Modelling the effects of temperature, water activity and storage atmosphere on the viability of stored maize and paddy

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Abstract

Controlled atmosphere storage offers a pesticide residue-free alternative to conventional storage and protection techniques. Grain in commercial sealed storage is not readily accessible for routine quality evaluation, and thus methods of predicting the safe storage period from the outset of storage are desirable. Samples of white maize (cv. Manning White) and paddy (cvs. Pelde and Calrose) were stored under a range of controlled temperatures, water activities and storage atmospheres with 0.2 to 100% oxygen or 7.5 to 60% carbon dioxide concentrations (dry basis). Grain viability was monitored during storage, and half-lives for each sample were estimated and fitted to a range of storage viability models. The data were well described by both a kinetic model and one using both linear and quadratic temperature terms, but not by models employing the estimated probit of viability at the start of storage. The variation in viability was also better described by a term for grain water activity than for grain moisture content. Temperature and water activity effects were dominant, although slight but significant effects were observed for oxygen and carbon dioxide in some cases.

Introduction

There has been an increasing trend of consumer resistance to pesticide-treated cereals over recent years. Of the alternative technologies available for insect control, controlled atmosphere (CA) storage has now found limited commercial acceptance in several countries.

CA storage involves alteration and maintenance of the gas composition surrounding the grain so that all stages of insect life are killed. This is typically achieved by holding carbon dioxide levels above 35% or oxygen levels below 1% for 2–4 weeks (Banks 1981). The cost of sealing the storages is offset by obviating the need for repeated disinfestation (the seal providing a barrier against reinfestation) and by providing high value residue-free grain.

During storage, grain quality changes at a rate dependent largely on the storage conditions (Gras and Bason 1990). Monitoring these changes is not practical in sealed storages. Therefore predictive techniques are needed which will provide grain storage managers with the necessary information for preventing downgrading of the product during storage. Loss of viability is a sensitive measure of other chemical changes in grain during storage (Banks 1981), and is of immediate importance for grain stored as seed.

Loss of grain quality during storage can be quantified for predictive purposes by constructing mathematical models and fitting experimental data to these by normal regression techniques. These models typically incorporate terms for grain temperature, moisture or water activity, type and initial quality of the grain, storage period and sometimes gaseous atmosphere.

Ellis and Roberts (1980a,b) developed a grain viability model in the form

$$V = K_i - P / 10^{(-\alpha - \nu \log M - \beta T - \gamma T^2)} \qquad (1)$$

where V is probit viability (probit 50% = 0), P is storage period (days), M is moisture content (% as is), T is temperature (°C) and α, ν, β and γ are constants. (Note that the use of the same constant terms in this and subsequent equations should not be taken to necessarily imply equality in all of their values, but rather only to indicate qualitative correspondences in the models.) K_i, the 'seed lot dependent constant' (probit viability at time zero), will usually vary for samples with different histories before storage (harvest dates, locations or pre-storage treatments). Rather than indicating a single value which can be estimated by fitting Equation (1), K_i values must be pre-determined for each of the i seed lots from which data have been obtained, before fitting this model. Ellis and Roberts suggested estimation of each K_i value by probit fitting the declining viability data from the stored sample.

Equation (1) built upon earlier work by Roberts (1960, 1961) where storage life of rice and other seed types was modelled. Dickie et al. (1990) subsequently applied this equation to a diverse range of plant species (not including rice or maize) and suggested 'universal' values of 0.0329/°C for β and 0.000478/°C for γ.

This equation covers the total viability curve, with the storage conditions affecting the slope of the probit viability curve. Alternatively, a single point of the curve has also been used as an index of loss in viability (Roberts et al. 1960 1961; Bason et al. 1987). Commonly this value has been the inverse of the half-life (time to 50% viability), although time to 95% viability has been used in barley where this level relates directly to the minimum acceptable value for malting grade (Bason et al. 1993). For the purposes of this study and to retain consistency with earlier work, Equation (1) can be made specific for 50% viability, and terms for oxygen and carbon dioxide added, to become

$$\log(1/t_{50}) = -\log(K_i) + \alpha + \nu \log M + \beta T + \gamma T^2 + \tau \log[O_2] + \mu[CO_2] \qquad (2)$$

where t_{50}, the time to 50% viability, replaces P, $[O_2]$ and $[CO_2]$ are in mol/m^3, τ and μ are constants, and zero, the probit of 50%, is substituted for V. Note that the linear form of the model is preferable not only because it lends itself to multiple linear regression analysis, but also because the error structure is normal for viability data in this space (Bason et al. 1993). This does necessitate the step of back-transforming the t_{50} estimate when using these models.

