Variation in quality and performance of stored seed of green panic (*Panicum maximum*) attributable to the events of the harvest period

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Abstract

A search for causes of low quality in commercial seed of the pasture grass green panic (*Panicum maximum*) was directed at the successive events of the harvest period. Seed samples were taken at points before and during the direct combine-harvest, transport and drying of 7 commercial seed crops in central Queensland. The samples were then stored and periodically subjected to laboratory, greenhouse and field tests over a period of 3 years to determine the course of change in their viability, germination and seedling emergence from soil. The changes in quality attributes were then linked to the separate stages in the harvest.

An average of 34% of pure seeds in the standing crop at harvest contained immature and thus inferior caryopses. Seed was physically damaged during harvesting, an effect attributed to threshing. The damage caused some immediate death and shortened life expectancy of the seed population as a whole, but also accelerated dormancy breakdown. Accordingly, it first stimulated but later depressed the germination of seeds in laboratory tests and the emergence of seedlings from soil, and reduced numbers of seeds surviving in soil. It reduced the viability of stored seed at any one time by about 15% and shortened life expectancy under normal storage conditions by at least 1.5 years. Ill-effects of subsequent transport and drying were detectable, but were inconsistent or less severe. Viability and properties dependent on it were sometimes reduced both as a result of prolonged periods spent in the truck bin (up to 10 hours, when seed tended to overheat) and by conventional bulk-drying, but without marked effects on dormancy. The combination of the ubiquity of immaturity and the need to accept some threshing damage restrict the scope for improvement of quality of seed entering storage.

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Introduction

In Australia, seed of green panic, a pasture grass of the species *Panicum maximum*, nominally cv. Petrie (Oram 1990), is produced mostly in the Rockhampton hinterland of central Queensland. While total annual production averages 80–100 t (Smith 1996), there is great annual variation reflecting the seed crop's dependence on rainfall in a drought-prone region.

Low vital quality has long been a problem in commercially marketed seed of this grass. Seed merchants have estimated that about half the seed passing through their hands has less than 25% germination (the former Queensland Minimum Standard, still serving to some extent as a benchmark of saleability). Fresh green panic seed is strongly dormant, its dormancy breaking progressively, mainly during the first year of storage (Harty *et al.* 1983). The merchants' estimates indicate that seed has commonly deteriorated to an unacceptable extent by the time it has emerged from dormancy.

In investigating the problem, we first had to determine when the deterioration occurred. Two broad possibilities existed: seed might already have been in a damaged state by the time it entered storage; and/or it might have deteriorated excessively through aging during the 1–3 years it normally spent in storage. To judge them, we took account of what was already known about the aging of green panic seed (Harty *et al.* 1983) and what could be inferred about customary storage conditions. In conjunction with the general principles of aging of seed in storage (Roberts 1972), they indicated that storage deterioration alone was insufficient to explain the overall low average

level of green panic seed quality. This suggested that significant pre-storage damage occurred. Seed may have been defective at harvest, and/or damaged during harvest, post-harvest handling or drying. At the time, work was already under way to address some of these issues in north Queensland grass seed crops. We were aware of the possibility of low pre-harvest quality due to high immature caryopsis contents, and of the dangers of death from suffocation and overheating of the freshly harvested bulk, and of too-rapid drying (Hopkinson and English 1985; Hopkinson *et al.* 1988, 2003), though the relevance of these factors to green panic in central Queensland conditions was untested.

There was also the unresolved question of whether or not threshing damaged seed. Although it has long been known that the threshing action of a combine-harvester may damage seeds of many kinds (Kepner *et al.* 1978), the effects are so specific to the size, type and state of the seed and to the settings and conditions of flow through the threshing cylinder that no general conclusions may be drawn. No records are available to indicate what the effects on tropical pasture grass seeds might be.

For these reasons, we directed our attention at the changes and points of change in seed quality during the sequence of events that constituted the commercial harvest of green panic seed crops in central Queensland. Almost all green panic seed is harvested by direct combine-harvesting of standing crops. Harvested seed normally contains over 50% moisture, and must be dried before being cleaned and stored. During harvest, it accumulates in the grain tank of the harvester, and is periodically discharged into a truck-bin where it may remain until the end of a day's work, when it is driven to a central drier. Most drying is done with forced draught and elevated temperature in bins designed for the work, though a small proportion of seed is sun-dried. Each of these events demanded attention.

In February–March 1981, a favourable season produced abundant seed crops over a brief period in the district around Biloela (24°S, 150°E) where most green panic seed is produced, enabling the investigation to be set in motion.

Methods

The plan of the investigation was: to sample as many crops as possible at critical points during the harvesting and drying sequence; to store the samples over a period comparable with that of the normal commercial life of a seed lot in conditions equivalent to normal commercial ones; to test them periodically in order to record changes in seed properties; to link any changes that might occur to specific events of the harvest sequence; and thus to separate causes of poor performance and enable the importance of each to be judged.

