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Assessment of Potato Breeding Progress in the USA over the Last Century

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ABSTRACT

Potato (*Solanum tuberosum* subsp. *tuberosum*) production has increased six-fold (per unit area) in the USA since the 1920s. Direct comparison of potato cultivars released during the past century can help us understand how potato breeding has contributed to these production improvements and to other important traits associated with marketing and utilization. Our objective was to study trends in potato genetic improvement during four subjective breeding periods (BP) (pre-1900 = BP I; 1930 to 1949 = BP II; 1950 to 1969 = BP III; 1970 to present = BP IV), and also to compare performance between and within the three major cultivar types (round-white, long, and red-skinned). In field trials conducted from 1990 to 1992, under best management practices (with scheduled irrigation) in Michigan, the greatest total yield potential was observed in several cultivars released during BP I and II. These cultivars also had late vine maturities. On average, BP II had the greatest marketable yield. Cultivars released in BP III had the lowest total yield, earliest vine maturity, highest scab resistance and most favorable tuber appearance. General trends over periods were for earlier maturity and improved tuber appearance. Round-white cultivars improved for chip-processing ability and dry matter content over breeding periods, while long types increased in percent marketable yield only in BP IV. No trends were observed for scab resistance. When cultivars were grouped according to tuber type, there were no differences in total yield; however, the long types had the lowest marketable yield and the red-skinned types had lowest dry matter content.

THE POTATO (*Solanum tuberosum* L.) is considered one of the world's major food crops following rice (*Oryza sativa* L.), wheat (*Triticum aesitvum* L.), and maize (*Zea mays* L.) in importance (Ross 1986). In the USA, the potato is the highest ranking vegetable crop in production. In relation to grain crops, the potato is relatively new to the northern hemisphere (approximately 400 yr; Hawkes 1990), and breeding efforts in North America can be traced back to the 1850s (Goodrich, 1863).

Potato breeding in the USA has involved both the public and private sectors since 1850 (Plaisted and Hoopes, 1989; Stuart, 1937). During this period, over 250 cultivars have been named and released in North America (Chase, 1992), but only a few have had major impact on total commercial potato production. However, usage trends during the past 100 yr show that cultivars have changed, and more recent cultivars bred by North American breeders have replaced many of the older ones (Sieczka and Thornton, 1993). It is assumed that newer cultivars provide marketing advantages over the cultivars they replace.

Between 1920 and 1989, potato production in the USA increased from a national average of 5.6 t ha^{-1} to over 33.6 t ha^{-1} (Lucier et al., 1990). During this period production more than doubled to approximately 44.8 million metric tonnes. This production increase has been attributed to factors such as improved cultural practices, use of fertilizer, irrigation, pest management, and a shift in production to the western USA, along with the introduction of improved cultivars through public breeding efforts (Lucier et al., 1990).

In maize, 60 to 90% of the yield increase in the USA can be attributed to cultivar improvement (Duvick, 1984). Yield gains in the USA from genetic improvement during the twentieth century have been shown for other major crops such as soybean [*Glycine max* (L.) Merr.] (Specht and Williams, 1984), wheat (Cox et al., 1988; Schmidt, 1984; Waddington et al., 1986), cotton (*Gossypium hirsutum* L.) (Meredith and Bridge, 1984), barley (*Hordeum vulgare* L.) (Wych and Rasmusson, 1983), oats (*Avena sativa* L.) (Wych and Stuthman, 1983), and sorghum [*Sorghum bicolor* (L.) Moench] (Miller and Kebede, 1984).

Evaluating the contribution of breeding to potato improvement is complex. Different cultivars have different uses. Red-skinned cultivars have a low dry matter content (specific gravity below 1.070) and are used mainly for fresh-market consumption. Round-white cultivars are used for either chip-processing or tablestock. Those used for chip-processing generally have higher specific gravity (1.080 or greater) and accumulate less reducing sugars (less than 0.35 g kg^{-1} glucose on a fresh weight basis).

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Abbreviations: BP, breeding periods; TAR, tuber-appearance ratings; SFA, Snack Food Association.

Long-white or long-russet types are targeted for frozen-processing, dehydration, and tablestock. For frozen processing, desirable cultivars are long and blocky with a high specific gravity (greater than 1.080). In general, all fresh-market cultivars, regardless of tuber type, should have an attractive appearance for successful marketing.

We need to determine what effect breeding has had on the improvement of potatoes, in terms of both yield and quality. Moreover, the quality in potato differs with its utilization types, and the relative importance of markets, which determines utilization, has changed over time. Therefore, can we document an increase in quality traits with the introduction of new cultivars within these market classes?

In this paper, we report on a series of field trials to analyze trends in genetic improvement in potato from 1860 to present. We also compare the performance, within and between, the three major cultivar types: round-white, long (white and russet), and red-skinned.

MATERIALS AND METHODS

Plant Material

Twenty-three potato cultivars were used in a series of three field trials. These cultivars are listed in Table 1 along with their year of release and tuber type. To prevent seed source effects, virus-free tubers of the cultivars were obtained from Dr. N.S. (Bud) Wright, Agriculture Canada, Vancouver, BC. These were increased at the Lake City Experiment Station, Lake City, MI, in seed plots during 1988 and 1989. These tubers were used for the 1990 field experiment and also for further increase to produce seed for the 1991 and 1992 trials.

