

Effect of altering the physiological age of potato seed-tubers in the fall on subsequent production in a short-season environment

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Knowles, N. R. and Botar, G. I. 1992. **Effect of altering the physiological age of potato seed-tubers in the fall on subsequent production in a short-season environment.** Can. J. Plant Sci. 71: 275–287. The efficacy of utilizing “controlled seed-tuber aging” as a technique to enhance yield and improve tuber quality in areas with relatively short growing seasons was investigated in a 3-yr study. Prior to planting in the field, five physiological ages of Russet Burbank, Carlton, Norchip and Superior seed-tubers were produced by varying the heat-unit accumulation over a 200-d storage interval. Total yield increases of up to 90% and substantial improvements in tuber grade were achieved by planting aged (600–900 degree-day (dd)) seed-tubers. Plant growth from aged Russet Burbank seed-tubers was modelled to identify the mechanisms by which yield and quality were altered. Growth analysis demonstrated that the age-induced yield increases were due to faster emergence, faster leaf-area establishment, and tuberization earlier in the growing season compared with that from younger seed-tubers. The annual life cycle was thus accelerated, allowing plants from older seed-tubers to utilize the short (120-d) growing season more efficiently than those from younger seed-tubers. This was reflected in a higher harvest index: plants from 739 dd seed-tubers partitioned 63% of their total fresh weight into tubers compared with 48% for those from 66 dd seed-tubers (based on the quadratic model describing the relationship between seed-tuber age and and harvest index at 121 d after planting). The technique appears to be very promising for enhancing yield and/or promoting ‘earliness’ of potatoes in regions with short growing seasons.

Key words: *Solanum tuberosum*, seed-tuber age, plant growth, yield

Knowles, N. R. et Botar, G. I. 1992. **Effet de la manipulation de l'âge physiologique des plantons de pomme de terre en automne sur la production subséquente en saison de végétation courte.** Can. J. Plant Sci. 71: 275–287. On a examiné pendant trois ans l'utilité du vieillissement contrôlé des plantons sur le rendement et sur la qualité de tubercules dans les régions à saison de croissance relativement courte. Préalablement à la mise en terre au champ, cinq âges physiologiques ont été obtenus sur des plantons des cultivars Russet Burbank, Carlton, Norchip et Superior en variant les sommes de degrés-jours pendant une durée de conservation de 200 jours. Des accroissements de rendement total pouvant aller jusqu'à 90% et des améliorations substantielles de la qualité des tubercules ont été réalisés par la maturation (600 à 900 degrés-jour) des tubercules. La croissance obtenue à partir des plants de Russett Burbank vieilliss a été modélisée, de façon à cerner les mécanismes agissant sur le rendement et sur la qualité. L'analyse de la croissance a pu montrer que les accroissements de rendement liés à l'âge du planton sont dus à une levée et à une croissance foliaire plus rapides ainsi qu'à une tubérisation plus précoce que chez les plantons ‘jeunes’. Le cycle biologique annuel a ainsi été accéléré, permettant aux plantes issues de plantons vieilliss de mieux mettre à profit une saison de végétation courte (120 jours). Cet avantage s'est traduit par un indice de récolte plus élevé: 63% du poids frais total des plantes issues de plantons exposés à un vieillissement de 739 degrés-jours consistaient en tubercules, contre seulement 48% dans le cas des plantons exposés à 66 degrés-jours (d'après le modèle quadratique décrivant les rapports entre l'âge du planton et l'indice de récolte 121 jours après la plantation). La technique s'annonce très prometteuse pour accroître le rendement ou pour hâter la croissance des pommes de terre dans les régions de végétation courte.

Mots clés: *Solanum tuberosum*, âge physiologique des plantons, croissance, rendement

The current practice in North America is to wound-heal seed-tubers at 10–15°C during the initial 10 d of storage and then reduce and maintain the temperature at a holding level of 4°C until planting (Thornton and Sieczka 1980). This practice results in tubers that are physiologically younger than those held in storages with poor temperature control, because of the low holding temperature. Storage temperature and duration interact to dictate physiological age, which subsequently influences plant development. Hence, different ages can be produced by storing seed-tubers above 4°C for various intervals during the storage season.

Utilizing physiologically older seed-tubers for production may result in higher and/or earlier yields in areas with relatively short growing seasons (Perennec and Madec 1980; O'Brien et al. 1983; Iritani and Thornton 1984). Despite evidence in support of this, in-depth studies to characterize the effects of seed-tuber physiological age on the annual life cycle of potato in short-season areas are lacking, and the efficacy of this technique remains to be established.

Yield of late season potatoes in Alberta averages approximately 25 t ha⁻¹, substantially lower than the average yield of 60 t ha⁻¹ attainable in the Columbia Basin region of Washington State (Dean et al. 1981). The yield discrepancy may be partially attributed to differences in length of the growing season. The Columbia Basin averages just over 200 d, compared with 110–130 d of available growing season in potato-producing areas of Alberta. Indeed, most potato-production areas within Canada have significantly shorter growing seasons than those within the United States. Hence, any production strategy that will increase yield in short-season areas will be of potential benefit to Canadian potato producers.

The annual life cycle of late season potato cultivars (e.g., Russet Burbank) can be as long as 180–190 d (from planting to foliar senescence). This requires that growers in short-season areas apply desiccant to kill foliage prior to harvest. Yield thus tends to be lower in a short-season area, as plants do

not have the opportunity to complete their life cycles within the constraints of the abbreviated season. Hence, any treatment that accelerates the annual life cycle of potato may also permit the crop to utilize a shorter growing season more efficiently.

In the first paper on this subject, we demonstrated that plant emergence and establishment were significantly quicker from older seed-tubers under controlled environment conditions (Knowles and Botar 1991). If this accelerated early development of plants from aged seed-tubers also translates into earlier tuberization and increased leaf-area duration, then it may be possible to substantially increase yield by planting seed-tubers with greater physiological age. This paper presents results of production studies on the effects of seed-tuber age on potato yields in a short-season environment.

The objective of this study was to assess the efficacy of utilizing aged seed-tubers to enhance yield and earliness in a short-season area (120 d). Accordingly, age-induced changes in plant development were modelled, and the yield components most influenced by seed-tuber age were identified for the Russet Burbank cultivar growing under dryland and irrigated conditions. The relative concentrations of tuber soluble carbohydrates and starch were profiled through the season to assess the effect of seed-tuber physiological age on physiological maturity of the harvested crop, an important concern of potato processors. The effects of advanced seed-tuber age on earliness, grade and yield of Carlton, Superior and Norchip potatoes were also compared.

