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Wound Healing and Weight Loss of Sweet Potatoes Harvested at Several Soil Temperatures

William M. Walter, Jr.
Agricultural Research Service, U.S. Department of Agriculture, and North Carolina Agricultural Research Service, Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624

Larry K. Hammett[1]
Agricultural Research Service, U.S. Department of Agriculture, and Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609

Francis G. Giesbrecht
Department of Statistics, North Carolina State University, Raleigh, NC 27695-8203

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Abstract. **Roots of three sweet potato [*Ipomoea batatas* (L.) Lam] cultivars, Centennial, Jewel, and Pope, were harvested at three soil temperature ranges, cured for 1 to 7 days at 30°C and 90% to 95% RH, and stored at 13° to 13.5° and 90% and 95% RH. Wound healing during curing was evaluated using a rapid color test and histochemical methods. The color test was a good indicator of the lignification phase of wound healing for 'Centennial' and 'Jewel', and a fair indicator for 'Pope'. Wound healing rates for the cultivars were similar. Roots harvested from the warmest soils (22° to 25°) had higher color scores (most wound lignification) up to 3 days of curing. After 5 days, there were ≈2.7 layers of lignified cells and one layer of wound periderm. After 16 weeks of storage, roots harvested at soil temperatures of 10° to 12° and 22° to 25° had lost more weight and developed more rots than did roots harvested at 15° to 17°, despite the fact that wound healing progress was similar. Thus, factors other than wound healing strongly influence storage stability.**

One of the principal reasons for curing sweet potatoes is to heal harvest-inflicted wounds. Breaks in the periderm can serve as an entrance for pathogenic microorganisms. Storage life is increased if wounds can be healed promptly, since the healed surface of a wounded sweet potato forms an effective barrier against microbial invasion (Lauritzen and Harter, 1926; Weimer and Harter, 1921). Artschwager and Starret (1931) showed that wound healing in sweet potato occurs in two stages. The first stage is deposition of "suberin" on the cell walls adjacent to the lesion, followed by the second stage, wound periderm formation. Temperatures around 30°C and relative humidities of 85% to 95% are optimal for rapid wound healing (Artschwager and Starret, 1931; Weimer and Harter, 1921).

The time recommended for curing has steadily declined from 14 days (Morris and Mann, 1955) to the present recommendation in North Carolina of 4 to 7 days (Wilson et al., 1980). The range of 4 to 7 days is provided because of supposed different responses to the curing process as a function of environmental conditions and germplasm variability. In the southeast, sweet potatoes are harvested from August through mid-November, resulting in wide variation in soil temperatures at harvest. Lutz and Simmons (1948) reported that the curing time required depends on the average outside temperature. Later work with 'Goldrush' (Moore and Anderson, 1956) and 'Porto Rico' (McCombs and Pope, 1958) indicated that 5 days of curing were sufficient. Kushman and Deonier (1958) reported that curing for 7 days at 29.4°C gave the greatest storage life, regardless of harvest conditions, but that roots harvested early in the season (warm soil temperature) and late in the season (cool soil temperature) did not store as well as those harvested during mid-season.

The wound healing process is considered to be complete when wound periderm (wound cork) is no longer being formed. Considerable sample preparation difficulties preclude real-time evaluation of the progress of wound healing via histological methods. Recent reports (Walter and Schadel, 1982, 1983) have described a rapid, objective method to evaluate wound healing progress.

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[1]Present address: AG South, Inc., 11705 Trottenham Drive, Raleigh, NC 27612.

These studies showed that the initial response to wounding is deposition of a lignin-like material, rather than suberin, on the inside of several layers of cells below the wound surface. When the wound tissue was removed and treated with an acidic solution of phloroglucinol, the color developed was indicative of the extent of lignification. Wound cork formation was observed to occur simultaneously with development of the most intense color, indicating that the test may be useful in the evaluation of curing progress.

