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Potential longevity (K_i) of malting barley (*Hordeum vulgare* L.) grain lots relates to their degree of pre-germination assessed through different industrial quality parameters

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ABSTRACT

Barley (*Hordeum vulgare* L.) grain germination is required to perform the malting process. Maintenance of barley seed viability during storage is crucial for the malt industry; and modern cultivars are bred for rapid grain dormancy release after physiological maturity. Low dormancy level combined with rain close to harvest induces pre-germination/pre-harvest sprouting damage. Pre-germination might not affect viability in the short term after harvest, but it could reduce potential longevity (K_i) of a barley seed lot. K_i value is inherent for each barley lot; however, its determination is time-consuming which precludes its assessment at an industrial scale. In this study we sought quantitative relationships between K_i and the pre-germination degree of barley grain lots, assessed through quality tests routinely performed by malthouses [Falling Number (FN), α-Amylase Activity and Carlsberg]. Field pre-germinated lots from one old barley cultivar (Quilmes Palomar) and artificially pre-germinated lots from major varieties currently grown in Argentina were used. Associations between K_i and values obtained from all quality tests analysed were found for Q. Palomar. However, FN was the parameter that yielded the best and simplest explanation of K_i variability. A significant positive linear K_i -FN relationship was also obtained for each modern barley cultivar.

1. Introduction

Barley crops (*Hordeum vulgare* L.) in Argentina are grown almost exclusively for malting purposes. Germination capacity and germination energy, and protein content are grain major trade parameters for this end-use (Brookes, 1980; SAGPyA, 2007a). Protein content is defined at crop harvest and remains virtually invariable during the storage period. Germination capacity (i.e., seed viability) and germination energy (i.e., lack of dormancy), in contrast, continue changing throughout storage, depending on grain post-harvest management. The malting process requires the germination of grains and the associated production of hydrolytic enzymes for degrading starch into soluble sugars (Savin et al., 2004). Hence, barley lots with low viability cannot be malted. In this respect, a minimum 95% (ideally 98%) germination capacity is established by the malting industry (FAO, 2009). For the same reason, a low dormancy level at harvest (i.e., high germination energy) is a desirable characteristic so that the grain can be processed immediately after harvesting. Selection pressure led to the development of genotypes whose dormancy is terminated well before harvest maturity. In these genotypes, a short exposure (<24 h) to rain water during the period from physiological to harvest maturity, may trigger embryo growth and thus, lead to pre-germination or pre-harvest sprouting (Benech-Arnold, 2001; Del Fueyo et al., 2003; Gualano and Benech-Arnold, 2009). Both processes have different adverse consequences on the malting quality of grains. If damp conditions persist for several days, the germination may proceed towards a "point of no return" beyond which the embryo loses desiccation tolerance (Schopfer et al., 1979). This process is known as pre-harvest sprouting and implies that, upon desiccation, the grain losses its viability and becomes useless for

Abbreviations: AA, α-Amylase Activity; C, Carlsberg method; DU, dextrinixing units; FN, Falling Number; K_i, seed potential longevity; V_i, initial seed viability.

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malting. In contrast, pre-germination takes place when embryo growth begins but is interrupted by desiccation before going through the "point of no return". Commonly, no visible signs can be detected as a result, and seeds will be able to germinate immediately after harvesting. Pre-germination in the mother plant could be regarded as an advancement of germination analogous to that aimed with seed priming. The benefits of this technique are well known (rapid germination, uniformity of seedling emergence), but there are many reports showing its detrimental effect on longevity during storage (Argerich et al., 1989; Tarquis and Bradford, 1992). Therefore, it could be hypothesized that pre-germination, whereas not affecting grain viability immediately, might reduce seed longevity dramatically. At harvest time, malthouses receive large amounts of grain in a short period, which exceeds their industrial processing capacity. Consequently, the grains must be stored and malted throughout the year. Hence, pre-germination might affect seed lot storability, shortening the period until barley lots can be malted.

Pre-germination and pre-harvest sprouting trigger the synthesis of endosperm degrading enzymes as, for example, α-amylase (Benech-Arnold, 2001). The malting industry developed Falling Number (FN), α-Amylase Activity (AA) and Carlsberg (C) as methods for assessing the presence of these post-germinative enzymes and, hence, the level of pre-germination damage in barley lots (EBC, 1987). They are routinely performed on a sample upon grain receipt.