Choice of the cultivars for BP I and II was based on their relative national importance during the early twentieth century (American Potato Yearbook, 1948) and availability of virus-free tuber stocks. The small number of cultivars chosen for this study reflects the limited number of cultivars that achieved national importance. The most recently released cultivars used for this study were chosen on their performance and commercial potential in agronomic trials conducted from 1986 to 1989 in Michigan (Chase et al., 1990).

To evaluate breeding progress, the cultivars were placed into four groups according to date of release: BP I (nineteenth century), BP II (1930–1949), BP III (1950–1969), and BP IV (1970–present). No cultivars of importance were released from 1900 to 1929. In addition, the three major tuber types (round-white, red-skinned, and long-white or russet) were compared.

Field Evaluation

Three field trials were conducted at the Montcalm Research Farm, Entrican, MI, between 1990 and 1992. The 1990 trial was planted 8 May and harvested 26 September (139 d) while the 1991 trial was planted 13 May and harvested 24 September (134 d). In 1992, the trial was planted on 7 May and was harvested 26 September (140 d). Each trial was planted as a randomized complete block design with four replications. In preparation for planting, seed was removed from 4°C storage, warmed to 13°C and hand-cut seed pieces weighed approximately 42 to 56 g. Each plot consisted of 23 plants with a single plant used as a border at row-ends. Spacing was 30.5 cm between plants and 86.4 cm between rows. Soil at Montcalm Research Farm is a McBride sandy loam (coarse, loamy, mixed frigid, Alfic Fragiorthod). Non-limiting levels of moisture and fertility were maintained and preventive disease and insect control programs were used. Weed control was adequate in all trials. Vine desiccant (diquat, 6,7-dihydrodipyrido[1, 2-α: 2′, 1′ *c*]pyrazinediium ion) was applied 10 to 14 d prior to the September harvests according to manufacturer's label.

Table 1. Potato cultivars tested at the Montcalm Research Farm, Entrican, MI, from 1990 to 1992.

Breeding period	Cultivar	Year of release	Type
I (19th Century)	Early Rose	1861	Long white
	Russet Burbank†	1876	Long russet
	Irish Cobbler‡	1876	Round white
	Bliss Triumph§	1878	Red
	Green Mtn.	1885	Long white
	White Rose	1893	Long white
II (1930–1949)	Katahdin	1932	Round white
	Sebago	1938	Round white
	Ontario	1946	Round white
	Kennebec	1948	Round white
	Red Lasoda	1948	Red
	Red Pontiac	1949	Red
III (1950–1969)	Norland	1957	Red
	Superior	1961	Round white
	Norgold Russet¶	1964	Long russet
	'Norchip'	1968	Round white
IV (1970–present)	Atlantic	1978	Round white
	Shepody	1980	Long white
	Sangre#	1982	Red
	Eramosa¶	1988	Round white
	Russet Norkotah	1988	Long russet
	Snowden	1990	Round white
	Ranger Russet‡	1991	Long russet

† Burbank released in 1876 while its Russet sport was released in 1914.
‡ Tested in 1991 and 1992.
§ Tested in 1992.
¶ Tested in 1990 and 1991.
# Tested in 1990 and 1992.

Agronomic Evaluations and Grading

Prior to vine desiccation, maturity ratings were collected from the three full-season trials by two-person teams using a five-point linear scale with 1 = 100 d and 5 equivalent to a 140 d or later maturity. Trials were mechanically harvested, then graded according to size for round-shaped cultivars (oversize = greater than 8.26-cm diam., Grade A = 5.1 to 8.26 cm, Grade B = less than 5.1 cm) and graded by weight for long-shaped cultivars (oversize = greater than 283.5 g, Grade A = 113.4 to 283.5 g, Grade B = less than 113.4 g). Yield data were collected on each grade category. Marketable yield (U.S. #1 grade) was determined by summing weights in the Grade A and oversize grades. Non-marketable growth-related defects were graded and recorded as culls. Using the formula [(wt. in air/(wt. in air − wt. in water)], 4- to 5-kg tuber samples of A size potatoes were used to measure specific gravity. Approximately 20 kg of Grade A size tubers were composited to evaluate external appearance. Tuber appearances were evaluated by a three-person team using a five-point scale with 1 equivalent to a very desirable appearance. A tuber with desirable appearance had good size, a smooth shape, was free of external defects, and had uniform appearance among tubers. A deep, uniform red color, a bright skin, and a uniform russet skin was considered desirable for red-skinned, white-skinned, and russet-skinned potatoes, respectively.

Chip-Processing

A 25-tuber sample was composited from the four replications for each chip-processing cultivar. Samples from the 1990 and 1991 trials were processed within 2 wk of harvest, while in

1992 two samples were stored at 10 and 7.2°C (commercial storage temperatures) for 5 mo then processed directly from storage. Chip-processing was determined by taking a two-slice sample (1.6 mm) from longitudinally sliced tubers from the cultivar composite sample. Chip-frying and color determinations were according to Snack Food Association (SFA) standards (Gould and Plimpton, 1985).