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Gras, Banks, Konik and Bason (unpublished data) modified Equation (1) for application to barley viability by replacing the moisture term with one for water activity (a_w) which better describes their data, and adding terms for oxygen and carbon dioxide concentration, to give

$$\log(1/t_{95}) = -\log(K_i-1.6449) + \alpha + \beta T + \gamma T^2 + \delta\log(a_w) + \tau\log[O_2] + \mu[CO_2] \tag{3}$$

where t_{95}, the time for viability to fall to 95%, was used since it defines the minimum acceptable value for malting grade barley, necessitating the constant 1.6449, the probit of 95%, in the equation. The effects of temperature and water activity were dominant, with slight but significant effects of oxygen and carbon dioxide concentration demonstrated. Assuming linearity of the probit viability loss, t_{50} can be substituted for t_{95}, with the change absorbed into the model constants. Such linearity has been reported before (Ellis and Roberts 1980a,b) and was observed consistently in this study. Equation (3) made specific for 50% viability is

$$\log(1/t_{50}) = -\log(K_i) + \alpha + \beta T + \gamma T^2 + \delta\log(a_w) + \tau\log[O_2] + \mu[CO_2] \tag{4}$$

Bason et al. (1993) demonstrated that the use of the K_i term as above poorly described the effects of differing initial quality on subsequent longevity for malting barley which had varying levels of sprout damage. Even in sound grain, K_i is tedious to estimate, since it requires at least one germination test and preferably an accelerated storage procedure followed by several germination tests. Furthermore, errors in the estimate of K_i can be quite large. Therefore, random error was assumed for K_i and the term was removed from subsequent equations. Equation (4), assuming random error distribution of K_i and absorbing it into α, becomes

$$\log(1/t_{50}) = \alpha + \beta T + \gamma T^2 + \delta\log(a_w) + \tau\log[O_2] + \mu[CO_2] \tag{5}$$

An alternative equation was developed by Bason et al. (1993) in the form

$$\log(1/t_{95}) = \alpha + \beta T + \gamma T^2 + \delta\log(a_w) + \psi DI \tag{6}$$

where ψ is a constant and *DI*, the damage index, was measured alternatively as the Falling Number, Stirring Number or probit waterbath score of the sample (Bason et al. 1993). This model, with terms for oxygen and carbon dioxide added, and made specific for 50% viability, is

$$\log(1/t_{50}) = \alpha + \beta T + \gamma T^2 + \delta\log(a_w) + \psi DI + \tau\log[O_2] + \mu[CO_2] \tag{7}$$

where the intercept term α takes into account the effect of altering the time variable.

In earlier studies (Bason et al. 1986 1987), the viability of rice and maize were modelled using a kinetic model, which in logarithmic form was

$$\log(1/t_{50}) = \alpha + \beta/T + \delta\log(a_w) + \tau\log[O_2] \tag{8}$$

where *T* is absolute temperature (*K*). A similar equation was shown to provide a good description of yellowing in milled rice (Gras et al. 1989) and paddy (Bason et al. 1990) where the rate of colour development (as change in Minolta b* values per day) is substituted for $1/t_{50}$. The colour change was also highly correlated with sensory evaluation of the rice (Gras et al. 1990).

The goal of the work reported here was to compare and assess the ability of the above models to quantify loss of viability in maize and paddy. This was done with a view to developing storage equations in future work that could be used to help avoid loss of quality in grain during both CA and conventional storage.

Materials and Methods

Samples

Bulk samples of white dent maize cv. Manning White from the 1985, 1986 and 1987 harvests were obtained from Morpeth, New South Wales (NSW), Australia. Bulk paddy rice samples of cvs. Pelde (1985 and 1986 harvests, long grain) and Calrose (1984 and 1986 harvests, medium grain) were obtained from Leeton, NSW. All samples were free from rain damage.