As in many other species, viability loss throughout storage in barley can be described with the Viability Equation developed by Ellis and Roberts (1981) [1] (Pieta Filho and Ellis, 1991). The equation describing this model is:

$$V = K_i - p \Big/ 10^{(K_E - C_w \log m - C_H T - C_Q T^2)} \quad (1)$$

where V is probit of percentage viability after a period p (days) of storage at a given seed moisture content (m) and temperature (T,°C). Parameter K_i indicates the initial (i.e., prior to storage) seed quality in *probit* units, and it is a measure of the potential longevity of the seed population in any storage environment (Ellis and Roberts, 1980a, b). The parameter σ depends on the rate of seed physiological deterioration: the higher the deterioration rate (e.g. due to high seed moisture content and/or temperature), the lower is σ. K_E, C_W, C_H and C_Q are species-specific constants that reflect plant species response to storage conditions.

Parameters and constants of the seed viability equation are easy to measure or even available, with K_i as an exception. Indeed, seed moisture content and temperature during storage can be recorded, and the species-constants are available on the Internet (Flynn and Turner, 2004; http://data.kew.org/sid/viability/index.html). In contrast, some difficulties arise with K_i estimation. K_i is different for each grain lot, since it depends on genotype, pre-storage environment and their interaction (Ellis and Roberts, 1981). An adequate assessment of K_i requires a controlled deterioration test to be performed on each grain lot at the laboratory (Ellis and Roberts, 1980a), which takes several days and is obviously incompatible with malting industry analysis requisites of feasibility and rapidity. This fact limits the use of the viability equation to long-term seed storage (Pritchard and Dickie, 2004), and precludes its use for post-harvest grain management at the scale of the malting industry.

It is known that the environment during seed development and maturation affects seed longevity. Such an effect was found in rice (*Oryza sativa* L.), barley, and wheat (*Triticum aestivum* L.) (Ellis et al., 1993; Kameswara Rao and Jackson, 1996; Pieta Filho and Ellis, 1991). Moreover, pre-germination and pre-harvest sprouting reduce seed potential longevity in sorghum (*Sorghum bicolor* L. Moench.; Del Fueyo et al., 2003) and wheat (Stahl and Steiner, 1998), respectively. Bason et al. (1993) found a decrease in storability of pre-germinated malting barley lots.

In this work, we sought quantitative relationships between the potential longevity (K_i) of a grain lot and its degree of pre-germination, assessed through different industrial parameters (FN, AA, and C), for several malting barley cultivars grown in Argentina. The final aim was to develop a tool to predict the viability of barley lots during storage at malthouses. This information would allow the assignment of malting priorities between lots with different pre-germination degree. Furthermore, it should lead to the designing of the storage environment conditions according to pre-germination degree and industry requirements in order to obtain a desirable grain viability decay dynamics.

2. Materials and methods

2.1. Plant material

Commercial malting barley grain samples from cultivar Quilmes Palomar and the three most important barley cultivars grown at present in Argentina (Quilmes Ayelén, Scarlett, and MP2122; SAGPyA, 2007b) were used for experiments. Quilmes Palomar variety has currently almost disappeared from the commercial seed market in Argentina. Samples came from barley crops harvested during 1998 (Quilmes Palomar cv.) and 2008 (Quilmes Ayelén, Scarlett, and MP2122 cvs.) campaigns at different locations in the south of Buenos Aires province, Argentina (between 37°28′S, 60°13′W and 38°23′S, 63°04′W). All samples were provided by Maltería Pampa SA.

In the case of barley cv. Quilmes Palomar, naturally pre-germinated grain samples were received, with a pre-germination range sufficient for developing experiments (see Table 1). However, due to excellent harvesting conditions during the 2008 campaign, only samples with very little or null pre-germination damage from the rest of the three barley cultivars were received. In this latter case, we induced the pre-germination process artificially. Each of the cultivar samples were pooled and then divided into 30 aliquots of 200 g. Pre-germination was induced by soaking these aliquots in distilled water throughout different periods (0, 2, 3, 4, 5, 6, 8, 10, 12,

Table 1
Seed lot pre-germination degree [estimated through Falling Number (FN), α-Amylase Activity (AA) and Carlsberg (C)], Initial viability (V_i), Potential longevity (K_i) and Storability (Stor. $V_{95\%}$) [days to reach 95% viability under commercial storage conditions (i.e., 12% seed moisture content and 25 °C temperature)] values for Quilmes Palomar cv. barley lots. Storability is not shown when initial viability is lower than 95%. Lots in bold indicate those for which survival curves are shown in Fig. 1.

