Using Ethylene as a Sprout Control Agent in Stored 'Russet Burbank' Potatoes

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ABSTRACT. The effect of ethylene on tuber sprout growth and quality in potato (*Solanum tuberosum* L. 'Russet Burbank') was tested in laboratory and commercial studies for 6 and 3 years, respectively, in comparison with untreated (laboratory study) and CIPC-treated tubers (laboratory and commercial studies). In both studies, ethylene was applied continuously at 166 $\mu\text{mol}\cdot\text{m}^{-3}$ for at least 25 weeks, beginning in early December (laboratory study) or early December to early January (commercial study). In the laboratory study, ethylene delayed the appearance of sprouts for 5 to 15 weeks, compared with untreated tubers. In the ethylene-treated tubers in both studies, sprouts appeared on many eyes but most of them remained very small (<5 mm long). Longer sprouts (>5 mm) appeared after 15 weeks but did not exceed 12 and 59 mm in the laboratory and commercial studies, respectively. Sprouts on ethylene-treated tubers were more easily detached up to 6 weeks after ethylene treatment ended, compared with untreated tubers. In both studies, ethylene treatment was not associated with decay, disorder or internal sprouting problems. In both studies, the Agtron fry color [or U.S. Dept. of Agriculture (USDA) color grade] of ethylene-treated tubers was darker than CIPC-treated tubers at almost all sampling times. Continuous exposure to ethylene was an effective sprout control agent but it produced a darker fry color, compared with CIPC-treated potatoes.

As part of the effort to reduce chemical additives to our food and to the environment, researchers are trying to find an alternative to the use of CIPC (chlorpropham; 1-methylethyl-3-chlorophenyl-carbamate) to control sprout growth on potato tubers during storage (Prange et al., 1997). CIPC is among the three pesticides found in highest concentrations in the diet of the average American and comprises 90% of the total synthetic chemical residue in United States potatoes (Gartrell et al., 1986; Gunderson, 1988; Vaughn and Spencer, 1991). In addition, CIPC residues in potato products are used as a non-tariff trade barrier by some governments. The aim of our research is to find a replacement for CIPC on 'Russet Burbank' potato, which is the major cultivar used in many countries for commercial French fries. In the course of evaluating various alternatives, e.g., Daniels-Lake et al., 1996, we hypothesized that ethylene may be an acceptable replacement for CIPC.

The effect of continuous long-term exposure of potato tubers to ethylene on sprout growth and tuber quality is not well understood. It is recognized that potato tubers produce ethylene (Creech et al., 1973; McGlasson, 1969; Poapst et al., 1968). The rate is normally very low, 0.008 to 0.015 $\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$, but can be as high as 0.1 to 0.4 $\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ when the tubers are stressed or sprouting (Creech et al., 1973; McGlasson, 1969; Okazawa, 1974). Burton (1952) suggested that ethylene may be one of the endogenous volatile

substances in potato tubers involved in sprout suppression although Burton (1989) and Rylski et al. (1974) later stated that this was incorrect. Studies using exogenous ethylene do not clearly indicate the effect of long-term exposure (>6 months), mainly because many of them are short-term studies, e.g., ≤ 40 d. Furthermore, some conclusions are based on responses while ethylene was applied and others are based on responses after ethylene was removed. Thus, some of these short-term studies have concluded ethylene breaks dormancy and stimulates sprout growth (Alam, 1992; Alam et al., 1994; Rosa, 1925; Vacha and Harvey, 1927), or does not hasten sprouting of dormant potatoes (Denny, 1926) and/or suppresses growth of sprouts, roots or stems (Elmer, 1932, 1936; Furlong, 1948; Huelin, 1933; Hughes et al., 1973; Metlitskii et al., 1982; Timm et al., 1986). In a review by Kader (1985), the author concludes that ethylene can have a dual effect on potato tubers: it shortens the duration of rest markedly, but inhibits the elongation of sprouts. Shortening rest would be desirable for seed potatoes but not for table or processing potatoes in the author's opinion. This conclusion is based on research by Rylski et al. (1974), which showed that ethylene treatment of nonsprouting tubers shortens the duration of rest markedly, with sprouting being promoted by short (up to 72 h) exposures. In the same study, inhibition of sprout elongation was observed when sprouting tubers were exposed continuously to ethylene over a 14-d study period. The only study examining exposure to ethylene over typical commercial storage periods of 6 months or longer was Metlitskii et al. (1982). They reported that an ethylene-generating liquid (Hydrel) suppresses sprouting and disease development in stored potatoes for more than 6 months.

