

Effects of pre-harvest and post-harvest factors on grain hardness and stress cracking in three maize hybrids

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Abstract

The effects of several pre-harvest factors (hybrid, nitrogen, harvest grain moisture content) and post-harvest drying factors (drying temperature and relative cooling rate) on grain physical attributes and stress cracking were investigated. While the proportion of hard endosperm (H/S ratio) increased in all three hybrids with nitrogen application, the effects of nitrogen on grain hardness and drying rates were small. Stress cracking and the stress crack index (SCI) in grain were significantly affected by the main effects of hybrid, nitrogen, harvest moisture, drying temperature and cooling rate. As drying temperature increased from 50°C to 80°C, the percentage of grains with multiple and checked stress cracking increased. As cooling rate reduced from 1.11 to 0.23 °C/°C/minute x 10⁻², the numbers of sound grains (non-stress cracked grains) significantly increased. At the lowest cooling rate of 0.23 °C/°C/minute x 10⁻², checking was minimal and less than 15% of the grains had multiple stress cracks. Prediction curves indicated that hybrid P3902 had the lowest SCI among the three hybrids, the SCI being around 205 at 0 kg N/ha and 240 at 230 kg N/ha, respectively. The SCI value for hybrids Furio and P3753 was more than 300 irrespective of nitrogen. Stress cracking in grains was affected more by cooling rate than any other factors.

Additional key words: Zea mays, hybrid, nitrogen, grain hardness, stress cracking index, drying temperature, cooling rate.

Introduction

Several studies have shown that maize grain hardness and breakage susceptibility are inherited characteristics (Johnson and Russell, 1982; Paulsen *et al.*, 1983), indicating that these physical characteristics could be improved by hybrid selection and crop management. One of the most important cultural practices related to grain hardness and breakage susceptibility is the use of nitrogen fertiliser (Bauer and Carter, 1986). Recent studies have shown that as plant available nitrogen increased, grain hardness (i.e., the ratio of hard to soft (horny to floury) endosperm) increased and breakage susceptibility was reduced; this could improve corn dry milling quality (Ahmadi *et al.*, 1995; Oikeh *et al.*, 1998).

Although hybrid selection and crop management can improve the physical quality attributes of the grain,

improperly controlled drying may reduce grain quality (Brooker *et al.*, 1992). Particularly, problems can be compounded when grain harvested at high moisture contents (above 30%) is subjected to exposure to high drying-air temperatures. Weller *et al.* (1990) found that stress cracks increased significantly as harvest grain moisture increased from 18 to 30%, irrespective of whether the drying air temperature was 49, 71, or 93°C. Stress cracking associated with high temperature rapid drying from high grain moisture can be reduced significantly if grains are cooled slowly after drying. This process called, 'dryeration' (or tempering) has long been known (Thompson and Foster, 1963) and is applied in practice with multi-pass, multistage drying systems. However, the extra cost involved in these systems has limited their use (Bakker-Arkema *et al.*, 1996).

Nitrogen availability and grain moisture at harvest are important agronomic factors that may affect grain quality. However, there has been little information on the effect of harvest moisture and nitrogen on the level of stress cracking following drying. The objectives of this study were: 1) to determine the effect of hybrid and nitrogen on grain hardness (hard to soft endosperm ratio), and 2) to determine the effect of hybrid, nitrogen, harvest moisture, and drying and cooling rate on stress cracking in maize grains.