Weight loss during storage after curing is due to a combination of transpiration and respiration, confounded by losses from decay. Transpiration losses are due to evaporative loss of extracellular water caused by the vapor pressure differential between the root interior and the outside environment. Respiration loss entails dry matter loss. Transpiration has been shown to be the most important contributor to weight loss in sweet potatoes during storage (Kushman and Pope, 1972; Picha, 1986). The curing period should be of sufficient duration that losses in weight due to physiological processes and decay are minimized.

The purpose of this study was to evaluate the color test as a predictor of wound healing progress by comparing color scores with histochemical assessment of wound healing for three cultivars harvested at three soil temperatures that were selected to represent conditions for early, mid, and late harvests. In addition, weight loss during storage was compared to the extent of wound healing occurring during curing.

Materials and Methods

'Centennial', 'Jewel', and 'Pope' sweet potatoes were grown at the NCDA Horticultural Crops Research Station in Clinton, N.C., from 1982 through 1984. The plants were set in early June each year and grown using recommended horticultural practices (Wilson et al., 1980). Roots were harvested after 110 to 140 days when the soil temperature had been in the desired range for 24 hr or more. The temperature ranges were 22° to 25°, 15° to 17°, and 10° to 12°C. In 1983, cold, wet weather conditions prevented the 15° to 17° harvest. The roots were not of the same physiological age, although the mean root weights were similar for the three cultivars and for the soil harvest temperatures (Table 1). No attempts were made to control soil moisture levels.

Roots were hand-harvested after digging with a turning plow. The entire harvest was hand-placed in vented wooden containers and transported to Raleigh, N.C., where the roots were immediately placed in a laboratory area (21° to 23°C) and held overnight. For each cultivar, the entire harvest was placed on a table, and random samples were obtained for wound healing and weight loss experiments.

Color test. Seven lots of 10 roots each were selected from each cultivar. Each root was hand-wounded in three areas by removing a circular patch of tissue about 10 mm in diameter and 1 to 2 mm in depth. One wound each was used for the color test and histological tests, and one wound served as an extra. The roots were then put in open, perforated paper bags and then placed in vented wooden boxes. All samples were held in a ventilated curing room at 90% to 95% RH and 30°C. One set of 10 roots from each cultivar was removed daily for 7 days. For the color test, a piece of wound tissue from each root was removed and held in a saturated solution of phloroglucinol (PG) in 18% HCl for 10 min. The tissue was removed, blotted, and the color score assigned on a 1 to 4 basis, with 1 being no change in color and 4 being a dark purple. A color print made from tests on a control series of sweet potatoes served as the standard for evaluating color scores.

Histological evaluation. Tissue blocks containing an entire wound from each root were excised and placed in 3% glutaraldehyde solution. The samples were obtained simultaneously with the color score tissues. Five wounds from each cultivar for days 3, 5, and 7 were dehydrated with an ethanol–tertiary butyl alcohol series, embedded in paraffin, and sectioned (15 μm) on a rotary microtome. The sections were deparaffinized with xylene and rehydrated before staining. Some sections were stained with acidic PG and examined with a light microscope. The number of layers of pink-stained, lignified cells was enumerated. Other deparaffinized samples were stained with safranin and fast green, and the number of layers of wound cork cells were counted (Walter and Schadel, 1982). Since the numbers of layers of cells were not continuous, each wound was scored as a range (i.e., 1 to 2, 2 to 3, etc.). For the purpose of data analysis, each range was assigned a number as follows; 1 = no observable development; 2 = zero to one layer; 3 = one to two layers; 4 = two to three layers; 5 = three to four layers; 6 = four to five layers.