Ethylene has various effects on fry color, which was not measured in any of the above studies. Haard (1971), using a 24-h ethylene treatment, concluded it darkens fry color in some cultivars but improves it in others. Parkin and Schwobe (1990) showed

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that ethylene applied for 9 weeks at 1000 $\mu\text{L}\cdot\text{L}^{-1}$ delays fry color darkening at 3 °C by slowing the conversion of sucrose to hexoses. Unfortunately, in both studies ethylene was applied at storage temperatures of 3 to 4 °C, a temperature that can induce low-temperature sweetening and darker fry color in potato tubers.

The objective of this study was to examine the effect of continuous ethylene exposure over a 25-week storage period on sprouting of cured 'Russet Burbank' potato tubers held at normal storage temperatures. In addition, possible effects on tuber quality were evaluated in terms of fry color, disease development and tuber disorders.

Materials and Methods

This study was repeated for 6 years in the laboratory, from 1990–91 (year 1) to 1995–96 (year 6), and also for 3 years in a commercial storage (1992–93, 1993–94, and 1994–95).

In the laboratory study, commercially produced 'Russet Burbank' potatoes were obtained from four separate locations, i.e., four grower replications, in New Brunswick, Canada (years 1 to 3) or two sites in New Brunswick and two in Prince Edward Island, Canada (years 4 to 6). They were suberized (≈ 4 to 5 weeks at 13 to 15 °C to allow wound healing) commercially before they were received in the laboratory (years 1 to 4) or after they were received (years 5 and 6). Treatments began in the first week of December in each year (mid-December in year 1), after suberization. Each grower replication was stored at 9 °C in a separate 64 L PVC barrel (IPL Ltd., Moncton, N.B.) in a temperature-controlled room for 25 weeks. Within the room there were three rows of four barrels, for control (air), CIPC and continuous 166 $\mu\text{mol}\cdot\text{m}^{-3}$ (4 $\mu\text{L}\cdot\text{L}^{-1}$) ethylene, respectively. Within each barrel, five 2-kg samples (≈ 10 tubers) of potatoes were stored in mesh onion bags. Following a split-plot design, the experimental factors were assigned and randomized. The three treatments (main plots) were assigned to the three rows and the four growers (subplots) were assigned to the four barrels within each row. The five removal dates were assigned to the five samples within each barrel. In the final year, each treatment was applied to a single 0.67- m^3 stainless steel cabinet with an air-tight acrylic lid and water-trough seal. The five samples from each grower replication were contained in a ventilated PVC basket, and each cabinet held four baskets, one from each grower.

All barrels were ventilated with air at 0.5 to 0.7 $\text{L}\cdot\text{h}^{-1}$ for 6 consecutive hours each day. In the final year, the cabinets were ventilated during two 6-h periods per day, interspersed by two 6-h static periods without ventilation. Each ventilation period consisted of 5.75 h at 4 $\text{L}\cdot\text{min}^{-1}$ and 15 min at 15 $\text{L}\cdot\text{min}^{-1}$. Control potatoes (air) received no additional treatment, while the CIPC treatment was applied by dipping the tubers in Sprout-Nip EC (Stanchem Inc., Etobicoke, Ont.) at a concentration of 10 $\text{g}\cdot\text{L}^{-1}$ at the start of each storage season. In 1990–91, the CIPC dip was repeated at 5-week intervals during the storage term. Ethylene gas was applied at 166 $\mu\text{mol}\cdot\text{m}^{-3}$ (133 $\mu\text{mol}\cdot\text{m}^{-3}$ in year 1) by addition to the ventilation airstream. Ethylene was measured by drawing a 1-mL headspace sample manually from each chamber and injecting into a GC (Carle Instruments, Anaheim, Calif.), equipped with a flame ionization detector, a 2.4-m stainless steel column hand-packed with 60 to 80 alumina (Chromatographic Specialties, Brockville, Ont.), with helium as the carrier gas. Detector output was processed by LabCalc software (Galactic Industries, Salem, N.H.), and the results were assessed immediately. Chamber headspace was analyzed once per week, during the middle of a ventilation cycle to verify that treatment concentrations were being maintained. In the last year ethylene was measured automatically. A sample-and-return loop circulated headspace gases from the storage chamber through a motorized valve (Valco, Valco Instruments, Houston, Texas). Each chamber was

