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Physiological age index: a new, simple and reliable index to assess the physiological age of seed potato tubers based on haulm killing date and length of the incubation period

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Abstract

Chronological and physiological age of seed tubers have major impacts on potato yields. This paper presents a new, simple and reliable physiological age index (PAI) that considers and reconciles the effects of chronological and physiological age. PAI calculation is based on the haulm killing date of the seed crop (T_0) and the end of the incubation period of seed tubers, measured under standardized conditions. The PAI formula is T_1/T_2, where T_1 is the time from haulm killing date (T_0) to possible planting date and T_2 the time from T_0 to the end of the incubation period. The PAI expresses physiological ageing of seed potato tubers within a range from 0 (for physiologically young) to 1 (old) tubers. To test the PAI existing data were re-evaluated and re-elaborated and specific experiments regarding seed origin and storage conditions for different cultivars were performed during 1994–1999. The PAI proved useful in assessing differences due to differences in growing conditions, cultivar, haulm killing, seed origin and storage system, and pre-planting treatments. For example, for cv. Spunta 6 days after haulm killing the PAI was 0.025 and after 100-storage days the PAI was 0.56, 0.52 and 0.49 for seed tubers stored in heaps in the field, at relatively high temperatures, natural diffuse light and a cold (4°C) and ventilated store, respectively. The PAI is related to ground cover duration and yield of the future crop. For a PAI of 0.55 tuber yield was 55 t ha^{-1}, while for a PAI of 0.80 tuber yield was 40 t ha^{-1}. The PAI is easy to measure, non-invasive, objective, reproducible and reliable and could be used for modelling purposes to describe performance of seed tubers.

Keywords: *Solanum tuberosum*; Potato; Haulm killing; Incubation period; Chronological age; Physiological age; Tuber yield

1. Introduction

Physiological age is a well-known limiting factor in potato (*Solanum tuberosum* L.) production (Caldiz and Gaspari, 1997) and its causes and effects upon crop growth, development and yield have been intensively studied since the 1950s (Went, 1959). The physiological age of the seed tubers affects future crop performance, i.e. emergence rate, percentage of emergence, number of emerged stems per mother tuber, time to tuber initiation, crop vigour and growth, dry matter distribution and tuber yield (Reust, 1982; O'Brien et al., 1983; Vakis, 1986; Van Loon, 1987;

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Moll, 1994). The European Association for Potato Research (EAPR) published the following definition: the physiological age of a seed tuber is the physiological stage of the tuber which influences its productive capacity (Reust, 1986). The ageing process progresses even when there are no visible signs (i.e. sprouting or sprout behaviour) and until breaking of dormancy, physiological age is fully reflected by the mother tuber. After the onset of sprouting the behaviour of the sprout is influenced by the age of the mother tuber, but this effect may be modified by conditions and treatments that directly interfere with the functioning of the sprouts (e.g. diffuse light or de-sprouting). Perennec and Madec (1980) stated that the physiological age of a tuber at any given time depends, in part, on its chronological age, measured from the date of tuber formation in the field. Although it is recognized that the chronological age and environmental conditions affect the seed tuber since it is initiated from the mother plant (Van Ittersum, 1992), it is difficult to precisely measure tuber initiation under field conditions. However, tubers with the same chronological age could have, at a certain moment, different physiological ages due to the effect of different environmental and management conditions during growth (Van der Zaag and Van Loon, 1987) and storage (Hartmans and Van Loon, 1987).

Effects of physiological age differ between cultivars (Caldiz, 1994; Struik and Wiersema, 1999) and are important because seed tubers are planted in different zones of the same country or are shipped to overseas areas with double or triple cropping resulting in different age requirements (Fahem and Haverkort, 1988; Struik and Wiersema, 1999). Seed age can be modified by crop and storage management to make it suitable for different conditions (Van Ittersum et al., 1993). There is general agreement that rather young seed produces high yields in long growing seasons, while older seed is suitable to obtain high yields early in the season or in short cycle seasons (Wurr, 1979).