MATERIALS AND METHODS

Aging of Seed-tubers

The various studies reported herein were conducted over a 3-yr period from 1987 to 1989. Different physiological ages of Russet Burbank, Carlton, Superior, and Norchip certified potato seed-tubers were produced during storage by holding the tubers at 15°C ± 0.5°C for 25, 50, 75 and 100 d after an 11-d wound-healing period at 10°C ± 0.5°C. Following a particular aging treatment, tubers were moved to 4°C ± 0.5°C and held until planting. Controls were stored continuously at 4°C. The duration of the entire storage period was

approximately 200 d in all of the studies. Physiological age was quantified as heat-unit accumulation in degree-days (dd) above 4°C. The ages differed slightly from year to year, as heat-unit accumulation prior to obtaining the seed-tubers from growers in the fall was factored into the age calculation. However, the increment between successive ages was held constant at 275 dd in all of the studies.

Field Studies

GENERAL PLOT DESIGN AND MAINTENANCE. Field studies were conducted on irrigated and dryland test sites at the University of Alberta. All experimental plots were constructed in a randomized complete block design with a minimum of six blocks. Five different ages of seed-tubers were removed from storage, sorted for size (150–200 g each), and cut into 50- to 60-g seedpieces. Apical and basal seedpieces were treated with Captan and were assigned to different blocks. The cut seedpieces were planted within 2 d of cutting.

Individual treatment plots within each study consisted of 12 hills. Seedpieces were planted 25 cm apart within a row; rows were spaced 1 m apart, and a 1-m alley was left between plots. Guards, consisting of two Norland seedpieces, were planted at each end of each plot to minimize variation due to differences in competition between seedpieces at the end of a row and between treatment plots. In multiple harvest studies, a row of treatment plots alternated with a complete row of Norland guards. Harvesting a treatment plot during the growing season thus had no effect on adjacent treatment plots. Fertilizer was broadcast and incorporated prior to planting at each site to result in 225 kg ha⁻¹ N, 225 kg ha⁻¹ P₂O₅ and 450 kg ha⁻¹ K₂O. Irrigated and dryland soil types consisted of black silt and black sandy loams, respectively. All experiments were planted during the period 7 May to 12 May of each year of study. Standard weed and pest control practices were utilized in all of the studies. In irrigated studies, soil moisture was maintained at no less than 75% of field capacity by overhead sprinkler irrigation. Plant stands were greater than 95% for all cultivars in all studies except the 1988 studies on Carlton (see Results and Discussion).

LATE SEASON CULTIVAR IRRIGATED STUDIES. These studies were designed to model growth and development from five ages of Russet Burbank seed-tubers by incorporating multiple harvest dates in a two-factor factorial arrangement. The studies

were conducted during the 1987 and 1988 growing seasons. Eight harvest dates, beginning at 34 DAP and ending at 121 DAP, were incorporated into the 1987 study. Seven harvest dates, beginning at 42 DAP and ending at 119 DAP, were incorporated into the 1988 study.

At each harvest, the following yield components were recorded from the various seed-tuber age treatments: S_N , stem number per plant; L_N , leaf number per plant; L , leaf area per plant; W , plant (foliage plus tuber) fresh weight; W_T , tuber fresh weight per plant. Tubers 51 mm in diameter or greater were graded as marketable. Yield data were subjected to analysis of variance (ANOVA) and regression analysis to identify the optimum seed-tuber age for production of Russet Burbank potatoes.

The technique of two-dimensional partitioning (TDP; Eaton et al. 1986) was used to determine treatment effects on the yield components which contributed to tuber yield. The following model was proposed to account for variation in tuber fresh weight:

$$W_T = S_N(L_N/S_N)(L/L_N)(W/L)(W_T/W)$$

The yield components were calculated as ratios of the primary yield variables and were subsequently ln-transformed to create an additive model to describe tuber yield (see Knowles and Botar 1991). Because the results from TDP analysis were similar for both years, only the 1987 results are reported. Harvest index (HI) was calculated for yield data from the 1987 study by dividing total tuber fresh weight by total foliar (above-ground) plus tuber fresh weight, and expressing the result as a percentage.

In the 1988 study, bulking rates (tuber growth rates) were calculated from total and marketable yield data. Total bulking rates are the regression coefficients from linear plots of total yield versus DAP, calculated over the last four harvest dates (from 78 to 119 DAP). Marketable bulking rates were derived similarly, using yield data from the last three harvest dates (from 92 to 119 DAP). The correlation coefficients of the linear regressions of total and marketable yield versus DAP were 0.96 or higher.

To evaluate the effect of seed-tuber age on maturity and potential processing quality, samples of harvested tubers from each plot of the 1987 study were collected at each harvest. Differences in physiological maturity (Iritani and Weller 1980) were assessed by measuring total soluble carbohydrates, reducing sugars and starch in the tuber samples.

The tuber samples, consisting of approximately 100 g fresh weight cut (radially) from the middle portion of at least four tubers from each plot, were frozen at -20°C at each harvest. Tissue samples were then lyophilized and ground into a fine powder. For analysis of total soluble carbohydrates and reducing sugars, 100 mg of tissue was extracted (mortar and pestle) in 20 mL cold (4°C) phosphate buffer (20 mM, pH 7.2) containing 0.1% wt vol $^{-1}$ sodium bisulfite. The crude homogenate was centrifuged (1640 g, 10 min, 4°C) and the cold supernatant was analyzed. Reducing sugars were assayed colorimetrically by the methods of Nelson (1944) and Somogyi (1952) using a 100- μL aliquot of the supernatant. Soluble carbohydrates were determined on a 40- μL aliquot of supernatant with the phenol-sulphuric acid reagent (Dubois et al. 1956). Both reducing sugars and total soluble carbohydrates were quantified on the basis of a glucose standard. Non-reducing sugars (sucrose) content was estimated by subtraction of reducing sugars from total soluble carbohydrates.