sampled sequentially, with a purge cycle between chambers. A 1-mL sample of the headspace was automatically injected into a GC (Shimadzu, Kyoto, Japan), equipped with a 1.2 $\times$ 3.2 mm packed column with 80/100 mesh Porapak P, a photoionization detector, with nitrogen as the carrier gas. Detector output was processed by PeakSimple for Windows software (SRI Inc., Torrance, Calif.). Headspace gases were analyzed 12 times every day.

Sprout development, disease and disorder incidence were evaluated at the start of each year's experiment, and at each removal date during the storage term. Sprout development was evaluated by determining sprout mass per kilogram of initial tuber fresh mass (sprout mass), the length of the longest sprout in each sample (maximum length), and the mean number of sprouts per tuber (sprout number) in two categories, small (2 to 5 mm) and large (>5 mm). Disease and disorders were assessed by estimating the percentage of the tuber affected.

To assess the fry color of the tubers (year 2 to 6), a disc 50 mm in diameter was cut from an 8-mm-thick central longitudinal slice of each tuber. The discs were deep fried for 2.5 min in canola oil (Maple Leaf Foods, Moncton, N.B.) at 190 °C, and then allowed to cool to room temperature. Fry color of each cooled disc was measured using

Table 1. Effect of storage time and treatment on mean sprout mass (sprouts >5 mm) over 6 storage years in the laboratory study.

Treatment	Sprout mass/initial tuber fresh mass ($\text{g}\cdot\text{kg}^{-1}$)		
	Storage time (weeks)		
	15	20	25
1990–91			
Air	3.3	17.2	44.7
CIPC	0	0	0
Ethylene	0.1	0.8	4.9
1991–92			
Air	1.4	8.3	26.2
CIPC	0	0	0
Ethylene	0.0	0.0	0.0
1992–93			
Air	1.4	2.2	8.5
CIPC	0	0	0
Ethylene	0.0	0.0	0.0
1993–94			
Air	4.4	12.3	24.9
CIPC	0	0	0
Ethylene	0.0	0.0	0.1
1994–95			
Air	3.2	11.0	23.0
CIPC	0	0	0
Ethylene	0.0	0.0	0.5
1995–96			
Air	3.6	17.4	38.5
CIPC	0	0	0
Ethylene	0.0	0.0	0.0
All years combined ($\log_{10}$)^z			
Air	0.56	0.99	1.36
CIPC	0	0	0
Ethylene	0.00	0.01	0.12
SE (n = 120; df = 45) ^y		0.027	
Significant effects		S***, T***, S $\times$ T***	

^zAll years, except 1990–91, which had poor ethylene control.

^yStatistical analysis did not include CIPC treatment, which always had zeros.

***Significant at $p \leq 0.001$, where S = storage time and T = treatment.

Table 2. Effect of storage time and treatments on mean maximum sprout length over 6 storage years in the laboratory study.