Storage

Before storage, samples were conditioned to moisture contents determined in previous experiments (Bason and Gras 1988) to be in equilibrium with the required temperatures and a_w used in the storage trials (Table 1). Conditioned samples were held sealed for several days to allow moisture equilibration, then subdivided into 900 g lots and exposed in duplicate under a selected range of temperatures (30, 35, 47 and 60 ± 0.5°C), water activities (0.40, 0.60, 0.80 ± 0.02) and eight types of humidified and continually flushing atmospheres (Table 1). Four of the atmospheres consisted of 0.2, 2.0, 21 and 100% oxygen, balance nitrogen (dry basis), with the other four containing 7.5, 15, 30 and 60% carbon dioxide, each with 8.4% oxygen and balance nitrogen (dry basis). Two sets of storage exposures were conducted using the 60% carbon dioxide atmosphere, whereas only one was conducted for each of the other types of atmospheres. Techniques for mixing and humidifying the atmospheres, for temperature control and for grain exposure have been described previously (Gras et al. 1989).

Six to 12 subsamples (40 g for rice, 100 g for maize) were removed from each 900 g sample at regular intervals and stored at 4°C until tested for germination. Maximum exposure periods ranged from 3 to 364 days, depending on exposure conditions (Table 1). For each subsample, 150 kernels of maize and 200 of rice were assessed for viability using techniques described previously (Bason et al. 1986). Percent viability was scored after 7 days germination.

Analyses

Time for viability to decline to 50% (t_{50}, in days) was estimated by probit analysis using the routine of Moore et al. (1983) adapted to run on a PC. Estimates of K_i were similarly made for each conditioned lot of grain. Long-dead samples and those exhibiting dormancy were excluded from the analysis.

Grain lifespan data was fitted by multiple linear regression to the various viability models using Genstat (1989). Models were compared using the values of the root mean square of residuals (RMS) and adjusted r^2 (Chatterjee and Price 1991) which facilitated comparison between models with different numbers of fitted terms. Effect of cultivar was assessed by F-tests using the analysis of variance results from regressions fitting common and separate terms for the various coefficients, except for the intercept, T, T^2 and M (where present) terms of Equations (1)–(7), since these terms have previously been reported to be independent of cultivar (Ellis and Roberts 1980a,b).

Results and Discussion

Comparison of models

The paddy and maize germination data were fitted separately to Equations (2), (4), (5), (7) and (8). The RMS and adjusted r^2 values for the paddy fits, including and excluding cultivar effects, showed the best fits using Equations (5), (7) and (8), followed by (4) and (2) (Table 2). Fits of the maize data gave the best fits for Equations (4), (5), (7) and (8), followed by (2) (Table 3).

Note that the methods of fitting were designed to allow comparison of the models, retaining the assumption of cultivar-independency of the terms of Equation (1). Further work would be required to optimise the fit of any one of the models, checking for cultivar-dependency and significance of each of the terms.

In all cases, significant and dominant effects on longevity were observed for temperature and moisture or water activity (depending on which one was fitted). Slight but significant effects were observed for oxygen concentration in most cases, for carbon dioxide concentration for most fits of maize data, and of the K_i term when used as the damage index in Equation (7). For example, Equation (5) indicates that the t_{50} value of rice cv. Pelde stored in air at 25°C and 13% M [$a_w = 0.56$ from desorption isotherm, (Bason and Gras 1988)] would be halved if stored around 4°C warmer or 1.6% wetter. By contrast, reducing the oxygen concentration to 1% would increase the t_{50} value by only 21%, and elevating the CO_2 to 60%, with concomitant reduction in oxygen to 8.4%, would reduce the lifespan by only about 8%.

The coefficient K_i, when used as the seed-lot dependent constant as in Equations (2) and (4), failed to improve the fit of the data obtained in this study, as evidenced by comparing Equations (4) with (5) for both rice and maize. This was most likely due to all grain being of high quality without rain damage, and the inherent errors in estimating K_i despite the rigours taken to do so accurately. Significant cultivar effects were also observed even where K_i was used (Equations (2) and (4), Table 4). The K_i constant used as in Equations (2) and (4) has previously been reported to provide a poor estimate of the potential longevity of barley where rain damage had occurred (Bason et al. 1993). In view of these observations, and the amount of work required to generate the K_i value where simpler alternatives are possible (Bason et al. 1993), there seems to be little value in its continued use.