Starch content of the tubers was determined by extracting 30 mg lyophilized tissue for 20 min in 4 mL boiling 80% (vol vol $^{-1}$) ethanol. The ethanol was decanted after centrifugation (1640 g, 15 min) and the extraction repeated. The supernatants were discarded, the pellets were resuspended in 4 mL distilled water and the starch was gelatinized for 1 h at 100°C . Samples (50 μL) were then incubated with amyloglucosidase (E.C. 3.2.1.3, Sigma Chemical Co., St. Louis, MO) in 0.2 M acetate buffer (pH 4.7) for 1 h at 55°C (Davies and Ross 1984). The glucose released from the starch via the reaction with amyloglucosidase was quantified with glucose oxidase (Lloyd and Whelan 1969). Carbohydrate data were subjected to ANOVA and regression analysis to determine the effects of seed-tuber age and time on physiological maturity.

LATE SEASON CULTIVAR DRYLAND STUDIES. Studies were also conducted on dryland plots, since a significant amount of potato production in the central region of Alberta occurs under dryland growing conditions. Treatments consisted of five ages of Russet Burbank and Norchip seed-tubers in separate studies. Two experiments were set up for Russet Burbank in 1988; one was harvested at 90 DAP and the other at 103 DAP. The two studies on Norchip in 1989 were harvested at 91 and 103 DAP. Total and marketable (51-mm diameter or greater) tuber weights were recorded at each harvest. ANOVA and regression analysis were used

to determine the optimum seed-tuber age for production of these two cultivars under dryland conditions.

EARLY SEASON CULTIVAR DRYLAND STUDIES. Three additional studies, conducted during the 1988 and 1989 growing seasons, characterized the effects of seed-tuber age on the early season cultivars Carlton and Superior. In all of these studies, treatments consisted of five ages of Carlton and Superior seed-tubers in a two-factor factorial arrangement. The two studies conducted during the 1988 growing season differed only as to harvest date. One study was harvested at 90 DAP and the other at 103 DAP. In 1989, the plots were harvested at 103 DAP. Data collection and analysis were the same as for the Late Season Cultivar Dryland Studies outlined above.

RESULTS AND DISCUSSION

Late Season Cultivar Irrigated Studies

In the 1987 study, plants from older Russet Burbank seed-tubers emerged sooner and established more leaf area earlier in the growing season than those from younger seed-tubers (Fig. 1). At 34 DAP, leaf area of plants from 1166 dd seed-tubers was 147% greater than that from 66 dd seed-tubers; however, the difference in leaf area between the two extremes in tuber age attenuated with time (Fig. 1a). By 68 DAP, no effect of tuber age on leaf area could be detected and, as the 1987 growing season progressed, the leaf area of plants from 66 dd tubers actually surpassed that of the other age treatments.

This pattern of leaf area development was most likely caused by earlier tuberization of plants from older seed-tubers. When tuberization occurs, the plants' source-sink relationships change to favor tuber growth over foliar growth (Moorby 1968, 1970). Hence, earlier tuberization of plants from older seed-tubers would effectively decrease the rate of leaf area accumulation relative to that from younger seed-tubers. Age-related differences in the degree of tuberization were clearly evident by 48 DAP (Plate 1).

The earlier tuberization response of plants from older seed-tubers resulted in higher total yield earlier in the season compared with that from younger seed-tubers; however, the differences in total yield diminished as the

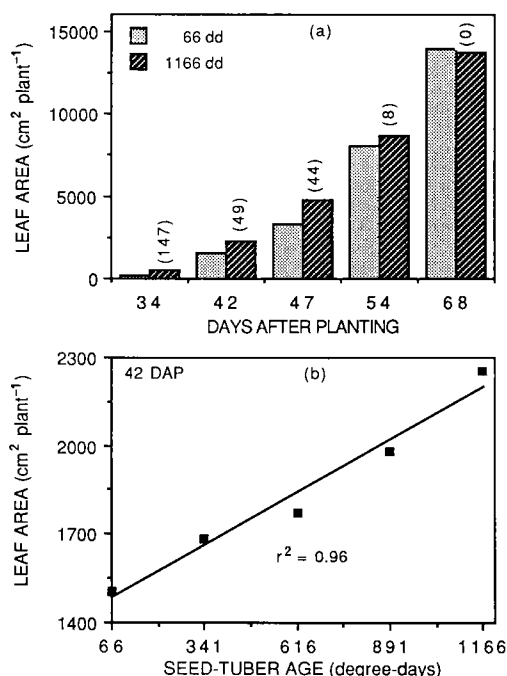


Fig. 1. (a) Time course of leaf area accumulation from plants growing from 66 and 1166 dd Russet Burbank seed-tubers under irrigated field conditions in 1987. Numbers in parentheses are percent increase over the 66 dd treatment. *F*-value for the age $\times$ time interaction was significant at the 0.01 level. (b) Trend in leaf area development with advancing seed-tuber age at 42 DAP. *F*-value for the linear trend was significant at the 0.01 level.

121-d growing season progressed (Table 1). The trends in total yield were linear at the early harvests and quadratic at the later harvests. By 121 DAP, significant differences due to age were no longer apparent, but the yields of marketable tubers (Fig. 2) from the 341, 616 and 891 dd treatments were 53, 43, and 42%, respectively greater, than that of the 66 dd control. Furthermore, of the total yield from 616 dd tubers, 87% reached the marketable grade compared with 60% for control. Similarly, plants from 341 dd seed-tubers produced 79% of their total yield as marketable, while 77% of the total yield from 891 dd seed-tubers was graded as marketable. The effect of tuber age on grade improvement was thus genuine and independent of apparent variation in total tuber yield at 121 DAP. The trend in marketable yield with advancing age at 121 DAP was quadratic, and the predicted age at which maximum yield occurred was 603 dd. Interestingly, this age corresponded very closely to the predicted age (589 dd) giving the shortest time to 50% emergence in controlled environment studies (Knowles and Botar 1991).

One way to quantify the efficiency with which a plant partitions its resources into structures of economic importance is to calculate the harvest index (HI). The HI increased linearly with advancing tuber age early in the study (Fig. 3, inset); however,

Table 1. Total yield response of Russet Burbank potatoes to seed-tuber age and time (DAP)^z

Tuber age (degree-days)	Total tuber yield (t ha ⁻¹) ^y days after planting					
	54	68	77	90	106	121
66	0.5	9.0	18.0	25.2	47.7	57.2
341	0.6	9.3	22.1	29.9	50.6	66.9
616	0.7	10.3	17.3	38.7	49.6	56.9
891	1.0	11.0	18.0	28.4	53.2	63.9
1166	1.4	11.4	21.2	29.0	46.2	58.6
Linear	0.01 ^x	0.05	—	—	—	—
Quadratic	—	—	—	0.05	0.05	—
Cubic	—	—	0.05	—	—	—

^zThe potatoes were grown under irrigated field conditions in 1987.