Material and Methods

Field trial

Three commercially grown maize hybrids (Furio, Pioneer 3902, and Pioneer 3753) were used. These are early maturing hybrids suitable for cool or short season areas such as the Manawatu in New Zealand (Eagles and Hardacre, 1985). The trial was conducted at a site at Massey University (40° 23'S) on a mottled, fine sandy loam soil. The field trial design was a split-split plot. There were three blocks and main plots were two levels of applied nitrogen (0 and 230 kg N/ha); within each main plot, the three hybrids were randomised. Each hybrid sub-plot was again divided into two levels of grain moisture at harvest (22 and 30%). Each sub-plot consisted of 16 rows, 0.75m apart between the rows and 25 stations within a row with a 0.15m interval between stations. At planting rows were oversown and thinned to achieve a density of 89,000 plants/ha (Hardacre *et al.*, 1992). Two rows between sub-plots were not sampled and four guard rows were planted on the outside of each block. At the end of each row five plants were also retained as guards. The crop was planted on 20 November 1995. Seeds were treated with an insecticide (Promet 300EW) at a rate of 40ml/kg (12 g/kg of furathiocarb) of seed prior to sowing. The pre-emergence herbicides Alachlor and Gesaprim were applied one day after sowing (21st of November) at a rate of 7 l/ha for Alachlor (3.36 kg/ha alachlor) and 3 l/ha for Gesaprim (1.5 kg/ha atrazine). After signs of infestation by cutworm (*Agrotis ipsilon aneituma* Walker), about one month after sowing Hallmark was applied at a rate of 450 ml/ha (22.5g/ha esfenvalerate). The nitrogen (N) treatments (0 and 230 kg N/ha) were applied as a side dressing using urea (46% N) at four times to avoid the loss of nitrogen by leaching and volatilisation. The first application of urea (46 kg N/ha) was made at 25 days after sowing (DAS), the second and third applications

(both 46kg N/ha) were added at 35 DAS and 60 DAS, and the last application (92kg N/ha) at 83 DAS.

The number of grains per cob (NOG), hundred grain weight (HGW), grain yield, bulk density and grain hardness (hard to soft endosperm ratio) were determined. For this, handpicked primary cobs (i.e., the cob located in the lowest position on the maize plant) from ten maize plants in each replicate were de-husked and dried at ambient temperature (approximately 20°C, 65% RH) to an average of 11% grain moisture. All cobs were then hand-shelled after drying and grain stored at room temperature before testing.

The number of grains per cob was determined by multiplying the average number of grains down the ear by the number of rows of grain at the centre of the ear. Hundred-grain weight was determined by measuring the weight of 100 grains for each replicate and adjusting the weight to 14% grain moisture content; grain yield was also expressed at 14% grain moisture. Bulk density of grains harvested at both 22 and 30% grain moisture was determined by using the method of Hardacre *et al.* (1997). The hard to soft endosperm ratio (H/S ratio) of corn grain was determined by using 25 grains harvested at 30% grain moisture. After drying, each grain was sectioned with a knife just above the top of the embryo region (about 2/3 of the distance from the tip cap to the crown) and the H/S ratio determined (Kirleis *et al.*, 1984).

Laboratory drying trial

The drying experiment was conducted in a laboratory where the temperature was approximately 20°C and relative humidity approximately 65-70%. For the drying experiment, approximately 40 cobs (12kg) were hand-harvested from each plot in the afternoon before a drying test. Due to differences in maturity and field dry down rate of the hybrids (Newton and Eagles, 1991), the moisture content among treatments was different. The cobs were hand-shelled and very small grains that passed through a 6.75mm sieve were discarded. Grain was sealed in a plastic bag and stored at 5°C. The harvest moisture was determined by the two stage moisture test (ISTA, 1996) using 20g sub-samples drawn from each sample. Before drying, about 300g of grains were spread evenly in a single layer in the drying tray. The grain was dried in 14.5cm (width) x 44.2cm (length) x 7 cm (height) rectangular metal trays with 0.3mm wire mesh bases. Each tray was divided into half with a cardboard

partition to allow two cooling treatments. The trays and grain were weighed before drying at 50, 60, 70 or 80°C ± 2°C. The treatments were randomised in the oven. An extra tray was re-weighed at 30-minute intervals for 4 hours, then 60-minute intervals to predict the desired grain moisture. When the grain moisture reached about 17%, one of the drying trays was removed from the oven for a 45°C cooling treatment. The others were removed when the grain moisture reached about 15%. Soon after removal from the oven, each tray was quickly weighed and the grain surface temperature measured using an infrared thermometer. The grain was then poured into a 250ml polystyrene cup and cooled at 45, 25, or 5 ± 1°C. During cooling, one polystyrene cup remained open for fast cooling. The other cup was covered with a lid and placed in a sealed polystyrene box to reduce the cooling rate. For cooling at 45°C, grain was first tempered at 45°C for 4 hours in an incubator and then cooled at 25°C for 20 hours; for the 25 and 5°C cooling, grains remained at each cooling temperature for 24 hrs. During cooling the grain temperature was periodically recorded. The six cooling rates of 0.23, 0.34, 0.55, 0.75, 0.81 and 1.11 °C/°C/minute x 10⁻² were established for the 45°C-slow (sealed) cooling, 45°C-fast (lid-open) cooling, 25°C-slow-cooling, 25°C-fast-cooling, 5°C-slow-cooling and 5°C-fast-cooling treatments (Table 1). The relative cooling rate (CR) associated with each treatment were defined as:

$$CR = \frac{(TR_0 - TR_{30})}{30}$$

Table 1. Relative cooling rate for maize grains in the slow and fast cooling systems at three cooling temperatures.

