The Relationship Between Respiration and Chip Color During Long-Term Storage of Potato Tubers

L. J. Copp, R. W. Blenkinsop, R. Y. Yada, and A. G. Marangoni*

Department of Food Science, University of Guelph, Guelph, ON Canada N1G 2W1.
*To whom correspondence should be addressed: phone: (519) 824-4120 (ext 4340); fax: (519)824-6631; e-mail: amarango@uoguelph.ca.

ABSTRACT

Processing potatoes, both sprout inhibited and untreated, were evaluated for respiration rate and chip color during storage under commercial conditions (12 C, approximately 95% relative humidity, in darkness) following three growing seasons. While absolute respiration rates varied depending upon growing season and treatment, all cultivars and treatments studied during the 1995, 1996, and 1997 storage seasons showed similar respiration profiles. The initial stage following curing and sprout inhibition treatment (if applied) showed essentially constant respiration rates for a period of time varying from two to 15 weeks, depending upon growing season, treatment and cultivar. This was followed by a stage that showed a linear increase in respiration rates. In some cases the respiration rates eventually stabilized, or decreased. There was an apparent correlation between respiration trends and chip color changes in most cases, though the statistical significance varied between cultivars and seasons. Qualitative analysis of the data showed that the point at which respiration rates began to increase coincided with the onset of the decline in chip color quality. These trends suggest that measurement of tuber respiration may provide a non-destructive and *in situ* method to predict changes in processing quality of stored potato tubers.

INTRODUCTION

The demands of the potato-processing industry often involve the long-term storage of potato tubers. Maintaining high-quality processing potatoes over long storage periods continues to be an important issue for growers and processors. Storage conditions must be set to minimize sprouting, respiration, dehydration, and disease. The most important problem of the potato-processing industry is to maintain a desirable light-colored product. Dark- and uneven-colored chips and French fries are unattractive to the consumer and often have an undesirable flavor (Fuller and Hughes 1984). While it is generally agreed that dark color development in processed tubers is primarily due to the Maillard reaction between the aldehyde groups of reducing sugars and the free amino groups of amino acids during frying operations (Habib and Brown 1957; Marquez and Añon 1986; Roe *et al.* 1990; Pritchard and Adam 1994; Brierley *et al.* 1996; Rodriguez-Saona *et al.* 1997), other tuber components implicated in processing quality include sucrose (Habib and Brown 1957; Mazza *et al.* 1983; Leszkowiat *et al.* 1990; Richardson *et al.* 1990; Rodriguez-Saona *et al.* 1997), ascorbic acid (Rodriguez-Saona *et al.* 1997) and dry matter (Mazza 1983; Pritchard and Scanlon 1997). To further complicate the prediction of process quality, the response to these components in tubers is dependent upon cultivar, growing season and location, storage temperature and ventilation, handling stress, treatment with sprout inhibitors, presence of wounds or disease, and the breaking of dormancy (Burton and Wilson 1978; Mazza 1983; Mazza *et al.* 1983; Sowokinos *et al.* 1987; Orr *et al.* 1994; Walsh 1995).

Low temperature (4 C) storage helps reduce problems of sprout growth and losses due to disease and rotting. However, the resultant low temperature sweetening (LTS) of the tubers reduces the chip quality within a short time period (Isherwood 1973; ap Rees *et al.* 1981; Viola and Davies 1994; Wismer *et al.* 1995 ; Duplessis *et al.* 1996).

Due to the undesirable effects of LTS and the lack of high-quality cultivars that are LTS resistant, potato tubers are stored at higher temperatures (8-12 C) and are treated with sprout inhibitors to allow for long-term storage while still maintaining processing quality. The potatoes will eventually chip to an undesirably dark color, due to senescent sweet-