^y*F*-values for the main effect of age (quadratic) and the age (quadratic) $\times$ time (linear) interaction were significant at the 0.01 level.

^xSignificance levels of the *F*-values for the indicated trends at each harvest.

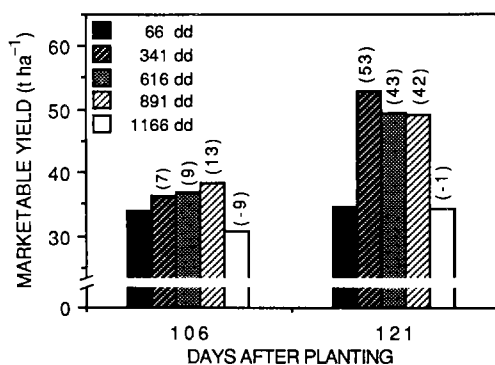


Fig. 2. Yield of marketable Russet Burbank potatoes as affected by seed-tuber age at 106 and 121 DAP. The potatoes were grown under irrigated field conditions in 1987. F -values for the main effect of age (quadratic) and the age (quadratic) $\times$ time interaction were significant at the 0.01 and 0.05 levels, respectively. At 121 DAP, marketable yield = $31.4 + 7.2\text{E-}2 \text{ age} - 5.97\text{E-}5 \text{ age}^2$, $R^2 = 0.90$. Numbers in brackets are percent increase in yield over the 66 dd treatment.

by 121 DAP the trend was quadratic (Fig. 3). For clarity, data for only two of the harvest dates are shown; however, HI was analyzed over the last six harvest dates ranging from 54 DAP to 121 DAP. The results indicated a significant ($P < 0.01$) age (quadratic) $\times$ time (linear) interaction over this time period. By the end of the study (121 DAP), plants from 66 dd seed-tubers had partitioned approximately 48% of their fresh weight into tuber production compared with 63% for those from 739 dd seed-tubers (calculated age giving the maximum HI based upon quadratic model). There was actually little difference between the predicted harvest indices for seed-tubers ranging in age from about 600 to 891 dd. This range encompasses the predicted age of 603 dd at which maximum yield of marketable tubers was calculated. Thus, plants from aged seed-tubers were clearly more efficient at partitioning fresh weight into tuber production, though the effect diminished beyond about 891 dd.

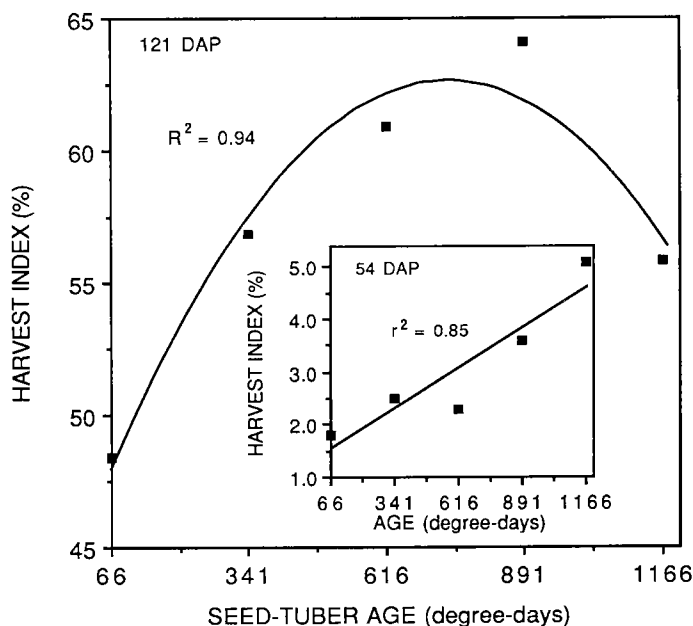


Fig. 3. Trend in harvest index (HI) with advancing age of Russet Burbank seed-tubers. The study was conducted under irrigated field conditions in 1987. Although data for only two of the harvest dates are shown, HI was analyzed over the last six harvest dates (54–121 DAP). F -values for the main effect of age (quadratic) and the age (quadratic) $\times$ time (linear) interaction were significant at the 0.01 level. At 121 DAP, HI = $44.9 + 4.8\text{E-}2 \text{ age} - 3.25\text{E-}5 \text{ age}^2$, $R^2 = 0.94$.



Plate 1. Root systems depicting the tuberization response of plants from 66 dd (a), 616 dd (b), and 1166 dd (c) Russet Burbank seed-tubers at 48 DAP. Scale bar equals 40 mm.

Sequential yield component analysis of the adjusted yield components showed that all variates contributed significantly to the model (see Materials and Methods) describing tuber yield (Table 2). Consistent with controlled environment studies (Knowles and Botar 1991), leaf number per stem accounted for the greatest proportion (64%) of the total variation in yield. Plant weight (foliage plus tuber) per leaf area contributed 13%. Therefore, in the assessment of yield over the course of a growing season, the most important and accurate developmental criterion is the number of leaves produced per stem for the Russet Burbank cultivar.

Of the treatment effects, time had the greatest influence on tuber yield: linear and quadratic trends accounted for 71% and 21%

of the total variation in yield, respectively (Table 2). This was expected in light of the tremendous change in tuber weight between successive harvest dates (see Table 1). The significant main effect of seed-tuber age and the age $\times$ time interactions, while accounting only for a minute percentage of the total variation in yield, were of greatest relevance in defining how seed-tuber age modified plant growth to alter yield (Table 2). Seed-tuber age influenced final yield by modifying stem number per seedpiece, leaf area per leaf, plant (foliage plus tuber) fresh weight per leaf area, and HI (W_T/W). While mainstem number increased only slightly with advancing tuber age, differences between ages in average leaf area per leaf were substantial (depending upon the stage of plant development). The leaves

Table 2. Two-dimensional partitioning of yield (tuber fresh weight) variation in Russet Burbank potatoes growing under irrigation in 1987^z