Treatment	Maximum sprout length (mm)		
	Storage time (weeks)		
	15	20	25
1990-91			
Air	49.1	157.5	301.0
CIPC	0	0	0
Ethylene	5.0	6.6	19.4
1991-92			
Air	33.1	132.4	246.2
CIPC	0	0	0
Ethylene	0.02	3.5	7.1
1992-93			
Air	46.0	32.1	173.2
CIPC	0	0	0
Ethylene	3.7	3.7	7.0
1993-94			
Air	64.6	109.2	168.8
CIPC	0	0	0
Ethylene	0.5	2.7	5.9
1994-95			
Air	32.7	110.4	156.8
CIPC	0	0	0
Ethylene	0.7	4.6	7.9
1995-96			
Air	73.5	170.8	290.7
CIPC	0	0	0
Ethylene	0.0	0.4	11.4
All years combined (square root)^z			
Air	1.68	1.99	2.31
CIPC	0	0	0
Ethylene	0.21	0.56	0.94
SE (n = 120; df = 45) ^y		0.058	
Significant effects		S ^{***} , T ^{***} , S × T ^{NS}	

^zAll years, except 1990-91, which had poor ethylene control.

^yStatistical analysis did not include CIPC treatment, which always had zeros.

NS,*** Nonsignificant at $p \leq 0.05$ or significant at $p \leq 0.001$, respectively, where S = storage time and T = treatment.

an Agtron reflectance colorimeter (Agtron M-35-D, Agtron Inc., Sparks, Nev.), calibrated using Agtron standard reflectance discs #00 as zero and #56 as 100%.

In 1 year (1993-94), in addition to the above measurements, the strength of attachment of the sprouts to the tubers (air and ethylene treatment only) was tested after 20 and 25 weeks storage and on separate samples held after these removal dates at 20 °C for an additional 3 or 6 weeks. The force required to detach the sprout from the potato was determined by measuring the load as the sprout was detached. The base of the sprout was held in a modified alligator clip which was connected to a digital electronic balance placed above the sprout. The tuber was attached to a motorized arm which pulled the tuber downward until the sprout was detached. The balance was connected to a computer which recorded the maximum force applied to the sprout as it was detached from the tuber.

Data from each characteristic in the laboratory study were analyzed by ANOVA, using the Genstat 5 statistical program (Genstat committee, 1993). Before statistical analysis the data for all years were combined so that each year was treated as a replication. To counteract the biasing effect of numerous zero values and to accommodate large changes from one removal date to the next as sprout

growth progressed, the data sets for the sprout characteristics were restricted to removal dates having measurable sprout growth, and then analyzed using either log₁₀ or square-root transformations, as appropriate. Only results significant at $P \leq 0.05$ are discussed.

In the commercial storage study, two identical adjacent bulk storage buildings were used, each holding ≈3 million kg of 'Russet Burbank' potatoes. In one, the potatoes were given the normal CIPC treatment (mid-December in 1992-93 and mid-November in 1993-94 and 1994-95) and, in the other, the potatoes were treated continuously with 166 μmol·m⁻³ ethylene, (beginning on 5 Jan. in 1992-93; 14 Dec. in 1993-94 and 1 Dec. in 1994-95). Treatment continued until the last week of June (1992-93 and 1993-94) and early July (1994-95). Potatoes were processed into French fries for resale after these dates. Ethylene was delivered from a compressed gas cylinder into the ventilation system and measured weekly with a GC (HNU Systems, Newton, Mass.) equipped similarly to the Carle GC above. Each week a 10 tuber sample was collected from each treatment and fry color was determined using a method similar to the one described above, except that the color was recorded using the USDA French fry color chart (USDA grade 1 = 88 to 100 Agtron units, Grade 2 = 70

Table 3. Effect of storage time and treatments on mean number of large sprouts (>5 mm) over 6 storage years in the laboratory study.

Treatment	Sprouts per tuber (no.)		
	Storage time (weeks)		
	15	20	25
1990-91			
Air	2.2	4.1	6.4
CIPC	0	0	0.0
Ethylene	0.2	0.2	6.7
1991-92			
Air	1.1	3.5	5.6
CIPC	0	0	0
Ethylene	0.0	0.0	0.0
1992-93			
Air	0.8	1.0	6.3
CIPC	0	0	0
Ethylene	0.1	0.1	0.3
1993-94			
Air	1.0	2.4	2.8
CIPC	0	0	0
Ethylene	0.0	0.0	2.8
1994-95			
Air	0.8	1.7	3.4
CIPC	0	0	0
Ethylene	0.0	0.2	2.3
1995-96			
Air	1.9	2.4	3.2
CIPC	0	0	0
Ethylene	0.0	0.0	0.4
All years combined (square root)^z			
Air	1.04	1.45	2.03
CIPC	0	0	0
Ethylene	0.04	0.18	0.90
SE (n = 120; df = 45) ^y		0.091	
Significant effects		S ^{***} , T ^{***} , S × T ^{NS}	

^zAll years, except 1990-91, which had poor ethylene control.