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ening (Burton 1978; Sowokinos *et al.* 1987; Davies and Viola 1992) or other metabolic changes. The difficulty in predicting an optimum storage time is that it varies from season to season, cultivar to cultivar, and even from storage bin to bin. To monitor all the implicated components would be expensive and time consuming. A simple quantitative parameter to predict chip color remains elusive. Sucrose rating (SR) (Sowokinos 1978) provides valuable information regarding chemical maturity and storage potential of potatoes, but does not identify the point at which tubers in storage will start to decline in quality. Also, a low SR does not necessarily mean that chip quality will be high (Mazza *et al.* 1983; Walsh 1995). Continuous monitoring of sucrose and reducing sugars in tubers during storage is also useful in determining when the sugars rise to concentrations detrimental to chip color (Sowokinos and Preston 1988; Coleman *et al.* 1996). Unfortunately, re-conditioning of the tubers at higher storage temperatures, in attempts to lower reducing sugar concentrations, is unreliable, especially as senescent sweetening (Hughes and Fuller 1984; Wiltshire and Cobb 1996) and long-term LTS are considered irreversible (Coffin *et al.* 1987). Also, chip color quality can decline even in the presence of low reducing sugar concentrations (Burton 1978; Roe *et al.* 1990; Walsh 1995; Rodriguez-Saona and Wrolstad 1997). Herrman *et al.* (1996) found that chip color sometimes darkened even before senescent sweetening was observed. A simple, non-destructive method for determining the point at which processing quality will decline, and which could be used *in situ* in storage facilities, is desirable.

This report presents the results of studies over three storage seasons evaluating whole tuber respiration rate changes as a way to predict and/or monitor chip color. Various commercially grown and cured chipping varieties of potatoes were examined under commercial storage conditions. Initial studies included analyses of sucrose, reducing sugars, and starch. The effectiveness of using tuber respiration rate or concentrations of starch, sucrose, or reducing sugars to predict changes in processing quality was compared.

MATERIALS AND METHODS

Tuber Treatment and Storage

All potatoes were grown on commercial farms and kindly supplied by W.D. Potatoes in Beeton, Ontario. In 1995 five commercial cultivars, Snowden, Monona, Niska, Novachip and Norwis, were cured after harvest and were not treated with sprout inhibitor. Sampling for components, respiration and chip color began October 19. In 1996 the same five cultivars were cured, and the sprout inhibitor iso-propyl-N-(3-chlorphenyl) carbamate (CIPC) was applied as a gas in early November. Sampling for respiration and chip color began November 13, approximately one week following CIPC treatment. In 1997 both CIPC-treated and untreated potatoes of the two cultivars, Snowden and Monona, were examined. CIPC treatment was as described for 1996. Sampling for respiration and chip color began November 25. For all three seasons potatoes were stored in darkness at 10-12 C and approximately 95% relative humidity for the duration of the studies.

Solids Determination

A 10- to 20-g sample of peeled and thinly sliced potatoes (n=5) was dried at 110 C for 48 h, with percentage of solids being determined from the mass difference before and after drying.

Potato Chip Color Determination

In 1995 one composite sample of tubers (n=12) and in 1996 and 1997 two replicates of six potatoes each were peeled, sliced, and fried at 175 C in vegetable shortening. Chips were considered to be finished cooking when bubbling ceased. Chip color for the composite samples was evaluated (average of three separate measurements) with an Agtron Model M30A colorimeter (Chism Machinery, Niagara Falls, ON). The Agtron was calibrated with reference reflectance disks (Agtron score = 0 for black and Agtron score = 90 for white). Agtron scores of less than 50 were considered commercially undesirable.

Sugar Analyses

The concentrations of sucrose, fructose, and glucose in the tuber samples were quantified using an HPLC technique based on that of Wilson *et al.* (1981). A 100-g sample of peeled and chopped tubers (n=5) was homogenized with 80 mL of methanol for 1.5 min at full speed in a Waring Commercial Laboratory Blender. The homogenate was added to 5 g activated carbon (50-200 mesh, Fisher Scientific) and shaken for 20 min at room temperature. Samples were then stored at least 1 h at 4 C, followed by vacuum filtration (Whatman #2, Fisher Scientific). The filtrate was incubated at 35 C overnight, to precipitate proteins, and then stored at 4 C until analysed by HPLC. A Beckman 110B HPLC, equipped with a Waters R401 Differential Refractometer, a Jones Apex

Amino column, 5 μ, 25 cm (Mandel Scientific) and a guard column with the same packing was utilized. The mobile phase was 75:25 (v/v) acetonitrile:water, run at room temperature and 2.0 mL min^{-1}.

