

Influence of storage conditions on survival and sowing value of seed of tropical pasture grasses. 1. Longevity

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Abstract

To find ways of improving the sowing value of seed of tropical pasture grasses through attention to the storage environment used commercially, fresh seed lots of *Panicum maximum*, *Brachiaria decumbens*, *Brachiaria humidicola*, *Setaria sphacelata* and *Chloris gayana* were stored under different conditions and sampled periodically for laboratory, greenhouse and field testing. Comparisons were made between seed lots stored in bags of open weave in a cool-room at 10°C and 50% RH and in an open store-room at ambient temperature. Seed lots of *P. maximum* in moisture-proof packets at 5 different moisture contents between 7.3 and 12.9% were compared. One seed lot was also freezer-stored at -12°C. Part 1 reports their viability and dormancy loss.

Viability loss of seed in woven bags in open storage was complete within 3 years while barely detectable in similar cool-stored seed. Rates of loss in sealed packets increased with moisture content at ambient temperatures. They were much higher in seed in woven bags at comparable average moisture contents, an effect attributed largely to spatial moisture content gradients. Cool storage temperatures and low seed moisture contents appeared to prolong dormancy, while freezer storage retained and even intensified it.

Introduction

By the early 1990s, our need to improve the storage environment of seeds of tropical pasture grasses had become urgent. A developing responsibility for maintenance of pedigree seed

stocks required a sound strategy for medium-term storage. Increasing pressure on the seed industry to improve the quality of its products for a competitive export market translated into demands upon us for information on storage that could not be adequately satisfied. Progress in understanding pre-storage influences on quality (e.g. Hopkinson and English 2004) emphasised our ignorance of subsequent seed history.

While general principles of deterioration of orthodox seeds in storage were well established (Roberts 1972; Ellis and Roberts 1980, 1981; Ellis 1988) and provided an invaluable starting point, little was known about their quantitative application to tropical pasture grass seeds. A number of reviews of storage of seed in tropical climates had been conducted (Delouche *et al.* 1973; O'Dowd and Dobie 1983; Ellis 1988), but grass seed had not received specific attention. A more recent review of tropical pasture seed storage was unable to bridge the gap between principle and quantitative effect with respect to loss of viability of grass seed (Chin and Hanson 1999). Influence of storage conditions on other changes, such as dormancy loss and vigour, was poorly understood, as were the combined effects of all these processes on field sowing value.

The construction of a cool-room at Walkamin Research Station in 1992 allowed us to compare the performance of seed stored in a single set of constant, defined conditions with that of seed of the same origin kept in conventional open storage. Comparisons were later extended to seed stored at a range of constant moisture contents. From these, we sketched the first bare outline of the effects of storage environment on subsequent seed characteristics.

This paper describes the experiments done, and reports the changes in viability and dormancy measured by laboratory tests under various storage conditions. Impacts on seedling emergence from soil, dormancy in soil, vigour and field sowing value will be covered in a second paper (Hopkinson and English 2005).

Materials and methods

Outline of investigation

The investigation ran for 8 years and comprised 3 experiments in which seed of identical origin and prior history was stored in different environments. The effects of storage conditions were measured in terms of the behaviour of samples extracted for testing at intervals over the storage period in the laboratory, greenhouse and field. Wherever possible, behaviour was expressed in terms of viability, dormancy, vigour and sowing value. The general procedure with all experiments was to take harvested, dried, cleaned seed, mix it thoroughly, divide it into the number of lots required, and store each lot in the appropriate conditions that comprised the experimental treatment. Samples were drawn on entry into storage for laboratory tests (moisture content and viability) and subsequently annually at the start of the local sowing season for laboratory tests and greenhouse and field seedling emergence and establishment tests.

Many details were common to all experiments and are described under separate headings following the outlines of the individual experiments below. Timetables and other details specific to individual experiments are provided in Table 1. Descriptions of greenhouse and field test methods are given in the second paper.

Experiment 1. The first experiment checked the appropriateness of choice of storage conditions, timetables and testing methods, while at the same time producing useful results. Seed of only 1 cultivar, *Panicum maximum* cv. Gatton (Gatton panic),

was used. The experiment included 3 treatments: open and cool storage of seed in woven bags, and (for the first year only) freezer storage in a moisture-proof, sealed packet. Samples were drawn at intervals for tests of viability and germination.

Experiment 2. This experiment was an expanded form of Experiment 1 and included seed of 5 species [Gatton panic, *Setaria sphacelata* (setaria) cv. Solander, *Brachiaria decumbens* (signal grass) nominally cv. Basilisk, *Brachiaria humidicola* (Koronivia grass, more commonly called humidicola) cv. Tully and *Chloris gayana* (rhodes grass) cv. Callide (Oram 1990)] subjected to 2 treatments, open and cool storage in woven bags. Samples were taken at intervals for tests of viability and germination.

Experiment 3. This experiment was designed to separate the effects of storage temperature and moisture content. Seed of Gatton panic was stored in both cool-room and open store at 5 different seed moisture contents [7.3, 8.7, 10.8, 12.2 and 12.9% (wet weight basis)], kept constant by being sealed in moisture-proof packets. Samples were taken at intervals for tests of viability and germination.