Source of variation	df	Adjusted yield components ^y					
		S_N	L_N/S_N	L/L_N	W/L	W_T/W	W_T^x
Block	4	0.11	1.57**	0.27**	0.35**	0.11**	0.04
Age							
Linear (l)	1	0.23*	0.02	0.00	0.00	0.06*	0.29**
Quadratic (q)	1	0.12	0.02	0.18**	0.03	0.00	0.01
Cubic (c)	1	0.11	0.24	0.01	0.01	0.00	0.02
Residual	1	0.38*	0.14	0.00	0.01	0.01	0.00
Time							
Linear	1	0.68**	24.68**	0.04	6.30**	0.01	71.12**
Quadratic	1	0.15	20.38**	0.64**	2.37**	0.15**	20.71**
Cubic	1	1.18**	0.38*	0.49**	0.70**	0.03	3.07**
Residual	4	0.67	2.34*	0.26	0.27	1.69*	1.68**
Age $\times$ time							
l $\times$ l	1	0.01	0.05	0.08	0.08*	0.05	0.30**
l $\times$ q	1	0.01	0.05	0.10*	0.00	0.01	0.02
l $\times$ c	1	0.00	0.06	0.00	0.05	0.11**	0.08**
q $\times$ l	1	0.08	0.27	0.02	0.04	0.01	0.00
q $\times$ q	1	0.00	0.04	0.02	0.01	0.00	0.00
q $\times$ c	1	0.00	0.01	0.03	0.02	0.01	0.00
c $\times$ l	1	0.01	0.01	0.03	0.01	0.00	0.01
c $\times$ q	1	0.01	0.52*	0.06	0.06*	0.01	0.00
c $\times$ c	1	0.03	0.01	0.05	0.00	0.02	0.00
residual	28	0.99	0.75	0.34	0.15	0.89	0.94
Exp. error	156	6.71	12.68	3.55	2.21	2.29	1.71
Total (%)	199	11.48**	64.22**	6.17**	12.67**	5.46**	100.00

^zVariation in yield is expressed as the incremental contribution of each yield component to r^2 , with treatment effects partitioned by ANOVA.

^yYield components (as defined in Materials and Methods) are $\ln_e$ -transformed, orthogonalized and scaled (Eaton et al. 1986).

^xThe total sum of squares for $\ln W_T$ was 7557.41.

*, ***F*-values for the indicated sources of variation were significant at the 0.05 and 0.01 levels, respectively; significance within a treatment row refers to ANOVA and within the total row refers to regression analysis.

of plants from older seed-tubers were larger than those from younger seed-tubers during establishment.

Physiological maturity refers to the relative carbohydrate content of tubers at harvest (Iritani and Weller 1980). Maximum physiological maturity is reached when the tuber concentration of starch (dry matter) is highest and the sugar concentration (especially reducing sugars) is lowest. At this point, tubers will have the highest specific gravity which will translate into high processing quality. Hence, tubers of maximum physiological maturity are highly desirable in the processing industry.

In the 1987 study, plants from older Russet Burbank seed-tubers tuberized earlier in the growing season and the bulking rate was faster relative to those from younger seed-tubers. It was therefore reasonable to expect that the physiological maturity of the potatoes produced by plants from older seed-tubers would be more advanced than that from younger seed-tubers.

To test this possibility, tuber tissue samples from each treatment of the 1987 irrigated Russet Burbank study were analyzed for carbohydrate content at each harvest date. No significant effects of seed-tuber age on total soluble carbohydrate, reducing sugar (glucose and fructose), sucrose or starch concentrations of the harvested Russet Burbank tubers could be demonstrated from our studies. The data from the various age treatments were thus averaged and plotted against time (Fig. 4). Based on the fitted lines, the concentrations of reducing sugars and sucrose (nonreducing sugars) declined from 53 DAP to 106 DAP and then leveled off at about 1.3 and 5.5%, respectively. Conversely, starch content increased quadratically over the same period to reach a maximum of 57% at 103 DAP. Starch concentration decreased by approximately 3% from 103 to 121 DAP. The quadratic equations for starch and total soluble carbohydrates were: starch = $-170.1 + 14.3 \text{ DAP} - 6.94\text{E-}2 \text{ DAP}^2$, $R^2 = 0.90$; total soluble carbohydrates = $314.7 - 4.6 \text{ DAP} + 2.11\text{E-}2 \text{ DAP}^2$, $R^2 = 0.96$. Although the time scale is different, the

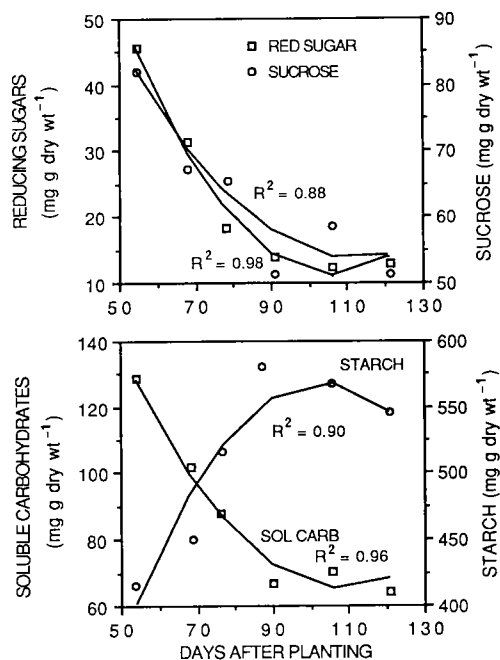


Fig. 4. Developmental changes in the carbohydrate content of Russet Burbank potatoes. The study was conducted under irrigated field conditions in 1987. Each point is the average of 60 tubers. *F*-value for the effect of time (quadratic) was significant at the 0.01 level for all of the carbohydrate pools.

general trends in tuber carbohydrate content are consistent with Iritani and Weller (1980). In this particular study, maximum physiological maturity was reached between 103 and 106 DAP.

