

Effects of Nitrogen and Sulfur Fertilization on Commercial-Scale Wheat Quality and Mixing Requirements

A. R. Wooding,^{1,2} S. Kavale,¹ A. J. Wilson,^{1,3} and F. L. Stoddard⁴

ABSTRACT

Cereal Chem. 77(6):791–797

The effect on physical dough properties of nitrogen and sulfur fertilizer applied during cultivation was observed in two trials using the bread wheat (*Triticum aestivum*) cultivar Otane. Wheat flours from both trials were evaluated for physical dough properties under laboratory conditions and also under industrial conditions in the second trial. The laboratory and industrial optimum mechanical dough development (MDD) work input (WI) significantly increased when nitrogen (N) fertilizer was applied without sulfur fertilizer (S) during crop cultivation. With combined N and S fertilization, laboratory and industrial WI remained close to levels for grain grown without fertilizer. Reductions in extensigraph resistance to extension (Rmax) and increases in extensigraph extensibility (Ext) due to S fertilization also were observed. None of the observed changes in WI, Rmax, or Ext due to S fertilization significantly affected end-product quality as measured by loaf volume, crumb grain, and bake score. The nexus between WI and Rmax was weakened by combined N and S fertilization

in the first trial, but remained strong in the second trial. Both WI and Rmax increased as N fertilizer and flour nitrogen increased, but at different rates. This observation indicated that by applying N fertilizer to improve dough strength, a disproportionate and disadvantageous increase in WI also resulted, which could be tempered by S fertilization. In this regard, an optimum N:S fertilizer ratio of 3:1 was indicated, although this ratio would be dependent on the balance of available N and S in the soil. Flour N:S ratios <12.5 kept WI to levels desirable in an industrial MDD bakery. Correlations between laboratory WI, mixograph development time (except in the SN1 trial), and farinograph development time were significant. The 125-g MDD mixers appeared to be more responsive when measuring mixing requirements than the mixograph and farinograph to variations in quality due to environmental and agronomic influences and correlated better with industrial performance.

In recent years, those bakeries in Australia and New Zealand using the mechanical dough development (MDD) process have found it increasingly difficult to mix doughs to the optimum consistency required for good bread quality. This trend was independently observed by Crop & Food Research (C&FR) staff during seasonal test baking of farmers' wheat lines at Lincoln, New Zealand (Griffin and Wooding 1992). In particular, the optimum MDD work input (WI) requirements for the bread wheat (*Triticum aestivum*) cultivar Otane appeared to have increased since its release in 1984. In general, the increased difficulty in mixing doughs to optimum consistency is believed to be due mainly to an emphasis in breeding programs on increasing dough strength (Wooding et al 1999). However, for the cultivar Otane another factor that could have been influential is a change in fertilizer treatment practice that may have created an imbalance in the proportions of nitrogen and sulfur in the soil, causing a decline in S availability.

A deficiency in sulfur can change the concentration of proteins, resulting in increased dough strength (Randall and Wrigley 1986). In the past, the use of superphosphate in New Zealand and the mineralization of S from soil organic matter apparently provided sufficient S for normal grain protein synthesis (Martin 1987, Martin et al 1989). Several factors may now have changed this situation: the use of concentrated nitrogen fertilizers lacking S; changes in the timing of fertilizer applications; declining soil organic matter levels; and the introduction of higher yielding cultivars that deplete the reserve of soil S. Interactions between N nutrition and S nutrition on dough and loaf characteristics were shown (Moss et al 1981). Extensigraph extensibility increased and resistance to extension decreased as S fertilization increased. N fertilization increased farinograph development time, extensigraph resistance to extension and MDD loaf volume over nonfertilized control flours, and also decreased mixograph development time, extensigraph extensibility, and farinograph breakdown.

This study investigates the effect of N and S fertilizer treatments on the relationship between optimum mixing requirements and dough strength for the MDD process. The research was conducted in two trials using the cultivar Otane. In the first trial, laboratory-scale dough tests were applied. In the second, where 2 t of grain was produced in each fertilizer treatment, dough and loaves were prepared in an industrial MDD bakery. Breakage of the direct relationship between mixing requirements and dough strength would provide an opportunity to adjust dough mixing requirements agronomically while maintaining or improving dough strength and other desirable characteristics such as extensibility.