Crops, harvests and sampling

Seven commercial seed crop harvests were sampled between February 12 and March 4, 1981. The crops are identified by the letters H, N, T, J, P, B and A. All were direct combine-harvested by commercial, self-propelled, conventional harvesters (*i.e.,* ones with cross-flow threshing cylinders and straw-walker separating systems). The aim was to obtain representative samples of seed in a sequence marked by the following sampling points:—

1. *The standing crop ahead of the harvester.*
2. *Combine-harvested seed immediately it entered the grain tank of the harvester.*
3. *Combine-harvested seed after it had lain in the grain tank, as it was discharged into the truck-bin.*
4. *Combine-harvested seed after it had lain in the truck-bin, as it was transferred to the drier.*
5. *Combine-harvested seed at the end of drying.*

The sampling sequence was incomplete in a number of crops because the combination of urgency to harvest and long distances between crops prevented the sampler from being present everywhere at the critical times, though the only crop which failed to provide a useful sequence was A (Table 1).

Table 1. Record of whether seed was (+) or was not (–) sampled at each sampling point in each crop.

Standing point	1 Standing seed	2 Into grain tank	3 Into truck bin	4 On to drier	5 Off drier
Crop					
H	+	+	+	–	+
N	–	+	+	+	+
T	+	–	+	+	+
J	+	+	+	+	+
P	+	+	+	+	+
B	+	+	+	+	+
A	–	+	+	–	–

To provide samples of standing seed, seed heads were hand-cut from 10 × 1 m^2 quadrats in each crop and sweated (Hopkinson *et al.* 2003) for 3 days to loosen the seed, which was then separated by hand-sieving and immediately dried. When properly conducted, sweating causes no measurable damage, either physical or physiological.

Fresh, bulk seed spent 1–2 h in the grain tanks of the harvesters before being transferred to the truck-bins, where it spent up to about 6 h (H, T, J, P and B) and up to 12 h in crop N. Bulk seed temperatures up to 43°C were recorded in crops N, T and B, and up to 40°C in P, though these were not necessarily the maxima.

Crops H, N, T and P were dried with forced-draught and heated air. Crop J was first spread out on hessian in the sun before being moved to a forced-draught, heated-air drier on the evening of harvest. All these seed lots took about 2 days to dry. Crop B was sun-dried at about 10 cm depth on hessian throughout, and when sampled after 2 days was still not fully dry.

Processing

Samples were taken to Rockhampton, dried where necessary, then sent immediately to Walkamin Research Station in north Queensland, where they were further dried together in the same dehydrator to ensure common moisture contents for subsequent storage. Dried at 35°C and 30–40% relative humidity in shallow layers with forced draught for 2 days, they reached 9.8% moisture content (wet weight basis, determined by oven drying for 2 h at 125–130°C). After drying, all seed was sieved to remove straw. Samples were packaged in resealable plastic bags, which were then put together in a sealed bag of thick polythene to minimise moisture exchange with the outside air.

Measurement of physical properties

Purity by weight of dry, sieved seed was determined by aspiration. Any seed unit (spikelet or floret) containing a recognisable caryopsis was classed as pure seed [International definition (International Seed Testing Association 1996)]. The quantity of pure standing seed available for harvest was estimated from the quadrat yields. No figure was possible for combine-harvested seed yield. Mature caryopsis content of pure seed was determined by observation of dissected spikelets under magnification. Two sub-samples of 100 pure seed spikelets (*i.e.*, ones containing a recognisable caryopsis) were taken for each determination. Mature caryopses were defined as those fully occupying the husk cavity and with clear (as distinct from chalky) endosperm. Their content is expressed as a percentage of total caryopses.

Storage and testing

Seed was processed and packaged as quickly as possible after receipt. Once packaged, primary samples were placed in the Walkamin Research Station (17°S, 145°E; 600 m elevation) seed store at uncontrolled temperatures ("ambient storage"), where they remained for most of the period of the investigation. However, interludes of cool or cold storage were introduced at various times to retard or arrest aging (Roberts 1972; Ellis and Roberts 1981) and loss of dormancy (for the effectiveness of which we have abundant unpublished evidence). Cool storage (refrigerator at +5°C) was used for relatively short periods to ensure common physiological age when different types of test were (for logistical reasons) conducted successively, when ideally they would have been done simultaneously. Cold storage (cold room at –15°C) was used for longer periods to permit seed samples of widely differing physiological ages to be tested simultaneously.

Tests were conducted on sub-samples drawn during these interludes. Times of testing are referred to as *Occasions*, numbered 1 to 4, and the times quoted for them are those of the start of each interlude. Two scales of age of seed at testing are given. One is time since harvest, provided for completeness in Table 2 but not otherwise used. However, the time spent in ambient storage (*effective age*) provides a better approximation of realistic commercial storage age and is used wherever changes over time are involved.

On completion of processing after receipt of seed, preliminary tests of quality were done (Occasion 1). From then until the start of the first sowing season (Occasion 2, when further tests were conducted), all seed remained in ambient storage. Over the interlude of Occasion 2, all seed was cool-stored, after which it was returned to open storage. The procedure was repeated at the start of the following season (Occasion 3). On Occasions 1 and 3, secondary samples from each original sample had been put in heat-sealed foil

packs and cold-stored until the third season after harvest (Occasion 4), when they were simultaneously tested along with seed that had not been cold-stored.