^yStatistical analysis did not include CIPC treatment, which always had zeros.

NS,*** Nonsignificant at $p \leq 0.05$ or significant at $p \leq 0.001$, respectively, where S = storage time and T = treatment.

to 87, Grade 3 = 54 to 69, Grade 4 = 36 to 53, Grade 5 = 21 to 35, Grade 6 = 5 to 20 and Grade 7 = 0 to 4). In the first year, the sample was taken randomly from the storage pile and in the second and third years the samples were prepared at the beginning from one grower and randomly selected throughout the storage season. In 1 year (1993–94), additional ‘Russet Burbank’ potatoes were collected from six different commercial sources across Canada and treated similarly to the ‘Russet Burbank’ sample mentioned previously. These samples were removed at 7- to 8-week intervals and measured for sprout mass, sprout number and maximum length as described for the lab study.

Results

Laboratory study

SPROUTING. In all years, sprouting was minimal in all treatments at 5 and 10 weeks of storage (data not shown), but increased progressively at successive removal dates. Sprout mass, maximum length and number of large sprouts per tuber (Tables 1, 2, and 3, respectively) increased dramatically in the air treatment at 15 weeks and at each subsequent removal. CIPC-treated tubers had negligible sprout production. In the ethylene treatment, the beginning of sprouting was delayed by 5 to 15 weeks, compared with the air treatment (data not shown).

Table 4. Effect of storage time and treatments on mean number of small sprouts (2 to 5 mm) over 5 storage years in the laboratory study. Data were not collected in year 1 (1990–91).

Treatment	Sprouts per tuber (no.)		
	Storage time (weeks)		
	15	20	25
1991–92			
Air	0.7	2.0	2.2
CIPC	0	0	0
Ethylene	0.0	0.5	3.5
1992–93			
Air	1.7	2.2	7.3
CIPC	0	0	0.1
Ethylene	0.0	0.0	0.4
1993–94			
Air	0.0	0.0	0.2
CIPC	0	0	0
Ethylene	0.1	3.8	12.2
1994–95			
Air	0.0	0.2	0.5
CIPC	0	0	0
Ethylene	0.0	4.4	7.9
1995–96			
Air	0.5	0.3	0.1
CIPC	0	0	0
Ethylene	0.2	2.7	7.0
All years combined (square root)			
Air	0.63	0.78	1.11
CIPC	0	0	0
Ethylene	0.21	1.30	2.29
SE (n = 120; df = 45) ^a		0.143	
Significant effects		S ^{***} , T ^{***} , S × T ^{***}	

^aStatistical analysis did not include CIPC treatment, which always had zeros.

^{***}Significant at $p \leq 0.001$, where S = storage time and T = treatment.

After sprouts appeared in the ethylene treatment, total sprout mass (sprouts >5 mm) was always less than untreated potatoes (Table 1). Total sprout mass on the ethylene-treated potatoes remained similar to the CIPC-treated potatoes for the entire storage period of 25 weeks. Except for 1990–91, when there was poor ethylene control (actual concentration was sometimes less than the desired concentration due to poor sealing), the maximum sprout mass never exceeded 0.5 g·kg⁻¹ of initial tuber fresh mass.

Maximum sprout length of ethylene-treated potatoes increased over storage time but was always much less than untreated potatoes (Table 2). The mean value never exceeded 12 mm on ethylene-treated tubers, except for 1990–91.