Lot	FN (s)	AA (DU)[a]	C (%)	V_i (%)	K_i (probit)	Stor. $V_{95\%}$ (d)
1	**408**	**<0.1**	**0**	**96**	**7.32**	**154**
2	369	<0.1	0	93	6.91	62
3	365	<0.1	0	95	6.95	70
4	321	<0.1	0	96	7.21	128
5	320	<0.1	0	97	6.81	38
6	308	<0.1	0	89	6.69	12
7	203	<0.1	0	91	6.68	10
8	203	<0.1	0	83	6.29	–
9	**189**	**0.1**	**1**	**91**	**6.51**	–
10	182	0.2	2	91	6.08	–
11	118	0.2	2	100	6.23	–
12	107	0.7	4	87	6.27	–
13	78	0.9	4	79	6.08	–
14	64	1.2	7	65	6.02	–
15	63	1.4	11	85	6.48	–
16	**62**	**2.1**	**21**	**69**	**5.94**	–
17	62	1.8	18	53	5.22	–

[a] DU: dextrinizing units.

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14 h) at room temperature (25 °C). Once pre-germination treatment finished, samples were dried in an oven at 35 °C until grains reached 12–14% (fresh basis) moisture content. The half of each grain aliquot (100 g) was sent to the malthouse for FN determination.

2.2. Grain quality tests for pre-germination damage assessment

FN, AA, and C tests were performed on Quilmes Palomar grain lot samples. The FN test was performed on Quilmes Ayelén, Scarlett and MP2122 cvs. samples. Briefly, the FN method measures the time taken (in seconds) for a plunger to fall to the bottom of a precision bore glass tube filled with a dough/paste made from ground barley grain and water. Sprout damage is related to a less viscous dough/paste and thus low FN values (AACC, 2000). The Carlsberg method estimates the percentage of germinated grains in a harvested barley lot by detecting the presence of the product of the action of a germination-associated lipase enzyme, which fluoresces under UV light when staining with a sensitive compound (EBC, 1987). α-Amylase Activity is a method that estimates activity in malt of this endosperm-degrading enzyme as the dextrinization time of a standardized starch solution in the presence of excess β-amylase (EBC, 1987). All quality tests were performed by the Malting Quality Control Laboratory of Maltería Pampa SA. Three replicates of each sample lot were evaluated for these and all subsequent determinations.

2.3. Initial seed viability and moisture content

These determinations were carried out immediately upon grain lot reception (Quilmes Palomar lots) or after drying once pre-germination treatment finished (Quilmes Ayelén, Scarlett, and MP2122 lots).

Germination assays were performed for seed viability percentage determination. For each barley lot sample replicate, 50 grains were incubated in Petri dishes (90 mm diameter) with two layers of Whatman No. 5 filter paper and 6 mL of distilled water, and incubated at 10 °C in the dark. The number of germinated grains (radicle protruding >1 mm) was recorded twice a week over a 15 d period. Viability of un-germinated grains was verified through topographical tetrazolium tests (ISTA, 1999).

Seed moisture content was evaluated by the high constant temperature oven method. A 5 g grain sample of each sample lot replicate was taken and weighed (fresh weight), and immediately dried at 130 °C during 2 h for dry weight determination. Percentage of grain moisture content was calculated and expressed on a fresh weight basis. All weight determinations were done with a precision balance (Mettler Toledo AB204, Switzerland; 0.1 mg resolution).

2.4. Seed moisture content adjustment

Initial seed moisture content of each sample lot replicate was adjusted up to 15 ± 0.5% (fresh weight basis) (Pieta Filho and Ellis, 1991). This adjustment was carried out in a climatic cabinet maintained at a temperature of 10 °C and 92–99% relative humidity. The period of adjustment extended from 24 to 72 h, depending on each seed lot. After adjustment of their moisture content, seeds were stored in sealed containers at 5 °C until the accelerated ageing test was begun one month later.

2.5. Accelerated ageing test and K_i estimation

Barley grains from each sample lot replicate were stored under accelerated ageing conditions with 15 ± 0.5% (fresh basis) seed moisture content and a temperature of 40 °C (Pieta Filho and Ellis, 1991). To avoid moisture loss from seeds during the accelerated ageing period, each sample lot replicate was divided into small seed aliquots placed in individual polyethylene zipper bags (4 × 7 cm) (one bag per replicate and day of extraction). All bags of the same day of extraction were packed together in a single insulated package made with larger polyethylene zipper bags. The storage period in which seeds were maintained under these accelerated ageing conditions varied between 18 and 27 d, depending on the lots. During this period, seed samples were extracted at frequent intervals (1 or 2 d) in order to assess the seed viability percentage through germination tests carried out as described above. For each sample lot replicate, seed extractions concluded only after three consecutive germination tests yielded zero germination. Seed viability values obtained from germination tests were verified through topographical tetrazolium tests (ISTA, 1999) performed in some random samples.

Germination percentage normal values were transformed into Probit scale and plotted against accelerated ageing storage period, for each barley sample lot replicate. Then, simple linear regression analysis was applied to each relationship. The *Y*-intercept of this regression line (i.e., germination percentage Probit value prior to storage) was the potential longevity K_i for each barley lot (mean of the three replicates).

