The effect of nitrogen fertilisation on maize grain quality and yield.

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Abstract

Variable grower payments based on grain quality are becoming increasingly common in the New Zealand maize grain industry. Grain quality attributes vary considerably among hybrids, resulting in grain processors specifying hybrids for different end uses. However, grain quality can also fluctuate within a hybrid. Previous research suggests nitrogen (N) fertiliser can modify grain quality. A trial was established to investigate the effect of N fertiliser rate and time of application on the yield and quality of maize grain from different hybrids in the Manawatu. Significant variation among hybrids occurred for all agronomic characteristics and for all grain characteristics measured, except bulk density. A significant hybrid × N fertiliser interaction for grain yield was detected; a result of hybrid differences in response to N fertiliser. Recovery of N fertiliser in the grain was low in all hybrids. Nitrogen fertiliser had no affect on grain N %, grain hardness and bulk density, but did significantly increase 200 grain weight. Correlations between agronomic characteristics and grain properties are discussed. The high grain N % achieved in the control treatment indicates that soil N levels were near optimum, limiting grain yield and quality responses to N fertiliser.

Additional keywords: *Zea mays L*., hybrid, lodging, grain N, bulk density, broken corn, grain hardness, energy to grind, resistance time, N recovery.

Introduction

The maize (*Zea mays L.*) grain industry, particularly the milling industry, increasingly views maize as a 'value-based' product destined for a variety of end uses. Historically growers have been paid primarily on a per tonnage basis and have thus grown crops to maximise returns from grain yields. Typically maize grain contracts have varying levels of specification for moisture content, test weight, broken corn and foreign material, and diseased grain. Some end users are now specifying preferred hybrids each with their own unique quality criteria (Anon., 1996a; Anon., 1996b). Growers are now presented with the opportunity to achieve premiums for grain which achieves minimum quality criteria (K. Dowie, pers. comm.).

Hybrid selection, crop management, and cultural practices have been highlighted as possible means of improving maize grain quality for specific end uses. Hybrids currently grown in New Zealand differ in their suitability to various growing environments and in grain quality attributes (Hardacre, 1997; Brenton-Rule *et al*., 1996).

Both the yield and quality of maize are strongly influenced by the availability of nitrogen (N). The yield components of maize under the most direct influence of N are grain number per ear and 200 grain weight. Both can be strongly decreased by insufficient N supply (Tsai *et al*., 1990). Other yield components, such as plant population and ears per plant, are mostly determined by crop management decisions such as planting rate and hybrid choice. The indirect influence of N on grain yield is principally through leaf area, leaf area duration, crop photosynthetic rate, proportion of radiation intercepted and radiation use efficiency, which all decrease under inadequate N supply (Uhart and

Andrade, 1995). This results in reduction of crop growth rate, dry matter (DM) accumulation and a delay in vegetative and reproductive development (McCollough *et al*., 1994). Inadequate N nutrition also reduces DM partitioning to the ear, ear growth rate and ear DM accumulation (Uhart and Andrade, 1995; Tsai *et al*., 1990).

In New Zealand the majority of maize is grown as part of a rotation with pasture and other crops, although some growers undertake continuous maize growing practices. Where maize is grown in a crop rotation in New Zealand little yield response to N fertiliser has been recorded (Douglas and Sinclair, 1972; Douglas *et al*., 1972). Steele *et al*. (1982a) found that, of 42 trial sites across New Zealand over three growing seasons, 20 sites produced no significant grain yield responses to N fertiliser. The authors state that "the N status of a field is characteristic of that particular field, and fertiliser recommendations cannot be extrapolated to other fields, even within the same soil type and farm". The lack of response to N fertiliser may be due to the mineralisation of soil organic matter which releases mineral N or the influence of other limiting factors such as soil compaction (Steele, 1983)

Steele (1983) describes methods of determining the N fertiliser requirements of maize for grain, utilising soil and foliage analysis. A number of soil testing procedures are available for determining the N status of soils; an anaerobic incubation test for N, which includes mineral and mineralisable N, has been incorporated into maize agronomic models in New Zealand (Reid *et al*., 1999).