Starch Quantification

Samples of approximately 100 g of peeled and chopped tubers were immediately frozen at -20 C, subsequently freeze-dried, vacuum packed and stored at room temperature until analysis. Freeze-dried potato samples were ground with a mortar and pestle and oven dried at 110 C. Samples were suspended in 25 mL water at a concentration of 1mg mL^{-1} and gelatinized by a 15-min incubation in a boiling water bath. Each sample was determined in duplicate by hydrolysis of a 0.1 mL aliquot of the gelatinized solution in 3.0 mL anthrone reagent (Sowokinos 1978), at 60 C for 4 h. The final absorbance of each solution was measured at 620 nm in a Beckman DU7400 spectrophotometer, and samples compared to a standard glucose solution (1 mg mL^{-1} in water), which had undergone the same hydrolysis treatment. A potato starch standard solution (1 mg mL^{-1}) was run with each hydrolysis to ensure the reaction had run to completion.

Respiration Determinations

Whole tuber respiration was evaluated by O_2 consumption and/or CO_2 production in sealed chambers equipped with external circulation pumps (sealed and modified aquarium pumps, circulating at approximately 5 L min^{-1}). Samples of gas were removed from the chambers at various time points and analysed using a Mocon Oxygen Analyzer (Mocon, Minnesota) in 1995 and 1996, or a Shimadzu 8A gas chromatograph equipped with an external 0.5 mL injection port, a HayeSepD column (30 ft x 1/8 in, 100/120 mesh) and a TCD detector (Mandel Scientific), run at 25 C and 30 mL min^{-1} helium, in 1997. Respiration rates were determined using the same potatoes for the full duration of the study. In 1995, two replicates of approximately 1 kg of each cultivar in 2.9 L plexiglass chambers were monitored, while in 1996 and 1997 three replicates of approximately 3 kg of each cultivar and treatment within 5.9-L polyethylene chambers were studied. Rates were calculated from linear regression of five to seven data points of concentration of O_2 or CO_2 with time.

RESULTS

General Observations

The tubers were examined for sprouting and water content over the three storage seasons. Sprouts were first observed in the third week of December in the 1995 season. By the first week of March 1996, representative sample of the cultivars Snowden, Niska, Novachip, Monona, and Norwis had 1.7%, 1.0%, 1.8%, 2.6%, and 0.4% sprouts by fresh weight (f.w.), respectively. The potatoes had become shrunken and spongy by mid-April. For the untreated potatoes in the 1997 season, sprouts were first observed in late January, with representative samples taken in the third week of April showing approximately 10% sprouts by f.w. in both Snowden and Monona tubers. No sprouting was observed in any of the CIPC-treated tubers during the studies.

Some of the cultivars (in all cases in 1995 and in Snowden and Monona in 1996) showed statistically significant decreases ($P \leq 0.01$) in water content over the study period for all three seasons, but the losses were small. The greatest decrease in water content was observed for Novachip in 1995, at 3.5% loss of water over the entire 28-week study period (results not shown). Therefore, the potato tubers are not considered to be dehydrating under the storage conditions.

Chip Color

Changes in chip color, as a function of storage time, for the cultivars studied over the three years are shown, along with respiration rates, in Figures 1-5. Considerable oscillations in chip color with time were observed in all cases. Fluctuations of more than 10 Agtron units were observed over a few weeks time, so that potatoes chipping at undesirable colors one week, might recover to Agtron scores of greater than 50 the next week. A statistically significant ($P \leq 0.01$) decline in chip color quality over the entire storage period was observed in all cases in 1995 and in Snowden and Monona in 1996. The lack of significance in the other treatments is for a variety of reasons: (1) the oscillations in chip color were large relative to the overall decline in chip color; (2) in the case of sprout-inhibited tubers, there often was an early phase of rising chip color scores after treatment with CIPC; and (3) in the case of Niska and Norwis in 1996, the chip color was maintained over the storage season. The relative changes in chip color between cultivars were not consistent from year to year.

Carbohydrate Component Analyses

Starch, sucrose, and the reducing sugars, fructose and glucose, were measured on a weekly basis for a 28-week storage period following the 1995 growing season. Overall, trends were very similar for all cultivars studied. As an