Common Scab (*Streptomyces scabies* Thax.) Trial

All cultivars in the field evaluation were also planted in the Michigan State University scab-infested field at the MSU Soils Farm, East Lansing, MI, from 1990 to 1992. The soil is a Matea loamy sand (Arenic Hapudalfs loamy, mixed, mesic). A randomized complete block design with five plants per plot and four replications was used. At harvest, a random 20-tuber sample from each plot was collected for evaluation of common scab. A rating scale of 1 to 5 based on the surface coverage and type of lesion (1 = no infection; 5 = >25% surface coverage with pitted lesions), was used for each sample (Ludlam, 1991).

Statistical Analyses

In each year, statistical procedures for a randomized complete block design were used to analyze total yield, marketable yield, percent marketable yield, specific gravity, vine maturity, tuber-appearance rating, scab rating, and chip-processing. For each year, cultivar means were calculated for total yield, marketable yield, and specific gravity, and these means were analyzed across years by using the SAS general linear models procedure (SAS, 1988). Cultivar effects were considered fixed while replication and year effects were considered random. Cultivars were nested within breeding periods and also within type. Mean separation was done by the Duncan's multiple range test or the least significant difference test. Vine maturity, tuber-appearance rating, scab infection and chip-processing data were analyzed by means of cultivar observations in each of 3 yr in a two-factor factorial analysis of variance. Phenotypic correlations were conducted between the overall trial means of each cultivar for the agronomic traits (total yield, marketable yield, and specific gravity) and maturity rating, tuber-appearance rating, and scab-infection rating.

RESULTS

In 1990, temperatures were very near the 15-yr average except that May was relatively cool (2.8°C below average), which resulted in a slow plant emergence. Temperatures above 32°C were recorded for only 2 d, and highs from 29 to 32°C were recorded for only 6 d. Rainfall was well-distributed during the season and was 51 mm above the 15-yr average. Plant growth rate during the 1991 season was higher than in 1990. Heat units accumulated very rapidly starting in April and continued through the season. There were only 2 d above 32°C and night temperatures were generally cool, which led to good vine growth and dry matter accumulation. Rainfall was above the 15-yr average for April through July but below average for August and September. A cool growing season occurred in 1992; however, May and June were warmer than the 15-year average, while the July through September period was below average. Rainfall in 1992 was 152 mm less than 1991 with May and June being the driest months (42-mm total).

Table 2. Individual and combined trial means for total yield, marketable yield, and specific gravity of the potato cultivars.

Breeding period	Cultivar	1990			1991			1992			Mean†		
		#1‡	Total§	Sp G¶	#1	Total	Sp G	#1	Total	Sp G	#1	Total	Sp G
		t ha^{-1}			t ha^{-1}			t ha^{-1}			t ha^{-1}		
I	Bliss Triumph	–#	–	–	–	–	–	34	42	1.066	34	42	1.066
	Early Rose	31	53	1.081	37	69	1.085	26	37	1.081	31	53	1.082
	Green Mountain	57	63	1.088	82	99	1.091	62	71	1.083	67	78	1.087
	Irish Cobbler	–	–	–	36	49	1.073	24	30	1.069	30	39	1.071
	Rus. Burbank	26	50	1.081	32	51	1.080	15	28	1.077	25	43	1.079
	White Rose	32	43	1.066	54	83	1.080	36	61	1.074	41	62	1.073
II	Katahdin	41	44	1.067	44	47	1.069	38	44	1.074	41	45	1.070
	Kennebec	60	65	1.075	70	86	1.076	36	44	1.066	55	65	1.072
	Ontario	51	56	1.074	67	78	1.075	48	61	1.075	55	65	1.075
	Red La Soda	53	58	1.062	43	49	1.060	42	46	1.068	46	51	1.063
	Red Pontiac	66	71	1.066	78	86	1.064	59	64	1.065	68	74	1.065
III	Sebago	39	44	1.071	48	55	1.069	48	54	1.077	45	51	1.072
	Norchip	28	33	1.072	39	46	1.072	26	35	1.084	31	38	1.076
	Norgold Rus.	29	47	1.072	29	47	1.068	–	–	–	29	47	1.070
	Norland	38	44	1.057	33	39	1.055	19	27	1.061	30	37	1.058
IV	Superior	38	43	1.07	41	48	1.070	33	40	1.087	37	43	1.076
	Atlantic	32	36	1.084	66	69	1.092	37	40	1.091	45	48	1.089
	Eramosa	30	33	1.063	36	41	1.060	–	–	–	33	37	1.062
	Ranger Russet	–	–	–	37	44	1.073	29	38	1.087	32	41	1.080
	Rus. Norkotah	28	41	1.066	51	61	1.068	18	27	1.071	32	43	1.068
	Sangre	39	43	1.064	–	–	–	35	41	1.072	37	42	1.068
	Shepody	42	51	1.081	47	62	1.078	37	44	1.079	42	52	1.079
	Snowden	52	56	1.082	63	68	1.083	33	38	1.088	50	54	1.084
Mean		41	49	1.072	47	61	1.073	35	43	1.076	41	50	1.073
LSD (0.05)		9.8	10.4	0.007	16.7	18.9	0.005	7.4	16.4	0.007	7.2	9.1	0.004

† Mean values based upon 1990, 1991, and 1992 trials.
‡ U.S. #1 yield.
§ Total yield.
¶ Specific gravity.
# – = not tested.

Agronomic Performance

Highly significant mean differences among cultivars were observed for total yield, marketable yield (U.S. #1 yield), and specific gravity (Table 2). In addition, year of trial and year × cultivar interactions were significant for all three traits (data not shown). The highest yields (total and marketable) were in 1991, while mean specific gravity was highest in the 1992.