Maize grain quality is primarily related to grain endosperm properties. Endosperm accounts for approximately 85% of total grain dry weight at maturity and contains about 70% of grain protein. Endosperm characteristics, although principally determined by genetics, may be influenced by the growing environment and agronomic practices, especially N fertiliser inputs (Sabata and Mason, 1992). Most endosperm protein consists of the protein zein, which plays an important role in determining grain texture; a high proportion of zein protein generally results in hard endosperm (Abdelrahman and Hosney, 1984). Hybrids with hard endosperm (eg flint hybrids) are preferred for products such corn chips which are made from dough (masa) using maize which has been cooked in a lime solution (Hardacre, 1997). Nitrogen fertiliser can increase grain N and grain protein, including zein (Tsai *et al*., 1992; Cerrato and Blackmer, 1990). Previous research has indicated that N fertiliser application increases grain vitreousness (Tsai *et al*., 1992), the proportion of hard endosperm and grain hardness (Ahmadi *et al*., 1995).

Little research has been published on the influence of N fertiliser on maize grain quality in New Zealand. This paper reports on an exploratory study initiated to investigate the influence of the rate and timing of N fertiliser application on maize grain quality in hybrids with different grain characteristics. The effect of N fertiliser rate and timing on grain yield is also discussed.

Materials and Methods

A field experiment was sown on 8 November 1995 at the AgResearch Aorangi Research Station into a Kairanga silt loam (Cowie, 1978). Soil tests (15 cm) taken in September 1995 revealed an Olsen P of 26 and total N content of 78 µg/g of soil (air dry), including 53 µg/g mineralizable N. The trial area had been in maize for the previous two seasons. A split-plot design with three replications was used, with each hybrid by fertiliser treatment plot consisting of two rows, 3.75 m long and 0.75 m apart. Six maize hybrids differing in comparative relative maturity (CRM) and physical grain characteristics used in this study are described in Table 1. Four N fertiliser treatments consisted of ammonium sulphate applied at three rates; 0kg N/ha, 125kg N/ha and 250kg N/ha applied six weeks after sowing, and a split application treatment consisting of 125kg N/ha applied six weeks after sowing followed by a further 125 kg N/ha applied at mid-silking. No other fertiliser was added.

Table 1. Comparative relative maturity (CRM), origin, and genotype of hybrids.

Hybrid	CRM	Breeder / Origin	Genotype	Kernel size, shape and hardness
Clint	90	Crop & Food, NZ	½ European flint ¼ US Corn belt dent ¼ Highland tropical	Large, round, very hard.
Furio	95	Unknown, Europe	European dent	Medium, flat, soft.
A665xNZ71	100	Crop & Food, NZ	⅞US Corn belt dent ⅛ Highland tropical	Medium, round, intermediate.
A82-8xNZ84	103	Crop & Food, NZ	¾ US Corn belt dent ¼ Highland tropical	Small, flat, soft.
N5901	105	Northrup King, USA	US Corn belt dent	Large, flat, intermediate.
P3514	106	Pioneer, USA	US Corn belt dent	Large, flat, intermediate.

Establishment to harvest

Hybrids were sown using a two-row precision air-seeder, at a rate of 42 seeds per row (150,000 plants/ha). Weed control involved pre plant application with a mixture of alachlor and atrazine at 6 litres and 3 litres per ha respectively. Rows were thinned to 26 plants per row (92,400 plants/ha) on 18 December 1995. Ammonium sulphate was applied to plots by hand, in bands, on 19 December 1995 when plants were 30-45 cm tall (four leaf collars visible). Mean silking date (50% of plants silking) occurred between 4 February 1996 and 14 February 1996 in all hybrids; plots requiring the split fertiliser treatment were treated at this time. Prior to harvest (10 June 1996) plant population and the % of plants suffering stalk/root lodging was measured in each plot. Stalk lodged plants were defined as those whose stem had broken below the primary ear. Root lodging was defined as those plants that were more than 10° from vertical.