Table 2. Timetable of storage and testing of seed. See text for explanation of terms.

Occasion[1]	1	2	3	4
Time since harvest (yr)	0.25	0.78	1.80	2.84
Effective age (yr) at testing:—				
Viability tests	0.25	0.75	1.52	2.20
Germination tests				
Not cold-stored		0.75	1.52	2.20
Cold-stored since Occasion 3				1.52
Cold-stored since Occasion 1				0.25
Field emergence tests		0.75	1.52 (failed)	
Greenhouse emergence tests:—				
Not cold-stored			1.52	2.20
Cold-stored since Occasion 3				1.52
Cold-stored since Occasion 1				0.25

[1] Occasion 1 = on completion of processing after receipt of seed.
Occasion 2 = start of the first sowing season.
Occasion 3 = start of the second sowing season.
Occasion 4 = start of the third sowing season.

Average mean daily store temperatures during ambient storage were as follows:— from receipt until Occasion 1–23.8°C; between Occasions 1 and 2 –22.2°C; between Occasions 2 and 3 –20.2°C; between Occasions 3 and 4 –24.7°C.

Estimation of viability

Viability as indicated by tetrazolium tests was measured at times corresponding to Occasions 1, 2, 3 and 4 on sub-samples of 2 × 50 (Occasions 1 and 2) and 2 × 100 (Occasions 3 and 4) pure seeds of each original sample. The tetrazolium test involves preparation followed by evaluation of a topographical colour reaction indicating presence of living tissue. One set of tests (1 × 100 seeds of each sample on Occasion 3) was conducted at the Queensland Seed Testing Laboratory (QSTL) employing their own method of preparation (Harty *et al.* 1983). All others were carried out at Walkamin by a different method, in that caryopses were de-husked before being allowed to imbibe overnight on moist filter paper in petri dishes, after which they were slit longitudinally and a few drops of 1% tetrazolium solution were added, followed by incubation at 35°C for 5 h before evaluation. Evaluation after both preparation methods followed guidelines established for *Festuca* caryopses (Grabe 1970). There was no cause to think that the different preparation methods produced different results. During the course of tetrazolium tests, numbers of seeds with visible physical damage, and the individual viabilities of these seeds were recorded.

Germination tests

Germination tests were conducted on a similar timetable (Table 2) to that of viability tests under standard conditions [8 h light at 35°C, 16 h darkness at 15°C, with (+K) and without (–K) potassium nitrate] at the QSTL. On each occasion, 2 × 100 pure seeds of each sample were tested in both +K and –K conditions. Tests ran for 28 d.

Field emergence

To simulate commercial conditions, field sowings were made in the sowing season after harvest (Occasion 2) at Kairi Research Station on the Atherton Tableland (17°S, 146°E; 700 m elevation) in a conventional seedbed on a cultivated cropping soil, a basalt-derived krasnozem. There were 5 successive sowings of 4 replicates of 100 pure seeds of each original sample. Each sowing was laid out as a separate experiment in a randomised block design with each replicate occupying one running metre of row. Conditions were very dry, with low but still useful levels of emergence. They were even drier in the following season (Occasion 3) when, after 2 sowings failed completely, field emergence tests were abandoned in favour of greenhouse tests.

Emergence from soil in greenhouse

On Occasions 3 and 4, the second and third seasons after harvest, greenhouse soil emergence tests were carried out at Walkamin. For each subsample of seed of each age, 4 replicates of 100 pure seeds were sown in 25 cm^2 compartments of seedling trays at about 2 mm depth in soil similar to that used for the field tests. Pots were watered daily, and seedlings counted and removed, until emergence ceased. Three such runs were carried out over the second season (Occasion 3) on seed of a single effective age, and a single run in the third season (Occasion 4) with seed of each of 3 effective ages (Table 2).

On Occasion 4, and after one run on Occasion 3, the soil was allowed to dry out after the tests ceased, and seed was exhumed, separated from

soil by conventional seed cleaning methods, and tested for viability by tetrazolium.

Data handling

All tabulated records of seed properties except those of purity and yield are expressed as percentages by number of pure seeds or caryopses in the sample examined or tested. Most percentages were in values that could legitimately be analysed without transformation. An exception was the results of the field emergence tests, to which the arcsin transformation was applied because of their predominantly very low values. Simple analyses of variance were carried out on transformed and untransformed percentages, and from them least significant differences were derived. Where records were bulked over times, times served as the equivalent of blocks in the analyses. Tabulated percentages are mostly rounded off to whole numbers for ease of viewing.

Results

Yield, purity and mature caryopsis content

Crops varied in the presentation yield of standing (hand-cut) seed, its purity (reflecting the proportion of spikelets containing caryopses) and the mature caryopsis content of the standing pure seed (Table 3). Judged from experience of green panic and the similar cv. Gatton in north Queensland, results were within the normal range. Only one crop, A, was of low purity, a condition attributed by the owner to its having been rain-affected.

Table 3. Physical properties of seed of each crop. Standard errors of means of paired estimates of purity are ±3.0%; of means of estimates of yield ±14 kg/ha; of means of estimates of mature caryopsis content ±2.1%.