| Cooling Temperature (°C) | Cooling Rate (°C/°C/minute x 10 ⁻²) | |
|--------------------------|--|------|
| | Slow | Fast |
| 45 [†] | 0.23 | 0.34 |
| 25 | 0.55 | 0.75 |
| 5 | 0.81 | 1.11 |

[†] Grain was tempered for four hours at 45°C prior to cooling at 25°C for 20 hours. At 25 and 5°C, grains were cooled for the entire 24 hours at these temperatures.

where, CR = Cooling rate (°C/°C/minute); TR₀ = grain temperature ratio at 0 minutes after drying (0 minutes after drying grain temperature (°C)/initial grain temperature (°C)); TR₃₀ = grain temperature ratio at 30 minutes after drying (30 minutes after grain temperature (°C)/initial grain temperature (°C))

After cooling, the samples were stored in ambient conditions (approximately 20°C and 65% relative humidity) for 4 weeks for moisture equilibration before stress cracking assessment.

Stress cracking was determined on a 50g sub-sample of each replicate containing from 130 to 170 grains. Stress cracking in each grain was evaluated by placing it on an illuminated glass panel. Stress cracks were assessed by examining the grain from both sides. Grains were classified into four stress-crack categories i.e. none, single, multiple and checked or crazed (Thompson and Foster, 1963). Stress cracking in soft grains of the three hybrids was not detectable due to their soft endosperm and low translucency. These were recorded as having no stress cracking. These data were used to generate a stress crack index (SCI; equation 1) (Kirleis and Strohshine, 1990) where:

$$SCI = \% \text{ single cracked grains} + 3 (\% \text{ multiple cracked grains}) + 5 (\% \text{ checked grains}) \quad (1)$$

The grain yield and quality data including the number of grains per cob, hundred grain weight, grain yield, bulk density and hardness ratio were analysed using the ANOVA and GLM procedures in SAS (SAS, 1985) appropriate for a split-split-plot experimental design. Values were considered different if *F* probabilities were less than 0.05%.

Where significant main effects occurred, means were compared using least significant differences (LSD). Significant interactions between independent variables were compared by plotting means on bar- or line-graphs along with appropriate LSD values. Stress cracking and stress crack index (SCI) data were analyzed using the same procedures and an empirical model was fitted to predict the average SCI for hybrid, nitrogen and drying temperature as a function of cooling rate by equation (2):

$$SCI = \frac{A}{1 + B \times e^{-(C \times CR)}} \quad (2)$$

where, A = asymptote; B = constant for initial value of SCI; C = rate increase in SCI to the asymptote within the range of drying air temperature of 50, 60, 70 and 80°C; and CR = cooling rate (°C/°C/minute x 10⁻²).

Results and Discussion

Field trial

Hybrid P3753 had a significantly higher grain yield and number of grains per ear than either hyb. P3902 or Furio. There was no significant difference in grain yield between hyb. P3902 and Furio (Table 2). Bulk density and hardness ratio (H/S ratio) were greatest for hyb. P3902, intermediate in hyb. P3753 and lowest for hyb. Furio. Nitrogen (N) application significantly increased hundred-grain weight, grain yield and bulk density. Although H/S ratio was also greater for the high N treatment, the increase was not significant.

There was a significant interaction between hybrid and nitrogen for hundred-grain weight and grain hardness (Table 2). Although hundred-grain weight and H/S ratio increased with nitrogen fertiliser for all hybrids, the increase was not always significant and the magnitude of the increase changed with hybrid. It is known that genetically different maize hybrids respond differently to the environment (Oikeh *et al.*, 1998) and variation in the magnitude of the response seems to reflect this.