Harvest

Plots were hand harvested 11-12 June 1996, by removing all cobs from the centre two rows of each plot, and mechanically shelled using a Hayban husker sheller operating at a drum speed of approximately 400 rpm. Following shelling, grain was weighed for yield determination, and a 500-700 gram sample from each plot was taken for grain quality determination. Grain moisture content (MC) and bulk density (BD) of harvest samples were determined using a Dickey-john GAC2000 grain analyser. Grain yields were adjusted to 14% MC. Bulk density is reported at 14% MC, calculated from harvest bulk density using the following equation (Dorsey-Redding *et al*., 1990):

Bulk density (14% MC) = wet bulk density + 2.9189 + 0.3401(harvest moisture - 14)

Grain quality

Samples were dried using heated air at 25-30 00 ^{0}C in a drying cupboard and reached 13-15% MC after 3-5 days. Following drying, broken corn and foreign material (BCFM) was screened from the harvest samples on a Clipper air screen cleaner using a 6.75 mm (17/64 inch) round hole perforated sieve. Any whole grains passing through this sieve but retained by a 4.76 mm (12/64 inch) round hole sieve were removed from the BCFM screenings and placed back into the cleaned sample (for grain size and shape determination in a further study). The BCFM screenings were then weighed and expressed as a percentage of the harvest sample prior to screening. The screened harvest samples devoid of BCFM were then sorted by hand to remove broken grains. Broken grains were defined as grain fragments and/or whole grains with visible pericarp splits or grain parts missing. Whole diseased grains were not removed. The broken grain portion of each sample was then weighed and expressed as a percentage of the pre-screened harvest sample.

After BCFM and broken grain determination, grain MC and BD were again measured, with BD not being adjusted for moisture content (dry BD with grain MC ranging from 11.6% to 13.2%). Two-hundred grain weight (GW), expressed on a dry weight basis, was subsequently determined.

Grain hardness was evaluated using a specialised Glen-Creston micro-hammer mill fitted with a digital tachometer and equipped with a computerised data logging system (Pomeranz *et al.*, 1985; Li *et al.*, 1996). The energy (kJ) required to grind a 20 g grain sample (energy to grind), along with the time taken to grind a 17 ml column of ground maize in a 20 mm diameter test-tube (resistance time), were determined in triplicate for each sample. The percentage of grit following grinding for each hybrid by fertiliser treatment (samples bulked together) was measured by brushing samples over a 0.5mm Endocott wire mesh sieve. Grit was defined as the proportion of the sample remaining on top of the sieve, and is expressed on a percentage weight basis of the pre-sieved sample.

Samples were analysed for total grain N using micro-Kjeldahl digestion followed by colourmetric analysis (Fertiliser and Lime Research Centre, Massey University).

N recovery for those plots receiving N fertiliser was determined by calculating total N removed in the grain using grain yield and grain N % and then applying the following equation:

%N Recovery =
(Grain N / ha (N treatment) - Grain N / ha (control)) / (N fertiliser (kg/ha) applied (N treatment))

All statistical analysis was performed using SAS software (SAS 1989). ANOVA *F* test probabilities are presented with LSD's used to identify significant differences between treatment means. Non-significant differences were deemed as those where the *F* test probability exceeded 5%. Pearson correlation analysis was used to examine any association between agronomic and grain characteristics and among grain characteristics.

Results

Climate

Long-term and 1995/96 season meteorological data for Kairanga are presented in Table 2. Rainfall over the November to June period was about 35% greater than the long term mean, mostly because of very high rainfall in February and April (Table 2). January was relatively dry. Mean daily air temperatures were higher during December and January and generally cooler over the rest of the season but overall the seasonal temperature was the same as the long term mean. Soil temperatures were consistently higher than the long-term average over the entire season. Thermal time accumulation over the 1995/96 season was close to the long term mean.

Table 2. Mean daily temperatures (^oC), rainfall (mm) and thermal time (TT) for the 1995/96 season (8 Nov 1995 – 11 June 1996) compared with the long term (1970 – 1990) mean (LTM).