In a similar study conducted in 1988, plants from aged Russet Burbank seed-tubers displayed comparable emergence and leaf area establishment trends (data not shown) as those characterized in the 1987 study. Results from 1988 showed that the total yield increased linearly with advancing tuber age at 78, 92, 105 and 119 DAP. Based on the linear trend ($P < 0.01$) at 78 DAP, plants from 1184 dd seed-tubers produced a 32% higher yield than those from 84 dd seed-tubers (24.5 versus 18.5 t ha⁻¹). The difference in total yield between the extremes in tuber age was 14, 19 and 19% at 92, 105 and 119 DAP,

respectively (based on significant linear models). Figure 5 shows the actual yields and calculated yield responses to advancing tuber age at 105 and 119 DAP. Based on the significant linear trends ($P < 0.05$), storing the seed-tubers for 100 d at 15°C (after wound-healing) resulted in a 7.9 t ha^{-1} increase in total yield at the 105-d harvest (yield = $37.4 + 7.2\text{E-}3 \text{ age}$) and a 7.2 t ha^{-1} increase in yield at the 119-day harvest (yield = $43.3 + 6.6\text{E-}3 \text{ age}$).

Despite a relatively low yield of marketable tubers at 105 DAP, the yield almost doubled (95% increase) as seed-tuber age increased from 84 dd to 1184 dd (Fig. 5). The highest predicted yield of marketable tubers occurred at 119 DAP from 695 dd seed-tubers (yield = $8.39 + 2.07\text{E-}2\text{age} - 1.49\text{E-}5 \text{ age}^2$). This age would result in a 56% (5.6 t

ha^{-1}) increase in marketable yield over control (based on quadratic model).

Tuber growth rate was calculated for each age using yield data from 78 to 119 DAP (linear phase of bulking). The rate of production of tuber fresh weight (i.e., bulking) increased to a maximum and then decreased as tuber age advanced (Fig. 5), and was thus best defined by a second-degree polynomial:

$$\text{Total bulking rate} = 526.8 + 5.35\text{E-}1 \text{ age} - 3.86\text{E-}4 \text{ age}^2$$

(The units for bulking rate and age were $\text{kg ha}^{-1} \text{ d}^{-1}$ and dd, respectively.) From this model, 693 dd seed-tubers would give the maximum bulking rate of $712 \text{ kg ha}^{-1} \text{ d}^{-1}$ compared with only $569 \text{ kg ha}^{-1} \text{ d}^{-1}$ from 84 dd seed-tubers (a 25% difference).

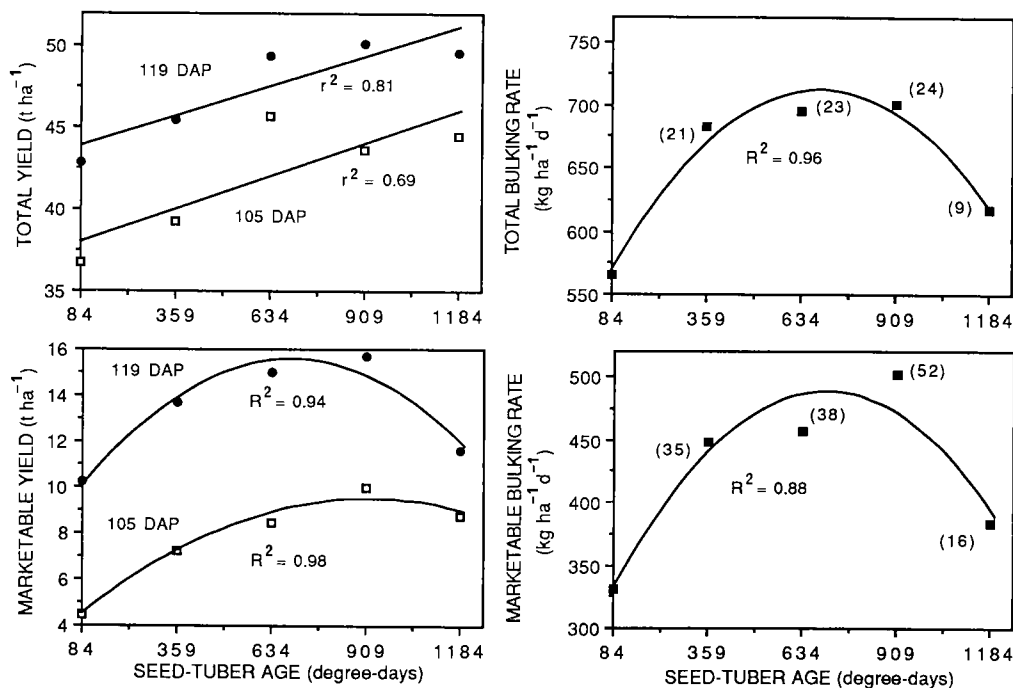


Fig. 5. Relationships between seed-tuber age, yield and bulking rates (total and marketable tuber growth rates) of Russet Burbank potatoes growing under irrigated field conditions in 1988. For clarity, data for only two of the seven harvest dates are shown; however, the complete data sets were subjected to ANOVA. F -values for the main effect of age (linear) and the age (linear) $\times$ time (linear) interaction were significant at the 0.01 level for total yield. For marketable yield, F -values for the main effects of age (quadratic) and time (linear) were significant at the 0.01 level. Numbers in brackets are percent increase over the 84 dd treatment.

The trend in rate of production of marketable tubers with advancing age was also defined by a quadratic equation (Fig. 5):

$$\text{Marketable bulking rate} = 284.8 + 5.77\text{E-1 age} - 4.10\text{E-4 age}^2$$

From this relationship, a seed-tuber age of 704 dd would be expected to give the maximum production rate of $488 \text{ kg ha}^{-1} \text{ d}^{-1}$ marketable tubers, compared with only $330 \text{ kg ha}^{-1} \text{ d}^{-1}$ from 84 dd seed-tubers (a 48% difference). The effect of seed-tuber age on stimulating the production of marketable tubers toward the end of the growing season was therefore greater than its effect on total tuber yield (a highly desirable trait for short-season areas). The results from this study were thus consistent with those from the 1987 field study.