Choice of seed

As a compromise to match our resources, we studied cultivars of 5 different species to obtain an outline of general behaviour (Experiment 2), and examined 1 of them, Gatton panic, in detail as we already understood its behaviour in other respects. These 5 species provided a reasonable cross-section of the grasses commonly grown in

Table 1. Seed types, timetables, and storage conditions of seed in the 3 experiments.

Experiment	1	2	2	2	2	2	3
Seed type ¹	Gatton	Gatton	Signal	Tully	Solander	Callide	Gatton
Harvest year	1992	1994	1994	1994	1994	1994	1997
Harvest date	17/01	08/03	01/04	09/03	24/03	18/05	13/02
Store entry date	12/02	23/03	13/04	23/03	30/03	02/06	20/03
Duration (yr)	8	6	6	6	6	6	2
Moisture contents of seed in woven bags (% wet weight basis)							
On entry	10.8	9.8	10.0	10.4	12.4	12.5	
Open store (average)	10.7	10.8	10.0	10.5	11.8	11.8	
Cool-room (average)	9.1	8.8	9.1	9.1	9.1	9.7	
Open store temperatures over period of storage (°C)							
Average	22.6	22.6	22.5	22.4	22.1	22.4	22.9

¹Gatton panic; Signal grass; Tully humidicola; Solander setaria; Callide rhodes.

north Queensland at the time. Wherever possible, we grew, combine-harvested, dried and cleaned the seed ourselves so that its history was known. The one exception was the signal grass seed, which was grown by a local farmer and its history was well documented. Each seed lot was freshly harvested when first put to use, and was typical of a good commercial product.

Methods of seed drying

Seed for Experiment 1 and of Gatton panic, Tully, Solander and Callide for Experiment 2 was dried for 2 days in shallow layers in trays in a forced-draught dehydrator running at 35°C. The commercial seed of signal grass had been dried in bins through which heated air at 35°C was forced. In both sets of conditions, the relative humidity of the drying air was reduced to 30–40%. The final moisture content of the seed varied with the prevailing dew point temperature (Table 1). In Experiment 3, we removed and checked samples of seed at different times during drying to obtain samples at the various moisture contents which covered the full realistic commercial range for study. The final drying temperature was raised briefly to 40°C to obtain the lowest moisture contents.

Choice of storage conditions

Open storage. The aim was simply to adopt conditions typically used for storage of commercial seed, that is, in bags of open weave stacked in an unsealed store without temperature control. Average temperatures in the room were estimated from a linear regression equation derived from previous daily records linking measured room and adjacent meteorological station screen maximum and minimum values. No running record of relative humidity was kept during the experiments, but averages derived from long-term screen records provide an approximate indication of conditions. Mean monthly dew point temperatures vary between 13.1°C in July and 20.4°C in February. These translate to monthly averages of store mean daily relative humidity between 65% and 78%, with an overall average of 71%. Substantial daily fluctuations occurred, with maxima frequently approaching saturation. As the store was at the mid point of the seed-growing district in terms of both position and elevation, the conditions provided a good approximation of average local commercial storage conditions.

Cool storage. The choice of conditions in the cool-store was a compromise between running costs and required life expectancies of stored seed. We aimed for useful storage lives of 12+ years. First approximations of life expectancies were made from application of the viability equations derived for other structurally similar crop seeds (Ellis and Roberts 1981). We found that a constant temperature of 10°C and a constant relative humidity of 50% were effective and maintained these throughout the period of the investigation.

Freezer. As some small lots of pedigree seed were to be cold-stored, storage in a chest freezer at –12°C was included in Experiment 1 in the first year. Cold storage was not included in the studies of long-term longevity. The main focus on cold-stored seed was on the effects on dormancy, as knowledge of other orthodox seeds indicated that viability would not decline detectably over any period of storage envisaged.

Packaging. The small volumes of seed (each about 5 dm³) used for Experiment 1 were stored in woven cotton sample bags. The greater volumes used in Experiment 2 (each about 60 dm³) were kept in woven polypropylene bags used commercially for seed. The open weave readily allows passage of water vapour (Warham 1986). In freezer-stored seed of Experiment 1 and all seed of Experiment 3, volumes of seed of about 70 cm³ were heat-sealed within small packets of laminated aluminium foil and plastic that were impervious to water vapour.

Measurement of moisture content

A standard gravimetric oven-drying method of measuring moisture content of grass seeds [130°C for 1 hour (Roberts and Roberts 1972)] was used on entry into storage and at sampling for testing. It provided an average value for each lot, without any attempt to measure within-lot variation. Intermediate values on bulk lots were simply estimated by gross weight change since the previous test.

Methods of seed testing

Viability tests. Incomplete dormancy breaking and death of dormant seed during the test prevents the use of conventional germination tests for estimation of viability. Instead, germination tests were conducted on de-husked caryopses

under standard conditions (35/20°C, 8-hour light period, seed on germination papers in petri dishes irrigated with pure water). De-husking predictably eliminated dormancy in all but some of the freshest seed (*cf.* Whiteman and Mendra 1982). Where dormancy was observed, tetrazolium tests of viability, also on de-husked caryopses, were substituted using previously described modifications (Hopkinson and English 2004) of a standard technique (Grabe 1970). De-husking increases the precision of both types of test but restricts replication through being very time-consuming.