When the cultivars were grouped by tuber type from the three trials, significant differences were observed for marketable yield and specific gravity but not for total yield (Table 3). The long-type cultivars had significantly lower marketable yield, while the red-skinned cultivars had significantly lower specific gravity.

Differences among breeding periods were observed for all three traits in the combined analyses (Table 3). BP II had the highest marketable yield, while BP III had the lowest marketable and total yield. BP I had the highest specific gravity. Only the long-type cultivars exhibited an upward trend in percent marketable yield over the breeding periods (Fig. 1). There was also an improvement in specific gravity among round-white cultivars destined for processing (Fig. 2).

Tuber-Appearance Rating

Tuber-appearance ratings (TARs) for the cultivars ranged from 1 to 4.5 on a five-point scale with 1 being most desirable (Fig. 3). The differences in mean TARs were significant among cultivars; however, the ratings tended to vary slightly for some cultivars over years. Two russet cultivars, Russet Norkotah and Norgold Russet, consistently had the best TARs, while 'White Rose' had the most undesirable appearance. The BP I cultivars had, on average, the highest TARs (poor appearance). In BPII, BP III, and BPIV, some cultivars showed improved TARs over BP I (Fig. 3).

Table 3. Marketable yield, total yield, and specific gravity by potato tuber type and breeding period based on means of 1990, 1991, and 1992 late trials.

	US #1 yield	Total yield	Specific gravity
	t ha^{-1}		
Tuber type			
Red	48.4a†	50.8a	1.063c
Round white	43.8ab	49.9a	1.075b
Long‡	40.0b	52.2a	1.079a
Breeding period			
I	39.3b	56.1a	1.081a
II	52.0a	56.3a	1.070c
III	32.3c	41.5b	1.070c
IV	39.9b	47.0a	1.077b

† Means followed by the same letter within a column and within a type or breeding period are not significantly different at the $P = 0.05$ level by Duncan's multiple range test.
‡ Includes long-white and long-russet types.

Maturity Ratings

Average maturity ratings differed among cultivars (Fig. 4). The cultivars had maturities which ranged from less than 100 d (maturity rating = 1) for Eramosa to more than 140 d (maturity rating = 5) for Green Mountain and Ontario. The latest-maturing cultivars were found in BP I and BP II, while the BP III and BP IV, on average, had cultivars with the earliest maturities. The long-type cultivars ranged in maturity ratings from 2 to 5, and the red-skinned cultivars ranged from 1 to 4, while the round-white cultivars were found in each maturity class.

Resistance to Common Scab

Cultivars differed in scab resistance (Fig. 5). Cultivars with the least infection were Ontario, Norgold Russet and Russet Norkotah, while 'Red LaSoda', 'Irish Cobbler', 'Shepody', 'Atlantic', 'Snowden', and Eramosa were the most infected. Both resistant and susceptible cultivars were found in BP I, BP II, and BP IV, while BP III did not have any highly susceptible cultivars. Russet-skinned

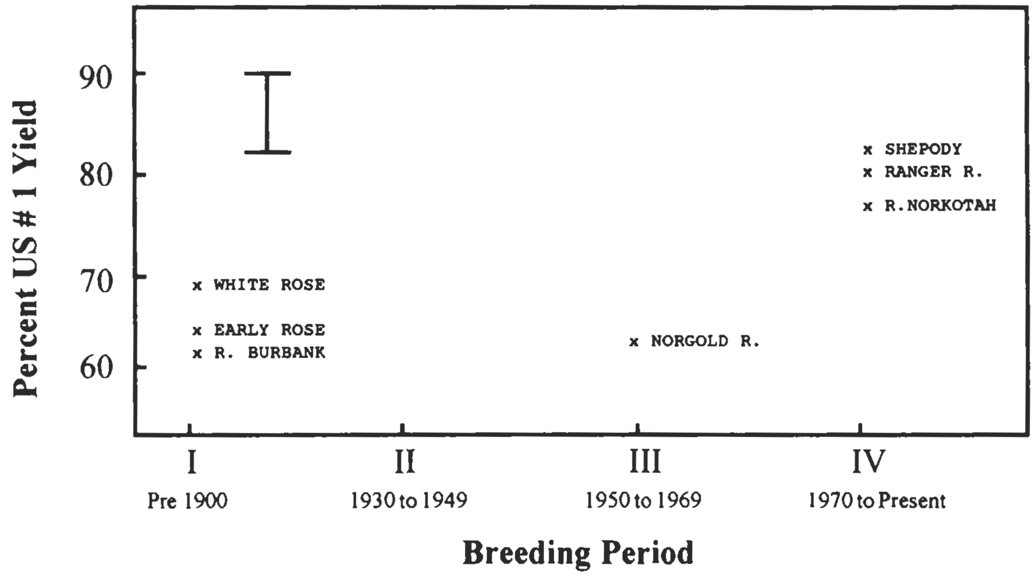

Fig. 1. Percent U.S. #1 yield of long-type cultivars that have been released over four breeding periods. The bar represents the least significant difference at $P \leq 0.05$.