Late Season Cultivar Dryland Studies

Linear increases in total and marketable yields of Russet Burbank tubers grown under dryland conditions in 1988 were characterized at 90 and 103 DAP in response to advancing seed-tuber age (Table 3). It was evident from the linear models (Table 3 footnotes) that 1184 dd seed-tubers produced a 28% (7.7 t ha^{-1}) increase in total yield and a 210% increase (4.4 t ha^{-1}) in marketable yield over controls (84 dd) at 90 DAP. At 103 DAP, total and marketable yields from 1184 dd seed-tubers were each increased by about 14 t ha^{-1} over that from 84 dd seed-tubers (based on linear models). This increase represented a 39% greater total yield and a 67% greater marketable yield from 1184 dd seed-tubers relative to control. The significance of these yield increases is magnified when considering the early harvest dates employed in this study. The normal harvest time for Russet Burbank potatoes in Alberta ranges from 120 to 140 DAP, depending upon location. In areas with longer growing seasons (e.g., Columbia Basin of Washington) yield declines as the age of Russet Burbank seed-tubers increases (Iritani et al. 1983). Hence, the optimum seed-tuber age for maximum yield depends on length of the growing season. In short-season areas, older tubers

Table 3. Yield response of Russet Burbank potatoes to seed-tuber age and time (DAP)^a

Tuber age (degree-days)	Tuber yield (t ha^{-1})			
	90 DAP		103 DAP	
	Total	Marketable	Total	Marketable
84	28.3	2.2	38.9	21.8
359	28.1	3.6	40.8	23.2
634	28.0	2.0	41.4	24.9
909	33.5	7.6	38.2	25.3
1184	34.7	5.4	58.2	37.7
Linear	0.01 ^y	0.01	0.01	0.01
Quadratic	—	—	—	—

^aThe potatoes were grown under dryland field conditions in 1988.

^ySignificance levels of the *F*-values for the indicated trends: at 90 DAP, total yield = $26.3 + 7.0\text{E-3 age}$, $r^2 = 0.76$; marketable yield = $1.76 + 4.0\text{E-3 age}$, $r^2 = 0.49$; at 103 DAP, total yield = $35.2 + 1.3\text{E-2 age}$, $r^2 = 0.46$; marketable yield = $18.8 + 1.2\text{E-2 age}$, $r^2 = 0.71$.

will give higher yields. Conversely, in long-season areas, younger tubers will give maximum yield. The optimum age for production in southern Alberta (140 d) will thus be different than that for central Alberta (120 d).

While the effects of advanced seed-tuber age on yield were quite well defined with the Russet Burbank cultivar, Norchip seemed to be less sensitive to aging treatments. Total yield was not affected by advanced seed-tuber age at 91 and 103 DAP; however, the yield of marketable tubers increased linearly with tuber age at 91 DAP (Table 4). Plants from 1332 dd seed-tubers produced a 50% greater yield of marketable tubers compared with those from 232 dd seed-tubers at 91 DAP (based on linear model). The positive effect of age on marketable tuber yield was not evident in the 103 DAP study.

Early Season Cultivar Dryland Studies

For the early cultivars Carlton and Superior, significant cultivar $\times$ age interactions characterized both total and marketable yields in the 90 DAP and 103 DAP studies conducted in 1988 (Fig. 6). Carlton was the more responsive to advancing tuber age: total and marketable yields were increased by 90% (19.5 t ha^{-1}) and 81% (17.0 t ha^{-1}), respectively, over control at 90 DAP (based on the linear

Table 4. Yield response of Norchip potatoes to seed-tuber age and time (DAP)²

Tuber age (degree-days)	Tuber yield (t ha ⁻¹)			
	91 DAP		103 DAP	
	Total	Marketable	Total	Marketable
232	25.1	10.3	36.9	24.5
507	27.7	14.3	36.1	25.4
782	28.7	13.6	38.6	24.3
1057	25.3	13.6	36.8	23.9
1332	31.9	17.6	31.7	23.8
Linear	—	0.01 ³	—	—
Quadratic	—	—	—	—

²The potatoes were grown under dryland field conditions in 1989.

³Significance levels of the *F*-value for the indicated trend: at 91 DAP, marketable yield = $9.93 + 5.0E-3$ age, $r^2 = 0.72$.

and quadratic models: Total yield = $17.7 + 5.02E-2$ age - $2.68E-5$ age²; Marketable

yield = $19.7 + 1.55E-2$ age). The predicted age giving maximum total yield of Carlton at 90 DAP was 936 dd. At 103 DAP, the total and marketable yields from 1184 dd Carlton seed-tubers were still 50% (16.0 t ha⁻¹) and 57% (16.2 t ha⁻¹) higher than the control, respectively (based on the linear and quadratic models: Total yield = $29.3 + 2.98E-2$ age - $1.21E-5$ age²; Marketable yield = $27.3 + 1.47E-2$ age). Over 90% of the total yield of Carlton potatoes were marketable.

Part of the positive effect of seed-tuber age on yield of Carlton was manifested through effects on stand establishment in 1988. In the 90 DAP study (Fig. 6), 84 dd and 359 dd seed-tubers produced stands of 58% and 83%, respectively. The remaining ages produced plant stands of 100%. Carlton, an early-season smooth-skin cultivar produced primarily for the fresh market, often produces

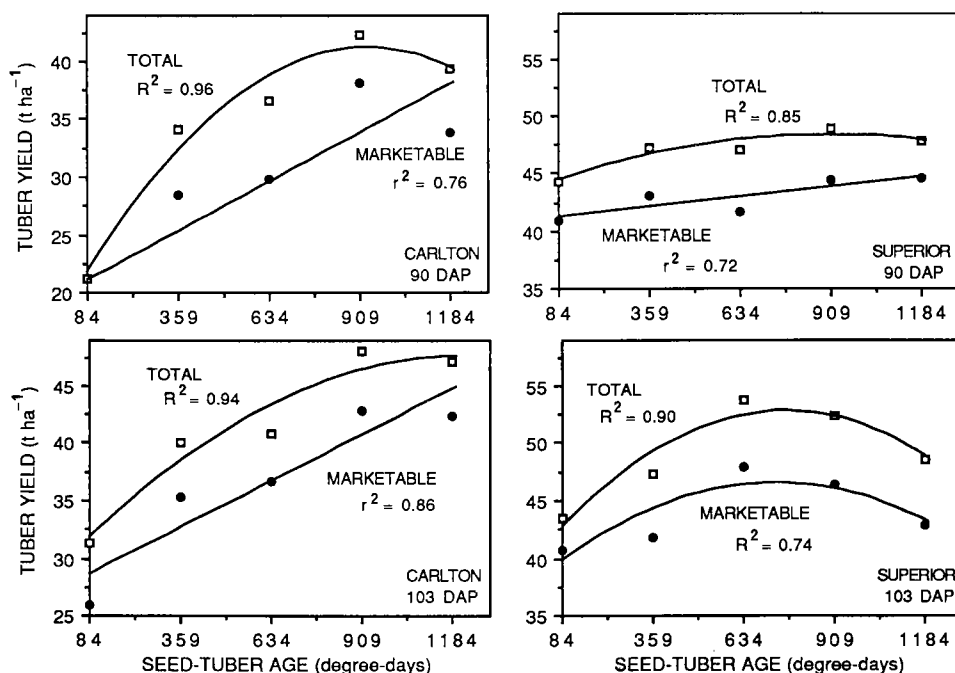


Fig. 6. Effects of advancing seed-tuber age on the yields of Carlton and Superior potatoes grown under dryland field conditions in 1988. At 90 DAP, *F*-values for the main effect of age and the cultivar × age interaction were significant at the 0.01 and 0.05 levels, respectively, for total and marketable tuber yields. At 103 DAP, *F*-values for the main effects of age and cultivar were significant at the 0.01 level for total yield, and the main effect of age and the cultivar × age interaction were significant at the 0.01 and 0.05 levels, respectively, for marketable yield.