A minimum of 2 replicates (frequently 3–6) of 100 caryopses each was used for each estimation, whether involving germination or tetrazolium or both. Samples were tested simultaneously where intended for direct comparison (as between storage treatments of seed of common provenance) and sequentially where not (as with different species).

Speed of germination. Where possible, speed of germination was recorded, as an indication of the persistence of dormancy in young seed. As the viability test method was deliberately chosen for its power to overcome dormancy, its use precluded more direct measurement. The dormancy influence retards germination (Harty *et al.* 1983) and it persists sufficiently in fresh de-husked caryopses to provide useful information. The method produces unambiguous results only with young seed, as aging deterioration also retards germination and thus confounds interpretation. Speed of germination was measured in terms of mean germination time (Ellis and Roberts 1980), when all or most viable seeds germinated within the test period (Experiments 1 and 2); or in Experiment 3 by expressing the number of seeds germinated by Day 3 (chosen as providing the most sensitive index) as a percentage of the total viable seeds.

Experimental variation and statistical treatment

Large differences in viability attributable to storage environment made statistical tests of differences between seed lots superfluous; in general, only standard errors are needed to provide some indication of reliability of means. For simplicity, in most cases single values derived from pooled variances are quoted. Differences attributable to different moisture contents were tested for significance using least significant differences calculated from analyses of variance.

Results

Storage temperatures and moisture contents

The cool-store maintained 10°C at the thermostat throughout the investigation. Daily defrosting cycles raised air temperature briefly but without measurable change to seed bulk temperature. Slight temperature gradients within the store were sometimes detected, with localised rises of up to 1°C. Mean monthly air temperatures in the open store, averaged over all years, fluctuated between 18.9°C and 25.5°C, the annual average being 22.7°C. The average values for the duration of storage of each seed lot are given in Table 1. The relative humidity of the cool-store air remained at 50%, apart from a brief rise during each defrosting cycle.

Measured moisture content of all seed in woven bags (Experiments 1 and 2) changed over time. That of cool-stored seed at first fell progressively, stabilising after the first 50 days with the rate of loss of moisture being most rapid initially. Quoted values (Table 1) can thus be regarded as constant over whole storage lives. Measured moisture contents of seed in open storage varied by about 0.5% either side of the quoted average values (Table 1).

Viability loss

Loss of viability followed similar patterns in all seed over the 8 (Experiment 1) and 6 (Experiment 2) years of storage (Figure 1). The viability of cool-stored seed remained essentially constant, except for Solander which showed a slight tendency to decline. The apparent early fall of Gatton panic seed of Experiment 2 from a high initial viability is probably due to the tetrazolium test over-estimating the viability of fresh seed. Meanwhile, viability was extinguished comparatively rapidly in all ambient-stored seed, with total death by the age of 3 years. The decline was more rapid in Tully and Solander seed than the rest.

The treatments of Experiment 3 had 2 potentially confounding effects, the intended one of effects of different seed moisture contents, and an incidental one of the effects of differences in initial drying conditions needed to achieve them. However, tests conducted immediately after drying revealed an overall average viability estimate of 85.4%. The mean values for each of the