The number of large sprouts (>5 mm) increased with storage time and, except for the first year, was always less in ethylene-treated potatoes than in untreated potatoes (Table 3). The mean number of large sprouts on ethylene-treated tubers never exceeded 1 per tuber after 20 weeks and after 25 weeks exceeded 1 per tuber in only 3 years.

The number of small sprouts (2 to 5 mm) increased with storage time (Table 4). It was the same in ethylene-treated potatoes as in untreated potatoes after 15 weeks. The number of small sprouts on ethylene-treated potatoes increased and exceeded untreated potatoes after 20 and 25 weeks. The mean number of small sprouts on ethylene-treated tubers exceeded one per tuber after 20 weeks in 3 of 5 years. At 25 weeks there was more than one sprout per tuber in 4 of the 5 years, reaching a mean value of over 12 per tuber in 1993–94. Although they were not counted, the number of eyes which produced sprouts also appeared to increase when the number of small sprouts increased.

FRY COLOR. When all years were combined (Table 5), the data showed that fry color improved (lightened) with storage time, regardless of treatment. The fry color of the ethylene-treated potatoes was darker than untreated or CIPC-treated potatoes at all storage times. This difference was greatest in the first 15 weeks, and progressively narrowed to no difference between untreated and ethylene-treated potatoes after 25 weeks.

SPROUT DETACHMENT. Removal force was measured after 20 and 25 weeks of storage in 1993–94. At removal, only the untreated potatoes had sprouts of sufficient size for evaluation (Table 6). After 3 and 6 weeks of holding tubers in air at 20 °C, measurable sprouts developed on the ethylene-treated tubers. Although the removal force increased in untreated and ethylene-treated tubers over the 6-week period, the sprout removal force for the sprouts on ethylene-treated tubers was consistently less than on untreated tubers.

DECAY AND DISORDERS. During the 6 years of the study there was neither decay nor disorders associated with any of the treatments (data not shown).

Commercial storage study

SPROUTING. In the 1 year (1993–94) when sprouts were measured, the CIPC-treated potatoes had the shortest sprouts and the smallest sprout mass until after week 22 (Table 7). Between week 22 and 29, the sprouts on the CIPC-treated potatoes had very large increases in length and mass. During the same time sprout length on ethylene-treated tubers appeared to be stable and very similar to lengths observed in the laboratory study. Although the mass of sprouts on ethylene-treated tubers increased 3-fold during this time, it remained considerably lower than sprouts on CIPC-treated potatoes at week 29.

FRY COLOR. The fry color in the commercial trial was generally darker in the ethylene-treated tubers than in the CIPC-treated tubers in all 3 years (Fig. 1). This was similar to the trends observed

Table 5. Effect of storage time and treatments on mean Agtron fry color over 5 storage years in the laboratory study. Data were not collected in year 1 (1990–91).

Treatment	Agtron value (% reflectance) ^z				
	Storage time (weeks)				
	5	10	15	20	25
1991–92					
Air	64.4	68.1	70.4	69.5	67.3
CIPC	64.5	65.7	67.1	74.9	75.4
Ethylene	61.2	64.9	66.5	67.7	68.8
1992–93					
Air	64.4	67.8	68.1	70.4	66.8
CIPC	62.5	67.5	66.0	71.6	70.1
Ethylene	64.6	67.5	66.3	67.8	70.9
1993–94					
Air	61.0	64.0	69.9	70.3	69.1
CIPC	69.1	68.0	72.9	77.5	66.2
Ethylene	56.1	56.7	64.3	66.2	69.9
1994–95					
Air	64.7	67.4	69.7	68.5	72.4
CIPC	69.8	70.9	67.7	71.9	78.2
Ethylene	58.2	63.8	57.5	64.4	67.2
1995–96					
Air	72.4	71.3	72.9	74.4	70.8
CIPC	70.4	73.5	73.7	77.2	74.9
Ethylene	44.9	52.1	56.7	64.2	63.1
All years combined^y					
Air	64.6	67.7	70.2	70.6	69.3
CIPC	67.3	69.1	69.5	74.6	75.2
Ethylene	57.0	61.0	62.2	66.1	68.0
SE (n = 300; df = 149)	0.82				
Significant effects	S ^{***} , T ^{***} , S × T ^{***}				

^zInitial Agtron values (day 0): 68.6 (1991–92); 50.0 (1992–93); 51.5 (1993–94); 75.0 (1994–95); 82.3 (1995–96).

