ± 0.62a (32)	4.30 ± 0.31a (32)
		2000	
ND 860-2	0.21 ± 0.01a (32)	7.78 ± 0.57a (32)	3.84 ± 0.42a (32)
Wis 1355-1	0.23 ± 0.01a (6)	7.26 ± 0.88a (6)	2.95 ± 0.36b (6)
V 0056-1	0.21 ± 0.00a (4)	6.18 ± 0.23b (4)	3.55 ± 0.12a (4)
Novachip	0.22 ± 0.01a (32)	7.30 ± 0.49a (32)	3.71 ± 0.32a (32)
Monona	0.19 ± 0.01b (22)	5.12 ± 0.40c (22)	3.79 ± 0.33a (22)

[a] Results are presented as means ± SD of (*n*) samples. For a given year, means within a column with the same letter are not significantly different ($P \leq 0.05$).

as a predictive test of the suitability of stored potatoes for processing into potato chips and French fries (*18*). Although reducing sugar content may be a strong predictor of chip color development, some potato varieties show considerable variation with this association (*6*). The nonreducing sugar sucrose does not participate directly in the Maillard reaction, yet it does contribute to chip color development via its hydrolysis during frying (*22*, *23*). However, low correlations between sucrose levels and chip (or fry) color have been reported (*18*, *24*, *25*). In this study, the 1997, 1999, and 2000 season results illustrate a trend in which the tubers with the lower reducing sugar content (i.e., the cold-tolerant selections) maintained higher chip color scores over the duration of storage. In the 1998 season, a year in which reducing sugar levels were slightly higher in ND 860-2 relative to Novachip, chip color quality did not differ significantly. Therefore, in a general sense, these trends support the assumption that the level of reducing sugars is the most important factor in chip color development. The quantitative relationship between reducing sugars and chip color will be evaluated and discussed further in the correlation and multiple regression analyses.

Dry Matter Content. In each year of study, and for all cultivars and selections, the dry matter content remained relatively constant over the duration of the storage experiment (i.e., maximum standard deviation of 1%) (**Table 1**), indicating that the storage conditions were adequate in limiting weight loss due to transpiration. The subtle year-to-year variations in the dry matter contents of ND 860-2 and Novachip may be a result of differences in H_2O loss during curing, differences in amount and rate of cell suberization and wound periderm formation, and seasonal variations in growing conditions (e.g., temperature, moisture supply, and light) (*26*, *27*).

Protein. In each year of study, and for both cold-tolerant and cold-sensitive tubers, protein concentrations did not change significantly over the 10-week storage period. In the 1997 and 1999 seasons, mean protein concentrations for ND 860-2 and Novachip were not significantly different (**Table 1**). In 1999, protein concentrations were, on average, at least 1.5 times higher than in 1997. During the 2000 season, mean levels of protein were not significantly different for Novachip, ND 860-2, and Wis 1355-1, whereas protein levels were significantly lower in V 0056-1 and Monona (**Table 1**). Protein concentrations during the moisture-stressed 1998 season were much higher and more variable than those observed during the other three years of the study (**Table 1**).

Protein content as a percentage of tuber fresh weight typically falls in the range of 0.66−1.20% (*28*). Of the four seasons of study, levels of protein were highest in the moisture-stressed 1998 season. Davies et al. (*29*) observed that tubers subjected to water deficit stress contained greater concentrations of protein relative to unstressed tubers. However, a physiological explanation for this occurrence was not given. No significant overall increases or decreases in total protein concentration were observed during storage, consistent with previous findings (*30*).

Total Nitrogen. During all four years of study, no significant overall changes in total nitrogen were observed over the 10-week storage period. In 1997 and 1999, the mean levels of total nitrogen were not significantly different for ND 860-2 and Novachip (**Table 1**). In the 2000 season, there were some fluctuations in total nitrogen levels with time; however, the mean levels were not significantly different for ND 860-2, Novachip, Monona, and V 0056-1, whereas levels for Wis 1355-1 were significantly lower. In 1998, total nitrogen levels were higher than in the other three years of the study. Novachip had a significantly higher mean total nitrogen content relative to ND 860-2.

In potato tubers, nitrogen occurs primarily in the form of protein, many different nonprotein organic compounds (such as free amino acids), and inorganic nitrogen (*27*). Total nitrogen as a percentage of fresh weight is typically between 0.24 and 0.36% (*28*). However, nitrogen levels may vary depending on fertilization practices (*20*, *31*−*33*). Of the total nitrogen content, protein nitrogen constitutes 37.5−63.7% and nonprotein nitrogen makes up the remainder (*28*). Other studies suggest that typically ∼50% of the total nitrogen content is true protein, the amide and free amino acid fraction accounts for ∼40%, with the remaining 10% of the total nitrogen unrelated to proteins (*34*, *35*).