Weight loss. Ten weighed roots (serving as one replicate sample) were placed in an open, perforated, Kraft paper bag. The mean weight of individual roots ranged from 277 to 316 g (Table 1). Five replicates of each cultivar were used for each of the 7 days of curing period. The roots were then placed in a ventilated curing room held at 30°C and 90% to 95% RH. Each day for 7 days, five replicate samples (50 roots total) were removed, weighed individually, and then placed in a ventilated storage area held at 13° to 15.5° and 90% to 95% RH. Roots were again weighed individually at 8 and 16 weeks after harvest. Visibly decayed roots were classed as rots and discarded. Weight losses were expressed as a percentage of the at-harvest weight. Rot losses were expressed as a percentage of the total number of at-harvest roots used in each replicate.

Statistical analysis. Analysis of the data was performed on pooled means for each year's data. Analysis of variance was used to identify statistically significant trends and to identify differences between means (SAS, 1982).

Table 1. Mean weight (grams) and SDs of sweet potatoes selected for wound healing and weight loss studies.

	Mean wt (g)		
	Harvest soil temperatures (°C)		
Cultivar	22–25 (H1)	15–17 (H2)	10–12 (H3)
Centennial	285 ± 110	268 ± 94	277 ± 108
Jewel	311 ± 134	288 ± 72	313 ± 122
Pope	284 ± 106	276 ± 77	316 ± 115
All cultivars	294 ± 118	277 ± 82	302 ± 116

Results and Discussion

Color test. The trend for the three cultivars was for roots harvested at 22° to 25°C soil temperatures (H1) to have the highest overall color scores (Fig. 1). Samples from harvest 2 (H2, soil temperatures 15° to 17°) also tended to have higher color scores than roots at harvest 3 (H3, soil temperatures 10° to 12°C) for the first 3 days of curing (Fig. 1 A–C), but not later. The rate of increase in color scores for all cultivars declined considerably by day 5, indicating that lignification was nearly complete. Thus, color scores were affected both by harvest and number of days cured (Table 2).