	Period	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total/ Mean
Mean rainfall (mm)	LTM	62	69	67	49	70	56	84	86	543
	1995/96	75	101	37	123	75	166	124	31	732
Air temp (^OC)	LTM	14.2	16.0	17.5	17.6	16.4	13.6	10.7	8.7	14.3
	1995/96	14.1	17.6	18.2	17.5	14.5	14.6	10.0	7.7	14.3
Soil temp @ 10cm (^OC)	LTM	14.9	17.2	18.4	17.8	16.2	12.8	9.4	7.2	14.2
	1995/96	15.1	18.0	20.6	20.3	17.4	16.4	12.3	9.2	16.2
TT (base 10^oC)	LTM	194	248	296	269	260	194	147	108	1716
	1995/96	158	299	317	285	231	215	134	32	1671

Table 3. Effect of hybrid and nitrogen (N) fertiliser on grain yield (t/ha), root lodging (%), stalk lodging (%), grain harvest moisture content (%), broken corn and foreign material (BCFM) (%) and broken grain (%).

	Yield (t/ha)	Root lodging (%)	Stalk lodging (%)	Grain moisture (%)	BCFM (%)	Broken grain (%)
Hybrid						
A82-8xNZ84	17.4a	7.4ab	24.8a	23.5d	2.6b	7.2b
P3514	16.8b	4.4b	1.2b	25.4b	2.1c	5.6c
N5901	14.8c	7.6ab	1.2b	25.5b	2.6b	7.9a
Furio	14.3cd	2.8b	0.5b	23.5d	3.2a	8.6a
A665xNZ71	13.9d	12.3a	1.8b	24.3c	2.0c	5.6c
Clint	13.2d	2.2b	3.1b	26.7a	3.2a	3.7d
Significance	0.0005	0.01	0.0001	0.008	0.02	0.0001
Nitrogen (kg/ha)						
0	14.7b	8.4a	4.8	24.5	2.7	6.3
125	15.4a	1.9b	4.7	24.5	2.6	6.4
250	15.1a	7.7a	6.7	24.3	2.5	6.4
125/125	15.2a	6.6ab	5.6	24.3	2.4	6.7
Significance	0.05	0.02	ns	ns	ns	ns

Note: Means with the same letter within columns are not significantly different at $P \leq 0.05$

Grain yield, lodging, N recovery and harvest characteristics

Hybrid type significantly affected all of the agronomic characteristics measured (Table 3). A significant hybrid by N fertiliser interaction (P = 0.02) was observed for grain yield. At 125 kg N/ha grain yield for Clint and Furio was the same as the control while all other hybrids achieved higher yields. There was no further response to additional N however the yield of N5901 and P3514 decreased in response to the 250 kg N/ha and split fertiliser treatments respectively.

The only agronomic characteristic apart from yield to be significantly influenced by N fertiliser treatment was root lodging (Table 3). Across hybrids the application of 125 kg N/ha significantly reduced root lodging compared with the control and 250 kg N/ha but was no different to the split application treatment. The lack of any significant difference between the 125 kg N/ha treatment and the split application of N fertiliser is not surprising, as the second 125 kg N/ha applied at silking for the split N treatment would have been too late to impact on the vegetative development of these plants. Correlations between root and stalk lodging with other agronomic characteristics across hybrids and N fertiliser treatments were generally weak and not significant. Individually however, grain yield in A665xNZ71 and N5901 was significantly ($P \leq 0.01$) negatively correlated with root lodging (r = -0.67 and r = -0.76, respectively).

Grain moisture content at harvest was significantly ($P \leq 0.01$) negatively correlated with broken grain levels (r = -0.47). However, unexpectedly, broken grain levels were not correlated with BCFM levels.

Table 4. Effect of hybrid and nitrogen (N) fertiliser on bulk density at 14% MC (kg/hL), 200 grain weight (g), energy to grind (kJ), resistance time (seconds), grain N (%) and grit recovery (%).