low stands in commercial production. Our results suggest that using aged Carlton seed-tubers for production may be an effective means of achieving better stand. Moreover, correcting the marketable yields at 90 DAP for stand revealed that seed-tuber age increased the yield beyond that which was attributable to differences in plant stand. For example, marketable yield of Carlton potatoes increased linearly ($P < 0.05$) with advancing tuber age (marketable yield = $29.2 + 7.16E-3$ age, $r^2 = 0.56$), and the difference in yield between 1184 and 84 dd seed-tubers was 26% (7.8 t ha^{-1}) after correcting for stand (based on linear model).

In the 103 DAP study (Fig. 6), plant stands were 84%, 93% and 96% from the 84 dd, 359 dd and 634 dd seed-tubers, respectively. The two oldest ages produced stands of 100%. A significant ($P < 0.05$) linear increase in marketable yield remained after correcting for plant stand (Marketable yield = $31.9 + 1.06E-2$ age, $r^2 = 0.88$) at 103 DAP. Based on the linear relationship, the 1184 dd seed-tubers produced 11.6 t ha^{-1} more than the 84 dd controls; a 35% increase in marketable yield. Planting aged Carlton seed-tubers is thus advantageous for both stand and yield improvement.

The yields of Superior were less responsive to advancing seed-tuber age (Fig. 6). Significant quadratic trends ($P < 0.05$) described the relationships between total yield and age at 90 and 103 DAP (at 90 DAP: Total yield = $43.6 + 1.05E-2$ age - $5.76E-6$ age²; at 103 DAP: Total yield = $40.0 + 3.35E-2$ age - $2.20E-5$ age²). Based on these relationships, the calculated ages giving maximum total yields at 90 and 103 DAP were 911 and 761 dd, respectively. These ages would be expected to give a 4 t ha^{-1} (9%) increase in total yield at 90 DAP, and a 10 t ha^{-1} (24%) increase at 103 DAP, relative to that produced by the 84 dd treatment. Age-induced increases in marketable yields were linear ($P < 0.01$) at 90 DAP (marketable yield = $40.9 + 3.2E-3$ age) and quadratic ($P < 0.05$) at 103 DAP (marketable yield = $37.9 + 2.36E-2$ age - $1.61E-5$ age²). Based on these models, 1184 dd seed-tubers gave a

3.5 t ha^{-1} (8%) increase in marketable yield at 90 DAP, while 733 dd seed-tubers would be expected to give a 6.7 t ha^{-1} (17%) increase in marketable yield at 103 DAP, compared with that from 84 dd seed-tubers.

A similar study on Carlton and Superior was conducted in 1989. Yield responses from seed-tubers ranging in age from 128 dd to 1228 dd (275 dd intervals) were assessed at 103 DAP. Unlike the previous year's study, plant stand was over 95% for both cultivars. Although total yields were variable, the interaction of cultivar $\times$ age (linear) ($P < 0.05$) characterized the marketable yield response in this study. A 9.2 t ha^{-1} (28%) increase in marketable yield of Carlton was predicted for 1228 dd seed-tubers over the 128 dd treatment (Marketable yield = $32.3 + 8.40E-3$ age, $r^2 = 0.83$). This increase was thus consistent with that recorded in the 1988 study where corrections were made for stand. The marketable yield response from Superior was also linear ($P < 0.05$) with advancing seed-tuber age (Marketable yield = $35.9 + 3.71E-3$ age, $r^2 = 0.69$). Based on the linear model, 1228 dd seed-tubers would be expected to produce 4.1 t ha^{-1} (11%) more yield than 128 dd seed-tubers. Superior was thus much less responsive to age-induced increases in yield than Carlton, as was also demonstrated in the 1988 studies.

SUMMARY AND CONCLUSIONS

Our results demonstrate that potato yield, grade and earliness can be substantially improved in a short-season environment by planting seed-tubers of the proper physiological age. The increase in yield from older seed-tubers was due to quicker plant establishment and earlier tuberization, which led directly to a longer bulking period within the constraints of the available growing season. Hence, the annual life cycle of plants from older seed-tubers was accelerated, allowing the plants to utilize the relatively short growing season more efficiently. In longer growing-season areas, younger seed-tubers will eventually outyield older seed-tubers since earlier vine senescence occurs in the latter (Wurr 1978; Iritani et al. 1983; Van Der Zaag and Van Loon 1987).

The cultivars varied in sensitivity to the aging treatments: Carlton was the most responsive, followed by Russet Burbank, Norchip and Superior. The optimum age of Russet Burbank seed-tubers appeared to range from about 600 to 900 dd. These ages are easily created by holding tubers at 15°C for 50–75 d following an initial wound-healing interval (approximately 11 d at 10°C). The aging treatment should be given at the beginning of the storage season (while the tubers are dormant) to avoid excessive sprouting. The storage temperature should then be lowered to 4°C for the remainder of the storage period.

It must be stressed that the proper seed-tuber age depends upon cultivar and length of the growing season. Compared with younger seed-tubers, the yield increase from older seed-tubers rises to a maximum and then falls as the growing season progresses. In short-season areas, it is thus possible either to harvest earlier in the season from plantings of aged seed-tubers (while still maintaining the average yield of plantings of younger seed-tubers) or harvest later and realize a significant increase in yield. A grower may therefore gain a significant economic advantage by marketing his tubers earlier or by reaping a higher yield later. The technique appears to be very promising for enhancing yield of potatoes in regions with short growing seasons.

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