Many attempts have been made to develop an indicator of the physiological age of seed tubers. Physiological indicators like sprout type (Krijthe, 1958), sprouting capacity (Krijthe, 1962), length of the longest sprout (O'Brien and Allen, 1981) and the length of the incubation period (Claver, 1953; Reust and Munster, 1975; Caldiz, 1991) have been used to establish physiological age. Biochemical indicators based on tuber or sprout contents of sugars (Van Es and Hartmans, 1984), enzyme activity (Van Es and Hartmans, 1987; Caldiz et al., 1996), organic acid content (Reust and Aerny, 1985), polyamine content (Apelbaum, 1984), ATP, ADP and bound phosphate levels (Biotto and Siegenthaler, 1991) and electrolyte leakage (De Weerd et al., 1995) have also been developed. Bio-physical indicators include accumulated day-degrees from dormancy break (O'Brien et al., 1983), storage temperature sum (Scholte, 1987) — who actually warned against the use of storage temperature sum (K. Scholte, personal communication, 1999; Struik and Wiersema, 1999) — and relative growth vigour indices (Bodlaender et al., 1987; Van Ittersum, 1992). Indicators are needed in order to quantify and explain cultivar differences in rate of ageing (such as the interaction between cultivar and storage conditions) and the effect of seed age on crop growth and yield. However, comparisons using existing indicators and their relationships with tuber yield have not been successful; often the effect of the chronological age of the seed tuber is not considered. In many cases, similar figures for the same indicator do not exactly reflect the same physiological age (Caldiz et al., 1985; Van der Zaag and Van Loon, 1987) or differences are masked by other factors (Sacher and Iritani, 1982; W. Iritani, personal communication, 1989). Hence, a quantitative and comparable indicator of the physiological age is lacking.

The physiological age index (PAI) presented in this paper may overcome some of these difficulties. An index should be: (a) easy to measure, objective, reproducible and reliable; (b) able to account for effects of environment, cultivars and their interaction; (c) able to account for seed treatments; (d) able to account for differences among seed lots of different origins or with different storage histories. An index should also be (e) able to reconcile chronological with physiological age.

Based on these statements the objectives of this research were to develop a PAI that will have application in future research and to determine if this index can successfully distinguish differences between varieties, environmental conditions and crop management.

2. Materials and methods

2.1. Calculation of the PAI

The calculation of the dimensionless PAI is based on easily measured variables derived during the life cycle of a seed tuber. The first variable is the haulm killing date of the seed crop (T_0), the time seed tubers start their independent life. Another key-date is the sampling or possible planting date when physiological age is relevant for crop performance. At that time, samples of 30–50 tubers for each lot (10 tubers $\times$ $3-5$ replications for each origin, cultivar, storage system, etc.) were exposed to standardized growing conditions (darkness, 17°C, 90–95% relative humidity) to measure the length of the incubation period. The incubation period is defined as the time elapsed from sprouting until new tuber formation on the sprouts (Claver, 1951, 1953). At sprouting two measurements were taken, the date when 80% of the tubers bear sprouts longer than 5 mm and the sprouting date for each individual tuber of each replication. Previous studies report significant differences between sprouting time considered as the moment when 80% of the tubers bear sprouts > 5 mm (Reust, 1986) and when based on average sprouting date (sprouts > 5 mm) resulting from measurements of individual tubers within each replication. As this last assessment was considered more accurate for establishing the length of the incubation period, it was used, whenever possible, both for the re-elaboration of the data and the calculation of the PAI. The end of the incubation period is the average value resulting from recording twice or thrice a week which individual tubers had formed tubers on their sprouts; this is the other key-date needed to calculate the index. The index is calculated as $\mathrm{PAI} = T_1/T_2$, where T_1 is days from T_0 (haulm killing date) to possible planting date and T_2 is days from T_0 to the end of the incubation period. This index ranges from 0 for very young seed tubers, when planted immediately after haulm killing, to 1 for old seed tubers when planted incubated or at the "little potato" stage.