2.6. Validation of K_i -FN experimental models

The K_i -FN relationship generated under laboratory conditions was validated with an independent data set obtained under field conditions (i.e. following an agronomic management within the typical schedule in the region) during the 2008 growing season, for each one of the three modern barley cultivars. Upon reception, FN and K_i values from grain samples were determined by methods above mentioned.

2.7. Statistical analysis

Pre-germination treatment data were analyzed by ANOVA. Means between treatments were compared by LSD (significance level $\alpha = 0.05$).

Regression analysis was applied for studying relationships between K_i and pre-germination values. Simple linear regression was used for relationships with FN (all barley cultivars). Non-linear regression was applied for relationships between K_i and AA and C (Quilmes Palomar lots only). Linear regression parameter values were compared through the F test.

3. Results

3.1. Seed survival curves from Quilmes Palomar cv. barley lots with different degree of pre-germination

Seed survival curves (germination normal percentage plotted against storage time under accelerated ageing conditions) from Quilmes Palomar cv. barley lots with three contrasting pre-germination degrees assessed by FN value (low, intermediate and high; lots 1, 9, and 16, respectively: see Table 1) are shown in Fig. 1a. All survival curves followed a sigmoid pattern. Lots with low pre-germination degree (i.e., high FN; low AA or C values) retained seed viability for a longer time than lots with high pre-germination level. After 6 d of storage, germination percentage was above 80% for the former, while it was around 30% for the latter (almost all seeds were dead after only 12–14 d of storage in this case). In fact, seed lot potential longevity (K_i) and storability values were positively associated with a low pre-germination degree (Table 1; Fig. 2). Barley lots with moderate pre-germination degree exhibited an intermediate behavior in their seed viability decay (Fig. 1a).

When these same survival curves were plotted using a Probit scale, three parallel curves with the same seed viability loss rate (slope depends only on storage environment conditions; Ellis and

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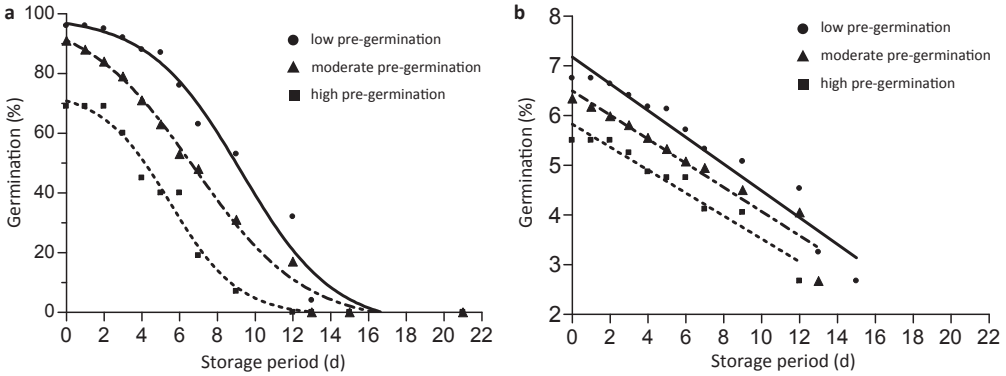

Fig. 1. Seed survival curves (germination percentage plotted against storage time under accelerated ageing conditions) for Quilmes Palomar cv. barley lots with three contrasting pre-germination degrees as determined by their Falling Number (FN) value [low (FN = 408 s; lot 1), moderate (FN = 189 s; lot 9) and high pre-germination (FN = 62 s; lot 16)]. Germination percentage was plotted on: a) Linear scale; b) Probit scale.

Roberts, 1980b) and different *y*-intercepts for each seed lot were observed (Fig. 1b). These *y*-intercepts are the K_i values for each barley grain lot (Ellis and Roberts, 1981) (Fig. 1b).

3.2. Relationships between pre-germination degree (evaluated through Falling Number, α-Amylase Activity and Carlsberg tests) and K_i, for Quilmes Palomar cv. barley lots

Potential longevity of Quilmes Palomar cv. barley lots was related to the values resulting from three tests routinely used by the malting industry to evaluate pre-germination degree of barley grains upon reception (FN, AA and C). All three tests showed significant relationships with K_i. α-Amylase Activity and Carlsberg relationships presented determination coefficients (r^2) of 0.64 and 0.63 ($p < 0.05$) respectively, with a negative exponential association with the K_i parameter (Fig. 2a,b). High values of both tests indicate high enzyme activity due to initiation of the grain germination process (i.e., increased pre-germination level of the barley lot), and then a lower K_i value (Fig. 2a,b).