Laboratory drying trial

At the conclusion of the drying trial, the proportion of checked and simple cracking in grains varied significantly, along with SCI, among the five treatments (Table 3). Although many of the two and three way interaction terms were statistically significant, they do not invalidate discussion of the main effects. In all possible comparisons among the variables the treatments ranked in the same order as the main effects. The interactions among the variables for stress cracking and SCI were, however, of relatively minor practical importance when compared to the *F*-values of the main effects (e.g., SCI cooling rate; $F_{CR}(3695.19) \gg F_{HYB \times CR}(54.97)$). The interaction terms were therefore of little use in interpreting these data.

The hard hybrid P3902 had a significantly lower proportion of checked grain and SCI than hyb. Furio or P3753. It is known that stress cracking in maize grains normally occurs in the protein matrix between starch granules (Balastreire *et al.*, 1982), and thus maize hybrids which have different endosperm characteristics show different stress crack susceptibility. Kirleis and Stroshine (1990) reported that hard grains had a higher percentage of stress cracks than soft grains, but hard grains had better milling characteristics. The results of this study, however, do not agree with their results. For example, there was no significant difference in H/S ratio between hyb. P3753 and P3902 at 230 kg N/ha (Fig. 1

Table 2. The effect of maize hybrid and nitrogen on the number of grains per ear, hundred grain weight, grain yield and bulk density.

| | | NOG ¹ | HGW (g) | Yield (t/ha) | Bulk Density (kg/hl) | Hardness (H/S ratio) |
|----------------------------------|----------------|------------------|------------|-----------------|-------------------------|-------------------------|
| Hybrid (HYB) | Furio | 511.0 | 30.9 | 14.3 | 72.2 | 2.0 |
| | P3753 | 569.8 | 31.0 | 15.7 | 74.7 | 2.7 |
| | P3902 | 504.7 | 32.2 | 14.8 | 76.2 | 2.9 |
| Significance | | *** | ** | * | *** | ** |
| LSD (5%, df _{error} =8) | | 23.2 | 0.7 | 1.0 | 0.4 | 0.5 |
| Nitrogen (N) | 0 kg N/ha | 519.2 | 30.4 | 14.0 | 73.8 | 2.1 |
| | 230 kg N/ha | 537.8 | 32.4 | 15.8 | 74.9 | 2.9 |
| Significance | | NS | * | * | * | NS |
| LSD (5%, df _{error} =2) | | - | 1.8 | 1.6 | 0.5 | - |
| Interactions | HYB x N | NS | ** | NS | NS | * |

¹NOG=Number of grains per cob; HGW=Hundred grain weight. Yield and bulk density were adjusted to grain moisture content of 14% (wet basis). NS, *, **, or ***; Non significant or significant *F*-test at <0.05, 0.01, 0.001, respectively.

(B)), but hyb. P3902 had a significantly lower stress cracking percentage than hyb. P3753 with elevated drying air temperatures (Fig. 2).

Hybrid P3902, which had the highest H/S ratio, was generally less susceptible to stress cracking than the other two hybrids (Table 3 and Fig. 2). Hybrid P3902

Table 3. The effects of maize hybrid, nitrogen, harvest grain moisture, drying temperature, and cooling rate on the percentage of various types of stress cracking and the stress crack index (SCI) in maize grains.