To determine the efficacy of the PAI data from two sources were used. Included were pre-existing data from past experiments and data from experiments with variable seed origin, seed management and storage conditions for different cultivars performed specifically for this study. Experimental treatments were selected that could quantitatively illustrate specific trends in PAI caused by agronomically relevant factors.

2.2. Appraisal of PAI under different growing conditions

Data from Claver (1973), for tubers of cv. Katahdin grown at different temperatures during 1972 in a study in which the incubation period was used as an indicator of physiological age were re-analyzed to test PAI. In the original experiment, samples were taken immediately after harvesting the tubers and at that time the incubation period was measured.

2.3. Appraisal of PAI across cultivars

A field trial to study differences in the PAI among cultivars was carried out during 1997–1998 in Balcarce, Argentina (37°51′S, 113 m elevation), with cultivars Frital INTA, Huinkul MAG, Keluné INTA, Kennebec, Russet Burbank, Shepody and Spunta. Certified seed tubers previously stored in a cold store were planted by mid-October 1997. Crops were sprinkler irrigated, fertilized and pests and diseases controlled as normally done in the area. For each cultivar, haulm senescence occurred between 30 January and 28 February 1998, and it was assessed by a visual scale from 0 (complete senescence) to 10 (all green). After harvest, which took place in each case 2 weeks after haulm killing, the seed tubers were stored in a cold store at 4°C. Samples to measure the PAI were taken on May and October 1998.

2.4. Appraisal of PAI after different haulm killing dates

To test the effect of different haulm killing dates on PAI, data from Panelo and Caldiz (1989) in which the incubation period was used as an indicator of physiological age, were recalculated. These experiments were carried out at Miramar, Argentina (38° 10′S, 100 m elevation) during the period 1983–1987 in order to test the effect of different haulm killing dates on physiological age and tuber yield. Each year, after harvest which was performed within 2–4 weeks from the haulm killing date, seed tubers were stored in heaps in the field until June–July when the PAI was assessed.

2.5. Appraisal of PAI values over storage time

Certified seed crops of cv. Kennebec grown in the area of Tres Arroyos, Argentina (38°19′S, 120 m elevation) by two different growers were haulm killed on 14 and 16 February 1998, respectively. Seed tubers were harvested 7 and 9 days later and stored in a cold store at 4°C until planting, on 21 October 1998 and 19 February 1999, in the medium-late crop at Otamendi (38°S, 100 m elevation) and the late crop in Villa Dolores (31°57′S, 600 m elevation), respectively. Samples to obtain the PAI were taken at harvest (February 1998), in August, September and October 1998 and February 1999.

2.6. Appraisal of PAI for cv. Spunta under different storage systems

A field trial to study differences in PAI for cv. Spunta, a cultivar that is very sensitive to physiological ageing, Caldiz (1991) carried out in Villa Dolores (31°57′S, 600 m elevation) during 1997–1998. Seed tubers grown in the medium-early crop (July–November) were haulm killed on 13 November 1997, harvested 6 days later and stored for about 100 days in three different systems until planting the late crop (February–June) on 24 February 1998. The seed tubers were stored in (a) heaps in the field; (b) with natural diffuse light under a roof; (c) a cold room with forced air ventilated at 4°C. Tuber samples to assess the PAI were taken at harvest and at planting time.

2.7. Appraisal of PAI for different cultivars under different storage systems

Data from a study by Escande et al. (1985) on effects of cultivar and storage systems in which the incubation period was used as an indicator of physiological age, were recalculated to test the PAI.

2.8. Appraisal of PAI in distinguishing pre-planting treatments

The experiment described in Section 2.5 was continued to perform different pre-planting treatments. Seed tubers were harvested 7 and 9 days after last killing and placed in cold storage at 4°C until 1 month before planting, 28 September, 1998. At that time part of the tubers: (a) remained in a cold store at 4°C, (b) were stored under natural diffuse light at ambient temperature and (c) were stored in darkness at 17°C. PAI was evaluated before and after these pre-planting treatments. Planting was carried out with a 4-row planting machine on 21 October 1998. Crops were sprinkler irrigated and pests and diseases controlled as common in the area.