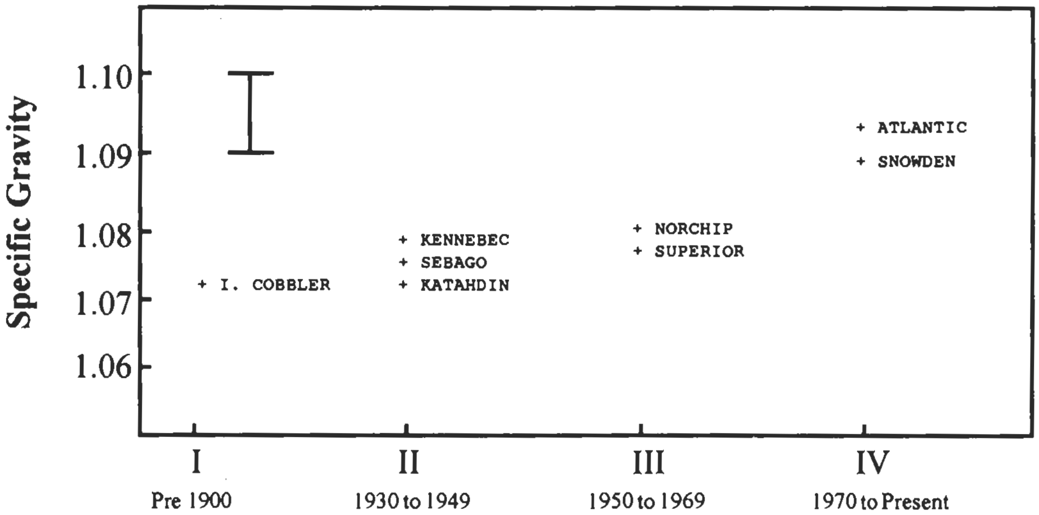

Fig. 2. Specific gravity of chip-processing cultivars that have been released over four breeding periods. The bar represents the least significant difference at $P \leq 0.05$.

cultivars had the highest ratio of resistant cultivars. There was no trend in scab resistance over breeding periods; however, some of the cultivars released during BP IV were most susceptible.

Chip-Processing Evaluation

Significant differences for chip-processing were observed for the round-white cultivars (Table 4). Based on SFA color scale (1 = lightest, 5 = darkest), values ranged from 1.0 to 3.5 where <2.5 is acceptable. Current cultivars used by industry processed best in 1990 (Snowden, Atlantic, and Norchip) along with the tablestock cultivar Superior. Tablestock cultivars Eramosa and Ontario produced the darkest chips. In 1991, only Atlantic and Snowden produced high-quality chips out of the field, while Norchip, Katahdin, Kennebec and Irish Cobbler produced unacceptable chips. Snowden produced the most acceptable chips out of 10°C storage. Atlantic, Norchip and Kennebec showed slight darkening in the chips. The 7.2°C storage led to higher SFA scores (darker chip color) for all cultivars except Snowden.

Phenotypic Correlation Analyses

Based on cultivar means of the three full-season trials, vine maturity was significantly correlated with total yield, marketable yield, and specific gravity (Table 5). Correlations of tuber appearance and scab resistance with yield and specific gravity were not significant.

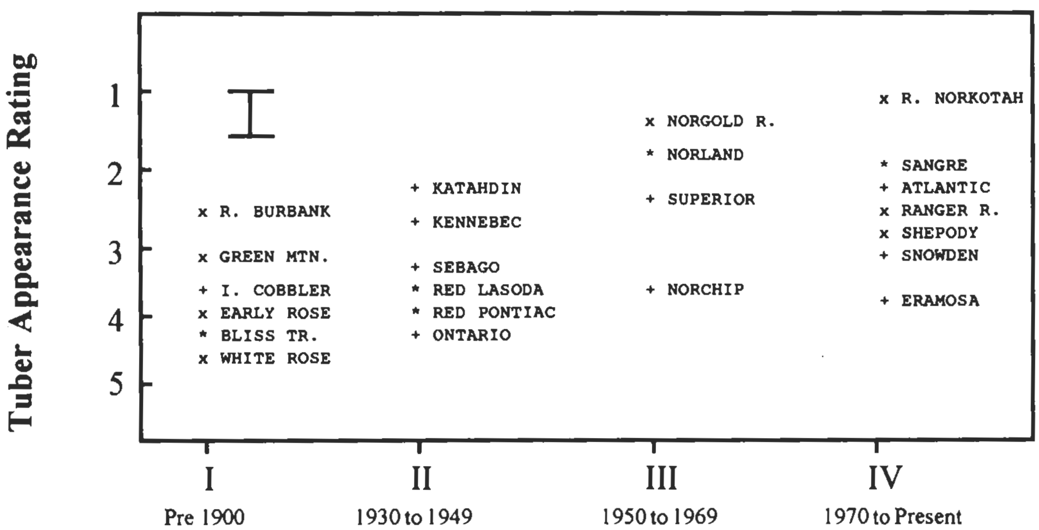

Fig. 3. Ranking of tuber appearance for cultivars which have been released over four breeding periods (1 = best, 5 = worst). Round-white, long, and red-skinned cultivars are denoted by "+", "x", and "*", respectively. The bar represents the least significant difference at $P \leq 0.05$.