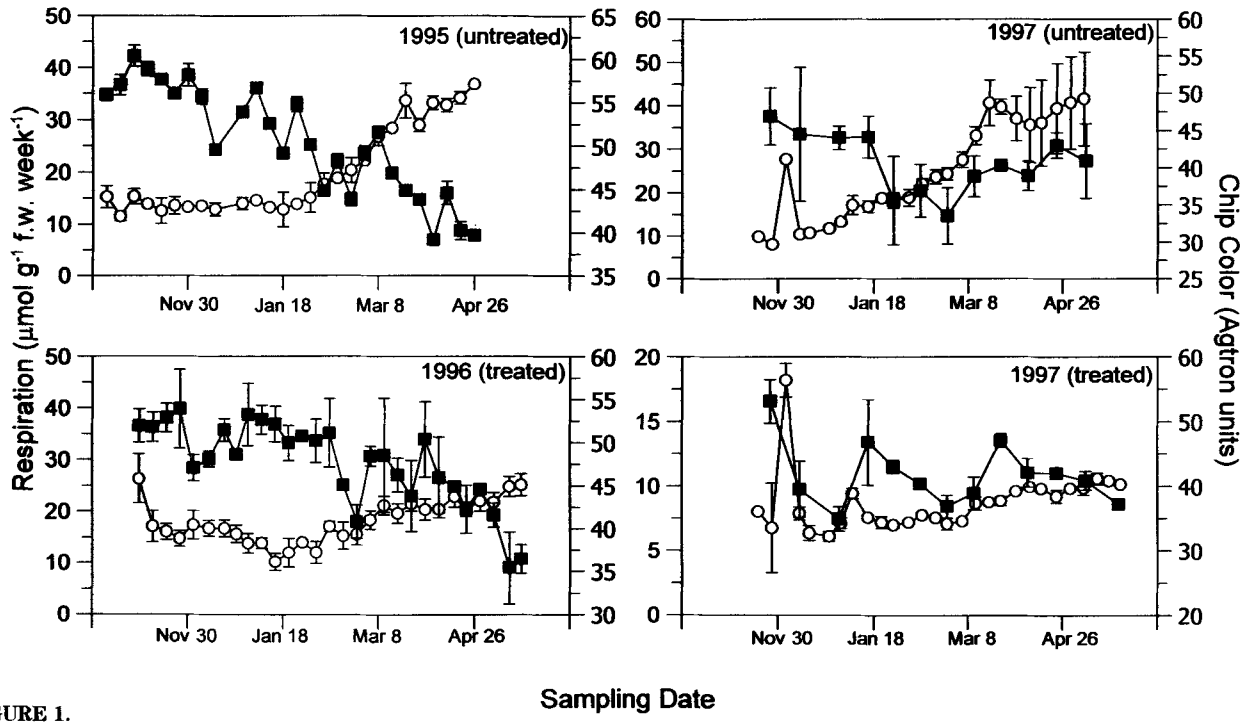

FIGURE 1.
Respiration rates (o) and chip color (▪) for whole Snowden potato tubers, with or without treatment with CIPC in early November, stored at 12 C, in darkness and approximately 95% relative humidity. Data expressed as the mean ± standard error (n=2 for chip color and respiration 1995, n=3 respiration 1996 and 1997). f.w. = fresh weight of tuber.