Histological evaluation. Lignified cell scores increased with

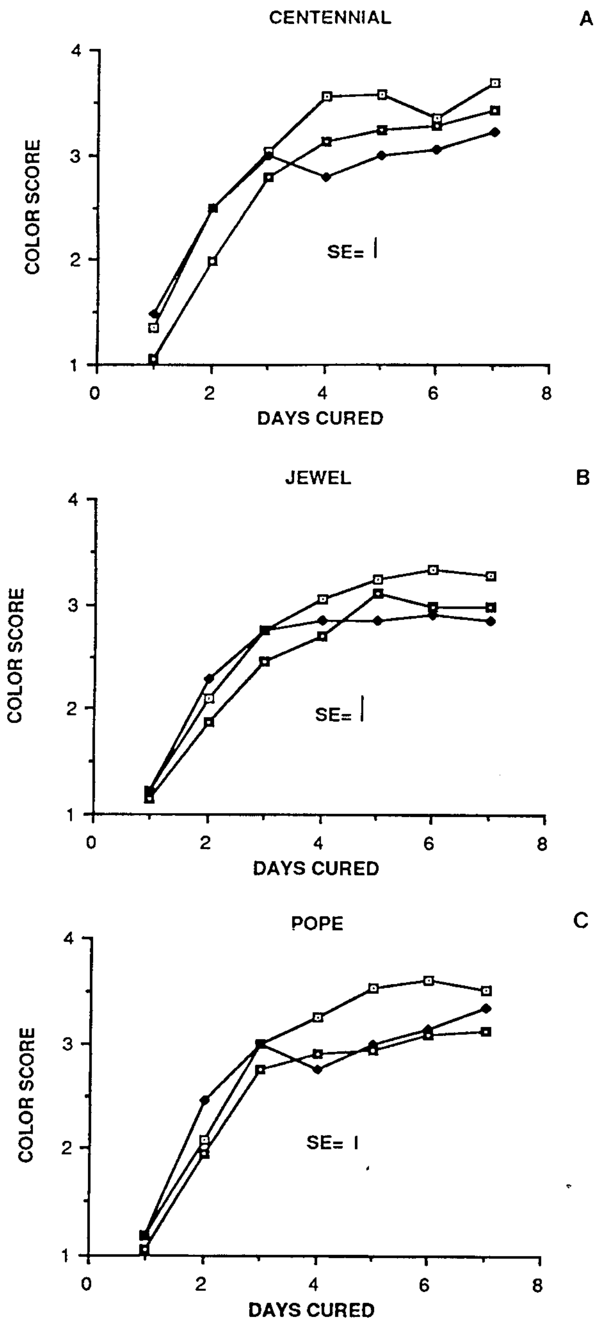

Fig. 1 Color scores for 'Centennial' (**A**), 'Jewel' (**B**), and 'Pope' (**C**) sweet potatoes. The scores were assigned on a 1 to 4 basis, with 1 being no change in color and 4 being a deep purple. Pooled data for 3 years. Harvest 1 (⊡), 22° to 25°C; Harvest 2 (♦), 15° to 17°; Harvest 3 (□), 10° to 12°.

increased curing time (Tables 2 and 3). By day 7, lignified cell scores tended to be highest for H1 in 'Centennial' and 'Pope' and also for 'Jewel', while lignified cell scores for H1 and H3 were greater than for H2. However, with the exception of the lignified cell score for 'Centennial', no statistically significant effect of harvest date was observed (Table 2), because histological evaluation of wound healing progress was not employed until day 3, while color test scores showed changes with harvest date up to 3 days.

Wound periderm formation did not begin until after 3 days of curing (Table 3) in agreement with an earlier study (Walter

Table 2. Analyses of variance for color score and histological evaluation scores (lignification score and wound periderm score) for three sweet potato cultivars

		Cultivar[z]		
Source	df	Centennial	Jewel	Pope
Color score				
Year	2	**	NS	**
Harvest temperature	2	**	*	**
Days cured	6	**	**	**
Histological evaluation scores				
Lignification				
Year	2	*	NS	*
Harvest temperature	2	*	NS	NS
Days cured	2	**	*	**
Wound periderm				
Year	2	NS	NS	NS
Harvest temperature	2	NS	NS	NS
Days cured	2	**	**	**

*,**$P \leq 0.06$ or $P < 0.001$, respectively.

and Schadel, 1982) and increased with time of curing. H1 had a higher wound periderm score than either one or both H2 and H3 (both in 'Centennial', Table 3). It appeared that roots harvested from warm soil had a slight advantage in the overall rate of wound healing. No statistical differences among cultivars was obtained when scores for all harvests were pooled, indicating that wound healing rates were similar. There were 3.3 layers of lignified cells after 7 days of curing and 2.7 layers of wound periderm, for a total of 6.0 layers of healed wound tissue (the sum of lignified cell and wound periderm scores). Walter and Schadel (1982) have found a 7-day cure for 'Jewel' resulted in 4.3 layers of lignified cells and 3.2 layers of wound periderm, for a total of 7.5 layers of healed wound tissue.

Comparison of the color scores and wound lignification scores from the present study revealed that the color scores tended to increase more slowly after 3 days than did the lignification scores. Response of the wound tissue to acidic phloroglucinol in the color test depends on the number of layers of lignified cells and on the thickness of the lignified layers, while the lignified cell scores are a measure of the number of layers of lignified cells only. The cultivars added 0.7 layers of lignified cells between days 5 and 7, while the color score rate of increase slowed considerably, to 0.1 color unit per day from a rate of 0.2 color units per day between day 3 and day 5. Color score sensitivity declined as the amount of lignification increased.