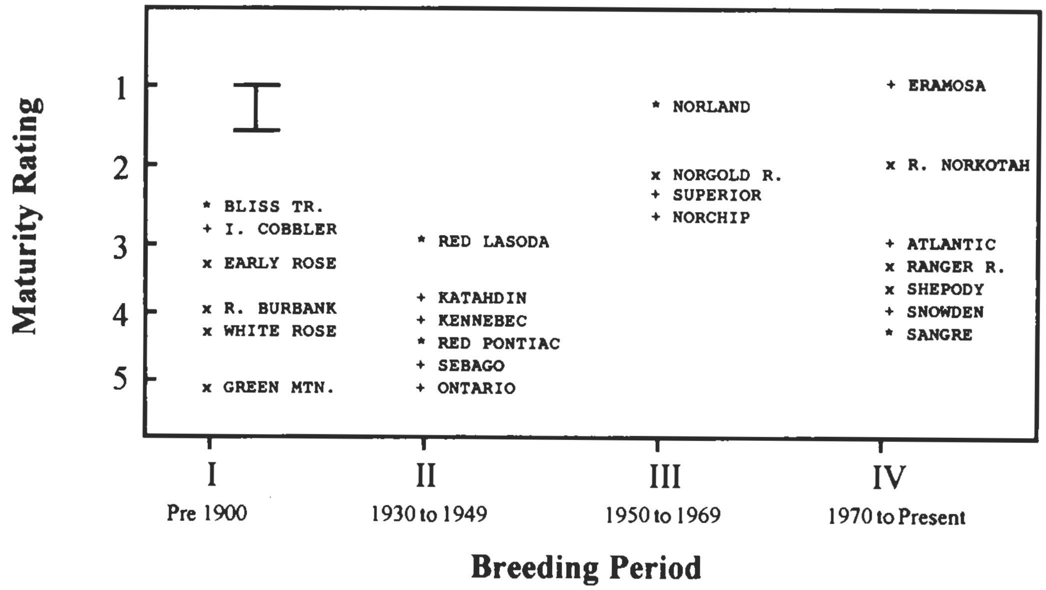

Fig. 4. Ranking of vine maturity for cultivars which were released over four breeding periods (1 = 100 d, 5 = 140 d). Round-white, long, and red-skinned cultivars are denoted by "+", "x", and "*", respectively. The bar represents the least significant difference at $P \leq 0.05$.

DISCUSSION

Potato cultivar development in the USA can be divided into a few key phases (Plaisted and Hoopes, 1989). The first one ranges from 1850 to 1900. During this time, cultivars were developed by private breeders with many of the seedlings being derived from open pollination (rather than controlled crosses). Between 1900 and 1930 no commercially important cultivars were released; however, the USDA potato breeding program was established in 1910. The USDA release of Katahdin in 1932 marked the next important development in potato breeding: release of cultivars by public agencies (USDA and state agricultural experiment stations). Since 1932, through a cooperative effort among public agencies, an emphasis was placed on breeding cultivars with resistance to pests, yielding ability, and market quality. For this study, we sub-divided this period into three 20-yr intervals to examine breeding progress.

During the last 60 yr, potato utilization in the USA has changed. In the 20th century, the demands of two world wars created rapid progress in drying technology and led to the development of quick rehydrating dried mashed potatoes. The post WWII era of convenience foods and development of frying technology converted the "french fries" American GIs had seen on street corners in Belgium to the largest worldwide outlet for potatoes: retail and institutional frozen products (Willard, 1993).

With the rise in popularity of frozen-processed pota-

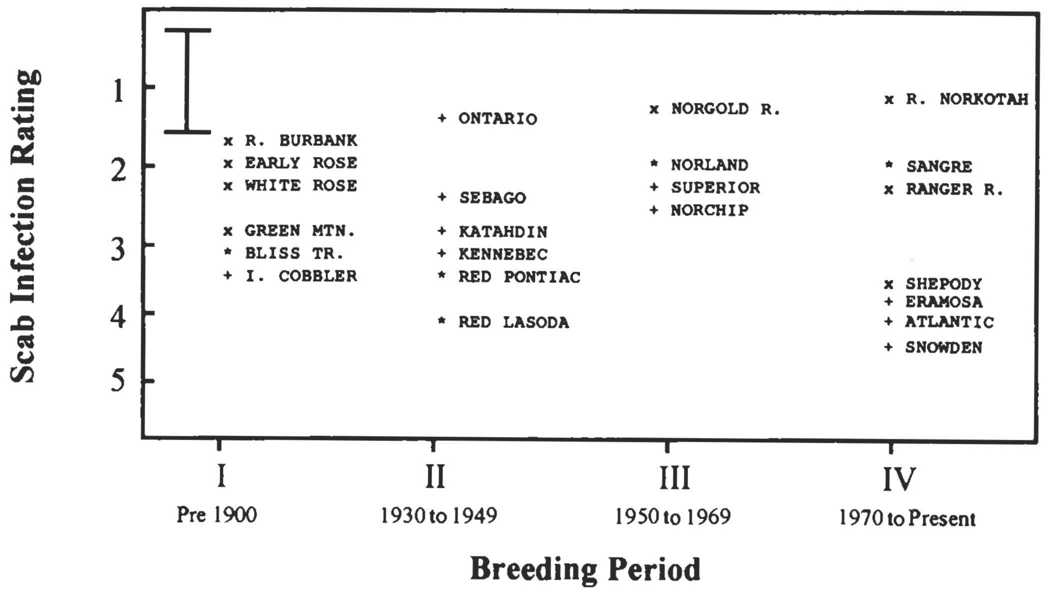

Fig. 5. Ranking of scab infection for cultivars which were released over four breeding periods (1 = least infection, 5 = greatest infection). Round-white, long, and redskinned cultivars are denoted by "+", "x", and "*", respectively. The bar represents the least significant difference at $P \leq 0.05$.