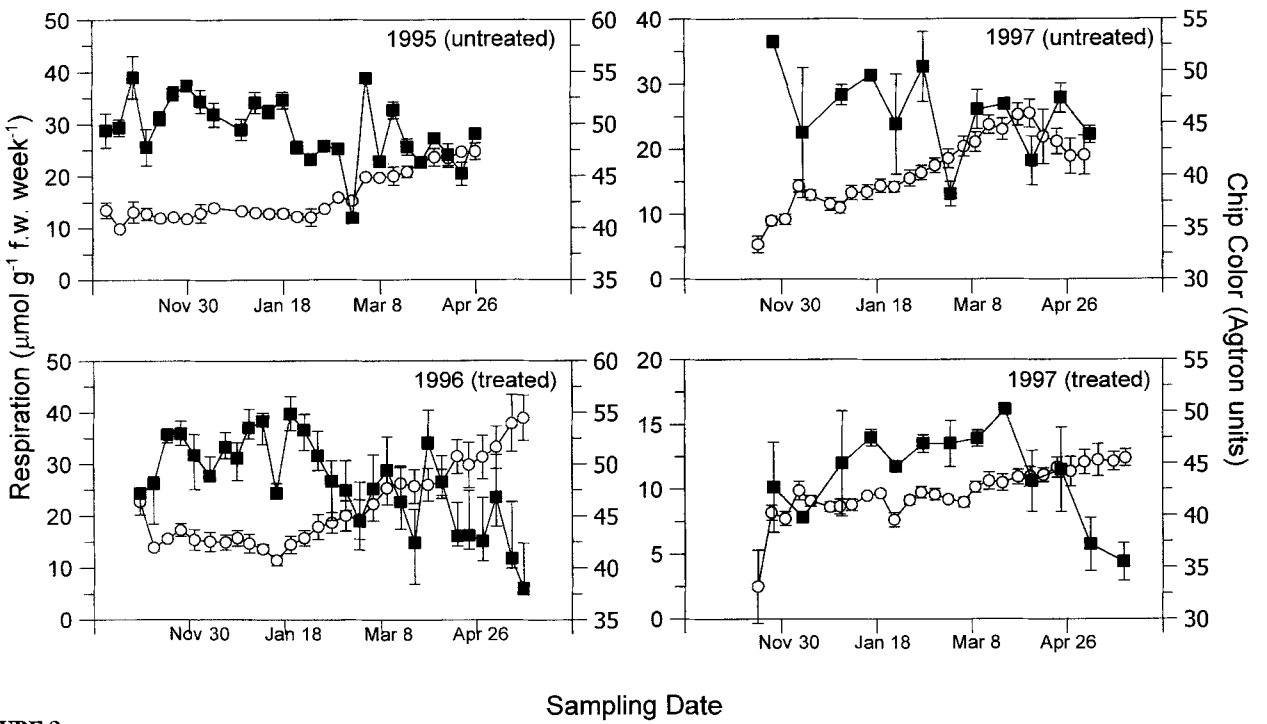

FIGURE 2.
Respiration rates (o) and chip color (▪) for whole Monona potato tubers, with or without treatment with CIPC in early November, stored at 12 C, in darkness and approximately 95% relative humidity. Data expressed as the mean ± standard error (n=2 for chip color and respiration 1995, n=3 respiration 1996 and 1997). f.w. = fresh weight of tuber.

TABLE 1.—*Correlation coefficients (r) of carbohydrate components (mg g^{-1} f.w.) vs chip color (Agtron units) for potatoes grown in the 1995 season.*

Cultivar	Starch	Sucrose	Fructose	Glucose	Total reducing sugars
Snowden	-0.501*	-0.727**	-0.531**	-0.063	-0.276
Monona	-0.443	-0.157	0.169	0.120	0.156
Niska	-0.621*	-0.076	-0.404*	-0.137	-0.217
Novachip	-0.701**	-0.284	-0.335	-0.065	-0.200
Norwis	-0.669**	-0.065	-0.335	-0.226	-0.277

**P≤0.01
*P≤0.05

example, Figure 6 shows the changes in carbohydrate component concentrations over the time course for Snowden potatoes. The reducing sugars, fructose and glucose, remained quite low, at less than 0.035% for most of the study. The ratio of glucose to fructose was approximately 2:1 for the first 10-12 weeks of storage, then approached unity for the remainder of the storage season. Sucrose concentrations decreased gradually over the first 10-12 weeks, then increased for the remainder of the study, reaching 1.3 to 2.3 mg g^{-1} f.w. for the five cultivars studied. The assay for starch concentration was not sensitive enough to reflect any degradation that would result in the observed increases in sugars. However, starch concentrations either did not vary significantly with storage time ($P \leq 0.05$) or increased slightly (Snowden, Novachip, and Norwis), although this is likely an artifact of the slight water losses from the tubers.

The various carbohydrate components were poorly correlated to chip color (Table 1). Where one would expect to see a strong correlation between color and reducing sugars, little or nor correlation was observed. Consistent significant correlation between chip color and sucrose concentration was not observed. The concentration of starch actually showed a negative correlation with chip color for four of the five cultivars, but that is likely due to the effect of water loss from the tuber upon the starch determination.

Respiration

The respiration rates observed for the various cultivars and treatments over the three years of study are shown, along with chip color, in Figures 1-5. In general, respiration rates were linear over a 6-h time course. The respiration rates calculated from decreasing O_2 were equivalent to those calculated from increasing CO_2 for 1997 season potatoes (data not shown). Therefore, all respiration rate data shown and used in regressions are calculated from changes in CO_2 concentrations. In 1997, the only season in which both CIPC-treated and untreated tubers were studied, respiration was lower throughout the entire storage period for CIPC-treated tubers (Figures 1 and 2). In general, after an initial equilibration where rates decline after tuber handling, respiration rates remained constant for a certain length of time. A period of linear increase in respiration rate followed. It is clear from the data that the absolute rate of respiration and the increase in rate in later storage varied considerably with season, cultivar and treatment.