	Bulk density (kg/hL)	200 grain weight (g)	Energy to grind (kJ)	Resistance time (sec)	Grits (%)	N (%)
Hybrid						
Clint	74.5	65.4c	8.0a	24.4a	77.5	1.57b
A82-8xNZ84	74.5	62.3d	5.7d	15.5cd	73.1	1.28e
P3514	74.2	70.2a	6.4b	17.0b	73.2	1.47c
Furio	73.8	63.0d	5.8d	14.9d	74.0	1.37d
N5901	73.2	68.5b	6.1c	15.8c	73.9	1.60b
A665xNZ71	72.5	64.9c	6.4b	16.8b	74.3	1.71a
Significance	ns	0.002	0.0001	0.0001	-	0.0001
Nitrogen (kg/ha)						
0	77.9	64.8c	6.1	16.6	74.6	1.48
125	78.3	66.7a	6.7	18.1	74.4	1.53
250	78.4	65.5bc	6.3	17.4	73.5	1.48
125/125	78.6	65.8ab	6.4	17.6	74.7	1.51
Significance	ns	0.04	ns	ns	-	ns

Note: Means with the same letter within columns are not significantly different at P<0.05

Total grain N uptake, the product of grain yield per hectare and grain N percentage (Table 4), differed significantly among hybrids (P = 0.03, data not presented). N fertiliser did not significantly influence total grain N (P = 0.06).

Hybrid had no influence (P = 0.07) on N fertiliser recovery in the as grain (data not shown). Recoveries were generally low ranging from 0.6% (Clint) to 11.2% (A665xNZ71).

Similarly, N fertiliser had no influence (P = 0.09) on N recovery (data not shown). The N recovery was generally low; 12.5%, 2.8% and 4.7% for the 125 N/ha, 250 kg N/ha and 250 kg N/ha split treatments respectively, indicating that soil N was sufficient to attain close to maximum grain yield without addition of N fertiliser for most hybrids (Steele *et al*., 1982b).

Physical grain characteristics and grain N content

Hybrid had a significant influence on all physical grain characteristics except BD (Table 4). Clint had significantly higher energy to grind and resistance time than all other hybrids. However grain N% was highest in A665 NZ71, while GW was highest in P3514. Nitrogen had a significant effect on GW, but only at 125 kg N/ha and 250 kg N/ha split. No significant N fertiliser effects on BD, grain hardness characteristics or grain N% were detected. Although deemed not significant, grain hardness and grain N were highest at 125 kg N/ ha.

Correlations between agronomic characteristics and grain properties

Grain yield was negatively correlated (r = -0.47) with grain N across hybrids and N fertiliser treatments (Table 5). Stalk lodging was negatively correlated (r = -0.44) with grain weight but not with root lodging. Grain MC at harvest was positively correlated (r = 0.45) with resistance time, a measure of grain hardness. Broken grain level was negatively correlated (r = -0.49) with dry grain BD and, energy to grind and resistance time (r = -0.69 and r = -0.74, respectively).

Table 5. Simple correlations between agronomic characteristics: relative maturity, stalk lodging (%), grain yield (t/ha) N yield (kg/ha) and grain characteristics: 200 grain weight (g), bulk density (kg/hL), energy to grind (kJ), resistance time (seconds), grain N (%) across hybrids and nitrogen (N) fertiliser treatments.

	Grain weight	Bulk density	Energy to grind	Resistance time	Grain N
Relative maturity	0.36	-0.17	**-0.54**	**-0.62**	-0.08
Stalk lodging	**-0.44**	0.18	-0.21	-0.14	**-0.49**
Grain yield	0.23	0.21	-0.35	-0.35	**-0.47**
Nitrogen yield	**-0.63**	0.15	0.09	-0.02	**0.45**

Note: Bold = significant at P<0.01

Table 6. Simple correlations between grain characteristics: bulk density (kg/hL), energy to grind (kJ), resistance time (seconds), grits (%), gain N (%), and broken grain (%) across hybrids and N fertiliser treatments.