	Hand-cut		Combine-harvested	Mature caryopsis content	
	Purity	Pure seed yield	Purity	Hand-cut	Combine-harvested
Crop	(%)	(kg/ha)	(%)	(%)	
H	57	150	64	71	72
N	—	—	88	—	88
T	55	171	67	55	55
J	46	101	51	50	54
P	56	137	62	53	59
B	58	156	66	60	61
A	—	—	36	—	70
Average of comparable pairs (HTJPB)				58	60

Combine-harvested seed was consistently of higher purity than hand-harvested seed, a normal consequence of partial selection for pure seed in detachment during threshing and in winnowing during separation. It displayed slightly higher mature caryopsis content in the pure seed, though differences failed to reach significance.

Physical damage

No samples of hand-cut seed showed any external signs of physical damage, but all samples of combine-harvested seed contained some damaged pure-seed spikelets. Detectable damage took the form of: (a) membranous parts (glumes and lower barren floret) partially or wholly stripped, exposing the fertile floret ("superficially damaged"); or (b) as for (a) but with the husk of the fertile floret damaged, most commonly as a split lemma, but sometimes with lemma edges eroded or the seal between lemma and palea breached ("severely damaged"). Table 4 shows the extent of such damage in combine-harvested seed (bulked from all sampling points). It also links visible damage to loss of viability as viability of damaged seed was reduced – to a limited extent when superficially damaged, and drastically so when severely damaged. It further shows that the severity of damage differed substantially across crops, with A and N relatively lightly damaged and J and B suffering particularly harshly.

Table 4. Extent of visible damage to combine-harvested spikelets, and viability of caryopses contained in damaged spikelets, compared with overall levels of viability of caryopses of whole populations from which damaged spikelets were drawn.

Fraction	Whole population	Superficially damaged		Severely damaged	
Attribute	V[1]	C	V	C	V
Crop			(%)		
H	67	5.0	52	2.3	0
N	85	1.9	75	0	—
T	65	9.2	53	1.0	0
J	47	13.0	35	6.8	19
P	63	7.7	44	1.8	29
B	58	14.0	37	3.0	25
A	81	7.5	86	1.0	0
Combined[2]	67	8.3	47	2.3	17

[1] V = percentage viability; C = percentage content by number of seed at each level of damage. Combined values for V of damaged seed are derived from overall totals, and are not averages of percentages in columns.
[2] Differences in combined viabilities between fractions are significant at $P < 0.01$.

Seed behaviour when tested

The sampling system and subsequent testing sequence were designed to examine the 3 main sources of variation in seed characteristics. Seed lots from different crops differed as a consequence of undefined pre-harvest history; seed of each crop changed as it experienced the successive events of the harvest sequence; and properties changed over time in storage as seed aged. Results are presented in 3 different ways. The tables record differences between sources and sampling points but not changes over time. The graphs of Figure 1 illustrate changes over time, but only of hand-harvested (Sampling Point 1) and the combine-harvested samples next in sequence (from Sampling Points 2 and 3, combined because they were essentially identical). Subsequent sampling point records are omitted because no other significant time-related changes occurred. Figure 2 shows the changes occurring over time in seed from successive sampling points. In both figures, average values for the 5 most completely recorded crops (HTJPB) are presented. For this, the 2 relatively insignificant gaps in sequence are filled as follows. The T2 record (Table 1) is treated as being identical with that of T3 on the grounds that Sampling Points 2 and 3 produced virtually identical seed in other crops. The H4 record is arbitrarily taken as the mean of H3 and H5, a convenience that can introduce no more than a trivial error because of the limited change between Points 3 and 5 in Crop H.

Viability

Seed lost viability with age in a manner consistent with established principles (Roberts 1972). Figure 1a shows the course of change in the 2 examples that best illustrate the difference between hand- and machine-harvested seed. Probit analysis supported the interpretation that the rates of loss were the same in all seed populations, and that differences reflected only differences in viability on entry into storage.

The consistency of viability loss allows viability values for all occasions to be legitimately combined to calculate average viabilities that summarise differences between seed samples of different histories (Table 5). Analyses of variance were carried out on both untransformed and probit-transformed percentages, and led to identical conclusions. Here the untransformed records are tabled because they are more meaningful to the reader.

The greatest and most consistent loss of viability occurred between Sampling Points 1 and 2–3, that is, as a result of gathering of seed and its passage through the combine-harvester. It was apparent in all crops where it could be measured, and averaged about 15% loss of viability