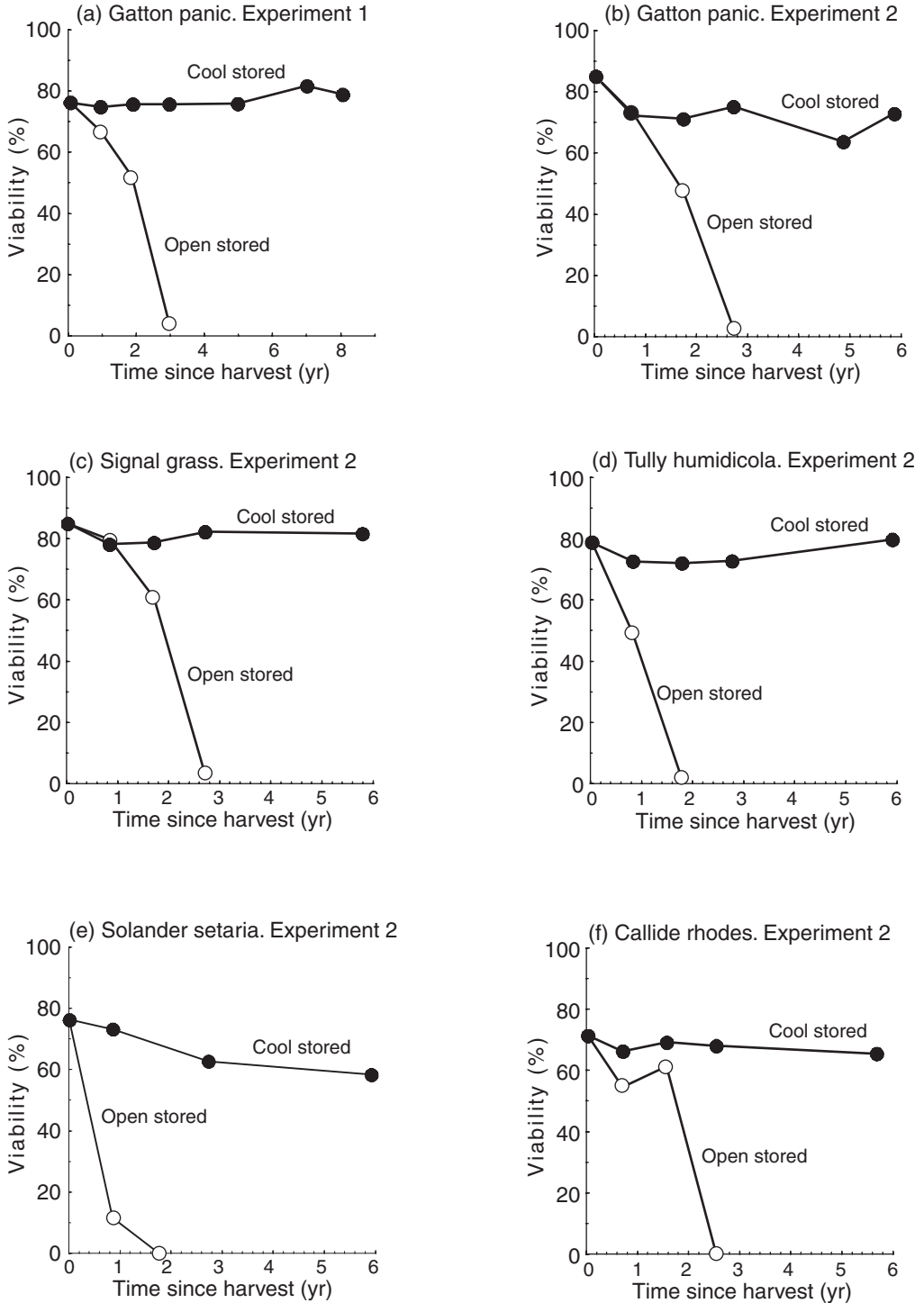


Figure 1. Patterns of loss of viability of seed of 5 species over time in both cool-room and open storage in Experiments 1 and 2. A s.e. of $\pm 2.9\%$, derived from the pooled variances of all but values below 20%, provides an adequate estimate of variation about individual means.

5 seed lots differed within a range of 5.4% about the mean, with an estimated standard error of means of $\pm 3.03\%$ and a variance ratio of treatments to residual of 0.6. As individual means formed no discernible pattern in relation to drying treatment or moisture content reached, we concluded that any differences could be attributed to random sampling variation and there was no reason to invoke effects of drying *per se*. Later differences were therefore attributed wholly to differences in storage moisture content.

Loss of seed viability in Experiment 3 was very low in cool-stored seed, regardless of moisture

content (Figure 2). At ambient temperatures, it showed the expected pattern of increasing rate of loss with rise in stored seed moisture content, and seed at the highest 2 moisture contents was dead within 2 years.

The most productive way to summarise these patterns of loss of viability quantitatively for purposes of comparison is to apply Roberts's model (Roberts 1972), which relies on the assumption that, in conditions of uniform storage, the viability periods of the individual seeds of a population are normally distributed. This leads to the transformation of percentages of viability to probits, the