The correlations between respiration rate and chip color are summarized in Table 2. Significant correlation was observed for the 1995 season for all cultivars studied, while weaker correlations were observed during storage in 1996, and in only half of the treatments studied in 1997. There are several reasons for the poorer correlations. In CIPC-treated tubers, there is an initial depression of chip color, which is fully reversed with time, but which is not reflected in differing respiration rates. Also, there are large fluctuations in chip color, particularly in 1996 and 1997. In the case of CIPC-treated Snowden potatoes in 1997, almost no change in respiration or chip color was observed over the storage period.

Intuitively, one would expect respiration and weight loss to be very highly correlated because the respiration rate represents the loss of carbon from the tuber. A high correlation with respiration rate, and therefore, chip color would make

TABLE 2.—*Correlation coefficients (r) of respiration rate (μmol g^{-1} f.w. $week^{-1}$) vs chip color (Agtron units).*

Cultivar	1995	1996	1997
Snowden (untreated)	-0.818**		-0.329
Snowden (CIPC treated)		-0.602**	-0.197
Monona (untreated)	-0.345*		-0.529*
Monona (CIPC treated)		-0.781**	-0.481*
Niska	-0.555**	-0.263*	
Novachip	-0.646**	-0.220*	
Norwis	-0.532**	-0.235*	

**P ≤ 0.01
* P ≤ 0.16

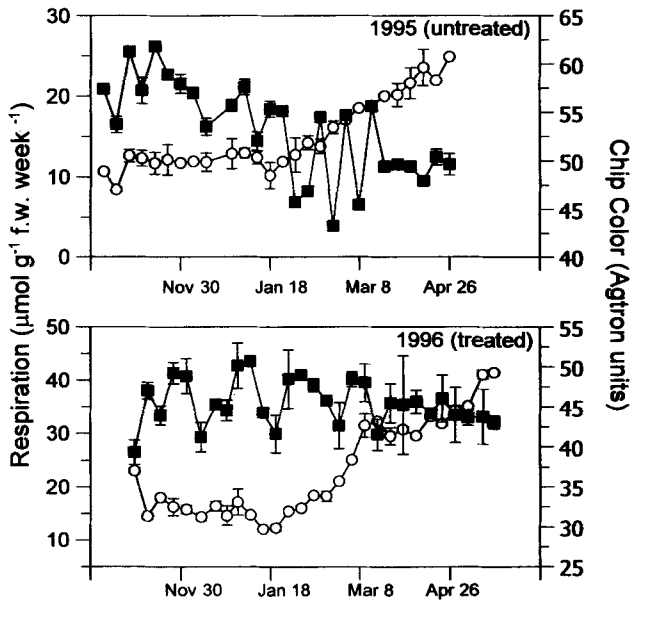

FIGURE 3.
Respiration rates (o) and chip color (▪) for whole Niska potato tubers, with or without treatment with CIPC in early November, stored at 12 C, in darkness and approximately 95% relative humidity. Data expressed as the mean ± standard error (n=2 for chip color and respiration 1995, n=3 respiration 1996 and 1997). f.w. = fresh weight of tuber.

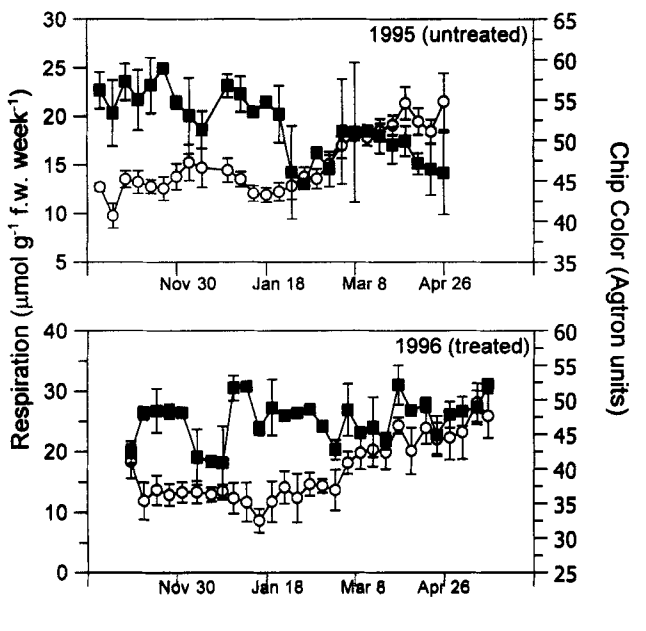

FIGURE 4.
Respiration rates (o) and chip color (▪) for whole Norwis potato tubers, with or without treatment with CIPC in early November, stored at 12 C, in darkness and approximately 95% relative humidity. Data expressed as the mean ± standard error (n=2 for chip color and respiration 1995, n=3 respiration 1996 and 1997). f.w. = fresh weight of tuber.