The nonprotein nitrogen fraction of potato tubers contains both organic and inorganic nitrogen. The organic nitrogen fraction consists of free amino acids, purine and pyrimidine derivatives, and the steroid alkaloids, including glycoalkaloids (*28*). The inorganic nitrogen fraction contains nitrate and nitrite. From a processing standpoint, the most important component of nonprotein nitrogen is the free amino acid fraction, which accounts for 40−50% of the total nonprotein nitrogen in potato tubers (*36*). Free amino acids have been reported to be highly relevant to problems of potato processing because of their involvement in Maillard browning (*37*, *38*) and observed anomalies in the relationship between reducing sugars and chip color (*20*, *39*, *40*). The amides glutamine and asparagine have consistently been found to comprise a large proportion of the free amino acid pool in potato tubers in a number of studies (*40*−*43*). Brierley et al. (*40*) observed that these amides accounted for 50−90% of the total free amino acid content of tubers. The concentration of free amino acids is significantly affected by fertilization practices: increasing nitrogen fertilization has been shown to increase the concentration of free amino acids (*20*, *44*) as well as the degree of browning per unit reducing sugar (*20*, *33*).

Ascorbic Acid. The ascorbic acid content of potato tubers is highly variable and depends on a number of factors including variety, temperature, soil composition, nitrogen fertilizer application, handling of the tubers, storage temperature, and storage duration (*6*, *45*−*47*). Ascorbic acid is typically found in potato tubers at concentrations ranging from 8 to 30 mg 100

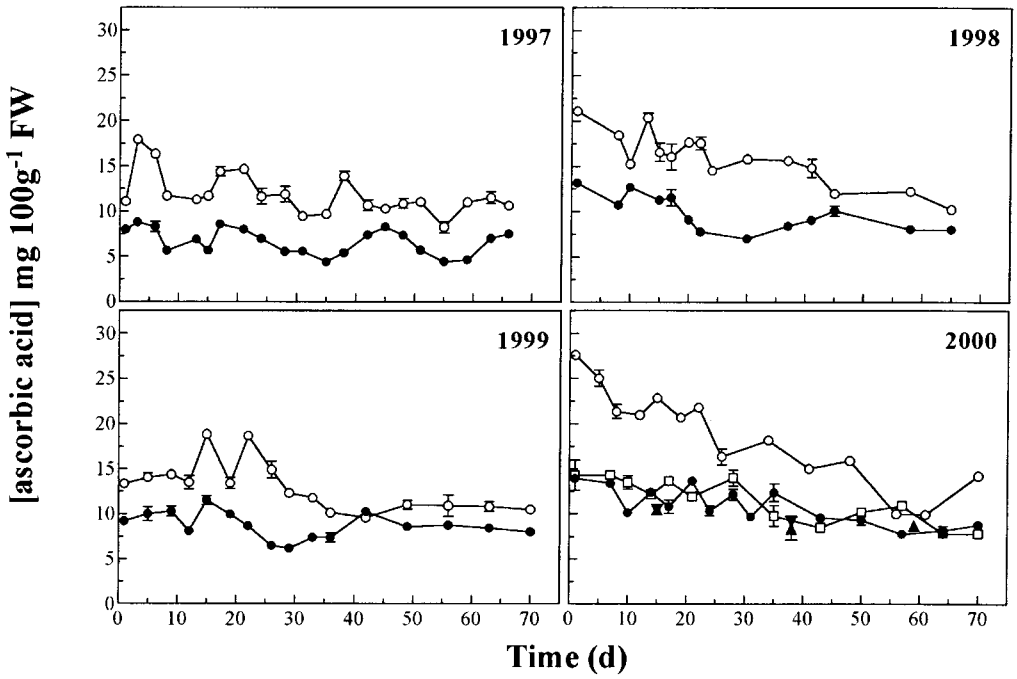

Figure 4. Ascorbic acid concentrations for potato tubers stored at 4 °C, 1997–2000 seasons: (●) ND 860-2; (○) Novachip; (□) Monona; (▼) V 0056-1; (▲) Wis 1355-1. The data are presented as the mean ± standard deviation of two replicates (one determination per replicate).

g^{-1} of FW (*25*, *36*). Concentrations of ascorbic acid were significantly higher for Novachip during all four years (**Figure 4**). In 1997, ascorbic acid concentrations were highly variable during the storage period for both ND 860-2 and Novachip tubers. Ascorbic acid levels decreased dramatically with time in Novachip tubers, whereas only a slight overall decrease was observed in ND 860-2 tubers. Similar temporal patterns were observed during the 1999 season. In the 2000 season, ascorbic acid concentrations for Novachip were higher, and the overall decrease over time was greater than in any of the previous three seasons of the study. Over the 10-week storage period, ascorbic acid levels in Novachip tubers decreased by ~56%, compared to a loss of 37% in ND 860-2 tubers. Levels in Monona tubers decreased by 45% over the same period of time. Ascorbic acid levels were evaluated at only a few time points during the storage period for Wis 1355-1 and V 0056-1; however, levels were consistent with those observed for ND 860-2. In 1998, levels of ascorbic acid in ND 860-2 and Novachip decreased over time in a pattern similar to that of 1997 and 1999; however, absolute concentrations were higher.