2.9. Effect of PAI on ground cover duration and yield

During 1995–1996 seed tubers of cv. Spunta grown during November–February in two different regions of Argentina: Tafí del Valle (26°56′S, 2000 m elevation) and Balcarce (37°51′S, 113 m elevation) were harvested 2 weeks after haulm killing and stored in a cold store at 4°C until the new planting seasons in the early and medium-late crops grown in the north, at Tucumán (26°48′S, 481 m altitude) and in the central-eastern part of the country, at Balcarce, respectively. At haulm killing and at each planting date the PAI was assessed as already described. In both locations tubers were hand-planted in 4-row plots of 10 m with four replicates at 5 plants m^{-2}. Fertilization was carried out with N–P–K (18–46–0) at 300 kg ha^{-1} and crops were sprinkler irrigated to maintain the soil close to field capacity. After emergence, periodical observations (5 per plot) of ground cover (GC), following the procedure described by Centro Internacional de la Papa (1986), were performed. These measurements were used to calculate ground cover duration (GCD) by applying the formula proposed by Watson (1952) for leaf area duration, as presented in Hunt (1982): $\mathrm{GCD}_{1-2} = \frac{1}{2}(\mathrm{GC}_1 + \mathrm{GC}_2)(T_2 - T_1)$, where GC is ground cover and T time. GCD provides an estimate of the fraction of the incident radiation intercepted by the canopy (Burstal and Harris, 1983). Crops died naturally and at harvest, which was performed over 5-row sections of 2 m length per plot, tuber weight was recorded.

2.10. Statistical analysis

Results of the experiments especially conducted to assess the PAI were analysed by ANOVA and means separated using Tukey's test ($P < 0.05$) by using the Statgraphics program V. 2.0.

3. Results and discussion

3.1. Meaning and use of the physiological age index

The meaning and use of PAI can be easily described as follows. Shortly after the haulm killing date (T_0) PAI $\cong$ 0; it increases with chronological age or a decrease in the incubation period which can result for both chronological ageing and environmental conditions. PAI $\cong$ 1 when the seed tubers at planting are incubated or at the "little potato" stage. For example, data on cvs. Spunta and Kennebec show that immediately after haulm killing PAI = 0.025 and 0.05, respectively. However, at planting, after a period of storage, PAI = 0.56 and 0.74 for Spunta and Kennebec, respectively. The following results will also illustrate how the effect of different factors can be assessed and compared with the PAI.

3.2. Assessment of PAI in distinguishing different growing conditions

The re-elaborated data from Claver (1973) show that the PAI can be applied to assess the effect of different growing conditions on the physiological status of the seed tubers. High temperatures during the growing period advanced the physiological age of the seed tubers, thus reducing the length of the incubation period (Table 1). However to explain an advanced physiological age with a lower figure (114 days instead of the 140 at 17°C) may be counter-intuitive, because a large figure would mean that the tubers are younger. This is not the case with the PAI values where a high figure means older tubers (Table 1). This is an advantage for the index regarding the use of the incubation period alone as an indicator of the physiological age.

3.3. Assessment of PAI across cultivars

By 30 May, about 40–60 days from T_0, PAI was close to 0, an indication that the seed tubers were young (Table 2). On this date, higher values were registered in cvs. Shepody and Spunta. The latter cultivar is well known for its sensitivity to physiological ageing (Escande et al., 1985; Caldiz, 1991). Shepody, Kennebec and Huinkul MAG followed, while Frital INTA, Keluné INTA and R. Burbank showed a lower PAI. On the planting date (21 October), after seed tubers had been stored at 4°C, PAI was higher in all cases (Table 2) and cv. Spunta achieved the highest value. Differences between cultivars were statistically distinct as a result of using PAI (Table 2) and are in agreement with previous behaviour for the same cultivars (Caldiz, 1994).