| | | Types of stress cracking ¹ (%) | | | | Stress Crack Index (SCI) ² |
|--|----------------|---|------|------|------|---------------------------------------|
| | | NSC | SSC | MSC | CSC | |
| Hybrid (HYB) | Furio | 26.7 | 10.0 | 51.3 | 12.1 | 224.2 |
| | P3753 | 25.7 | 12.2 | 53.1 | 9.0 | 216.4 |
| | P3902 | 40.0 | 18.3 | 39.8 | 1.9 | 147.3 |
| Significance | | *** | *** | *** | *** | *** |
| LSD(5%, df _{err} =8) | | 4.3 | 2.5 | 3.1 | 3.3 | 11.9 |
| Nitrogen (N) | 0 kg N/ha | 33.6 | 13.7 | 46.3 | 6.4 | 184.8 |
| | 230 kg N/ha | 28.0 | 13.3 | 49.9 | 8.8 | 207.1 |
| Significance | | * | ** | NS | NS | ** |
| LSD(5%, df _{err} =2) | | 3.8 | 0.1 | - | - | 9.7 |
| Harvest Moisture (HMC) | 22% | 35.2 | 12.5 | 44.8 | 7.5 | 184.4 |
| | 30% | 26.4 | 14.5 | 51.3 | 7.8 | 207.4 |
| Significance | | *** | * | *** | NS | ** |
| LSD(5%, df _{err} =12) | | 3.7 | 1.9 | 2.9 | - | 14.2 |
| Drying Temperature (DT) | 50°C | 37.0 | 16.2 | 42.2 | 4.7 | 166.1 |
| | 60°C | 30.6 | 13.2 | 48.0 | 8.2 | 198.2 |
| | 70°C | 30.5 | 12.5 | 48.8 | 8.2 | 199.8 |
| | 80°C | 25.0 | 12.2 | 53.3 | 9.5 | 219.7 |
| Significance | | *** | *** | *** | *** | *** |
| LSD(5%, df _{err} =72) | | 1.8 | 1.1 | 1.6 | 1.1 | 6.6 |
| Cooling rate (CR)³ (°C/°C/minute x 10 ⁻²) | 0.23 | 77.7 | 16.7 | 5.5 | 0.1 | 33.6 |
| | 0.34 | 63.8 | 19.7 | 15.5 | 1.0 | 71.3 |
| | 0.55 | 16.3 | 18.2 | 60.4 | 5.2 | 225.2 |
| | 0.75 | 10.2 | 10.2 | 68.7 | 10.8 | 270.7 |
| | 0.81 | 8.3 | 8.8 | 70.3 | 12.6 | 282.7 |
| | 1.11 | 8.4 | 7.5 | 68.0 | 16.1 | 292.1 |
| Significance | | *** | *** | *** | *** | *** |
| LSD(5%, df _{err} =480) | | 1.8 | 1.5 | 1.8 | 0.9 | 5.2 |
| Interactions | HYB x DT | NS | *** | *** | *** | ** |
| | HMC x DT | *** | ** | NS | NS | * |
| | HYB x CR | *** | *** | *** | *** | *** |
| | N x CR | NS | ** | NS | *** | *** |
| | HMC x CR | *** | *** | *** | NS | *** |
| | DT x CR | *** | *** | *** | *** | *** |
| | HYB x N x CR | NS | * | *** | * | NS |
| | HYB x HMC x CR | ** | NS | *** | NS | *** |
| | HMC x DT x CR | *** | *** | ** | NS | * |
| | HYB x DT x CR | NS | *** | *** | *** | *** |

¹NSC, non-stress-cracking; SSC, single stress cracking; MSC, multiple stress cracking; CSC, checked stress cracking.

²Stress Crack Index (SCI) = %Single + 3 x (%Multiple) + 5 x (%Checked)

³The cooling rates created by the different cooling temperatures and cooling systems (see Table 1).

NS, *, **, or *** ; Non significant or significant *F*-test at <0.05, 0.01, 0.001, respectively.

has a dark yellow colour in its hard endosperm and looks less translucent than the other hybrids selected in this study. Thus it is suspected that instead of H/S ratio, endosperm characteristics related to colour and translucency in grain may affect the susceptibility to stress cracking. Although not measured this study, the amounts and properties of starch granules and protein bodies in hard endosperm, or structural differences in hard endosperm due to differences in genetic or cultural background may also be involved in stress cracking (Peplinski *et al.*, 1994).

Grain hardness (vitreousness) increases as soil fertility increases (Oikeh *et al.*, 1998). That is, higher soil nitrogen produces a larger proportion of hard endosperm in maize grain than lower soil nitrogen (Bauer and Carter, 1986; Ahmadi *et al.*, 1995). Ahmadi *et al.* (1995) also reported a positive relationship between nitrogen concentration and grain hardness and between grain protein (zein) content and grain hardness. They concluded that higher soil nitrogen rates increased overall grain hardness due to increased nitrogen concentration in the grain, and apparently reduced breakage susceptibility in most hybrids. Although it has previously been reported that a high grain moisture content at harvest increases stress cracking and grain breakage (Weller *et al.*, 1990), in this study the effect of

nitrogen and harvest grain moisture content on stress cracking was small (Table 3). This might be due to the predominant effect of post-drying cooling condition (i.e., cooling rate) on stress cracking (Fig. 2).