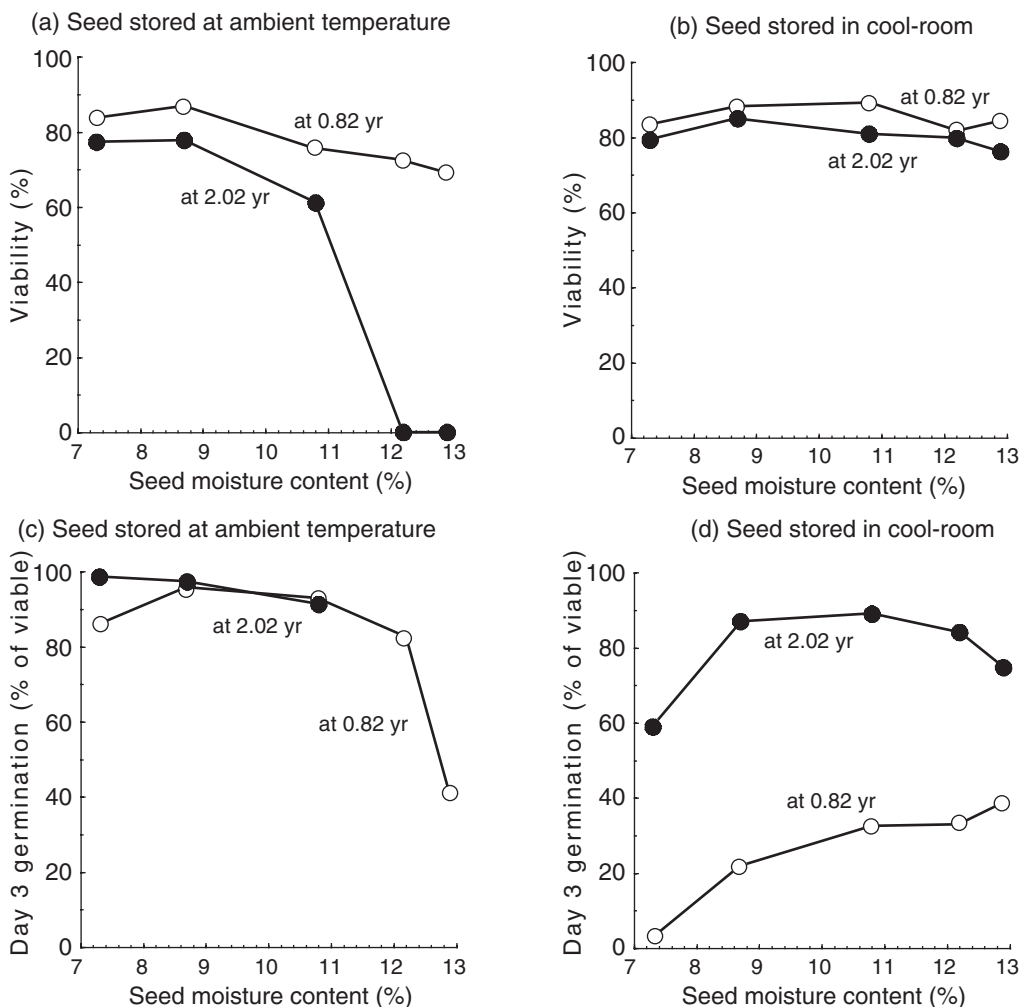


Figure 2. Viability and speed of germination of seed of Gatton panic stored in sealed packets at different moisture contents at ambient and cool-room temperatures and tested on 2 occasions in Experiment 3. LSDs of 12.4% ($P = 0.05$) apply to all differences between individual viability estimates (except zero values, excluded from calculations), and 11.8% ($P = 0.05$) to differences between Day 3 germination values within the range 10–90%, respectively.

rate of decline of which is constant over time and characteristic of the particular species and conditions of storage. It provides a single value, independent of initial viability, with which to express the rate of viability loss. The value chosen may be σ , the standard deviation of the distribution of viability periods and the time taken for a fall of one probit unit to occur, or (as in Figure 3) its negative reciprocal, $-1/\sigma$, the slope of the line obtained by probit analysis and the best estimate of the general rate of loss of viability.

Figure 3 records all calculated values of $-1/\sigma$ from the 3 experiments in a way that shows how they change with seed moisture content. All values of $-1/\sigma$ of cool-stored seed remained close to zero. In the Gatton panic seed of Experiment 3 sealed in moisture-proof packets at different

constant moisture contents, changes with rising moisture content were imperceptible. Linear regression analysis shows a slope barely differing from zero and an insignificant proportion of the variance attributable to the regression. The other types of seed stored in the cool-room, whether in moisture-proof packets or open-weave bags, also had values close to zero. Clearly, loss of viability at 10°C was too little to be detectable against the background of experimental variation.

Seed stored at ambient temperature presented a very different picture. Values of $-1/\sigma$ of Gatton panic seed in sealed packets rose with a progressively increasing rate of change as moisture content rose. Seed in woven bags in open storage deteriorated more rapidly, and $-1/\sigma$ rose more sharply with rising moisture content than with