^y***Significant at $p \leq 0.001$, where S = storage time and T = treatment.

in the laboratory data for the same years (Table 5).

SPROUT DETACHMENT. During removal of the potatoes at the end of the storage period, almost all of the sprouts on the ethylene-treated potatoes readily fell off the tubers while being handled by the loading equipment. This observation was in agreement with the data from the sprout removal force measurements in the laboratory (Table 6).

DECAY AND DISORDERS. In the commercial tuber samples there were no decay or disorder differences between CIPC- and ethylene-treated tubers, with the exception of internal sprouting. There was more internal sprouting in CIPC-treated tubers, 0.538% (1993–94) and 0.697% (1994–95), compared with ethylene-treated tubers, 0.0045% (1993–94) and 0.054% (1994–95).

Discussion and Conclusions

The laboratory and commercial studies over 6 and 3 years, respectively, showed that continuous ethylene treatment at 166 $\mu\text{mol}\cdot\text{m}^{-3}$ had several consistent and repeatable effects during long-term storage of 'Russet Burbank' potatoes. In the presence of continuous ethylene, sprouts appeared later than in untreated tubers, which appears to contradict the claims of earlier authors, i.e., that ethylene shortens the duration of rest markedly (Kader, 1985; Ryłski et al., 1974). This may be rationalized by explaining that our results were based on continuous exposure whereas the above conclusion was based on sprouting after ethylene-treated tubers were put in air. Although most of the treatments of Ryłski

Table 6. Sprout removal force of air and ethylene treatments immediately after storage and after 3 and 6 weeks re-conditioning in air at 20 °C in the 1993–94 laboratory study.

Storage time (weeks)	Treatment	Removal force (N)		
		Reconditioning time (weeks)		
		0	3	6
20	Air	5.2	5.8	6.4
	Ethylene	---	1.9	4.0
25	Air	9.0	6.2	8.6
	Ethylene	---	1.9	3.1
SE (n = 80; df = 567)		0.48		
Significant effects		T ^{***} , T × S ^{**} , S × T × R [*]		

^{*, **, ***}Significant at $p \leq 0.05$, 0.01, or 0.001, respectively, where S = storage time, T = treatment, and R = reconditioning time.

Table 7. Effect of storage time and treatments on sprout number, mass and maximum sprout length in the 1993–94 commercial trial.

Treatment	0	Storage time (weeks)			
		7	15	22	29
Sprouts/tuber (no.)					
CIPC	0	0 (0.000) ^z	0 (0.030)	0.08 (0.285)	7.97 (2.823)
Ethylene	0	0.01 (0.121)	0.03 (0.178)	1.09 (1.042)	7.83 (2.798)
SE (of square root, n = 96; df = 68)			0.124		
Significant effects			S ^{***} , T ^{**} , S × T [*]		
Sprout mass/initial tuber fresh mass (g·kg ⁻¹)					
CIPC	0	0 (0.00) ^y	0.01 (0.003)	0.08 (0.033)	33.36 (1.536)
Ethylene	0	0.05 (0.020)	0.09 (0.036)	2.10 (0.492)	6.73 (0.888)
SE (of Log ₁₀ , n = 96; df = 68)			0.0553		
Significant effects			S ^{***} , T ^{NS} , S × T ^{***}		
Maximum length (mm)					
CIPC	0	0 (0.00) ^y	0.3 (0.10)	3.3 (0.629)	112.8 (2.056)
Ethylene	0	1.3 (0.352)	7.0 (0.905)	35.9 (1.567)	18.3 (1.286)
SE (of Log ₁₀ , n = 96; df = 68)			0.1002		
Significant effects			S ^{***} , T ^{***} , S × T ^{***}		

^zValues backtransformed from square root used in statistical analysis; square root values in brackets.