The effects of post-harvest drying factors including drying temperature and cooling rate on stress cracking were highly significant. As drying temperature increased from 50 to 80°C, the percentage of multiple and checked stress cracked grains and the SCI increased significantly. There was no significant difference in the proportion of checked grains or SCI for grain dried at 60 and 70°C. Increases in drying temperature might increase heat stress in maize grain. At higher drying temperatures, grains were visco-elastic and had bigger moisture and temperature gradients, thus resulting in a higher percentage of checked stress cracking and SCI.

As cooling rate increased from 0.23 to 1.11 °C/°C/minute x 10⁻², SCI in grains increased significantly. The difference in SCI was greatest at cooling rates between 0.34 and 0.55 °C/°C/minute x 10⁻² (Table 3). As already noted the *F*-value for cooling rate was the greatest of all the factors (not shown), indicating that cooling rate was the most important factor affecting stress cracking and SCI. Irrespective of hybrid, nitrogen, harvest moisture and drying temperature, at the lowest

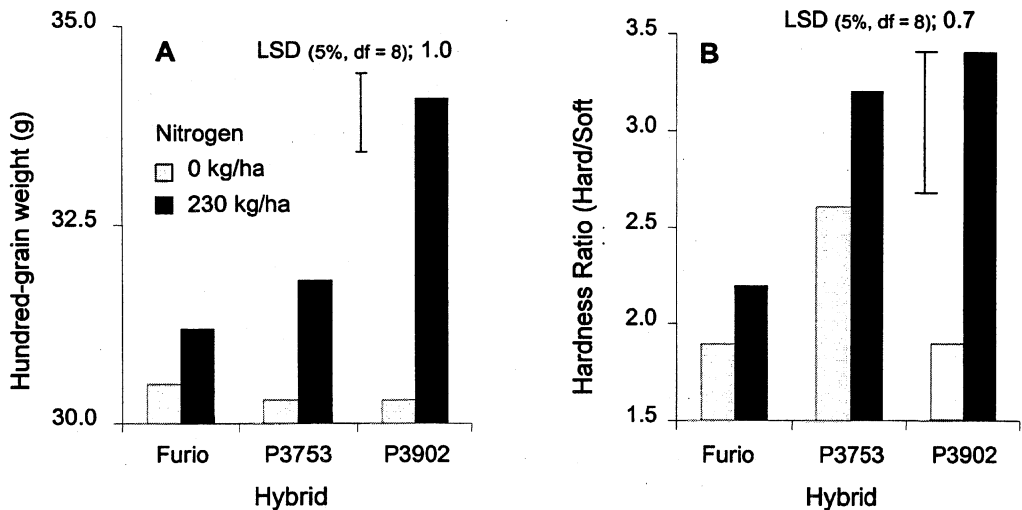


Figure 1. The interaction between hybrid (HYB) and nitrogen (N) for hundred-grain weight (HGW) (A) and hardness ratio (B).

cooling rate of $0.23 \text{ }^{\circ}\text{C}/^{\circ}\text{C}/\text{minute} \times 10^{-2}$ (45°C -slow cooling (tempering)), checking was minimal and SCI was less than 100 ((Table 3; Fig. 2). This indicated that decreases in cooling rate might reduce the moisture and temperature gradients between outer and centre parts of the grain. Thus stress cracking in grains dried at high

temperatures could be reduced by slow cooling (Hardacre and Pyke, 1998). Decreases in cooling rate will relieve drying stress by allowing equilibration of moisture in the grain (Brooker *et al.*, 1992).

The effect of drying temperature and cooling rate on the SCI can be predicted in the model developed in Fig.