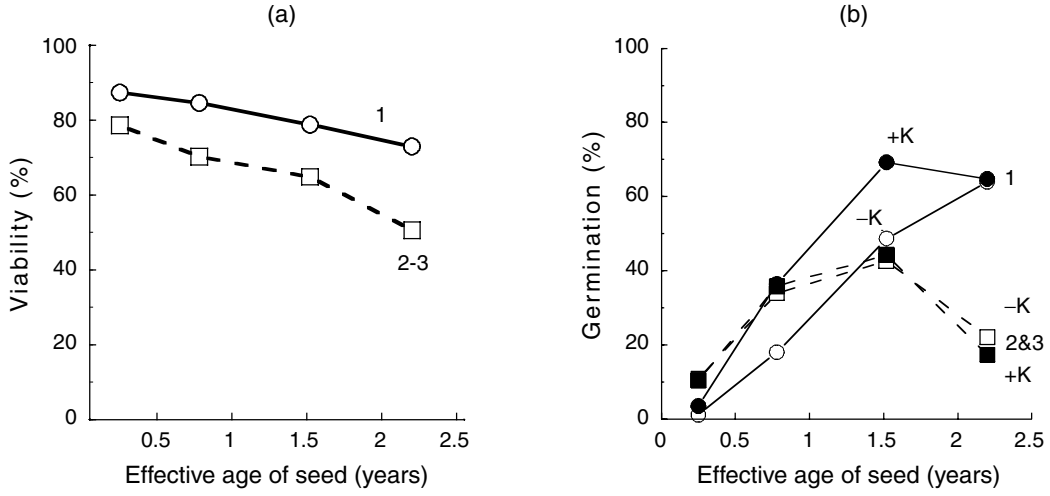

Figure 1. Courses of change of stored seed over time in (a) viability and (b) laboratory germination, with (+K) and without (–K) potassium nitrate. Values are averages for 5 crops (HTJPB) at Sampling Points 1 (before harvest) and 2 & 3 (entering grain tank of harvester and entering truck bin). At common ages, all differences between points in viability and those differences in germination exceeding 5% may be taken as significant at P = 0.05.

(Table 5) or a shortening of population life expectancy by about 1.5 years in normal storage (Figure 1a). The reductions in viability of seed of each crop correlate quite closely (r = 0.795) with the extent of visible physical damage (Table 4).

Table 5. Viability percentages determined by tetrazolium and averaged across Occasions. Statistically significant differences are shown only between values for adjacent sampling points.

Sampling point[1]	1		2	3		4		5
Crop								
H	82	*	75	75		na		69
N	na[2]		90	90	*	84		86
T	82	***[3]	na	65		62		62
J	80	***	54	55		55		51
P	81	***	68	73	**	64	***	49
B	79	***	65	68	***	55		60
A	na		78	80		na		na

[1] Sampling points: 1 = before harvest; 2 = entering grain tank of harvester; 3 = entering truck bin; 4 = entering drier; 5 = at end of drying.

[2] Data not available.

[3] Level of significance applies to difference between SP1 and SP3 in the absence of a record from Sampling Point 2.

Viabilities of seed from Points 2 and 3 were essentially identical, indicating that no detectable damage was sustained in the comparatively brief time that seed spent in the grain tank of the harvester. Evidence of subsequent damage was inconsistent. This would be expected as different individuals have different methods of handling seed. Crops H, T and J showed no evidence of loss of viability during their time in the truck bin, while crop N showed some, and crops P and B much more. Crops N, P and B were hot on discharge, and N and P were held in the truck bin until late in the evening of the day of harvest. Crop P appeared to suffer further damage in the course of drying, though for no detected reason.

Figure 2f illustrates the general trends in viability levels across combined crops, emphasising the substantial damage sustained in passage through the harvester, the absence of change during time in the grain tank, and a small but distinct tendency for seed to deteriorate after each subsequent experience.

A point of observation is that caryopses from mechanically but not hand-harvested samples frequently showed patchy staining with tetrazolium, with sharp boundaries between stained and unstained areas. Unstained areas often included vital tissues, and such caryopses were therefore deemed non-viable. The effect closely resembled signs of physical damage in seeds of other types (Moore 1973). It was most common in the delicate structures of the embryonic axis, where it was sometimes accompanied by visible tiny fractures. The axis lies in what seems to be a particularly vulnerable position. It is close to the surface of the embryo, which is closely pressed to the under-surface of the lemma, which bulges to accommodate the embryo. Such a structure seems likely to attract, concentrate and transmit forces of impact. It is thus reasonable to attribute patchy staining to bruising and fracture caused by violent impact, and to attribute its presence to harvesting damage.

Laboratory germination

Laboratory germination percentage is of commercial importance in that seed saleability depends on it. However, results are difficult to interpret in terms of causes and effects because changes with time reflect the opposing effects of loss of viability on the one hand and dormancy breaking on the other. Dormancy-breaking test methods are at best incomplete, and only partially overcome the interpretation problems. Despite these complications, average germination percentages analysed in the same way as viabilities showed similar differences to those of the viability records (Table 6). Germination percentage was consistently and substantially reduced by passage through the harvester, and in the case of crop P, by the time spent in the truck bin. Other reductions in germination attributable to damage caused during drying, particularly in crop N, were small and difficult to explain.

With respect to changes in germination during storage, the main differences were between hand-harvested seed and the rest. To simplify presentation and to focus on the effects of mechanical harvest, data for seed from Sampling Points 1 and 2–3 only are presented (Figure 1b). These records show a general rise in germination percentage of all seed samples, reflecting primarily progressive early dormancy breaking and being most obvious where dormancy-breaking methods were employed. In the absence of potassium nitrate, early germination was greater in seed of SP2-3 than of SP1. The initial rise was followed by a decline in germination of seed of SP2-3 but not of SP1, a consequence of the greater loss of viability of SP2-3 and possibly of an accompanying decline in vigour.