^yValues backtransformed from Log₁₀ used in statistical analysis; Log₁₀ values in brackets.

NS, *, **, *** Nonsignificant, significant at $p \leq 0.05$, 0.01, or 0.001, respectively, where S = storage time and T = treatment.

et al. (1974) were ≤ 72 h, they did conduct one experiment using continuous ethylene at $2 \mu\text{L}\cdot\text{L}^{-1}$ for 40 d, which inhibited sprouting, compared with an air treatment. After the ethylene was removed on day 40, sprouts appeared and grew at a rate similar to tubers in air. Since they had concluded from their other results with 72 h treatment that ethylene shortens rest, they speculated that this 40 d treatment also terminated rest but continuous exposure somehow inhibits bud elongation. Compared with untreated potatoes, continuous ethylene in our study did not increase the number of large sprouts but it increased the number of small sprouts and tuber eyes producing sprouts. Although Rylski et al. (1974) did not observe any changes in the number of small sprouts or sprouting, it can be suggested that, as an extension of what they had speculated, continuous ethylene treatment terminates rest at the biochemical and cellular level in tuber eyes but appears to inhibit visible sprout cell differentiation and elongation.

Large sprouts that developed on the ethylene-treated potatoes after storage were much easier to detach, compared to sprouts on untreated tubers. Although ethylene is recognized as an abscission promoting agent in many crops (Reid, 1985), we believe this to be the first report of abscission enhancement in stem tissue. Furthermore, there was a residual abscission effect after ethylene treatment stopped.

In both the laboratory and commercial studies, there were no decay, disorder or internal sprouting problems in ethylene-treated tubers. The internal sprouting observed in the commercial potatoes treated with CIPC is a problem that is sometimes observed in CIPC-treated tubers and is associated with an inadequate amount of CIPC on the tubers (Hruschka and Heinze, 1967).

Fig. 1. USDA fry color grades of potatoes in the commercial study in three storage seasons (1992–93, 1993–94, and 1994–95) (closed circle = CIPC, open circle = ethylene).

Lulai et al. (1995) showed that several jasmonate compounds control tuber sprouting. Since reports of stimulation of internal ethylene production with the application of methyl jasmonate on tomatoes (Saniewski and Czapski, 1985; Saniewski et al., 1987b) and apples (Saniewski et al., 1987a) have been published, it is possible that the mode of action of jasmonates and other sprout control compounds may be partly related to the stimulation of internal ethylene in the tubers.

Although it was not obvious in all years in the laboratory and commercial studies, continuous ethylene in several years resulted in a drop in fry color, observable at the first sample date after ethylene was applied. This was not permanent and fry color recovered (higher Agtron values) over time. In the laboratory study, the fry color of potatoes continuously treated with ethylene was frequently similar to untreated potatoes, especially after longer storage times when the untreated potatoes were producing many sprouts. However, the fry color of ethylene-treated tubers was almost always darker than tubers treated with CIPC in the laboratory and commercial studies.

Since the results of this study showed that continuous ethylene treatment at $166 \mu\text{mol}\cdot\text{m}^{-3}$ substantially suppressed tuber sprouting during long-term storage, the conclusion of Kader (1985) that ethylene treatment is desirable for seed potatoes but undesirable for table and processing potatoes is not entirely correct. If fry color has little or no effect on market value, e.g., table stock, continuous ethylene treatment is a viable option. The use of continuous ethylene for long-term storage of seed potatoes is also appealing since it reduced apical dominance and caused more uniform sprouting. However, it may result in excessive sprout abscission during the planting process, if sprouts are already present. For applications in which fry color is important, e.g., French fries or chips, then continuous ethylene may be a viable alternative to CIPC, under one or both of the following circumstances:

- 1) French fry and/or chip market consumers will accept a darker fry color as a trade-off in reducing chemical residues in the product.
- 2) A method is developed to minimize the darkening of fry color following ethylene exposure.

Continuous ethylene treatment could also be useful in warmer climates, even for French fry and chip potatoes, where the higher storage temperatures result in greater losses of CIPC and other commercial sprout inhibitors through volatilization.

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