3.4. Assessment of PAI after different haulm killing dates

Haulm killing date is recognized as an important event during the life cycle of a seed tuber and its effects on physiological age, growth and yield have already been studied (Hutchinson, 1978; Panelo and Caldiz, 1989; Caldiz et al., 1994). When data from different haulm killing date trials (Panelo and Caldiz, 1989) were re-analyzed, the results obtained (Table 3) were similar to those reported above.

Differences in the length of the incubation period are better expressed and better assessed when the PAI was used, which means that (a) the length of the incubation period is related to seed age (Claver, 1953; Caldiz, 1991) and (b) that PAI can really explain

Table 1
PAI for tubers of cv. Katahdin grown at different temperatures

Temperature (°C)	T_0[a]	Sampling date[a]	T_0 to sampling (T_1)[b]	Incubation period[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
20	114	235	121	140	261	0.46 b
27	114	235	121	114	235	0.51 a

[a] In Julian days.
[b] Number of days. Data re-elaborated from Claver (1973).
[c] Means followed by the same letter are not significantly different at $p = 0.05$.

Table 2
PAI for different cultivars grown in Balcarce, 1997–1998

	T_0[a]	Sampling date[a]	T_0 to sampling (T_1)[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
30 May 1998					
Frital INTA	43	150	107	274	0.39 c
Keluné INTA	49	150	101	259	0.39 c
Huinkul MAG	53	150	97	243	0.40 c
Kennebec	43	150	107	251	0.43 b
R. Burbank	57	150	93	237	0.39 c
Shepody	43	171	128	251	0.51 a
Spunta	43	150	107	240	0.45 b
21 October 1998					
Frital INTA	43	294	251	324	0.78 c
Keluné INTA	49	294	245	313	0.78 c
Huinkul MAG	53	294	241	300	0.81 b
Kennebec	43	294	251	314	0.80 b
R. Burbank	57	294	237	293	0.81 b
Shepody	43	294	251	321	0.79 bc
Spunta	43	294	251	291	0.85 a

[a] Julian days.
[b] Number of days.
[c] For each date means followed by the same letter are not significantly different at $p = 0.05$.

differences in physiological age. Re-elaborated data for 1986–1987 in cv. Ballenera clearly showed the effects of a warm and dry growing season on seed age, resulting in a high PAI value of 0.65 and 0.59 for the early killing and natural death treatments, respectively (Table 3), compared with the 0.43–0.48 values for the same treatments in 1984–1985 and 1985–1986.

3.5. Assessment of PAI values over storage time

At the first sampling, carried out 13 days after T_0, PAI was close to 0, as shown in Table 4. This was due to the short time elapsed from T_0 to the sampling date and, of course, the long time elapsed from T_0 to the end of the incubation period (13/255: 0.05 PAI for

Table 3
Results of applying the PAI to incubation measurements used to express physiological age for seed of cv. Bonaerense La Ballenera from different haulm killing dates

Treatment	T_0[a]	T_0 to sampling date (T_1)[b]	Incubation period[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
1984/1985					
Early killing	61	123	133	256	0.48 a
Natural death	65	119	135	254	0.47 a
1985/1986					
Early killing	60	136	157	293	0.46 a
Natural death	80	116	152	268	0.43 b
1986/1987					
Early killing	80	123	67	190	0.65 a
Natural death	107	96	67	163	0.59 b

[a] Julian days.
[b] Number of days. Data recalculated from Panelo and Caldiz (1989).
[c] For each season means followed by the same letter are not significantly different at $p = 0.05$.