'Universal' temperature coefficients

Dickie et al. (1990) proposed 'universal' values for the coefficients of T and T^2 as 0.0329 and 0.000478, respectively. Equations (2), (4), (5) and (7), which incorporate linear and quadratic temperature terms, were fitted with these fixed values as well as estimating them by normal least squares methods. In all cases the use of the 'universal' temperature coefficients of Dickie et al. (1990) substantially reduced the fit, that is, increased the RMS. Our data thus does not support the concept of there being common coefficients for all orthodox (low moisture seed) plant species. We do however note that the work of Dickie et al. (1990) was based on germination percentage assessed when all grains that could showed signs of viability, whereas our data are based on a 7 day assessment, in line with normal seed testing practice for these species.

Table 1. Exposure conditions used for experimental storage of paddy rice cvs. Pelde and Calrose, and maize cv. Manning White[a,b]

Cultivar	Storage temperature (°C)	Water activity	Maximum storage period (days)	Moisture content (% as is)[c]
Pelde	30	0.60	182	2.6, 12.4
	35	0.60	248	12.0, 12.0
	35	0.80	105	14.9, 15.0
	47	0.40	182	9.2, 8.7
	47	0.60	35	11.5, 11.5
	47	0.80	11	15.0, 14.6
	60	0.40	42	8.4, 8.4
	60	0.60	7	9.3, 10.2
Calrose	30	0.60	182	12.8, 12.4
	35	0.60	63	12.3, 12.3
	47	0.40	175	9.0, 9.0
	47	0.60	28	12.0, 11.9
	47	0.80	28	14.7, 14.8
	60	0.60	6	9.7, 9.6
Manning White	35	0.60	294	12.6, 12.6
	35	0.80	105	15.8, 15.8
	47	0.40	315	9.0. 8.8
	47	0.60	70	11.1, 11.6
	47	0.80	21	16.2, 16.0
	60	0.60	10	10.4, 10.5

[a] Samples were continuously flushed with gas humidified to the given water activities. Eight types of gas mixtures were used (one replicated) at each combination of temperature and water activity, being 0.2, 2.0, 21 and 100% oxygen, balance nitrogen, and 7.5, 15, 30 and 60% carbon dioxide, with 8.4% oxygen and balance nitrogen (all compositions dry basis).

[b] Viability did not decrease to 50% or below during storage in some cases

[c] The two moistures are for the oxygen and carbon dioxide gas sets respectively.

Table 2. Regression results from fitting half–life data from two cultivars of paddy rice to various lifespan models[a]

Equation and fit type[b]	Free T fit		Fixed T fit	
	RMS[c]	adj. r^2	RMS[c]	adj. r^2
(2) Common	0.229	0.843	0.249	0.780
Cultivar-dependent	0.222	0.852	0.242	0.792
(4) Common	0.209	0.871	0.306	0.671
Cultivar-dependent	0.184	0.898	0.277	0.726
(5) Common	0.204	0.877	0.296	0.668
Cultivar-dependent	0.175	0.909	0.262	0.736
(7) Common	0.202	0.880	0.296	0.666
Cultivar-dependent	0.173	0.909	0.262	0.732
(8) Common	0.205	0.877	-	-
Cultivar-dependent	0.174	0.909	-	-

[a] Fixed fits used pre-defined values for the temperature coefficients of 0.0329 °C^{-1} for T and 0.000478 °C^{-2} for T^2 from Dickie et al. (1990), free fits derived temperature coefficients by normal least squares methodology.
[b] Equations are given in the text.
[c] RMS is root mean square of residuals from the regressions, in log10 days. Adjusted r^2 values were used to facilitate comparison between models.