MATERIALS AND METHODS

Materials

A factorial designed 3*3*2*2 N and S fertilizer trial (SN1) of spring-sown Otane wheat with three replicates arranged in randomized complete blocks was planted in plots (13 × 1.5 m²) on a heavily cropped site at Lincoln, Canterbury, New Zealand. The fertilizer treatments consisted of a combination of two application times with varying levels of N and S. The treatments were applied just after sowing and at booting (after the end of stem extension), which was consistent with current farming practice for bread wheat in New Zealand. The levels of N and S applied at sowing were 0, 75, and 150 kg/ha and 0, 25, and 50 kg/ha, respectively. The levels of N and S applied at booting were 0 and 75 kg/ha, and 0 and 25 kg/ha respectively. Levels are subsequently referred to as 0N, 75N, and 150N, and 225N for the combined application of 150 kg/ha N at sowing and 75 kg/ha N at booting. A second N and S fertilizer trial (SN2) of spring-sown Otane was designed as a randomized complete block experiment. Two replicates were sown in a factorial design with three N (0 and 75 at sowing, 150 at sowing and 75 at

TABLE I
Soil Test Before Sowing Nitrogen (N) and Sulfur (S) Fertilizer

Trial	Soil Depth (cm)	pH	N and S Fertilizer		
			N (ppm)	S (ppm)	N:S Ratio
SN1	0–15	6.0	21	8	2.6:1.0
	15–30	5.9	15	5	3.0:1.0
SN2	0–15	6.3	5	3	1.7:1.0
	15–30	6.0	3	4	1.0:1.3

¹ New Zealand Institute for Crop & Food Research Ltd, Private Bag 4704, Christchurch, New Zealand.

² Present address: 2 Turi Ave, Whenuapai, Auckland, New Zealand.

³ Corresponding author. E-mail: wilsona@crop.cri.nz Phone: +64 3 3256 400. Fax: +64 3 3252 074.

⁴ Plant Breeding Institute, Woolley Bldg., University of Sydney, NSW 2006, Australia.

booting) and two S (0 and 50 at sowing and 25 at booting) fertilizer treatments planted in plots (130 × 38 m²) the following year at Methven, Canterbury, New Zealand. The S was applied as gypsum (CaSO₄·2H₂O, 18.6% S) and the N as urea (H₂NCONH₂, 46.6% N). Soil S and N levels before sowing for these trials are shown in Table I.

Methods

All grain samples from the SN1 trial were conditioned to 15.5% moisture content (mc) for 16 hr before milling on an experimental mill (Buhler MLU202). The bran was captured and fed through a bran finisher to maximize the flour extraction rate (approx. total extraction 75%) and thus to be more representative of industrial extraction rates.

The preparation and quality testing of samples from the SN2 trial differed from SN1 as approximately 2 t of wheat were produced from each fertilizer treatment for industrial-scale milling and baking. The grain matured late due to bad weather, with the grain harvested in late March at 18–20% mc and dried to 14–16% mc in grain dryers. Once dried, the grain was transported to a small industrial SIMON roller mill (with a capacity of 2 t/hr) where it was conditioned to 16% mc for 12 hr before milling. Grain samples from each of the fertilizer treatments in the SN2 trial also were milled on the Buhler experimental mill as outlined for the SN1 trial.