Table 4
PAI over time for cv. Kennebec grown by different seed growers and stored in a cold store at 4°C

Treatment	T_0[a]	T_0 to sampling (T_1)[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
February 1998				
Grower A	45	13	255	0.05 a
Grower B	47	11	275	0.04 a
September 1998				
Grower A	45	226	326	0.69 a
Grower B	47	224	344	0.65 b
October 1998				
Grower A	45	254	343	0.74 a
Grower B	47	252	344	0.73 a
February 1999				
Grower A	45	370	429	0.86

[a] Julian days.
[b] Number of days.
[c] Within each month means followed by the same letter are not significantly different at $p = 0.05$.

Grower A). This shows that tuber ageing can take place even in the absence of sprouts, as shown by Krijthe (1962) and Van Ittersum (1992), but denied by O'Brien and Allen (1981). PAI values increased with time, as shown for both seed growers (Table 4). These results showed that: (a) the incubation period was longer in physiologically young tubers, as already shown in Table 1 (see also Claver, 1975; Madec and Perennec, 1956; Hartmans and Van Loon, 1987; Caldiz, 1991), but rejected by Tizio and Tizio (1981), and (b) even small physiological age differences, like those due to seed origin, can be measured with the PAI (Table 4). Moreover, when seed tubers from one of these origins (Grower A) were stored until February 1999 for planting in the late season crop, the resulting PAI was very high due to the even shorter incubation period (Table 4).

3.6. Assessment of the PAI for cv. Spunta stored in different systems

These experiments were part of an ambitious project to evaluate the effect of crop and storage management on seed age of cv. Spunta for the late cropping season in the Villa Dolores area, Argentina. As previously shown PAI was close to 0 immediately after haulm killing (Tables 4 and 5). At planting time, tubers stored at 4°C had a lower PAI than those stored in heaps in the field. This was due to the high temperatures of the heaps, with the average daily temperature

Table 5
PAI for cv. Spunta stored under different conditions, Villa Dolores 1997–1998

	T_0[a]	Sampling date[a]	T_0 to sampling (T_1)[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
At harvest	315	321	6	240	0.025
At planting[d]					
Heaps in the field	315	423	108	193	0.56 a
Natural diffuse light	315	423	108	206	0.52 b
Cold ventilated at 4°C	315	423	108	220	0.49 c

[a] Julian days.
[b] Number of days.
[c] At planting, means followed by the same letter are not significantly different at $p = 0.05$.
[d] At planting, after being stored in different storage systems.

during storage >25°C period. The PAI of seed stored under natural diffuse light was intermediate at planting. Cultivar behaviour under storage was similar to that reported by Escande et al. (1986) and Caldiz (1991) using incubation period as an indicator of physiological age.

3.7. Assessment of the PAI in distinguishing between cultivars stored under different conditions

Physiological age measurements for cultivars stored in different systems (Escande et al., 1985) were recalculated using PAI as shown in Table 6. Differences between cultivars and storage systems can be perfectly assessed with the PAI. For example, for both years and cultivars seed tubers stored in heaps in the field showed the shorter incubation period and this was also reflected in a higher PAI at planting (0.86–0.90). On the other hand, when tubers of both cultivars were stored under more controlled conditions (silo, heaps–silo and cold store), they had a lower PAI (0.79–0.85) at planting as shown in Table 6. Moreover, these recalculated results are in agreement with cultivar behaviour as mentioned in the original work (Escande et al., 1985).

3.8. Assessment of PAI in distinguishing pre-planting treatments

The effect of different pre-planting treatments, such as pre-sprouting and storage temperature, were tested during the month before planting in order to study their effects on the PAI. Pre-sprouting and storage at 17°C for 4 weeks before planting resulted in higher PAI values than for seed tubers stored at 4°C for the same pre-planting period (Table 7).