Table 3. Regression results from fitting half-life data of maize cv. Manning White to various lifespan models[a]

Equation and fit type[b]	Free T fit		Fixed T fit	
	RMS[c]	adj. r^2	RMS[c]	adj. r^2
(2) Common	0.186	0.924	0.195	0.886
(4) Common	0.117	0.970	0.153	0.929
(5) Common	0.092	0.978	0.153	0.916
(7) Common	0.090	0.979	0.146	0.923
(8) Common	0.105	0.972	-	-

[a] Fixed fits used pre-defined values for the temperature coefficients of 0.0329 for T and 0.000478 for T^2 from Dickie et al. (1990), free fits derived temperature coefficients by normal least squares methodology.
[b] Equations are given in the text.
[c] RMS is root mean square of residuals from the regressions, in log10 units. Adjusted r^2 values were used to facilitate comparison between models.

Table 4. Effect of cultivar on the fits of the various lifespan models to rice viability data, using free fits of the temperature terms[a]

Equation	RSS[b]		F-value[b] (d.f.)	P-value[b]
	common	cv.-dep.		
(2)	12.85	11.92	9.44 (2,242)	< 0.001
(4)	10.62	8.14	24.50 (3,241)	< 0.001
(5)	10.13	7.37	30.04 (3,241)	< 0.001
(7)	9.88	7.17	22.61 (4,239)	< 0.001
(8)	10.29	7.36	24.10 (4,242)	< 0.001

[a] Equations (2), (4), (5) and (7) were fitted without cultivar-dependency for the intercept, temperature and moisture content terms where used (see text).
[b] RSS is residual sum of squares, equations variously fitted with common or cultivar-dependent (cv.-dep.) terms, F-value is the variance ratio and P-value is probability of the observed effect occurring by random chance, under the mill hypothesis.

Effect of cultivar in rice

Effect of cultivar was also assessed for the two rice varieties, by fitting separate estimates of coefficients for each cultivar as well as common estimates, and comparing the fits. Significant effects of cultivar were observed in rice for all fitted models (Table 4). This was despite the use of K_i as the seed-lot dependent constant in Equations (2) and (4), which has been reported to account for all of the sample (and thus cultivar) effects, and also despite use of common coefficients only for the intercept, temperature and moisture terms of Equations (2), (4), (5) and (7). Further work is required to define the actual terms in the models that exhibit significant cultivar dependency.

Effects of temperature, moisture, atmosphere and damage index

Temperature and moisture effects dominate in the various models, confirming their well known effects on retention of grain quality in storage. The results herein indicate no advantage of using either the linear plus quadratic term, as in Equations (1) to (7), or the inverse of absolute temperature, as in Equation (8). Over the experimental temperature range, the quadratic term was generally not significant (see Table 5). However, other reports, including work using wider temperature ranges (Ellis and Roberts 1980a,b; Gras et al. unpublished data), have shown T plus T^2 to be superior to $1/T$, and that T^2

contributes significantly. Therefore it would appear that the temperature terms as used in models (1) to (7) have a wider applicability than the quasi-kinetic approach of Equation (8).

Moisture effects have previously been shown to be better modelled using water activity rather than moisture content for barley (Gras et al. unpublished data). The same result is evident with these data for both rice and maize. The free fits from Equation (4) were better than those of Equation (2), where the only difference was the substitution of a term for water activity in place of one for moisture content (Tables 2 and 3). Water activity can be calculated from the temperature and moisture of the grain using various published moisture sorption isotherms or models (Iglesias and Chirife 1982; Bason and Gras 1988). It is also interesting to note the higher sensitivity of cv. Pelde to differing water activities as compared with Calrose (Table 5), implying a greater tolerance in some varieties to storage at high moistures.

The contribution of the atmospheric composition to grain longevity was relatively minor. For Equations (5) and (7), lowered oxygen concentrations provided a slight beneficial effect except in Calrose where the effect was not significant. This preserving effect on grain quality alone would be insufficient to justify its use, since similar results could be obtained by relatively slight cooling or drying of the grain. However, it does indicate that grain quality would not be compromised under low oxygen storage. One caution here is that there was some anecdotal evidence that very low levels of oxygen (0.2%) were harmful for maize at higher temperatures, presumably because seed respiration requirements were not fulfilled. However, such conditions would not be encountered under normal CA storage of grain where temperatures are generally below 30°C and the oxygen level is around 1%.