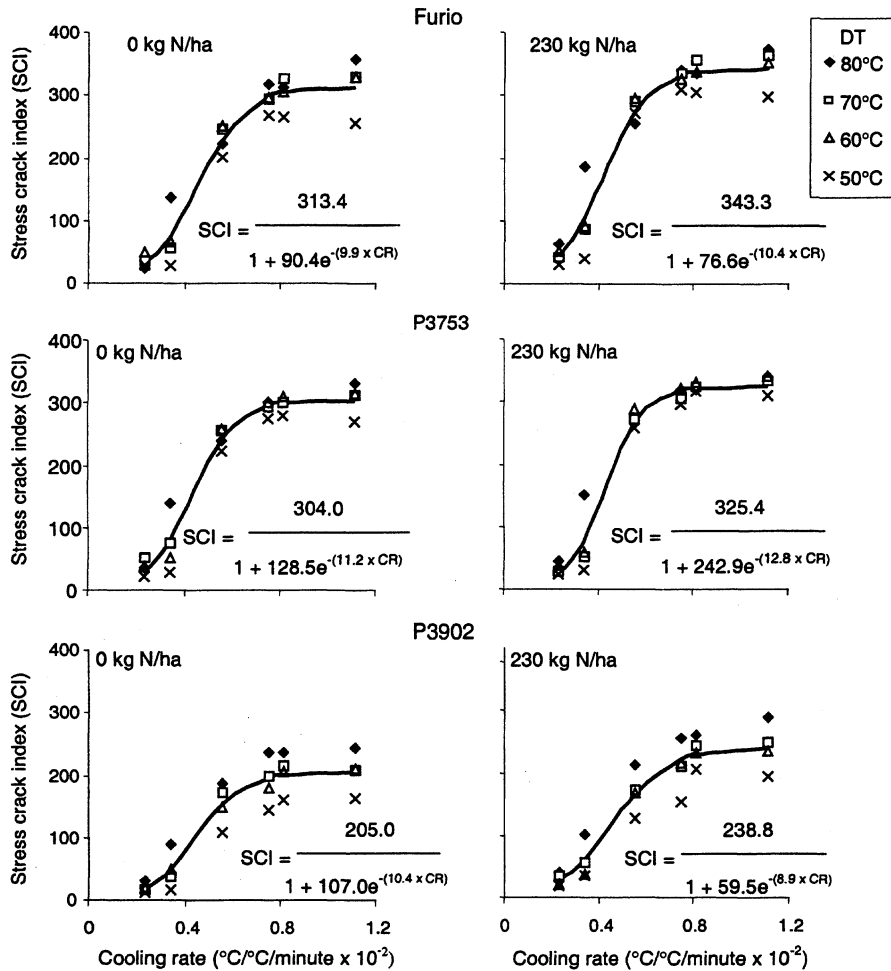


Figure 2. Models for stress crack index for three corn hybrids grown at different levels of applied nitrogen, dried at various drying temperatures (DT) and cooled at various cooling rates. N.B. The empirical model (a thick solid line) was calculated using the following equation:

$$\text{SCI} = \frac{A}{1 + B \times e^{-(C \times \text{CR})}}$$

where, A = asymptote, B = constant for initial value of SCI, C = rate increase in SCI to the asymptote within the range of drying air temperature of 50, 60, 70, and 80°C, and CR = cooling rate ($^{\circ}\text{C}/^{\circ}\text{C}/\text{minute} \times 10^{-2}$).

2. The predicted SCI of the three hybrids reached a maximum (asymptote) at a cooling rate of around $0.75\text{ }^{\circ}\text{C}/^{\circ}\text{C}/\text{minute} \times 10^{-2}$. At cooling rates between 0.34 to $0.55\text{ }^{\circ}\text{C}/^{\circ}\text{C}/\text{minute} \times 10^{-2}$, the SCI of all hybrids increased at similar rates (Fig. 2). Hybrid P3902 had a lower predicted maximum SCI (205-238) than the other two hybrids (304-343) for both nitrogen treatments. Increasing the level of N fertiliser increased the predicted maximum SCI in all three hybrids, but the difference in maximum SCI between the two nitrogen levels was small (Fig. 2).

The model developed in this study predicted the average SCI over the hybrid, nitrogen and drying temperature treatments. However, the model did not fit SCI values independently for hybrid, nitrogen, harvest moisture and drying temperature. Inspection of the data in Fig. 2 shows that the model adequately predicted the rate of development of maximum SCI for all except the 50°C drying treatment. At 50°C the rate of development of SCI was similar to the after-drying treatments, but the maximum SCI was lower than the after drying treatments.

Conclusions

These results confirmed that slow cooling after drying at high temperatures significantly reduced stress cracking. Stress crack development was also significantly affected by drying temperature, hybrid, harvest moisture and nitrogen. The data for SCI indicated that stress cracking could be reduced by using a slow cooling rate, a low drying temperature and by selecting a hybrid less susceptible to stress cracking.