Falling Number showed not only the best association with K_i ($r^2 = 0.71$, $p < 0.0001$), but also yielded a positive and linear association with this parameter (Fig. 2c). High FN values are a

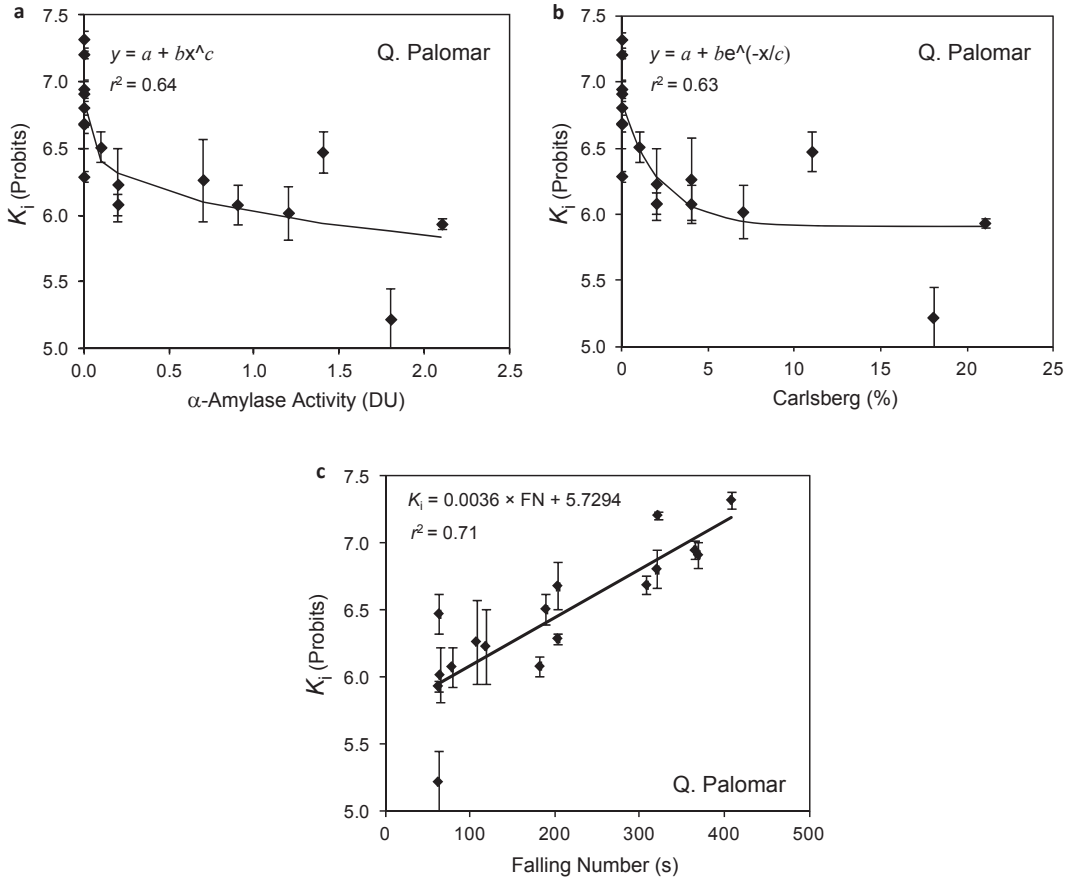

Fig. 2. Relationship between pre-germination degree estimated through α-Amylase Activity (a), Carlsberg (b), and Falling Number (c) tests and potential longevity (K_i), for Quilmes Palomar cv. barley lots. Vertical bars are mean SE when larger than the symbol. DU: dextrinixing units.

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consequence of a high viscosity and resistant dough due to a little activity of the enzyme α-amylase as a result of minor/null advancement of the germination process in the mother plant (i.e., low/null pre-germination degree of the grain lot), and therefore are related with high K_i values (Fig. 2c). Falling Number was highly ($r^2 = 0.83$, $p < 0.001$) and inversely correlated with α-Amylase Activity (data not shown), as it had been reported in several works previously (Bason et al., 1993; Skerritt and Heywood, 2000).

3.3. Pre-germination effects on lot initial viability, potential longevity and storability, for the three major barley cultivars currently grown in Argentina

Barley lots from Quilmes Ayelén, Scarlett, and MP2122 cultivars were induced to pre-germinate artificially (due to excellent harvesting conditions, only samples with little or null pre-germination damage were received). Low/moderate grain pre-germination (measured through FN method in this case) did not affect initial -prior to storage- viability significantly, but reduced potential longevity and storability ($p < 0.05$), of malting barley lots from these three major cultivars grown at present in Argentina (Table 2). Very low FN values indicate serious damage to the barley grain and, under these conditions, it is feasible that pre-harvest sprouting occurs together with pre-germination in the field, lowering the initial viability of the seed lots (Table 2).