In agreement with previous studies (*30*, *36*, *48*, *49*), there was a gradual but significant decrease in ascorbic acid content during storage for the cold-tolerant selection ND 860-2 and the cold-sensitive cultivars Novachip and Monona. In all years of study, the decrease in ascorbic acid concentration was greater for Novachip relative to ND 860-2. Although they were evaluated at only a few time points, the additional cold-tolerant selections, V 0056-1 and Wis 1355-1, showed temporal changes in ascorbic acid similar to those of ND 860-2. In all years of study the temporal decrease in ascorbic acid concentration was greatest for Novachip. The losses of ascorbic acid may indicate oxidation with formation of dehydroascorbic acid, which could participate in chip browning. Dehydroascorbic acid browns readily when heated and might have contributed to chip browning in this study. Dehydroascorbic acid content, however, was not determined in this study.

Ascorbic acid has been reported to play a role in unfavorable browning reactions such as the Maillard reaction, which occurs during chip-frying operations (*50*, *51*). This compound reacts with free amino acids during frying and produces a dark color in model systems (*50*). However, Mazza (*30*) did not find a significant correlation between ascorbic acid content and chip color development in stored Russet Burbank and Norchip potatoes. In a more recent study, Rodriguez-Saona and Wrolstad (*25*) found a significant negative correlation ($r = -0.7$) between ascorbic acid levels and chip color measurements of tubers from five potato cultivars. The authors also indicated that varieties with different concentrations of reducing sugars produced chips with similar color attributes, suggesting that reducing sugar levels alone do not account for the total variation in chip color. At low levels of reducing sugars (i.e., <60 mg 100 g^{-1} of FW), other constituents, including ascorbic acid, were found to have a significant effect on chip color.

Compositional Indicators of Chip Color Quality. The identification of metabolic and compositional factors that account for the variation in chip color quality among potato cultivars is an issue which has been addressed by many researchers (e.g., refs *6*, *30*, and *51*). Although reducing sugar levels may explain most of the variation in color development, some potato cultivars show deviations in this relationship (*6*, *33*). An analysis of the data from the four years of this study was performed to determine the relationship between chip color and the compositional parameters measured and to assess whether any of these parameters may be useful in predicting the chip color of cold-tolerant and cold-sensitive tubers from 4 °C storage.

The individual relationships between chip color and each of the compositional parameters measured in this study were assessed using correlation analysis (**Table 2**). Of the compositional factors measured, there was no single, common parameter that consistently demonstrated a significant relationship with chip color among all cultivars and selections over all four years. The variable that demonstrated the greatest number of significant correlations with chip color was reducing sugar concentration. In all four years of the study, there was a significant negative relationship between chip color and reducing sugars for Nova-

Table 2. Pearson Correlation Coefficients for the Relationship between Chip Color and the Compositional Parameters Measured for Potato Cultivars and Selections Stored at 4 °C, 1997–2000 Seasons[a]

	compositional parameter					
	reducing sugars	sucrose	dry matter content	protein	total nitrogen	ascorbic acid
			1997			
ND 860-2	0.07d	0.44d	0.16d	–0.36d	0.26d	–0.10d
Novachip	–0.75c	0.07d	0.46d	–0.58d	–0.11d	–0.02d
			1998			
ND 860-2	–0.83a	–0.05d	0.39d	–0.27d	–0.28d	0.58c
Novachip	–0.80a	–0.34d	0.41d	0.13d	0.27d	0.77a
			1999			
ND 860-2	–0.17d	–0.25d	0.51c	0.28d	–0.07d	0.65b
Novachip	–0.51c	–0.20d	0.08d	0.06d	–0.25d	0.71a
			2000			
ND 860-2	–0.73a	–0.60b	0.11d	0.31d	–0.49c	–0.07d
Wis 1355-1	–0.99b	–0.98c	–0.55d	–[b]	–	0.85d
V 0056-1	–0.97a	–0.77d	0.88c	–0.09d	–0.49d	0.69d
Novachip	–0.92a	–0.65b	0.18d	0.14d	–0.38d	0.81a
Monona	–0.82a	–0.67b	0.22d	–0.09d	0.03d	0.81a

[a] Significant at the (a) 0.0001 level of probability, (b) the 0.01 level of probability, and (c) the 0.05 level of probability, and (d) not significant at the 0.05 level of probability. [b] –, insufficient number of observations.