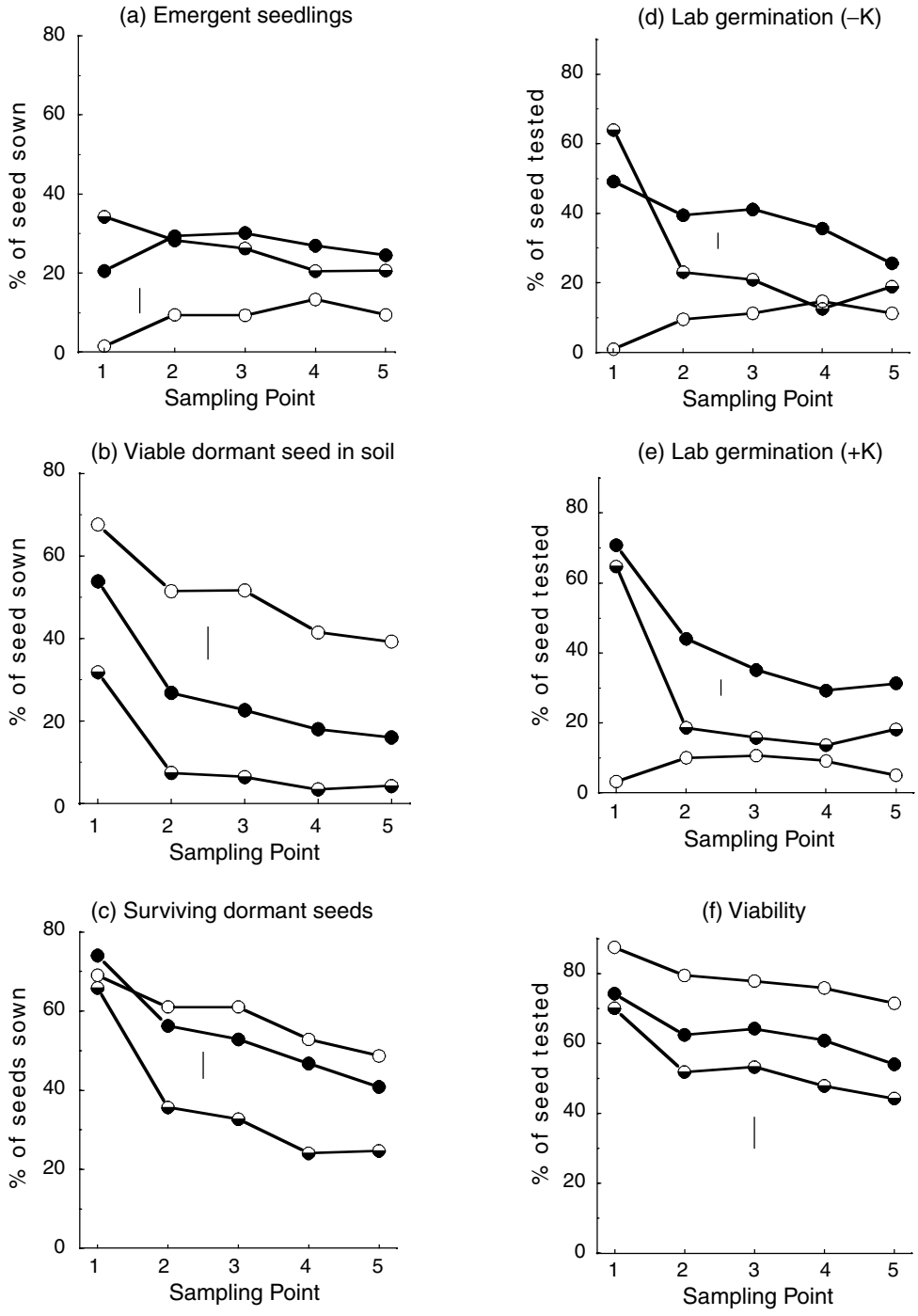

Figure 2. Changes in seed properties at different effective ages (y = years) over the sequence of harvest events marked by Sampling Points 1 to 5. Values are averages for 5 crops (HTJPB). Results shown are for: greenhouse tests in soil (Figures 2a, 2b and 2c); laboratory germination tests conducted with (+K) and without (-K) potassium nitrate (Figures 2d, 2e); and tetrazolium tests (Figure 2f). Open circles indicate seed of 0.25 yr effective age, filled circles of 1.52 yr and pied circles of 2.20 yr. Sampling points are: 1 = before harvest; 2 = entering grain tank of harvester; 3 = entering truck bin; 4 = entering drier; 5 = at end of drying. Vertical bars represent LSDs at P = 0.05.

Table 6. Average percentage germination values for all laboratory germination tests conducted, combining results of 6 sets of tests each including 2 test treatments (+K and –K)[1] and 5 effective ages of seed. Significant differences shown are between adjacent sampling points.