weight loss a very easy parameter to use as a monitor for changes in chip color. Weight loss rates were monitored throughout the three storage seasons and showed inconsistent correlations with respiration (Table 3). Weight loss rates did not consistently correlate with changes in chip color ($-0.052 \leq r \leq -0.664$ in 1995; $-0.035 \leq r \leq -0.458$ in 1996; and $-0.475 \leq r \leq -0.790$ in 1997). Clearly, respiration and weight loss are not always simply related. The reasons for these differences are currently under further investigation.

DISCUSSION

This study examined a variety of parameters in an effort to find a method to monitor, or predict, chip color during long-term storage. During the 1995 storage season, the concentrations of sucrose and reducing sugars did not rise over the accepted "safe" values of 1 mg g^{-1} f.w. and 0.035% (Sowokinos and Preston 1988) respectively, until very late in the storage period. Neither sucrose, nor reducing sugars, correlated reliably with chip color. A decline in chip color quality in the presence of low reducing sugars and sucrose has been observed by others (Herrman *et al.* 1996; Walsh 1995).

Tuber respiration rate patterns and values are in good agreement with other researchers (Paez and Hultin 1970; Burton 1974; Schippers 1977b; Burton 1978; Dwelle and Stallknecht 1978; Williams and Cobb 1992; Wiltshire and Cobb 1996), although O_2 consumption and CO_2 production were equivalent in our 1997 studies. This is in contrast to the work of Burton (1978) and Dwelle and Stallknecht (1978). The increase in respiration rate observed during storage has been

TABLE 3.—*Correlation coefficients (r) of respiration rate (mmol g^{-1} f.w. $week^{-1}$) vs weight loss rates (% $week^{-1}$).*

Cultivar	1995	1996	1997
Snowden (untreated)	0.942**		0.645**
Snowden (CIPC treated)		0.299	0.040
Monona (untreated)	0.621*		0.854**
Monona (CIPC treated)		0.596**	0.645**
Niska	0.879**	0.642**	
Novachip	0.848**	0.599**	
Norwis	0.459*	0.216	

**P ≤ 0.01
* P ≤ 0.05

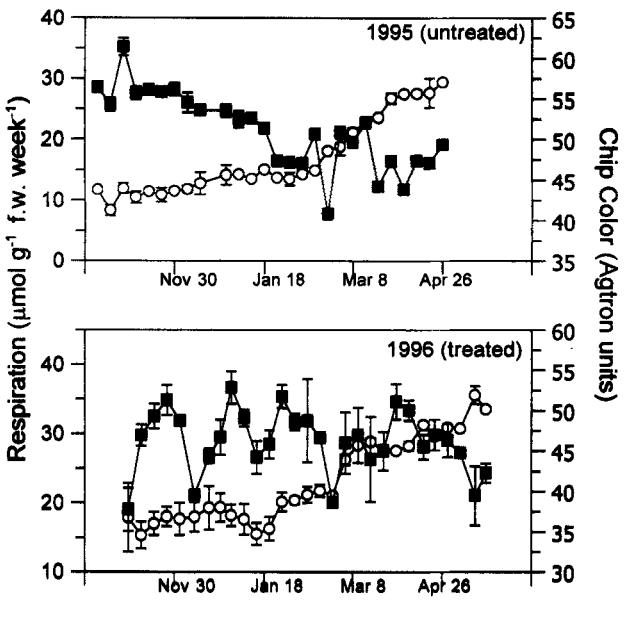

FIGURE 5.
Respiration rates (o) and chip color (▪) for whole Novachip potato tubers, with or without treatment with CIPC in early November, stored at 12 C, in darkness and approximately 95% relative humidity. Data expressed as the mean ± standard error (n=2 for chip color and respiration 1995, n=3 respiration 1996 and 1997). f.w. = fresh weight of tuber.

associated with sprouting and end of dormancy (Schippers 1977a, b; Burton 1978; Dwelle and Stallknecht 1978). It is interesting to note that in this study the increase in respiration rate is observed, whether or not the tubers are sprouting. Thus, while the change in respiration may be associated with the same physiological changes in the tuber resulting in sprouting, it is not directly due to the sprouts themselves.