3.9. Effects of PAI on ground cover duration and tuber yield

Seed tubers from Tafí and Balcarce had a lower PAI when planted at Tucuman than those later used at

Table 6
PAI for seed from different cultivars stored in different systems

Treatment	T_0[a]	T_0 to planting (T_1)[b]	Incubation period[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
Year 1980					
cv. S. Volcán					
Silo	71	273	69	342	0.80 c
Heaps–silo	71	273	70	343	0.79 c
Heaps	71	273	31	304	0.90 a
Cold store	71	273	61	334	0.82 b
cv. Spunta					
Silo	71	273	52	325	0.84 b
Heaps–silo	71	273	54	327	0.83 bc
Heaps	71	273	44	317	0.86 a
Cold store	71	273	61	334	0.82 c
Year 1981					
cv. S. Volcán					
Silo	71	253	43	296	0.85 b
Heaps–silo	71	253	49	302	0.84 bc
Heaps	71	253	27	280	0.90 a
Cold store	71	253	50	303	0.83 c
cv. Spunta					
Silo	71	253	60	313	0.81 b
Heaps–silo	71	253	57	310	0.82 b
Heaps	71	253	39	292	0.87 a
Cold store	71	253	55	308	0.82 b

[a] Julian days.
[b] Number of days. Data recalculated from Escande et al. (1985).
[c] For each season and cultivar means followed by the same letter are not significantly different at $p = 0.05$.

Table 7
PAI over time for cv. Kennebec grown in Tres Arroyos area by different seed growers, and with different pre-planting treatments, 1998–1999

Treatment	T_0[a]	T_0 to sampling (T_1)[b]	T_0 to end of incubation (T_2)[b]	PAI, T_1/T_2[c]
Grower A				
Cold	45	254	85	0.74 b
Darkness	45	241	67	0.75 b
Pre-sprouted NDL[d]	45	254	68	0.79 a
Grower B				
Cold	47	252	88	0.74 b
Darkness	47	239	67	0.75 b
Pre-sprouted NDL	47	252	77	0.77 a

[a] In Julian days.
[b] Number of days.
[c] For each grower, means followed by the same letter are not significantly different at $p = 0.05$.
[d] Pre-sprouted NDL, pre-sprouted in natural diffuse light.

Balcarce (Table 8). The effects of different PAI values were reflected both on GCD and tuber yield in both locations seasons. The results followed the well-known pattern for young and old seed (Caldiz, 1991, 1994), which means that crops originated from seed tubers with a low PAI has a large GCD and high tuber yield than those crops originated from physiologically old tubers, independent of their origin (Table 8). Future crop characteristics and tuber yield partially depend on the PAI. The PAI also has a close relationship ($r^2 = 0.98$) with the proportion of the potential yield achieved by a crop, as shown by Caldiz et al. (2000).

PAI is a very useful tool to establish and compare the physiological age of seed tubers. However, at its present stage of development is of no value in helping growers to make decisions on seed purchases or management practices. Nevertheless, PAI can be a useful research tool to properly establish and compare the seed age used in different experiments and/or to model effects of physiological age on crop growth and tuber yield.

4. Concluding remarks

PAI can be used to quantify physiological age of seed tubers of different cultivars exposed to dissimilar environments. PAI includes components of both chronological and physiological age and can explain differences in physiological age due to seed origin, haulm killing date, storage conditions and pre-planting treatments and allows in all cases comparisons between cultivars, crop and storage management and pre-planting conditions. PAI is related to GCD and yield of the crop grown from that seed. PAI is simple to measure, non-invasive and required investment is low. However, a disadvantage for PAI is the long time needed to obtain the final result which limits its predictive value for future plantings and for grower's

Table 8
Effects of PAI on GCD and tuber yield from seed of different origins grown at different planting times: early crop, Tucumán and medium-late crop, Balcarce[a]

Seed origin	Early planting (Tucumán)			Medium-late planting (Balcarce)		
	PAI	GCD	Yield (t ha^{-1})	PAI	GCD	Yield (t ha^{-1})
Tafí	0.56 a	65 a	51 a	0.82 a	59 a	38 a
Balcarce	0.55 a	66 a	55 a	0.80 a	57 a	39 a

[a] For each planting and column, means followed by the same letter are not significantly different at $p = 0.05$.

use. Further work is in progress to use the PAI as input of a simulation model to predict tuber yield based on seed age.

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