A dough probe (Wilson et al 1997) was used to sense changes in dough consistency and record WI required during mixing in an industrial mixer. WI was estimated from mixer motor power that

was calibrated against dough temperature rise measurements assuming 1 Wh/kg raises the dough temperature 1.33°C (Wilson et al 1997). In these experiments, the industrial mixer was a modified Convaire 200 (Tweedy-type mixer). Each dough consisted of 80 kg of flour combined with the host bakery's standard formula for 700 g of lidded white bread: water (48 kg, including some ice for high WI to achieve a final dough temperature of 32°C), yeast (2.1 kg), compound improver (1.60 kg, containing enzymes, soya flour, and ascorbic acid), sodium chloride (1.60 kg), sucrose (0.60 kg), gluten extender (0.60 kg), calcium acetate (0.16 kg), and malt flour (0.16 kg), for a total weight of ≈135 kg. The optimum industrial WI was located using Fourier power spectra optima (Wilson 1992) and WI values, calculated from the proportion of work expended at that time, assuming work is expended at a constant rate. All the doughs were slightly overmixed as a consequence of finding the mixing optimum. Experience with modern bread flours developed for the MDD process has shown that mixing just past the optimum appears to have a positive effect on end-product quality, whereas undermixing has a negative effect (Quail et al 1993). All doughs were passed through a molder, proved, and passed through a four-piece divider before baking. After baking, the loaves were cooled on cooling towers. Five high top and 10 lidded loaves were selected randomly from each batch made from the one sample of dough. Separate dough samples were prepared and tested for grain samples from each field plot. Loaf volume (LV, mL) of the high top loaves was measured using rapeseed displacement. The lidded loaves were sliced, bagged, and evaluated the following day for

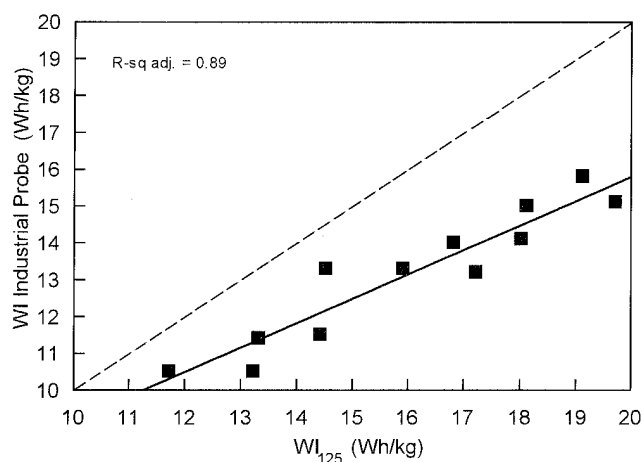


Fig. 1. Relationship between 125-g laboratory and industrial mechanical dough development (MDD) mixers. Broken line represents 1:1 relationship. WI = work input.

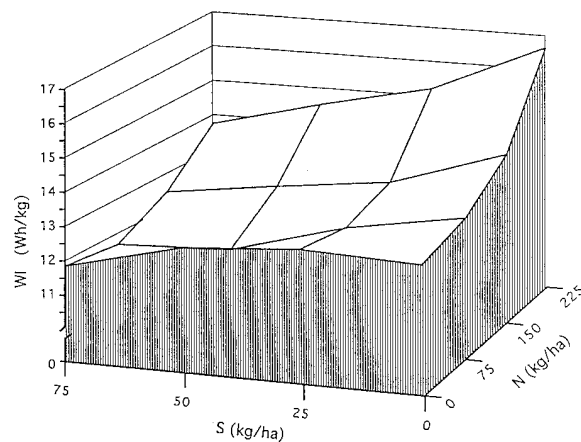


Fig. 2. Effect of total nitrogen (N) and total sulfur (S) applied during cultivation in SN1 trial on industrial mechanical dough development (MDD) work input (WI) for bromated doughs (standard error = 0.54).

TABLE II
Correlation Coefficients Between Wheat Flour Quality Attributes in Two Nitrogen (N) and Sulfur (S) Fertilization Trials^{a-c}