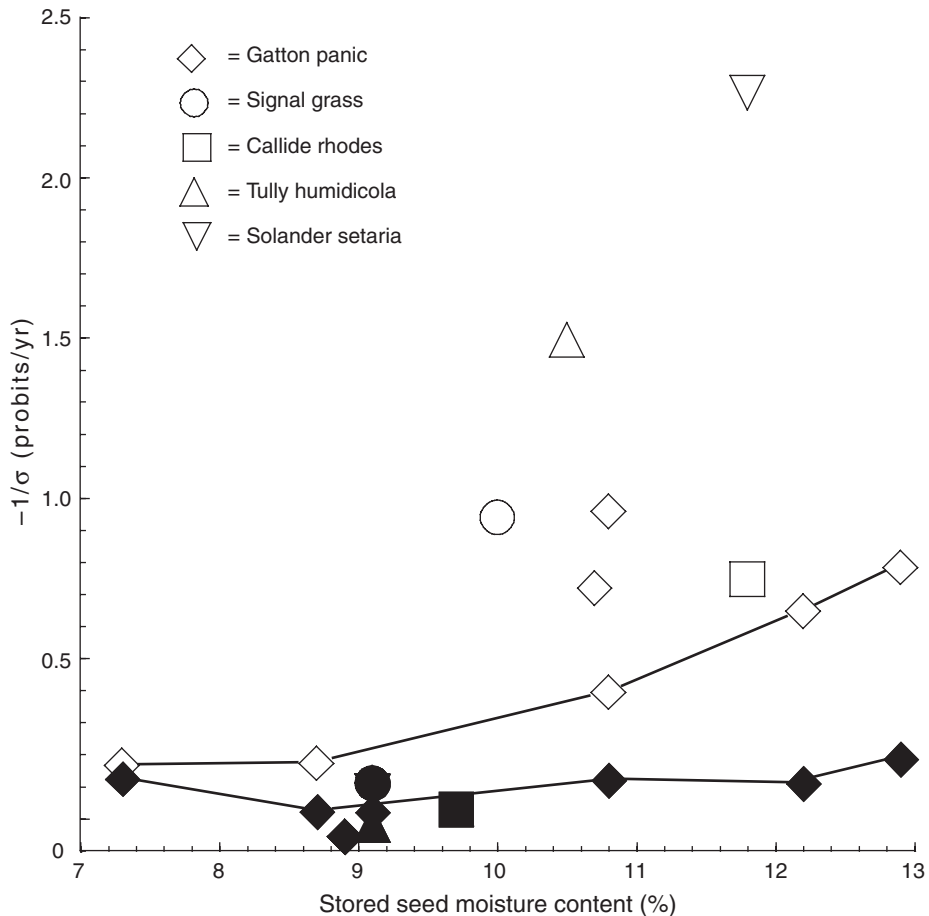


Figure 3. Values of $-1/\sigma$ in relation to stored seed moisture content across experiments. Filled symbols indicate values for seed stored in the cool-room and open ones for seed stored at ambient temperature. Lines link the 2 sequences of seed of Experiment 3 stored at constant moisture contents. All other points refer to seed of Experiments 1 and 2.

sealed seed at similar temperatures. Relatively high values of $-1/\sigma$ were recorded with seed of all 5 species, although there was some scatter of data points. The implications of this result are considered in the Discussion.

Speed of germination

The Gatton panic seed of Experiment 1 germinated from an early age, but initially only slowly (Figure 4). Mean germination time (MGT) decreased with age in both ambient-stored and cool-stored seed, though the change happened earlier in the former. After 2 years, it reached a constant level in the cool-stored seed (by which time the ambient-stored seed was dead). The seed stored for a year in the freezer behaved very differently; its germination was slower than it had been when fresh.

Although the Gatton panic of Experiment 2 initially showed signs of more complete dormancy than that of Experiment 1, its MGT was similarly shorter in open than in cool storage when 1 year old (Table 2). The same applied to the other types of seed whose records permit a comparison, signal grass and Tully. A year later, however, the position was reversed in signal grass and Callide seed (the only comparisons possible). The tendency for MGT to decrease with time in cool storage was general.

In Experiment 3, where speed of germination was measured in terms of Day 3 germination as a percentage of total viable seed, cool-stored seed was much the slower to germinate at age 0.82 years at all but the highest stored seed moisture contents, but only at the lowest moisture content a year later (Figure 2). Seed stored at low moisture content tended to germinate more slowly.

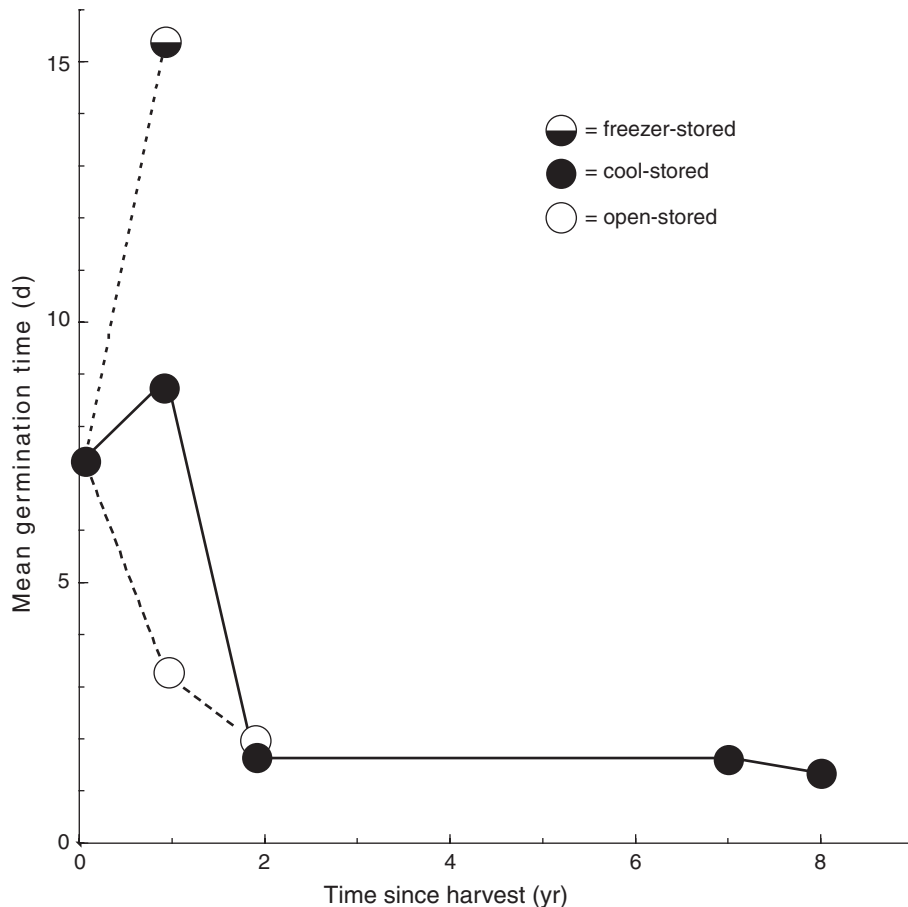


Figure 4. Mean germination times of naked caryopses of Gatton panic in laboratory tests in Experiment 1. Standard errors of means varied from ± 0.03 days for values below 5 to ± 2.7 days for the single value of freezer-stored seed.