	Bulk density	Energy to grind	Resistance time
Energy to grind	**0.55**		
Resistance time	**0.61**	**0.96**	
Grit	0.15	0.38	**0.46**
Grain N	-0.04	**0.49**	0.37
Broken grain	**-0.49**	**-0.69**	**-0.74**

Note: Bold = significant at P<0.01

Correlations among grain characteristics

Grain weight was not correlated with dry grain BD, any measures of grain hardness or grain N percentage across hybrids (Table 6). A weak correlation was found between BD following harvest and BD following drying. This may indicate that the equation used to adjust BD at different grain MC, which is based on USA data, may not apply to New Zealand-grown maize. Energy to grind and resistance time were strongly correlated (r = 0.96) as expected; both characteristics are measures of grain hardness. Both energy to grind and resistance time were positively correlated with grain BD (r = 0.55 and r = 0.61, respectively). Grit % was correlated with resistance time (r = 0.46) but not with energy to grind. Grain N content was correlated (r = 0.49) with energy to grind but not resistance time or grit %.

Discussion

Grain yield

Average temperature combined with above average rainfall over the 1995/96 season resulted in relatively high grain yields. Trial yields are generally greater than the regional average over the same growing season but may be similar to yields obtained by the best commercial growers (Hardacre *et al.*, 1991). Average yields of Furio and P3514 from growers in the Kairanga district were 12.3 t/ha and 13.5 t/ha respectively (Anon., 1996c) verses 14.3 t/ha and 16.8 t/ha respectively in this study. Temperate climates tend to produce high maize grain yields because delayed crop senescence results in an extended grain fill period (Wilson *et al.*, 1995).

The positive correlation between grain yield and CRM was expected as later hybrids generally possess a longer grain-filling period, and can thus move more assimilate to the developing grains (Tollenaar, 1977). In this study the relationship, though significant, was not particularly strong (r = 0.61) as different hybrids achieved better or poorer yield than their CRM would suggest. Hybrid A82-8xNZ84 displayed an exceptionally high yield for its CRM. This hybrid was selected and bred in the Kairanga environment and has performed extremely well in past agronomic trials (Hardacre, unpublished data). Hybrids P3514 and N5901 yielded less than A82-8xNZ84 even though they both have a higher CRM. These hybrids were not generally grown in the Manawatu because of their long CRM.

High grain yields, low N fertiliser recovery and the modest yield response to N fertiliser may indicate that substantial mineralisation of soil N occurred prior to planting and/or during the growing season. A test taken in September, prior to planting, indicated that the site had the potential to show a yield response to N fertiliser application.

Between September, when the soil N test was taken, and early November, when the crop was sown, it is possible that considerable mineralisation of soil N occurred, increasing the amount of soil N available for plant growth, resulting in an under-estimation of soil N available and an over-estimation of the potential response to fertiliser (Goh, 1983).

Hybrid grain yields responded differently to rate and timing of N fertiliser application. The hybrids used in this study covered a wide range of RM (90-106) and thus had varied yield potential. Tsai *et al*. (1992) found significant hybrid × N fertiliser interactions for grain yield. In their studies, shorter maturing hybrids reached maximum yields under lower N fertiliser levels than later maturing hybrids. Significant hybrid × N fertiliser interactions were also shown by Gardner *et al*., (1990), however, their significance was lost when their trials were analysed across growing environments. Generally, where hybrids of similar CRM and equal adaptation to a particular growing environment are utilised, no significant interaction between hybrid and N fertiliser rate occurs (Gardner *et al*. 1990).

Maximum grain yields for hybrids appeared to be reached at different N fertiliser levels. The yield of Furio was greatest at 0 kgN/ha, while the yields of A665×NZ71, A82-8×NZ84, N5901 and P3514 peaked at 125 kg N/ha. The yield of Clint peaked at 250 kgN/ha, which is surprising as it is relatively early maturing; typically early hybrids require less N than later maturing hybrids to reach maximum yield. The lower yields of Clint detected at 0 kgN/ha and 125 kgN/ha may be due to N leaching and/or denitrification during the early season, as a result of above average rainfall and soil temperatures (Table 2). It is possible that the high N treatments (250 kgN/ha) resulted in sufficient N remaining in the rooting zone of Clint to allow late season uptake. This is supported by the similar yield of Clint from the split N treatment. Unfortunately total plant N at mid-silking and soil N levels throughout the season were not determined to substantiate this. However, this would contradict the results of Tsai *et al*. (1992), who found that shorter maturity hybrids tend to absorb a higher proportion of their required N prior to, rather than following silking.