Table 4. Chip-processing evaluations for round-white potato cultivars.

Cultivar	1990†	1991†	1992‡ 10C Storage	1992‡ 7.2C Storage
	SFA scale§			
Irish Cobbler	–	3	2.5	3.5
Katahdin	2	4	3	4
Sebago	2	2	2.5	3.5
Kennebec	2	3.5	2	3
Superior	1.5	2.5	2	2.5
Norchip	1.5	3	2	3
Atlantic	1.5	1.5	2	2.5
Snowden	1	1	1.5	1.5
LSD (0.05)	0.9	0.9	0.9	0.9

† Evaluated out of the field, early post harvest (i.e., ≤2 wk).
‡ Evaluated directly out of 5-mo storage.
§ Snack Food Association scale (1 = light color, 5 = dark brown); ≤2 is acceptable.

toes, Idaho overtook Maine as the leading potato-producing state in the USA. Idaho, Washington, and Oregon now combine to produce over half the nation's crop (Sieczka and Thornton, 1993). The most significant trends in potato products have been the increase in frozen potato use and the decline in fresh use. For example, in 1959, only 4% of the crop was frozen processed; whereas, in the subsequent 30-yr period, utilization of frozen potato products climbed to 32% of all potatoes produced (Lucier et al., 1990). Over this period, U.S. annual per capita potato consumption increased from 48 to 57 kg, which, in addition to frozen products, is attributed to increased demand for potato chips and products made from dehydrated potatoes.

Our results demonstrate that the cultivars tested varied significantly for all traits measured in this study. When the cultivars were grouped by tuber types, significant differences were found for marketable yield and specific gravity indicating that genetic variation exists between the round-white, long, and red-skinned tuber classes. The lack in improvement for yield and specific gravity over breeding periods suggests that little advance has been made in improving potato cultivars for these important agronomic traits.

Vine maturity is an important trait in choosing a potato cultivar for commercial production because earlier maturity affords profitable market windows and broadens the fall harvest period. This study shows that several of the most recent cultivars have an earlier maturity (Fig. 4) than any of the cultivars released in the first breeding period. Of the early-maturing cultivars, Superior, Russet Norkotah, and Norland, are currently among the 10

Table 5. Phenotypic correlations between agronomic performance versus maturity, tuber appearance, and scab infection rating, based upon cultivar means across three full season trials from 1990 to 1992 (n = 23).

Agronomic performance	Maturity	Tuber appearance ratings	Scab infection rating
Total yield	0.55**	−0.40 NS†	0.13 NS
Marketable yield	0.58**	−0.34 NS	0.25 NS
Specific gravity	0.50**	0.14 NS	0.06 NS

** = significant at 0.01 level.
† NS = not significant.

most widely grown cultivars in the USA (Sieczka and Thornton, 1993).

Contrary to our results in potato, yield gains attributed to genetic improvement in other major field crops, have been reported in the 20th century (Feil, 1992). Yield increases in maize have occurred in a regular fashion between 1930 to 1980 (Duvick, 1984). These advances were most significant under high soil fertility levels and high plant densities (Castleberry et al., 1984). Waddington et al. (1986) found a 32% increase in bread wheat yield potential in Northwest Mexico over a 32-yr period, while Cox et al. (1988) has shown a surge in yield of hard red winter wheat in Kansas in the 1980s. In soybean, a 45% increase in genetic yield potential was observed over a 75-yr period; however, the improvements were not uniformly continuous (Specht and Williams, 1984). Wych and Stuthman (1983) documented 0.8% increases in grain yield per year in oats over a 50-yr period. In malting barley, where the requirements of acceptable malting and brewing quality in new cultivars has led to a narrowing of the germplasm base, genetic gains for yield have also been achieved (Wych and Rasmusson, 1983). In cotton, yield gains due to genetic improvement occurred between 1936 and 1960, but a yield plateau followed between 1961 to 1980 (Meredith and Bridge, 1984). Associated changes that have occurred in these crops include disease and insect resistance (soybean, barley and cotton), reduced lodging scores (wheat, maize, oats, barley, and soybean), improved fertility (wheat and maize), stress resistance (maize), improved biomass (wheat, oats, and maize), and increased seed size (soybean and barley).

Assessment of breeding progress in potato needs to encompass quality traits. Cultivars are selected and grown for specific market utilization types, and the definition of quality changes among these types. Tuber appearance, a trait critical to efficient processing and tablestock marketability, improved over the four breeding periods in our study. The cultivar Russet Norkotah has set a new standard for tablestock appearance among the long russet class. Despite undesirable TARs, the cultivars White Rose, Red Pontiac, and Ontario are still popular cultivars. It is unlikely that cultivars released today would be commercially acceptible with a TAR of four or greater.