This effect was particularly clear at 0.82 years in cool-stored seed, though it persisted to a lesser degree into the following year.

Table 2. Estimates of mean germination time (MGT) in germination tests on naked caryopses in Experiment 2. While standard errors of means increased with values of MGT, it is accurate enough to regard them as roughly ± 0.04 , ± 0.12 and ± 0.66 for means of <2, 2–3 and >3, respectively.

Approximate age (years from harvest)	Mean germination time			
	0.8	1.7	2.8	5.8
	(d)			
Gatton panic				
Ambient	2.72	– ¹	–	–
Cool-room	7.05	–	–	–
Signal grass				
Ambient	2.19	2.24	–	–
Cool-room	2.23	1.61	–	1.60
Tully				
Ambient	4.91	–	–	–
Cool-room	>7 ²	4.39	3.12	2.68
Solander				
Ambient	>4 ²	–	–	–
Cool-room	>4 ²	–	3.54	2.26
Callide				
Ambient	>3 ²	3.16	–	–
Cool-room	>3 ²	1.98	–	1.71

¹ Omissions result from test method details preventing accurate estimation.

² Minimum estimates used when a small proportion of seed remained dormant.

Discussion

Storage life

While patterns of extinction of viability in open storage were similar across seed lots, Solander and Tully had notably short lives. A relatively high moisture content partly accounts for the behaviour of Solander, but a possible contributory factor common to both was husk damage. Tully has to be vigorously threshed to detach seed at harvest, which causes more severe damage than normal. Solander seed appears to have a vulnerable husk, and it contained an unusually high content of fractured lemmas. Threshing severe enough to cause visible husk damage reduces life expectancy of seed of *Panicum maximum* (Hopkinson and English 2004), which has a similar structure.

To determine appropriate conditions for storage of seed of tropical pasture grasses, comparisons that provide estimates of changes

in viability under different storage conditions are necessary. The records of Gatton panic in Figure 3 allow such estimates to be made. Useful storage life can be taken as the time taken for viability to fall from 80% (a typical entry value for good quality seed) to 50% (a point at which market attractiveness is seriously in decline), and its duration under different storage conditions can be calculated.

Typical storage conditions for commercial seed are open-weave packaging, ambient temperatures close to those of the experiment, and average seed moisture content a little below 11%. In such conditions, useful storage life would be a little over 1 year. If the same seed were packaged to prevent moisture exchange, its useful life would at least double. If it were further dried to 8.7% moisture, sealed and left at ambient temperature, its useful life would extend to almost 5 years. If seed were dried to 8.7% moisture, sealed and placed in a cool-room at 10°C, or alternatively left in the cool-room in open-weave bags to equilibrate with its 50% relative humidity, useful life would be extended indefinitely. The period may be calculated as about 40 years, but this is arbitrary as the estimate of $-1/\sigma$ for these conditions has low accuracy.

Loss of viability in relation to moisture content

Loss of viability in cool-stored seed was too slow for effects of moisture content to be detectable against the background of experimental variation, but that of ambient-stored seed followed clear patterns in relation to moisture content (Figure 3). The changes in $-1/\sigma$ of seed in sealed packets were consistent with those for other species (*cf.* Ellis *et al.* 1986), as were those of seed stored in open-weave bags. The cause of the consistently high rates of viability loss of seed in woven bags warrants closer attention, as it raises the vexed question of the use of viability equations derived under rigorously standardised conditions for prediction of viability loss in normal commercial situations.

Re-examination of the source records (Figure 1f) leads us to regard the Callide estimate of $-1/\sigma$ as too inaccurate for the purpose. The 5 remaining records of seed of 4 species in woven bags may be compared with the 5 of Gatton panic in sealed packets (Figure 3). The difference, assuming that both conform to the semi-

logarithmic model noted above, may be described in terms of the seed in woven bags behaving as if it were at a constant moisture content between 2 and 5% greater than its actual recorded mean value. At comparable recorded moisture contents over the relevant range, the differences in estimates of rates of viability loss were about 2- to 4-fold.

How might such great differences have arisen? The comparisons are not rigorous, as records were from different experiments. They introduce the risk of other, confounding effects, though some can be dismissed immediately. The comparison includes Gatton panic in both sets of conditions, so species differences alone cannot be invoked. The method of data treatment eliminates effects of differences in origins and pre-storage histories. Effects of slight differences in average store temperatures over different periods (Table 1) were too small to account for more than minor differences in $-1/\sigma$. Moreover, similar temperature fluctuations were also experienced by the sealed seed.