Correlation coefficients between color scores and lignified cell scores were highest for 'Centennial' and 'Jewel', with r = 0.753 and r = 0.712, respectively (Table 4). For 'Pope', r = 0.588, indicating that the color score was not as good a predictor of cellular lignification as in the other cultivars. It is likely that a higher r value would have resulted had lignified cell scores been measured during the most linear portion of the color score change (days 1 and 2). Correlation between wound periderm scores and lignified cell scores ranged from r = 0.756 for 'Centennial' to r = 0.847 for 'Jewel' (Table 4), indicating that wound periderm formation and wound lignification were both increasing.

Wound healing data indicated that the color score is a good

Table 3. Effect of soil temperature at harvest on lignified cell score, wound periderm score and healed tissue score for sweet potato cultivars.

Cultivar	Soil temp at harvest (°C)	Days cured	Histological evaluation scores: Lignified Cell	Wound periderm	Healed tissue[z]
Centennial	22–25 (H1)	3	3.2	1.0	4.2
		5	3.9	2.0	5.9
		7	4.9	3.9	8.9
	15–17 (H2)	3	3.0	1.0	4.0
		5	3.4	2.0	5.4
		7	4.0	3.5	7.5
	10–12 (H3)	3	3.1	1.0	4.1
		5	3.7	1.9	5.7
		7	4.3	3.5	7.7
SE of the mean			±0.2	±0.4	±0.6
Jewel					
	22–25 (H1)	3	3.1	1.0	4.1
		5	3.9	2.0	5.9
		7	4.6	3.9	8.5
	15–17 (H2)	3	3.1	1.0	4.1
		5	3.3	1.6	4.9
		7	3.7	3.0	6.7
	10–12 (H3)	3	3.0	1.0	4.0
		5	3.9	2.7	6.5
		7	4.3	3.8	8.1
SE of the mean			±0.5	±0.4	±0.8
Pope					
	22–25 (H1)	3	3.0	1.0	4.0
		5	3.7	2.2	5.9
		7	4.8	4.1	8.9
	15–17 (H2)	3	3.1	1.0	4.1
		5	3.6	2.0	5.6
		7	4.1	4.1	8.2
	10–12 (H3)	3	3.1	1.0	4.1
		5	3.7	2.5	6.2
		7	4.0	3.6	7.6
SE of the mean			±0.2	±0.5	±0.6
All cultivars, SE of the mean			±0.3	±0.4	±0.6

[z]Sum of lignified cell score and wound periderm score.

Table 4. Pearson product moment correlation coefficient matrix for sweet potato cultivars.

	Lignification score	Wound periderm score
Centennial		
Color score	0.753**	0.552*
Lignification score	---	0.756**
Jewel		
Color score	0.712*	0.620*
Lignification score	---	0.847**
Pope		
Color score	0.588*	0.560*
Lignification score	---	0.811**

*,**Probability of observing this correlation or higher = 0.005 or 0.0001, respectively.

indicator of wound lignification for 'Centennial' and 'Jewel' and that wound and periderm formation begins after 3 days of curing. Wound healing rates were similar among cultivars, and Hl roots healed slightly better than those harvested at lower soil temperatures.

Weight loss. Percent weight loss during storage was affected by length of storage, numbers of days cured, and harvest soil temperature (HST). At 8 weeks after harvest, the highest weight loss was found in roots from the highest soil temperatures for all cultivars. After 16 weeks, roots from both H1 and H3 showed high weight loss. Not only did H2 roots show lower losses, but they also had fewer percent rots at 16 weeks than H1 and H3 roots (Table 5). Kushman and Deonier (1958) have reported that 'Porto Rico' sweet potatoes from early (warm soil temperatures) and late (cool soil temperatures) harvests did not store as well as those roots harvested at moderate soil temperatures.

Weight loss after 8 or 16 weeks' storage was not significant as a function of days cured for H1 roots, except for 'Jewel' (Table 6). The only soil temperature showing significance for all cultivars was that at H2. When the data for all harvests were pooled, a statistically significant trend ($P \leq 0.003$) relating weight loss and days cured was obtained for each cultivar for each of the storage times.