Sampling point[2]	1		2		3		4		5
Crop									
H	41	***	28		27		na[3]		24
N			53		52		51	***	44
T	45	***[4]	na		34	*	31	**	26
J	37	***	25	*	21		19		20
P	35	**	30		27	***	16	*	19
B	33	***	22		23		21	*	18
A	na		38		41		na		na

[1] K = potassium nitrate.
[2] Sampling points: 1 = before harvest; 2 = entering grain tank of harvester; 3 = entering truck bin; 4 = entering drier; 5 = at end of drying.
[3] Data not available.
[4] Level of significance applies to difference between SP1 and SP3 in the absence of a record from Sampling Point 2.

The extreme dormancy of fresh seed over-rode any possible early dormancy-breaking effect of potassium nitrate. The stimulus was negligible throughout the testing of SP2-3, presumably because harvesting had already broken much of the dormancy that test treatment would subsequently otherwise have broken. However, it was apparent at intermediate ages of SP1, though absent (as is common with aged seed) on the last testing occasion.

Figure 2 (d and e) reflects the same general trends. It further shows few or no differences in dormancy over Sampling Points 2 to 5. A progressive reduction in germination percentage over the same range of seed placed in cold storage on Occasion 3 provides some support, albeit inconsistent, for the conclusion drawn from the viability records that the later events of the harvest period caused further minor damage.

The most significant new point to note from the germination test results overall is that passage through the harvester had a substantial dormancy-breaking effect which, briefly during the early storage life of the seed, more than compensated for the already noted death that it also caused.

Emergence from soil

Field. The 5 field sowings in the first season after harvest (Occasion 2) all suffered seriously from lack of rain, with consequent low seedling emergence percentages. The results are combined for presentation (Table 7) because there is nothing extra to be learnt from scrutiny of the separate records of each sowing. The one clear consistent result was the very poor performance of hand-cut seed (Sampling Point 1). Even in the single crop (T) in which the difference from the closest combine-harvested seed (T3) was not statistically convincing, it may reasonably be argued from the behaviour of the T4 and T5 seed that the same effect existed but was masked by the anomalously and inexplicably poor emergence of T3 seed. In view of the results of the germination tests, the differences as a whole can be attributed only to the greater persistence of dormancy in the hand- than the combine-harvested seed.

Table 7. Average seedling emergence of 5 sowings in the field at effective age 0.78 years (Occasion 2), expressed as a percentage of pure seeds sown. Significant differences shown are between adjacent sampling points.

Sampling point[1]	1		2	3		4	5
Crop				(%)			
H	1.0	***	8.4	8.4		na[2]	7.2
N	na		13.3	13.7	**	7.0	7.1
T	3.6		na	4.8		8.1	10.1
J	1.4	**	3.6	3.9		4.4	4.7
P	0.8	***	8.5	11.2		8.2	4.7
B	1.9	**	4.2	5.6		8.9	3.4
A	na		8.1	9.4		na	na

[1] Sampling points: 1 = before harvest; 2 = entering grain tank of harvester; 3 = entering truck bin; 4 = entering drier; 5 = at end of drying.
[2] Data not available.

The only other result of note is the inferior emergence of N seed sampled after spending an unduly long time in the truck bin. It supports a similar effect on viability (Table 3) and strengthens the view that the experience must have been damaging.

Greenhouse. The failure through drought of field tests in the second sowing season (Occasion 3) leaves only the results of greenhouse tests to provide patterns of change over time (Figures 2a, 2b and 2c). The more benign conditions of the greenhouse produced far greater overall seedling numbers, and by exhuming ungerminated seeds, dormancy and death were separated as reasons for failure to emerge. The trends were unambiguous with the events of harvest causing enough damage to reduce overall survival in soil (seedlings plus dormant seeds) (Figure 2c). The most conspicuous difference was between Points 1 and 2 but the tendency was detectable, albeit less marked, over the remainder of the sequence.

However, these trends were not detectable in terms of seedling emergence, the patterns of which illustrate failure of 0.25-year-old seed, especially that of Point 1, but otherwise only minor and uncertain differences from point to point (Figure 2 a).

The reasons for this become apparent when the numbers of viable dormant seeds are examined (Figure 2b). Dormancy in soil disappeared with time, and did so much more rapidly as a result of the seed having been combine-harvested. The two progressive but opposing influences of dying and dormancy breaking served to cancel each other out remarkably consistently across points in terms of the numbers of seeds able to produce emergent seedlings (Figure 2a). Only in the earliest-tested seed did the dormancy of the Point 1 seed prevail excessively; and only on the final testing occasion did the same seed seem to be beginning to show the benefit of its superior retention of viability.

The differences between crops in patterns of emergence and survival in the greenhouse were small and inconsistent, so the details are not presented.

Discussion

Pre-harvest condition of seed

Seed was of variable quality as it stood in the ripe crop ready for harvest. The main cause was variation in mature caryopsis content between crops (54–88%; average 66%). The significance of this influence is reflected in the strong correlation (r = 0.934) between mature caryopsis content (Table 3) and viability (Table 5) of combine-harvested seed (using viability values from Sampling Points 2 and 3 only, to avoid variation due to subsequent influences). The subject of maturity has been dealt with in detail elsewhere (Hopkinson and English 1985), and only the implications relevant to the present focus need be raised. They are as follows. Variation in mature caryopsis content was an enduring and substantial cause of variation in seed quality, which was felt throughout the period of storage. Mature caryopsis content perhaps increased very slightly during harvest (if so, then probably through selectivity of detachment in the thresh). However, any possible benefit was trivial, and far too small to compensate for the reduction in viability through damage. Neither change nor variation in mature seed content interacted with other influences on quality. Mature seed content is a factor outside the control of the harvester, being largely determined by prior weather and not by harvest time. Thus, though mature seed content certainly influences the length of time that stored seed remains saleable, it may, in the present context, be relegated to the status of a chance variable.