Other trends in improvement are demonstrated within market classes. Percent marketable yield of the russet and long-white cultivars in BP I are well below the levels of the round-white and red-skinned cultivars (data not shown). An improvement in percent marketable yield would increase the profitability of these classes of cultivars. In BP IV, the russet and long-white cultivars have improved percent marketable yields over the three previous breeding periods. Among the round-white cultivars, improvement is seen for traits critical to the chip-processing market; specific gravity and chip-processing color. During the early years of the chip-processing industry, cultivars were not specifically bred for this market. Norchip was the first cultivar specifically bred for chip-processing (Johansen et al., 1969), followed by Atlantic and Snowden. These cultivars have set new industry standards for chip-processing color and specific gravity.

No overall trend was observed for cultivars with improved scab resistance; however, some of the most scab susceptible cultivars were released in BP IV. This may be due to a number of factors. Scab infection, due to a soil-borne bacterium, is a disease of regional importance. Secondly, efforts to breed resistance to scab vary between states; therefore, a trend for improved resistance among nationally important cultivars is unlikely. In addition, cultural practices have been implemented to reduce scab incidence (Powelson et al., 1993).

The results in our study suggest that a genetic yield potential has not improved among the nationally important cultivars despite breeding efforts in the twentieth century. Meanwhile, national yields (per area unit) have increased six-fold during this period because of improvements in management. The major influence on this lack of genetic improvement in yield potential can be explained by the correlation between yield and earliness. Our study observed a correlation of 0.55 between total yield and cultivar vine maturity (Table 5), and many of the cultivars from BP III and BP IV have earlier vine maturities than ones from BP I and BP II (Fig. 4). Therefore, to conduct a less-biased study to examine yield advances, a field trial should be based on cultivars within single maturity classes.

Another factor that may be contributing to this yield stasis is the number of quality traits for which selection is practiced in a breeding program. New potato cultivars must meet the varied demands of the grower, processor and consumer. Tarn et al. (1992) identified 18 traits related to fresh and processing uses, resistances to 17 pathogens and six pests, in addition to numerous agronomic traits that might be considered in selection. The challenge to combine the various utilization traits and resistances with improvements in yield potential into a commercially acceptable cultivar is formidable. During the past 60 yr, a shift in potato usage from fresh consumption to processing has occurred with processing now making up about 54% of the crop usage (Lucier et al., 1989). Greater constraints imposed by market requirements reduce the genetic base on which agronomic-yield improvement is based, hence limiting the genetic advance in agronomic traits.

The lack of yield improvement suggested by this study may also be due to the narrow genetic base of the cultivated potato in North America. Based on pedigree analysis, there is a high degree of relatedness among potato cultivars (Mendoza and Haynes, 1974), suggesting that the genetic base of potato should be expanded to overcome the yield stasis. In response to the narrow genetic base of the potato, diploid germplasm concurrent with the utilization of $2n$ gametes has been exploited (Peloquin and Ortiz, 1991).

Because of the inefficiency of the conventional breeding schemes numerous strategies have been proposed to improve genetic gain (Bradshaw and MacKay, 1994). Methods for potato breeding are not very efficient and have not changed much in the 20th century (Tarn et al., 1992; Kehoe, 1982; Neele et al., 1988; Douches and Jastrzebski, 1993; Caligari, 1992). Potato breeding is based on a phenotypic recurrent selection scheme that cycles every 5 to 9 yr. Tai and Young (1984) argue that intensive early generation selection is ineffective and may reduce genetic gain in environmentally influenced and polygenic traits such as yield. They believe that moderate selection intensity over several generations would give a better balance between genetic advance and loss of valuable genotypes. Neele et al. (1989) concluded from selection studies that retaining 20 to 50% of the first-year field seedlings followed by a 20% selection in the second clonal year would be the most economical selection procedure. This mild selection would also result in a greater proportion of clones in the late-maturing classes and higher specific gravity. For visual characteristics, Neele et al. (1991b) suggested that negative selection be applied according to heritabilities to avoid rejecting too many valuable genotypes at an early stage.

Potato improvement through breeding is also restricted by biological attributes of the potato. The need for tuber propagation leads to longer selection cycles since only one cycle of selection can occur each year (compared with some self-pollinated crops). Secondly, the potato loses vigor upon inbreeding and takes longer to reach homozygosity (Howard, 1970). Moreover, self pollination in potato leads to loss of fertility (Krantz, 1951). Another limitation in improvement may be that the breeder has been faced with the challenge of tetrasomic inheritance, imposed by this autotetraploid crop (Ross, 1986). This decreases the probability of finding transgressive segregants in an autotetraploid population below that of a diploid crop (Wricke and Weber, 1986).

The field design may have also influenced our results. The cultivars were tested in one location over the 3 yr under best management practices. By growing these cultivars under low fertility or dryland farming practices, other trends may emerge. Moreover, climatic differences of the northwest or northeast regions may provide additional insights. Because of seed availability and space considerations, one-row plots were used for evaluation. Vine competition between rows may have led to greater differences in yield between the maturity classes. The late-maturing cultivars tend to have larger and more prostrate vines. These genotypes tend to be more competitive in replicated one-row plots compared with the smaller-vined early maturing cultivars.

The demonstration of genetic improvement of crops over time is a valuable way to show the benefits of plant breeding (Cox et al., 1988). These results are important to breeders to gain perspective and assess breeding methodologies in potato. The most direct method to estimate breeding progress is to evaluate cultivars from different eras in a common environment. Our results suggest that a yield stasis has been found in potato cultivars in North America; however, the newer cultivars have been significantly improved for traits demanded by market utilization.

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