No significant effect was observed for carbon dioxide in this study, indicating its suitability as a CA gas. Available reports indicate either no effect or a very small effect of this gas (Banks 1981; Doran and Briggs 1993).

The K_i term, when used as a damage index, exhibited a small but significant effect in all cases except for Pelde. The degree of contribution of this term depended on the range of quality of grain, which for this study was narrow, the grain being sound. More convenient alternatives to K_i as the damage index term in Equation (7) are available, as discussed below.

Application

The best fits of the data were, for both rice and maize, Equations (5), (7) and (8), with Equation (4) equally acceptable for rice. On the basis of these results, any one of these equations could be further developed for predicting grain viability. Previous work on barley (Gras et al. unpublished data) has shown a better fit using the linear and quadratic temperature terms, as in Equations (4), (5) and (7), rather than the inverse of absolute temperature as in Equation (8). There would also seem to be little value in calculating K_i where alternatives exist.

This leaves Equations (5) and (7) as being more generally useful than the others. Note that non-significant terms, particularly for the quadratic temperature term and for carbon dioxide, have been retained for consistency with previously published equations and to allow comparisons between the models. These non-significant terms could have been removed in this study, but this would result in models of less general applicability, as shown in other work.

Use of Equation (5) would be restricted to sound grain only. Equation (7), by incorporating the damage index term, potentially can be used for both sound and damaged grain, although this has only been investigated fully for damaged malting barley. To date, alternatives to K_i that have been used as the

Table 5. Coefficients and standard errors from regressions of viability data from two cultivars of paddy rice and one of maize to Equations (5) and (7)[a,b]

Grain	Equation	Coefficient[c] for the fit of Int.	T	T^2	$\log(a_w)$	$\log[O_2]$	$[CO_2]$	K_i / DI[d]
Rice								
Pelde	(5)	–2.833	0.0483	0.000083	4.050	0.0631	0.0026	–
(s.e.)	(0.233)	(0.0105)	(0.000116)	(0.126)	(0.0224)	(0.0015)	–	
(7)	–2.536	0.0373	0.000198	4.202	0.0563	0.0019	0.007	
(s.e.)	(0.284)	(0.0117)	(0.000127)	(0.151)	(0.0224)	(0.0015)	(0.244)	
Calrose	(5)	–2.833	0.0483	0.000083	3.104	0.0361	0.0009	–
(s.e.)	(0.233)	(0.0105)	(0.000116)	(0.139)	(0.0242)	(0.0017)	–	
(7)	–2.536	0.0373	0.000198	3.038	0.0440	0.0015	–0.273	
(s.e.)	(0.284)	(0.0117)	(0.000127)	(0.174)	(0.0241)	(0.0017)	(0.130)	
Common	(5)	–2.849	0.0514	0.000029	3.670	0.0495	0.0019	–
(s.e.)	(0.272)	(0.0122)	(0.000134)	(0.138)	(0.0193)	(0.0013)	–	
(7)	–2.392	0.0363	0.000190	3.731	0.0496	0.0018	–0.368	
(s.e.)	(0.326)	(0.0135)	(0.000148)	(0.138)	(0.0191)	(0.0013)	(0.147)	
Maize								
Manning	(5)	–3.030	0.0468	0.000178	5.094	0.0417	0.0043	–
White (s.e.)	(0.256)	(0.0114)	(0.000121)	(0.101)	(0.0137)	(0.0009)	–	
(7)	–3.056	0.0519	0.000131	5.225	0.0379	0.0040	–0.209	
(s.e.)	(0.251)	(0.0114)	(0.000121)	(0.116)	(0.0136)	(0.0009)	(0.097)	

[a] Equations (5) and (7) are given in the text

[b] s.e. is standard error of the coefficient estimated, Int. is intercept

[c] Common coefficients were fitted to the intercept and temperature terms for both rice cultivars, to allow comparison of these equations with Equations (1) to (4) in assessing the effects of the other fitted terms.

[d] Grain soundness was estimated using K_i in Equation (5) and *DI* in Equation (7).

damage index in Equation (7) are the Stirring Number (SN), Falling Number (FN), log amylase activity and probit 'waterbath' score, a simple form of accelerated storage (Bason et al. 1993). Both SN and FN are readily determined by rapid and simple procedures, with coefficients of variation below those to be expected from determining K_i.