Table 3. Multiple Coefficients of Variation, Multiple Correlation Coefficients, and Regression Equations for the Relationship between Chip Color and the Compositional Parameters for Potato Cultivars and Selections Stored at 4 °C, 1997–2000 Seasons

year	cultivar/selection	multiple coefficient of determination (R^2)	multiple correlation coefficient (r)	regression eq[a]
1997	ND 860-2	–[b]	–	–
	Novachip	0.56	0.75	chip color = 41.31544 – 3.55241 × reducing sugars
1998	ND 860-2	0.66	0.81	chip color = 52.58153 – 7.26293 × reducing sugars
	Novachip	0.79	0.89	chip color = 29.10914 – 7.84513 × reducing sugars – 1.28796 × ascorbate
1999	ND 860-2	0.42	0.65	chip color = 16.78907 + 2.74843 × ascorbate
	Novachip	0.51	0.71	chip color = 5.57854 + 1.44850 × ascorbate
2000	ND 860-2	0.41	0.64	chip color = 47.82710 – 4.71871 × reducing sugars
	Novachip	0.91	0.96	chip color = 54.31872 – 2.78066 × sucrose – 5.59346 × reducing sugars
	Monona	0.87	0.93	chip color = 34.69490 – 3.56807 × sucrose – 0.00268 × protein + 1.62630 × ascorbate
	V 0056-1	–	–	–
	Wis 1355-1	–	–	–

[a] Multiple regression analyses performed using stepwise elimination. [b] –, no regression model as no variable met the 0.05 significance level for inclusion in the model.

chip; however, this relationship was only significant in 1998 and 2000 for ND 860-2 (**Table 2**). The negative correlation between chip color and reducing sugars was also significant for all cultivars and selections studied in 2000. With the exception of the 2000 season, sucrose concentrations did not correlate well with chip color (**Table 2**). Levels of ascorbic acid and chip color scores were found to be significantly and positively correlated for ND 860-2 in 1998 and 1999; for Novachip in 1998, 1999, and 2000; and for Monona in 2000 (**Table 2**). In general, neither protein nor total nitrogen concentrations were significantly correlated with chip color, with the sole exception being a significant negative correlation between total nitrogen concentration and chip color for ND 860-2 tubers during the 2000 season (**Table 2**).

A high dry matter content has been reported to be highly correlated with a lower sugar accumulation during storage (*52*, *53*). However, in this four-year study, dry matter content did not correlate well with reducing sugar concentration (data not shown). Furthermore, dry matter content was not significantly correlated with chip color (**Table 2**).

A backward elimination multiple-regression analysis for chip color was also performed for each year of the study (**Table 3**). The equations presented represent the relationships that describe the largest proportion of the variation in chip color. Ideally, the desired outcome of such an analysis is to find a simple, rapid test to estimate chip color quality. The results obtained from four years of measurement of compositional parameters clearly demonstrate that this relationship is complex. Of the cultivars and selections evaluated, the reducing sugar concentration explained most of the variation in chip color, as has previously been reported by many researchers (*18*, *20*, *21*, *30*, *51*). However, the regression equations were not reproducible from one cultivar or selection to another, nor were they consistent from one year to the next for a given cultivar or selection. This latter occurrence is almost certainly attributed to the seasonal variation in the absolute concentrations of the various metabolic and compositional parameters.

In conclusion, the four years of this study illustrate the dramatic seasonal variations in chip color and the compositional parameters of potato tubers stored at low temperature. In particular, the 1998 season results highlight the importance that the history of the tubers prior to harvest has on tuber composition during storage. The tubers evaluated in this postharvest study were grown under actual field conditions and, therefore, these results are highly relevant to both growers and the potato-processing industry.

It is evident that no single parameter consistently explained the variation in chip color quality for all cultivars and selections, as illustrated by the correlation tables. Although reducing sugar concentrations were significantly correlated with chip color for Novachip in all years, this relationship was not consistently observed for ND 860-2. Multiple-regression analyses demonstrated that there was no single regression equation that could be applied to all cultivars and selections studied, even within a given year. In most cases, the reducing sugar concentration explained the largest proportion of the variation in chip color; however, this relationship was not consistent among all cultivars and selections, and as a result, is of limited predictive value. Therefore, the correlation and multiple regression analyses reveal that the quantitative relationships between chip color and the compositional parameters measured were not sufficiently consistent to provide a general predictive index of chip color quality. Further investigations should include more diverse cultivars in which additional compositional parameters (i.e., dehydroascorbic acid and specific free amino acids) are included.

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