References

- Ahmadi, M., Wiebold, W. J. and Beuerlein, J. E. 1995. Physical characteristics of corn kernels as influenced by nitrogen fertilization. *Communications in Soil Science and Plant Analysis* 26, 145-153.
- Bakker-Arkema, F. W., Montross, M. D., Liu, Q. and Maier, D. E. 1996. Analysis of continuous-flow grain dryers. In: Grain Drying in Asia. Proceedings of an international conference held at the FAO regional office for Asia and the Pacific, Bangkok, 17-20 October 1995, (eds. B.R. Champ, E. Highley and G.I. Johnson). *ACIAR Proceedings No. 71*, 123-131.
- Balastreire, L. A., Herum, F. L. and Blaisdell, J. L. 1982. Fracture of corn endosperm in bending. Part II: Fracture analysis by fractography and optical microscopy. *Transactions of the American Society of Agricultural Engineers* 25, 1062-1065.
- Bauer, P. J. and Carter, P. R. 1986. Effect of seeding date, plant density, moisture availability and soil nitrogen fertility on maize kernel breakage susceptibility. *Crop Science* 26, 1220-1226.
- Brooker, D. B., Bakker-Arkema, F. W. and Hall, C. W. 1992. Drying and Storage of Grains and Oilseeds. Van Nostrand Reinhold, New York.
- Eagles, H. A. and Hardacre, A. K. 1985. Prospects of breeding maize cultivars specifically for New Zealand conditions. In: Maize-Management to Market. (eds. H.A. Eagles and G.S. Wratt). Agronomy Society of New Zealand Special Publication No. 4, 73-77.
- Hardacre, A. K., Brenton-Rule, R. and Clark, S. M. 1997. The analysis of maize grain quality in New Zealand and calibration of testing methods. Report No. 367. Maize Grain Quality Committee, New Zealand Manufacturers Association. NZ Institute of Crop & Food Research Ltd., Christchurch, New Zealand.
- Hardacre, A. K., Sinclair, K. I. and VanTilburg, M. P. 1992. Maize: a guide for growers. Agricultural Bulletin No.18. DSIR Crop Research, New Zealand.
- Hardacre, A. K. and Pyke, N. 1998. Influence of commercial drying on maize grain attributes. Arable update. No.10. Foundation for Arable Research, Lincoln, New Zealand.
- ISTA. 1996. International Rules for Seed Testing. Supplement to *Seed Science and Technology* 24, 1-310.
- Johnson, D. Q. and Russell, W. A. 1982. Genetic variability and relationships of physical grain quality traits in the BSSS population of maize. *Crop Science* 22, 805-809.
- Kirleis, A. W., Crosby, K. D. and Housley, T. L. 1984. A method for quantitatively measuring vitreous endosperm area in sectioned sorghum grain. *Cereal Chemistry* 61, 556-558.
- Kirleis, A. W. and Stroshine, R. L. 1990. Effects of hardness and drying air temperature on breakage susceptibility and dry-milling characteristics of yellow dent corn. *Cereal Chemistry* 67, 523-528.
- Newton, S. D. and Eagles, H. A. 1991. Development traits affecting time to low ear moisture in maize. *Plant Breeding* 106, 58-67.

- Oikeh, S. O., Kling, J. G. and Okoruwa, A. E. 1998. Nitrogen fertilizer management effects on maize grain quality in the West African moist savanna. *Crop Science* 38, 1056-1061.
- Paulsen, M. R., Hill, L. D., White, D. G. and Sprague, G. F. 1983. Breakage susceptibility of corn-belt genotypes. *Transactions of the American Society of Agricultural Engineers* 26, 1830-1841.
- Peplinski, A. J., Paulis, J. W., Bietz, J. A. and Pratt, R. C. 1994. Drying of high-moisture corn: changes in properties and physical quality. *Cereal Chemistry* 71, 129-133.
- SAS. 1985. SAS User's Guide: Statistics, Version 5th ed. SAS Institute, Cary, NC.
- Thompson, R. A. and Foster, G. H. 1963. Stress cracks and breakage in artificially dried corn. Marketing Research Report No. 631. Agricultural Marketing Service, United States Department of Agriculture, Washington, DC.
- Weller, C. L., Paulsen, M. R. and Steinberg, M. P. 1990. Stress cracking and breakage susceptibility as affected by moisture content at harvest for four yellow dent corn hybrids. *Transactions of the American Society of Agricultural Engineers* 33, 863-869.