The coefficients for Equations (5) and (7), and their standard errors, are given in Table 5. Since cultivar effects were observed, new values of at least one of the terms would need to be calculated where different varieties are used. Further work is required to establish which terms exhibit cultivar-dependency. Note also that the models strictly apply only over the range of moistures (30-60°C) and water activities (0.4–0.8, equivalent to about 9–16% moisture) employed, although small extrapolations such as in Figure 1 are probably reasonable given that this form of temperature fitting has proved accurate at these lower temperatures in other studies (Ellis and Roberts 1980b).

The RMS error terms of equations (5) and (7) imply an average error in lifespan estimates of about 25% for maize and 50% for rice in this study. Note that the errors are proportional to the estimates of lifespan when back-transformed into days. Rearranging the models allows estimates of safe storage conditions for a given storage period. For example, the estimated maximum safe combination of temperature and moisture to preserve 50% viability in rice cv. Pelde for a year, stored in air, is shown in Figure 1. The above error can be incorporated into this figure as either a reduction in safe temperature by about 2.5°C or in moisture by about 0.7% as is, for grain stored at around 25°C and 13% moisture.

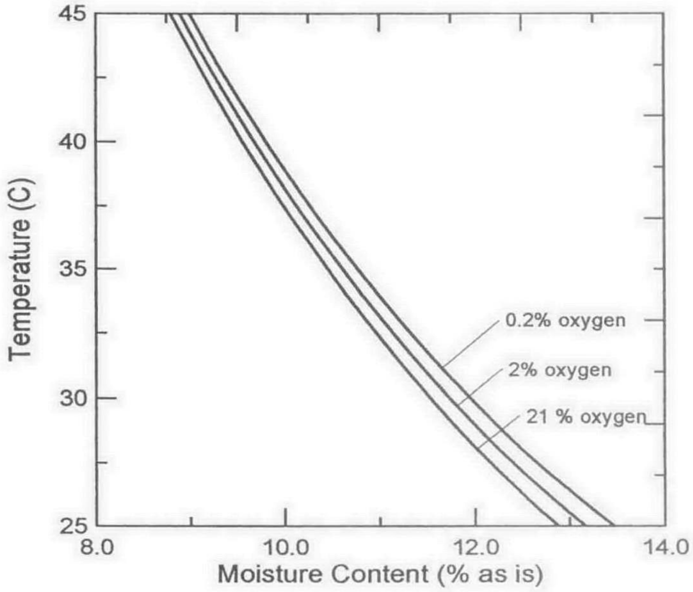

Fig. 1. Calculated maximum safe combinations of temperature, moisture and oxygen level in storage to preserve 50% viability in rice cv. Pelde for one year. Equation (5) was used to calculate the prediction curves (see text). Safe storage conditions lie to the lower left of the curves.

As the primary goal of this work was to assess and compare the models using the same set of data, further work is required to fully establish their predictive capacities. The models could also be further refined by incorporation of non-static storage conditions, such as changes in temperature over time. Software or look-up tables could then be generated, to provide grain storage managers with improved tools for ensuring maintenance of quality in their storages.

The use of predictive equations is clearly of advantage where sealed CA storage is in use, since grain is unavailable for monitoring during storage without breaking the seal. However, the models also apply to conventional storage. They could be used to help provide guidelines for setting maximum grain moistures and storage temperatures or for scheduling grain outloading. Current regulations, which cover only maximum moisture levels, are only a partial solution to prevention of quality loss. The above results highlight the interaction between moisture and temperature, such that quality can be lost at moistures below the current maxima permitted, provided that the storage temperature is high enough. High storage temperatures (above 25°C) are not uncommon in Australia. With the current increase in maximum permissible grain moisture receival levels in wheat to 12.5%, the need for careful management of storage temperature is evident. One solution could be to develop a measure of 'storability' based on both maximum temperature and moisture content of the grain, as already in place for oilseeds in NSW. In many cases, it will emphasise the need for grain cooling in storage where the grain is to be held for long periods. Models such as those given above would help in defining appropriate combinations of moisture and temperature for receival or during storage.

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