The only obvious factor is fluctuations in moisture content. In sealed packets, moisture content was constant; in woven bags, it certainly fluctuated. Since the rate of change of $-1/\sigma$ increases with rising moisture content, its value under moisture contents that fluctuate over time must exceed that of seed at constant moisture content equal to the mean of the fluctuations [*cf.* similar effects of fluctuating temperature (Ellis 1988)]. This must contribute to the difference, though, if the record of spot checks on moisture contents is a guide, it can explain only a fraction of the effect.

Probably more importantly, moisture contents at any one time varied spatially. The extent of such variation is largely unmeasured, but it may be inferred to be substantial. The open weave of plain bags presents effectively no resistance to the passage of water vapour relative to the resistance within the seed bulk itself (Warham 1986). Consequently, in conditions of high external relative humidity, water vapour readily passes into the surface layers of dry seed, but penetrates relatively more slowly along an inward-moving front. We recently measured substantial short-term rises in moisture content in the outer layers of bagged Gatton panic seed, with rates of gain in the outermost 15 and 150 mm of 0.31 and 0.015%, respectively, per day per 1% difference between internal moisture content and external equilibrium moisture content, while inner layers remained in

the short term unchanged (J.M. Hopkinson and B.H. English, unpublished records). Presumably, reverse trends occur when external humidity falls. Complex spatial moisture content gradients must thus arise. While they are far too complicated for us to model, a few simple calculations show that moisture content gradients must develop within bagged bulks of seed, which must in turn create substantial spatial differences in rates of viability loss. For example, using moisture content gains calculated from the above records in conjunction with values for consequent changes to $-1/\sigma$, we conclude that, after a mere 3 days in virtually saturated air (a frequent wet season state), the value of $-1/\sigma$ for the seed population as a whole in a commercial-sized bag initially at 10% moisture would have risen by over 50%. We cannot quantify the long-term effects, but conclude that, over long periods of a normal year's open storage in north Queensland, rates of viability loss of seed must materially exceed those predicted from records of average temperatures and moisture contents. The differences in Figure 3 primarily reflect this situation. Implications of this conclusion warrant more thorough investigation. Meanwhile, it provides a compelling reason for the adoption of moisture-proof packaging for open-stored seed.

Comparisons of viability loss patterns with those of other orthodox seeds

A more general issue is how values of $-1/\sigma$ for tropical pasture grasses compare with those for other seeds stored in the same conditions. The only records obtained in conditions that provide suitable comparisons of viability loss are those of the 10 samples of Gatton panic seed stored in moisture-proof packets. When the recorded $-1/\sigma$ values of each of these were compared with the comparable calculated values for barley and rice [the 2 most closely related similarly structured seeds, for which good records exist (Roberts 1961; Ellis and Roberts 1980)], close linear, almost proportional, relationships with both were obtained as follows:

$$(-1/\sigma)_{GM} = 0.0581 + 1.592 (-1/\sigma)_{RC} \quad (r^2 = 0.98)$$

$$(-1/\sigma)_{GM} = 0.076 + 0.398 (-1/\sigma)_{BC} \quad (r^2 = 0.96)$$

where the subscripts G, R and B refer to Gatton panic, rice and barley, respectively; M stands for measured values in the present experiments; and C for calculated values for the same temperatures and moisture contents.

The values for Gatton panic lie between those for rice and barley. The closeness of fit of the regression confirms that Gatton panic seed conforms with general patterns of behaviour of other similar orthodox seeds within the range of storage conditions covered. While the relationships appear appropriate for quantitative prediction of viability loss, to use them for this would be premature, its only present justification being the absence of anything better. Much needs to be done to check constancy across seed lots and species and to extend the range of storage conditions before confident prediction will be possible. Even then, it will be limited to seed stored at spatially uniform, constant moisture contents.

Dormancy

All available records of early dormancy in Experiments 1 and 2 (Figure 4 and Table 2) are consistent with the interpretation that dormancy slows down germination, as has previously been documented (Harty *et al.* 1983), and that the changes in MGT reflected changes in dormancy persistence. Thus, while dormancy tended to diminish with age in both sets of conditions, it persisted longer in the cool-room than outside. Meanwhile, the conditions in the freezer arrested dormancy loss and, indeed, seemed to intensify it without (as records documented in the second paper will show) impairing quality.

These interpretations do not apply to ambient-stored seed of more than 1 year old, when delayed germination through presumed loss of vigour due to aging [also previously documented (Harty *et al.* 1983)] began to take effect in the 2 seed types, signal and Callide, where suitable comparisons were obtained. Once such effects appear, their confounding influences preclude connections between MGT and dormancy.

Results of Experiment 3 reinforce the conclusion that low storage temperature and low moisture content prolong dormancy. The slow germination of the ambient-stored seed at the highest moisture content at 0.82 years (Figure 2c) cannot be interpreted because of the confounding effect of aging, in this case supported by the record of complete death a year later.

The implications of the conclusion that loss of dormancy was delayed by cool storage and by low storage moisture content, and arrested and even intensified by cold storage, will be left for the second paper, where they can be considered together with other evidence and effects on other seed properties.

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