	MDD Mixer		Mixograph		Extensigraph		Farinograph			Baking	
	WI	WA	MDT	MWA	Rmax	Ext	FDT	FWA	FST	FBK	LV
WI	...	...	...	0.577*	0.869***	...	0.875***	...	0.852***	-0.751**	0.580*
WA	0.279**	...	...	0.775**	...	0.682*	...	0.897**	...	...	0.604*
MDT	...	-0.814***	...	...	0.686*	...	...	...	0.770**	-0.657*	...
MWA	0.257**	0.619***	-0.572***	...	...	...	0.731**	0.661*	...	...	0.729**
Rmax	0.359***	-0.309**	0.463***	...	...	...	0.836***	...	0.969***	-0.762**	...
Ext	0.276**	0.611***	-0.581***	0.393***	...	...	...	...	...	...	...
FDT	0.329***	0.748***	-0.702***	0.578***	...	0.581***	...	...	0.789**	-0.640*	...
FWA	0.435***	0.895***	-0.832***	0.654***	-0.330***	0.594***	0.733***	...	...	...	...
FST	0.232*	...	0.334***	...	0.519***	...	...	...	...	...	...
FBK	-0.332***	-0.199*	...	-0.191*	-0.394***	-0.357***	-0.412***	-0.249**	-0.504***	...	...
LV	0.243*	0.649***	-0.588***	0.386***	...	0.493***	0.588***	0.539**	...	-0.237*	...

^a MDD, mechanical dough development; WI, work input; WA, water absorption; MDT, mixograph development time; MWA, mixograph water absorption; Rmax, extensigraph resistance to extension; Ext, extensibility; FDT, farinograph development time; FWA farinograph water absorption; FST, farinograph stability; FBK, farinograph breakdown; LV, loaf volume.

^b *, **, ***: P < 0.05, 0.01, 0.001 respectively.

^c Below diagonal, SN1 laboratory-scale trial (df = 106); above diagonal, SN2 industrial-scale trial (df = 10).

crumb grain (CG) by the bakery manager (empirical knowledge) and two senior researchers (subjective scale 0–14) (Swallow and Baruch 1986), who were unaware of the treatments to which the growing wheats had been subjected.

All flour samples were analyzed for flour N content (FN) at 14% mc by the Kjeldahl method (ISO 1975). Flour S content was determined by X-ray fluorescence spectrometry (Randall and Sakan 1983).

Physical dough properties were measured by extensigraph (Brabender OHG, Duisburg, Germany) using Approved Method 54-10 (AACC 2000). Rmax and extensibility (Ext) were determined after a rest time of 45 min.

Mixing requirements measured by mixograph (National Manufacturing Co., Lincoln, NE) included mixograph development time (MDT) and water absorption (MWA) using Approved Method 54-40A (AACC 2000). The mixograph results were recorded using a 5-kΩ linear taper potentiometer attached to the rotating bearing shaft of the mixer arm (Wooding and Walker 1992).

Farinograph tests (Brabender OHG) included farinograph development time (FDT), water absorption (FWA), stability (FST), and breakdown (FBK) using Approved Method 54-21 (AACC 2000). FBK was measured as the difference in Brabender units (BU) from the 500 BU lines to the center of the curve 10 min after the start of mixing.

The MDD laboratory mixers and baking system were designed and built by Crop & Food Research, Christchurch, New Zealand. WI and WA were calculated using the 125-g MDD mixers (Mk. II) as documented in Wooding et al (1999). Bread quality was evaluated in terms of loaf volume (LV), crumb grain (CG), and bake score (BS) according to Swallow and Baruch (1986) on bromated and nonbromated doughs. Bromated doughs were used in the laboratory because a standard enzyme preparation has not been adopted by all industrial bakeries to replace bromate. Furthermore, the response to enzyme preparations varies between bakeries, so it was necessary to retain bromate as a reference. The nonbromated laboratory doughs were used as the comparison with the industrial bakery in the SN2 trial.

Analyses

Correlation matrices, analyses of variance, and regression analyses (Sokal and Rohlf 1981, Ott 1988) were used to investigate the relationships between quality attributes and agronomic conditions using either SAS (SAS Institute, Cary, NC) or Genstat (Oxford Scientific Publications, Oxford, UK) statistical software. The two field trials were analyzed separately. Preliminary analyses indicated

that total fertilizer was more important than application time, so the split fertilizer treatments were pooled and plots with the same total fertilizer applications treated as replicates. For each trial, all quality tests were performed on flour samples using the same factorial design and randomization with respect to each of the field trials. In the laboratory, for SN2 samples, the two milling methods and two laboratory MDD mixers were used as subplot treatments. Samples from the SN2 trial milled on an industrial SIMON roller mill also were tested in an industrial MDD bakery using the field plot design with three mixing replicates per field plot, randomized over six days spread over a two week period, with three days in each week.