Weight loss during curing and storage in the absence of decay is a function of the rates of transpiration and metabolism (Kushman and Pope, 1972; Picha, 1986). Decay and/or internal breakdown cause additional weight loss. The sweet potato producer must balance weight loss during storage due to a too-short curing period with excessive weight loss due to elevated curing

Table 5. Effect of harvest soil temperature on weight loss and rot during storage for 'Centennial', 'Jewel', and 'Pope' sweet potatoes

Cultivar	Harvest soil temp (°C)	Weight loss at indicated weeks after harvest[z] (%) 8	16	Rots 16 weeks after harvest (%)[y]
Centennial	22–25 (H1)	11.3 a	14.1 a	8.0
	15–17 (H2)	6.41 c	8.23 b	2.3
	10–12 (H3)	9.07 b	14.9 a	13.0
Jewel	22–25 (H1)	8.94 a	11.2 a	4.0
	15–17 (H2)	6.24 b	8.04 b	3.4
	10–12 (H3)	6.42 b	11.2 a	5.0
Pope	22–25 (H1)	10.3 a	12.8 a	15.8
	15–17 (H2)	6.88 b	8.87 b	5.7
	10–12 (H3)	6.67 b	11.5 a	7.5

[z]For each cultivar, means separated by Waller–Duncan multiple range test.
[y]Expressed on basis of total number of roots at harvest for each cultivar and soil temperature.

temperatures for longer than required to heal wounds. Picha (1986) showed that, for 'Jewel' and 'Centennial', ≈34% of the weight loss 16 weeks after harvest had occurred during the 10-day curing period.

Weight loss data for the stored cultivars from this study indicated that when the results are calculated on a from-harvest basis (Fig. 2 A–C), there seems to be little advantage to curing more than 4 to 5 days, in agreement with McCombs and Pope (1958), but not with Kushman and Pope (1972).

Wound healing and storage weight loss. Evaluation of wound healing progress during this study by the color test indicated that wound lignification rates were greatest up to about 5 days for the cultivars used in this study (Fig. 1 A–C). Soil temperatures at harvest had a slight effect on wound lignification in one cultivar, but none on wound periderm formation (Table 2). Histological assessment of lignification indicated a range of two to three layers (mean of 2.7 layers), depending on the cultivar and harvest temperature and a wound periderm ≈1 layer thick after 5 days (Fig. 3 A–C). It can be inferred from the data in Fig. 2 that combination of lignified tissues and wound periderm present after 5 days' curing is fairly effective at retarding invasion by pathogens. The increased healed wound tissue present at 7 days (≈3.3 layers of lignified cells and ≈2.7 layers of wound periderm) apparently did not provide additional protection as reflected by no significant trend toward lower weight loss when the curing period was extended to 7 days.

However, the relationship between wound healing during curing and weight loss during storage is not clear. The H2 roots

Table 6. Effects of duration of curing on after-harvest weight loss for 'Centennial', 'Jewel', and 'Pope' sweet potatoes[z].