3.4. Relationships between pre-germination estimated through FN and K_i, for the three major barley cultivars currently grown in Argentina

Potential longevity from lots of three major barley cultivars currently grown in Argentina (Quilmes Ayelén, Scarlett, and MP2122) was related to their FN values, obtaining positive and significant ($p < 0.01$) relationships for all varieties (Fig. 3, Table 3). Since linear regression parameter values were very similar among barley cultivars, the K_i-FN relationship could be modeled by one single relationship, including data of all three varieties (Table 3). Comparison of slopes b and y-intercepts a of each cultivar relationship against those of the single K_i-FN relationship did not show significant differences for any of these parameters, for none of the analysed barley cultivars (Table 3).

Slope values of the K_i -FN relationships obtained for these three modern barley cultivars were significantly higher ($p < 0.01$) than that found for Q. Palomar cv. (Fig. 3). This fact would suggest that the relationship between K_i and FN is modulated by the barley genotype. However, it could be argued that confounding effects exist in this comparison, since grain pre-germination was generated in a different manner between Q. Palomar and the others genotype samples (naturally in the field vs. artificially in laboratory, respectively). Although with data from high quality lots only, when an independent field data set was plotted, points arranged around the same K_i -FN relationship obtained under laboratory conditions, for each modern barley cultivar (Fig. 3).

4. Discussion

Barley grain germination is one of the first steps in the malting and brewing process. A rapid and uniform germination is required at this stage to activate enzyme machinery responsible for degrading starch into soluble sugars fermentable by yeasts (Savin et al., 2004). Therefore, for malting, a viable and non-dormant barley grain lot is required. Hence, seed viability is crucial for the malting industry (which commonly establishes a minimum germination capacity value around 95%, ideally 98%). Further, to malt grain immediately after harvest, barley genotypes are bred for rapid dormancy release after physiological maturity. However, if wet/rainy weather takes place close to crop harvest, pre-harvest sprouting/pre-germination damage can occur. Although pre-germinated lots can be used for malting, on the basis of the analogy of pre-germination with the priming process (Alvarado and Bradford, 1988; Moradi and Younesi, 2009), it could be hypothesized that their potential longevity is negatively affected. In this context, technological tools for improving management of pre-germinated barley lots during malthouse storage could reduce grain deterioration and increase quality and profitability of malting and brewing processes overall.

Pre-germination of malting barley grains in the field did not have short-term effects on seed lot viability, for the three major malting barley cultivars grown at present in Argentina (Quilmes Ayelén, Scarlett, and MP2122). In fact, initial viability (V_i) (i.e., at beginning of storage) was not significantly different between lots with different pre-germination degree, at least under low/moderate pre-germination (Table 2). In contrast, pre-germination had medium/long-term adverse consequences on seed viability, since lot potential longevity (K_i) and storability were reduced (Table 2). Significant relationships between K_i and values resulting from pre-germination tests routinely performed by malthouses (Falling Number, α-Amylase Activity and Carlsberg) were found for Q. Palomar old barley cultivar lots (Fig. 2). Falling Number was the parameter that gave the best (i.e., highest r^2) and simplest (i.e., linear association) explanation of K_i variability for these lots and, thus, it was chosen for estimating K_i in the case of the three modern barley cultivars, obtaining significant linear associations for all of them (Fig. 3). These modern cultivars which represent more than

Table 2
Pre-germination degree estimated through Falling Number (FN), Initial viability (V_i), Potential longevity (K_i) and Storability (Stor. $V_{95\%}$) [days to reach 95% viability under commercial storage conditions (i.e., 12% seed moisture content and 25 °C temperature)] values of malting barley lots subjected to different soaking periods, for the three major cultivars grown at present in Argentina. Storability is not shown when initial viability is lower than 95%. Different characters means significant differences between lots (LSD Fisher < 0.05).