Harvest effects

When all records are considered, the evidence for physical damage during harvest reducing life expectancy while breaking dormancy, is overwhelming. The effects were clear and consistent across crops. The immediate reduction in viability, the diminished survival in storage and after sowing in soil, the physical evidence of damage to covering structures, and the topographic irregularities with tetrazolium staining all confirm the destructive effect and reinforce the link with behaviour. The beneficial effect on surviving seeds, dormancy breaking, is compatible with damage to seed during harvesting. There is ample prior evidence that the disruption of covering structures of hard-husked panicoid seeds breaks dormancy. It underlies the use of acid scarification in the testing of seeds of several closely related grasses, is shown in the results of experiments in which specific covering structures have been removed, and conforms to theory on the causes of dormancy (Renard and Capelle 1976; Whiteman and Mendra 1982; Adkins *et al.* 2002).

The damage must occur at some point between the cutting of the crop by the open front of the combine-harvester and the arrival of the seed in the grain tank. The obvious one is in the threshing cylinder. Here, the ingested bulk of the standing crop is compressed into about 0.5% of the cross-sectional area it occupied in the field. It is forced between rotor and concave surfaces spaced a few millimetres apart, passing one another with a speed differential approaching 100 km/h. It is subjected to massive forces of acceleration, impact and shear. Although it experiences other mechanical disturbance in its journey through augers, elevators, beater, racks and screens, none combines these forces as severely or inescapably as the action of the threshing cylinder. For these reasons we equate harvest damage with threshing damage.

There is no convincing evidence of changes to seed while in the grain tank of the harvester.

Every harvester operator is aware that bulk seed temperature rises noticeably as seed accumulates in the grain tank but, with the normal frequency of discharge, the rise is presumably too little or the duration too brief to cause material damage.

Effects of the later events of the harvest certainly existed, though overall they were slight. They were inconsistent across crops, reflecting the individual ways in which growers arrange their harvest operations. They were also often inconsistent across tests, emphasising both the difficulties of detecting small differences and the subtleties of response of seed lots of varying characteristics to tests that reflect different properties. The later events had more effect on seed survival than dormancy. While overall seed quality continued to decline progressively during transport and drying (this is best seen in Figure 2), the effects were insignificant relative to the impact of threshing.

Implications

Threshing damage was previously undocumented and was generally unrecognised in tropical pasture grass seeds. Yet, it appears to be commonplace, and its consequences are far-reaching. It has no immediate solution. Its effects are mostly severe, probably occur in all combine-harvested seed crops of panicoid pasture grasses, and are possibly unavoidable. It is a two-edged sword: while it kills, it also breaks dormancy. To the merchant, who judges seed quality by the length of time his seed retains the ability to exceed a certain germination percentage, threshing damage creates a problem (Figure 1b illustrates it vividly). To a user wanting high germination rates from first-year seed, the dormancy-breaking effect is an all-important asset, as the field record shows. We must consider what scope for improvement exists in such circumstances.

The extension of the principles of brush (Jensen *et al.* 1993) or air-flow harvesters (Wildin *et al.* 1993) to green panic harvesting would undoubtedly extend seed storage life, but to no advantage if, as seems inevitable, it failed to hasten dormancy breaking. A more promising approach, suggested by the record of crop N which combined the least physical damage with some of the best overall test results, might be to use relatively gentle threshing cylinder settings in the hope of their breaking dormancy without either killing seed or sacrificing recovery efficiency.

The demonstration of inconsistent damage attributable to transport and drying practices was less of a surprise. Damage from suffocation, overheating and too-rapid drying has previously been identified (see Introduction), and clearly applies to the central Queensland green panic crop, though by no means universally. Ways of eliminating this damage exist and are widely understood, although under the pressures of harvest they are sometimes overlooked. The present results illustrate the position and the penalties.

A final point about general levels of quality of seed entering storage needs to be made. The ubiquity of caryopsis immaturity and the apparent inevitability of threshing damage virtually ensure that the usual percentage viability of seed lots entering storage will be below that desirable for long storage life. This makes it particularly important to minimise further deterioration, of which physiological aging in storage is the dominant cause. Although rates of loss of viability in conditions chosen to imitate those of commercial storage can be determined from the records (*e.g.* Figure 1a), they are no more than a starting point, for neither the range of storage conditions experienced commercially nor the rates of extinction of viability of green panic seed in relation to them are known. Fortunately however, the directions of change predictable from the underlying principles are clear: reductions in storage temperature and particularly stored seed moisture content retard aging (Roberts 1972; Ellis and Roberts 1981; Ellis 1988). The possibilities for achieving them might therefore usefully be examined.

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