Cultivar and days cured	8 weeks: 22–25 (H1)	8 weeks: 15–17 (H2)	8 weeks: 10–12 (H3)	16 weeks: 22–25 (H1)	16 weeks: 15–17 (H2)	16 weeks: 10–12 (H3)
	Time after harvest; harvest soil temperatures (°C)					
	Weight loss (%)					
Centennial						
1	12.1	7.8	10.8	15.6	9.6	17.7
2	10.0	6.9	9.7	12.6	8.4	16.7
3	10.0	6.2	8.3	12.7	8.2	14.2
4	10.9	6.3	9.2	12.9	8.1	14.0
5	11.9	5.8	9.0	14.2	7.5	13.7
6	12.7	5.8	8.8	15.4	7.7	14.3
7	11.7	6.0	7.7	15.1	8.0	13.7
Trend	NS	***	*	NS	***	***
Jewel						
1	11.0	8.1	6.8	13.7	10.2	12.8
2	8.5	7.3	6.6	10.8	9.5	11.3
3	8.3	6.0	6.8	10.1	7.9	11.2
4	8.0	5.3	6.2	10.5	7.0	10.7
5	9.6	5.9	6.2	11.7	7.2	9.9
6	9.4	5.6	6.1	11.6	7.4	11.1
7	7.8	5.5	6.2	10.0	7.3	11.3
Trend	**	***	NS	**	***	*
Pope						
1	11.8	9.0	7.4	14.9	11.2	12.6
2	10.3	7.9	6.8	11.9	9.5	11.9
3	10.3	6.8	6.6	12.4	9.3	11.0
4	10.0	6.5	6.5	11.9	8.6	11.9
5	9.6	5.9	6.2	13.6	7.9	11.1
6	10.0	5.7	8.8	12.7	7.7	10.9
7	10.5	6.4	6.4	12.1	8.0	11.4
Trend	NS	***	NS	NS	***	NS

[z]Means are for three crop years.
[ns,*,**]Not significant or significant at $P \leq 0.05$ or 0.001, respectively.

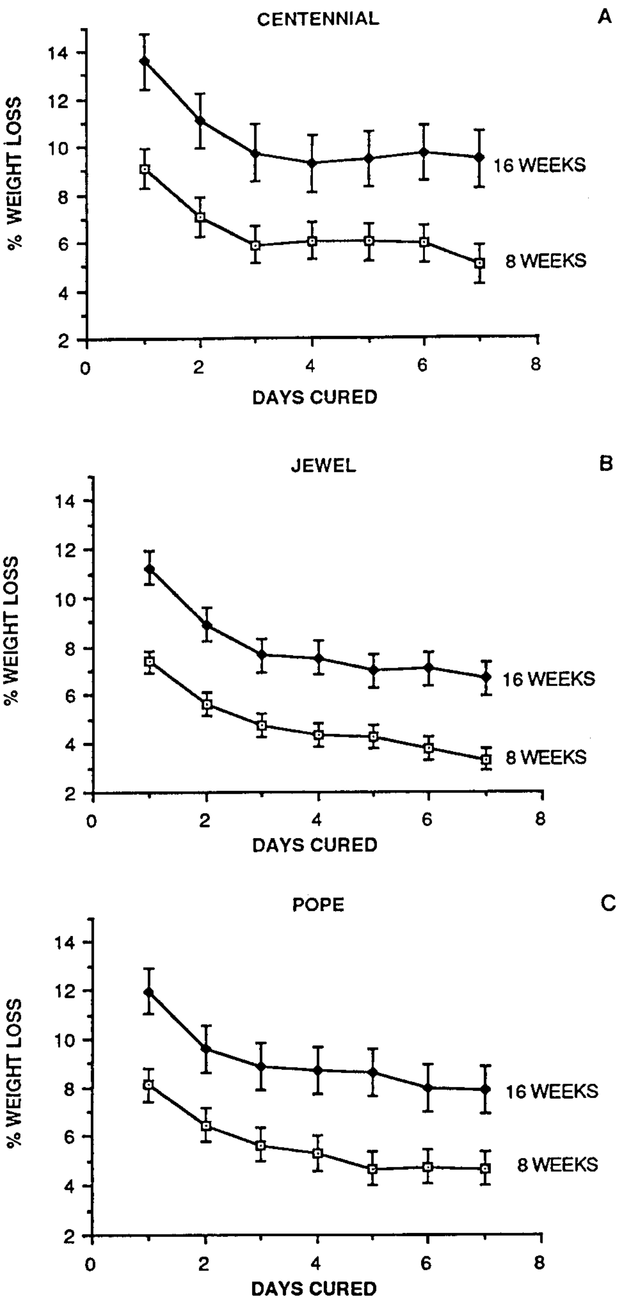

Fig. 2 Percent weight loss after harvest relative to days cured for 'Centennial' (**A**), 'Jewel' (**B**), and 'Pope' (**C**) sweet potatoes. Bars represent the SE of the mean. Data are for three soil temperatures for 3 years.