Soaking period (h)	Q. Ayelén				Scarlett				MP2122			
	FN (s)	V_i (%)	K_i (probit)	Stor. $V_{95\%}$ (d)	FN (s)	V_i (%)	K_i (probit)	Stor. $V_{95\%}$ (d)	FN (s)	V_i (%)	K_i (probit)	Stor. $V_{95\%}$ (d)
0	396 a	100 a	8.92 a	513 a	321 a	96 a	7.89 a	282 a	358 a	97 ab	8.28 a	369 a
2	391 a	97 a	8.35 b	384 b	312 a	96 a	7.67 a	233 a	344 a	99 ab	8.19 a	350 a
3	381 a	100 a	8.21 b	354 b	309 a	98 a	7.98 a	301 a	336 ab	96 ab	8.46 a	411 a
4	372 a	100 a	8.85 a	498 a	307 a	98 a	7.84 a	270 a	327 abc	95 b	7.25 c	138 c
5	360 a	99 a	8.48 ab	415 ab	304 a	98 a	7.39 a	168 a	322 abc	98 ab	7.45 bc	183 bc
6	356 a	100 a	8.48 ab	414 ab	287 a	99 a	7.64 a	226 a	287 abcd	99 ab	8.31 a	377 a
8	304 b	99 a	7.32 d	153 d	183 b	96 a	7.47 a	188 a	267 bcd	97 ab	7.18 c	121 c
10	293 b	99 a	8.11 bc	330 bc	95 c	81 c	5.33 c	–	254 cd	98 ab	6.85 c	47 c
12	288 b	99 a	7.70 cd	239 cd	74 c	92 ab	6.43 b	–	232 d	100 a	7.98 ab	303 ab
14	62 c	84 b	5.59 e	–	74 c	84 bc	6.17 bc	–	62 e	85 c	5.41 d	–

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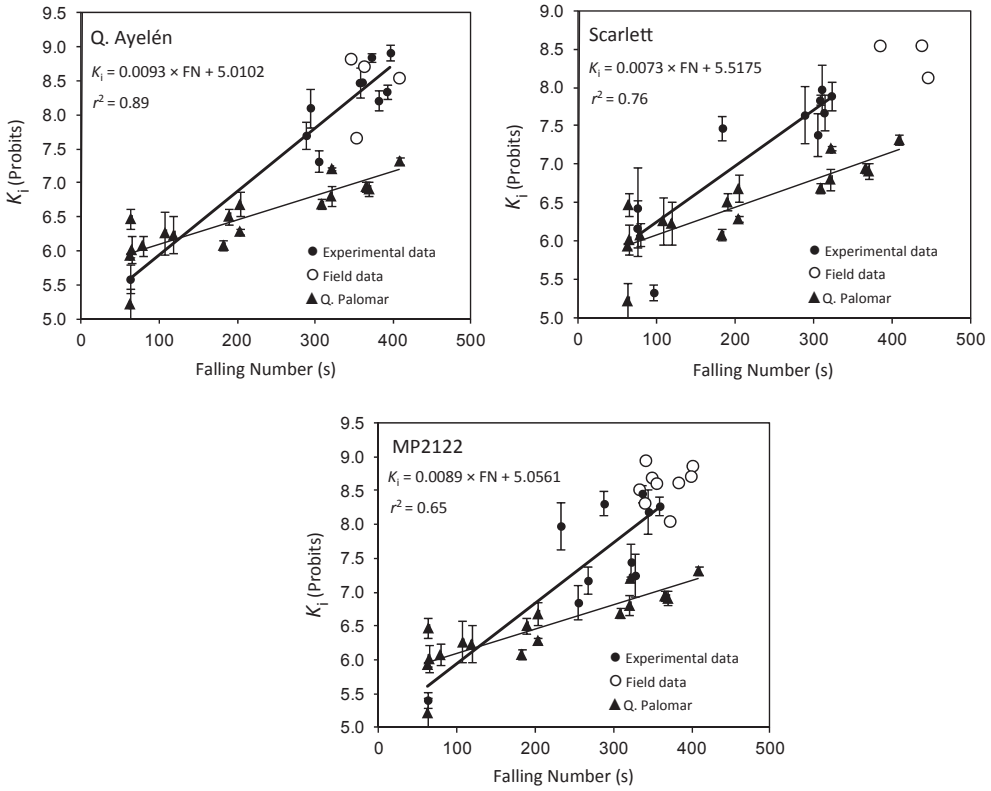

Fig. 3. Relationship between seed potential longevity (K_i) and Falling Number (FN) values of barley grain lots, for three different modern cultivars. Experimental samples were pre-germinated under laboratory conditions. Open circles indicate an independent field data set used for validation of the K_i-FN experimental model (data points were not included in the linear regression adjustment). K_i-FN relationship for Q. Palomar cv. is shown ($K_i = 0.0036 \times FN + 5.7294$; $r^2 = 0.71$). Vertical bars are mean SE when larger than the symbol.

95% of the sown area in Argentina, presented a very similar slope value in the response of K_i to FN (Table 3); however, this value was significantly higher than that observed in the case of the old barley cv. Q. Palomar (Fig. 3). This result suggests that the K_i -FN relationship might be modulated by the barley genotype.