The chip color data showed the seasonal variations observed by others (Herrman *et al.* 1996). Chip color was highly variable from week to week for all cultivars and treatments and may be responding to a dynamic metabolic system within the tuber. One striking feature was the effect of treatment with sprout inhibitor on chip color. Tubers treated with CIPC in early November showed lower Agtron scores, as compared with untreated, but gradually improved to equal or exceed Agtron scores for untreated tubers by January (Figures 1-5). Since storage bins are often sealed for several days following CIPC treatment, CO_2 concentration may rise and stress the tubers (Mazza and Siemens 1990), causing an increase in sugars. Whichever the cause, the tubers seemed to recover fully from the lower Agtron values induced by CIPC treatment.

Chip color was correlated with respiration rates to varying degrees over the three seasons and different cultivars and

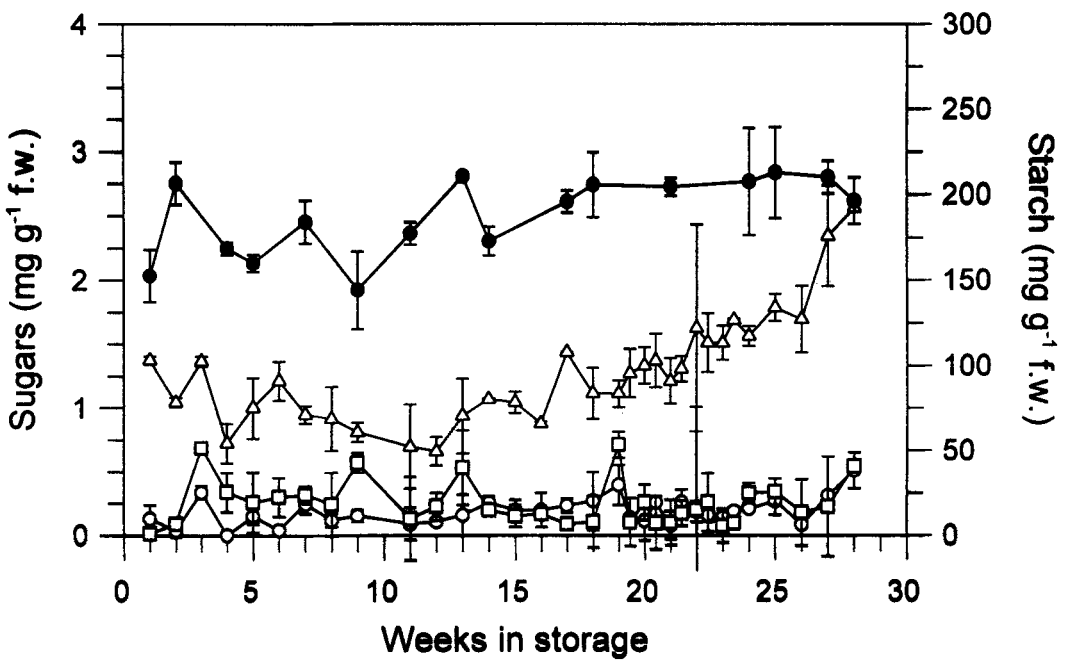

FIGURE 6.
Concentrations of the carbohydrate components starch (•), sucrose (△), glucose (□) and fructose (o) of Snowden tubers, stored at 12 C, in darkness and approximately 95% relative humidity following the 1995 growing season. Data expressed as the mean ± standard error (n=2). f.w. = fresh weight of tuber.

treatments studied (Table 2). More noteworthy than the statistical correlation between respiration rates and chip color is the connection between the onset of increasing respiration rates and a decline in chip color quality (Figures 1-5). In most cases the point at which increasing respiration rates were observed corresponded to the point at which chip color started to decline. In the case of a seasonal long decline in processing quality (e.g., Figure 1 1995), the increase in respiration was observed when the quality approached minimal commercial requirements. In a few cases (e.g., Niska and Norwis 1996, Figures 3 and 4) respiration increased without a decline in acceptable chip color quality, so that the change in respiration underestimated the optimal storage time. Monitoring respiration within actual storage bins may provide a continuous, non-destructive, *in situ* method for predicting the point at which tuber processing quality will decline.

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