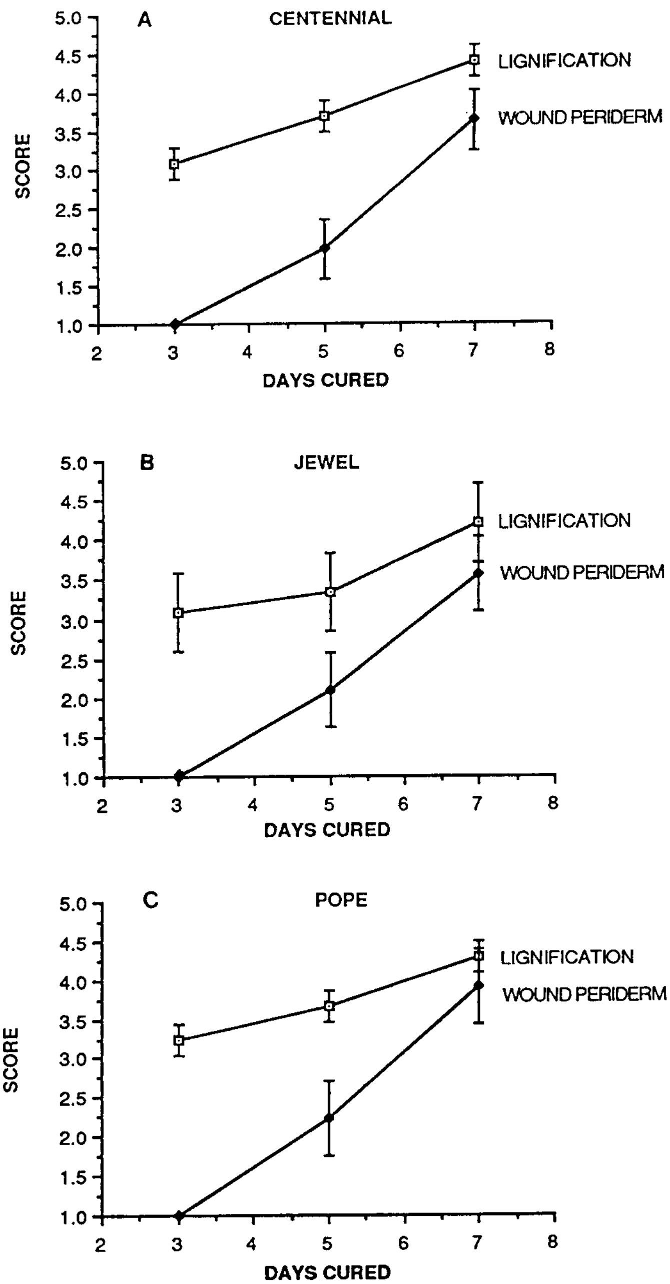

Fig 3. Scores for lignified cells and wound periderm cells formed in controlled wounds as a function of days cured for 'Centennial' (**A**), 'Jewel' (**B**), and 'Pope' (**C**) sweet potatoes. The scores were assigned as follows: 1 = no observable development; 2 = zero to one layers; 3 = one to two layers; 4 = two to three layers; 5 = three to four layers. Bars represent the SE of the mean. Data are for three soil temperatures for 3 years.

consistently lost less weight during storage for 16 weeks and had the lowest percentage of rotted potatoes (Table 5). However, wound healing data (color scores, wound lignification, and wound periderm formation) did not appear to be consistent predictors of storage losses because the H2 roots did not show a higher rate or extent of wound healing than the roots harvested at the other soil temperatures. These findings indicate that factors other than wound healing rates must also have a significant effect on storage stability.

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