The link between FN and K_i arises from the fact that FN is an indirect measurement of the α-Amylase Activity in harvested grains (Bason et al., 1993; Skerritt and Heywood, 2000) and, hence, of the extent to which the germination process has advanced in the mother plant. Falling Number is inversely correlated with AA since, as germination advances, synthesis and activity of enzyme α-amylase are increased, hydrolysis of endosperm starch increases and viscosity and resistance of dough are diminished, reducing the time taken by the plunger to fall through the paste, yielding lower FN values.

Table 3
Parameters (slope and *y*-intercept) and adjusted determination coefficient (r^2) of linear regression between Potential longevity (K_i) and Falling Number (FN), for each modern barley cultivar. Parameter comparison between each cultivar regression line and a single K_i-FN relationship including data of all three varieties. MSE stands for mean square error.

Cultivar	*n*	adjusted r^2	Slope	*y*-intercept	MSE	Comparison (*p* value)	
						Slopes	*y*-intercepts
Q. Ayelén	10	0.8885	0.0093	5.0102	0.1062	0.5744	0.8072
Scarlett	10	0.7646	0.0073	5.5175	0.1872	0.4740	0.9662
MP2122	10	0.6461	0.0089	5.0561	0.3088	0.8211	0.6894
Single K_i-FN relationship	30	0.8041	0.0084	5.2458	0.1820	–	–

Few studies explain the effect of advancement of germination on potential longevity and storability of grain lots. As discussed above, seed priming consists in controlled hydration of seeds upon a certain value, in order to induce first germination events but preventing radicle protrusion. Then, seeds are dried at a properly mild temperature, and stored until use. Similar events occur during pre-germination phenomena. The aim of priming is to increase percentage, uniformity and rate of germination of a seed lot, and its use is common in vegetable crop species. However, like pre-germination, priming reduces potential longevity of treated seeds. Several works confirm this effect in tomato (*Lycopersicon esculentum* Mill.) (Alvarado and Bradford, 1988); lettuce (*Lactuca sativa* L.) (Tarquis and Bradford, 1992); wheat (Nath et al., 1991); and grain sorghum (Moradi and Younesi, 2009). Ageing, which occurs inexorably throughout storage, leads to cumulative physiological damages of diverse kind in the seeds. For example, genetic damage, mitochondrial damage, modifications in structure and stability of cell membranes, and alterations in the functionality of repair enzymes (McDonald, 1999) can be metioned. Priming-treated seeds would present a reduced capacity to repair these damages (i.e., lower antioxidant and DNA repair enzymes activity, among others). Similar mechanisms may be operating in pre-germinated barley lots, diminishing potential longevity of grains.

At the best of our knowledge, studies relating industrial quality parameters routinely measured by malthouses (e.g., Falling Number) with the potential longevity of barley lots (a concept derived from seed science) did not exist until the present study. Izydorczyk (2004) related a malting industry quality parameter frequently used for determination of barley grain pre-germination degree (Rapid Visco Analizer, RVA) with long-term storability of malting barley lots from several varieties widely used in Canada. RVA is a

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dough viscosity test, and its values were positively related to barley grain storability. An important limitation of this study is, however, that, as storability prediction was not based on Ellis's Viability Equation solid framework (seed potential longevity was not estimated), the numerous possibilities and advantages of this equation cannot be used. Furthermore, prediction of lot storability was limited to only three pre-defined, non-continuous, ranges of storage environment conditions and to four ranges of pre-germination damage (i.e., prediction is not available for a continuous value range of these variables). Moreover, this work did not take into account the grain moisture content to generate the prediction of storability. These facts convert this study into a simple guide for advising barley growers and handlers about safe grain storage time, but preclude its professional use in the malting industry. Furthermore, the relationships established in our study, which have been demonstrated to be highly consistent across cultivars, were generated from both laboratory- and field-based studies and, most important, could be validated with independent data obtained from commercial crops grown in the barley production area.

5. Conclusions

Results obtained from our study establish a quantitative K_i -FN relationship for the major malting barley cultivars currently grown in Argentina. Therefore, the rapid and easily measured FN parameter can be used to estimate the more complicated K_i, for each barley lot. This fact opens the door to use Ellis's Viability Equation for industrial purposes (i.e., post-harvest management of barley grains at seed and malting industry). In this way, and from easy-to-gather data (i.e., lot FN, grain moisture content and storage temperature), the evolution of seed viability of a barley lot throughout its storage under virtually any commercial environmental conditions (Eq. (1)) might be predicted. This fact should allow assignment of malting priorities among different lots and designing of storage conditions (i.e., grain moisture and temperature), depending on lot pre-germination damage degree and malting industry requirements, in order to obtain a desirable viability loss rate of the barley lot. Barley post-harvest management, as a successive step of quality maintenance after grain production, could be improved.

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