Grain N

Grain N% differed significantly among hybrids (Table 4), consistent with known genetic effects on grain N concentration (Steele *et al*., 1982b). Cerrato and Blackmer (1990) and Steele *et al*. (1982b) state that maximum grain yields are associated with approximately 1.5% grain N, which broadly agrees with the results from this study (Table 4). Most research shows that there is a positive correlation between grain N% and grain yield within a hybrid when additions of N fertiliser increase grain yield (Pearson *et al*., 2004; Tsai *et al*. 1992; Cerrato and Blackmer, 1990). However, Cerrato and Blackmer (1990) state that grain N% has little utility in characterising the N status of maize in fields having near-optimal or excessive amounts of available N. In this study only one hybrid showed a significant positive correlation between grain N and grain yield; A82-8×NZ84 ($r = 0.73$), ($P = 0.008$); as the majority of hybrids reached maximum yield with little applied N, resulting in too few data points for strong, significant correlations to be attained. Conversely, across hybrids a negative correlation usually exists between grain yield and grain N (Tsai *et al*., 1992) as was the case in this study ($r = -0.47$). This is due to differences among hybrids in relation to yield potential and the amount of N required to reach maximum grain yield.

Lodging

The incidence of lodging was highest in A665 xNZ71 (root lodging) and A82-8 xNZ84 (stalk lodging) (Table 3). Under commercial conditions severe stalk lodging will reduce grain yield due to difficulty picking up lodged plants during harvesting. Consequently, the high yield of A82-8×NZ84 may not be observed in a commercial situation.

The influence of N fertiliser treatment on both root and stalk lodging is unclear. Nitrogen fertiliser did not affect stalk lodging and its effect on root lodging was inconsistent. For example, root lodging was greatest in the control and least in the 125 kg N/ha treatment.

Stalk lodging was negatively correlated with GW and grain N% (combined data). Stalk lodging limits the supply of water, nutrients and assimilates to grains in the developing ear, reducing GW, grain N% and grain yield. However, there was no significant correlation between stalk lodging and either GW or grain N for any individual hybrid.

Grain moisture content

Grain MC at harvest varied between hybrids. Newton and Eagles (1991) found differences in grain moisture at harvest were determined mainly by drying rates after physiological maturity (black layer), and not by time to silking or physiological maturity. However, with the exception of Clint, grain MC at harvest generally followed CRM ratings. Clint was the earliest maturing hybrid but had the highest grain MC. This is ascribed to Clint's high proportion of hard endosperm as indicated by grain hardness and percentage grit following grinding (Table 4). The density of hard endosperm is greater than that of soft endosperm making diffusion of water from the grain interior to the exterior more difficult, reducing the rate of grain dry-down (Newton and Eagles, 1991). Grain MC for A82-8xNZ84 was less than expected which may be due to faster grain moisture loss in this hybrid, resulting from very small and soft grains (Table 4).

BCFM and broken grains

Mean BCFM levels varied among hybrids from 1.9% to 3.2% while the mean % of broken grain ranged from 3.7% to 8.6%. The magnitude of BCFM and broken grain levels observed in this study are comparable to those commonly experienced commercially in New Zealand (K. Dowie, pers. comm.). Hybrid differences in BCFM are probably related to grain MC and physical grain characteristics (Chowdhury & Buchele, 1978; Pomeranz *et al*., 1986), although no obvious correlations between BCFM and these grain properties were discovered in this study. BCFM was not correlated with broken grain % as might be expected.

Across all hybrids, the % of broken grains was most closely associated with measures of grain hardness, followed by grain BD (Table 5). The strong negative correlation between broken grain levels and grain hardness (as measured by energy to grind and resistance time) was anticipated as grains with a high proportion of hard endosperm require a greater force for deformation (Shelef and Mohsenin, 1969). Broken grain levels showed a significant but weak negative correlation with grain MC (r = -0.47). Literature reports a strong negative relationship between grain MC and grain damage (Chowdhury and Buchele, 1978). The weak negative correlation between broken grains and grain MC could be due to the high grain MC and hardness of Clint. Drying temperature and post drying cooling may also influence broken grain %; high temperature with rapid cooling increases stress cracking (Kim *et al*., 2000), probably increasing susceptibility to breakage during subsequent handling (Gunasekaran and Paulsen, 1985).

Physical grain characteristics

Highly significant differences among hybrids for physical grain characteristics were recorded but BD was not influenced by hybrid. For example, Clint (high endosperm density) and A82-8×NZ84 (low endosperm density) have similar BD (Table 4). Hybrids with different grain density may have similar BD because of their grain size and shape characteristics (Srinivas *et al*., 1991). Consequently, it is probably more appropriate to view BD as a useful indicator of grain quality within hybrids rather than between hybrids (Hardacre, 1997).

Hybrids displaying higher values for both energy to grind and resistance time were visually more vitreous and produced a higher percentage of grit following grinding than softer grains (Table 4). However, the positive correlations between grain hardness characteristics and grit % following grinding were not particularly strong. Generally vitreous grains contain a greater proportion of hard endosperm (Li *et al*., 1996; Louis-Alexandre *et al*., 1991) and are harder than non vitreous grain (Li *et al*., 1996).

The strong correlation between energy to grind and resistance time and the similarity of hybrid rankings for grain hardness, irrespective of which hardness characteristic was utilised, shows that both methods of grain hardness determination were equally effective in detecting grain hardness differences among hybrids. Energy to grind and resistance time were not correlated with GW. Pomeranz *et al*. (1985) also found no significant correlations between GW and grain hardness in their study of three dent maize hybrids.

Bulk density was positively correlated with grain hardness parameters although not particularly strong ($r = 0.61$ and 0.55 for resistance time and energy to grind respectively). Li *et al*. (1996) reported correlations between BD and resistance time, and BD and energy to grind of 0.73 and 0.79 respectively. It would appear from the results of this study (Table 6) that resistance time and energy to grind are similarly related to BD, whereas Patwary (1995) found that the correlation between BD and resistance time was greater than that with energy to grind. Strong positive correlations between grain BD, grain hardness and grain N are typical (Pomeranz *et al*., 1986; Dorsey-Redding *et al*., 1991). In this study only energy to grind was correlated (moderately) with grain N.

Nitrogen fertiliser increased GW in this study. Tsai *et al*. (1990) indicated that N supply to maize grains influences the accumulation of proteins and carbohydrates; GW being greater under high N fertility conditions. Across all hybrids grain weight was not correlated with grain N% in this study, however, individually, hybrids N5901 and A82-8×NZ84 did show significant ($P \leq 0.01$) correlations between GW and grain N ($r = 0.61$ and $r = 0.77$ respectively).

Nitrogen fertiliser failed to produce a significant effect on grain hardness and grain N (Table 4). Kim *et al*. (2000) found that there was an interaction between N and hybrid on the ratio of hard to soft endosperm in three hybrids grown in the Manawatu. While N had no effect in Furio and P3753 it significantly increased endosperm hardness in P3902. Overseas research has found that increasing N fertiliser rates increased resistance to grinding, a good indicator of grain hardness (Ahmadi *et al*., 1995).

Conclusion

There were significant yield differences among hybrids; early maturing hybrids yielded less than later hybrids. Lodging was a problem in the two experimental hybrids, A82-8 x NZ84 and A665 x NZ71. The flint hybrid, Clint, produced significantly less broken grain, grain with higher energy to grind requirements and longer resistance time than all other hybrids. N fertiliser significantly increased grain yield, primarily by increasing grain weight. However, N fertiliser had no influence on any of the grain quality characteristics measured.

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