RESULTS AND DISCUSSION

Relationships Between Quality Attributes

In both trials, work input (WI) and mixograph development time (MDT) were both significantly correlated with extensigraph resistance to extension (Rmax), but not with each other in the SN1 trial (Table II). Farinograph development time (FDT) was positively correlated with WI in both trials and negatively correlated with MDT in the SN1 trial. FDT was not significantly correlated with Rmax in the SN1 trial, but it was in the SN2 trial. Ext was negatively correlated with MDT in both trials and positively with WI in SN1. In SN2, the WI results of the laboratory and industrial mixers correlated strongly with each other ($r^2 = 0.89$) (Fig. 1).

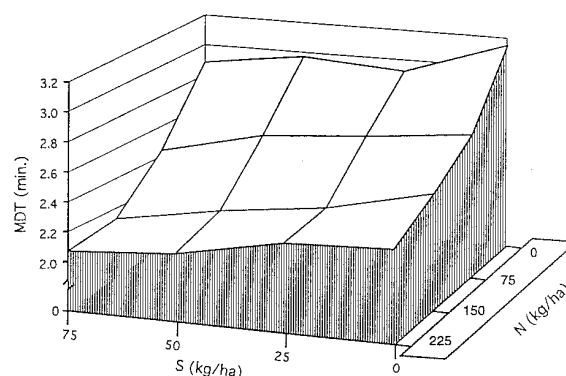


Fig. 3. Effect of total nitrogen (N) and total sulfur (S) fertilizer applied during cultivation in SN1 trial on mixograph development time (MDT) for bromated doughs (standard error = 0.11).

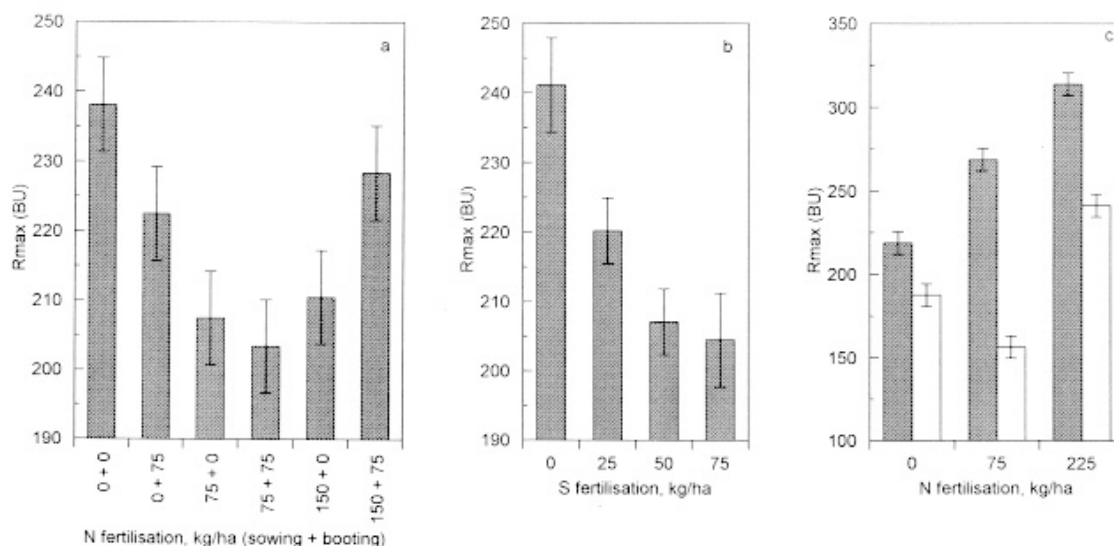


Fig. 4. Effects of nitrogen (N) and sulfur (S) fertilization on maximum resistance to extension (Rmax). **a**, SN1 trial, main effects of N; **b**, SN1 trial, main effects of S; **c**, SN2 trial, no sulfur (shaded bars), open bars 75 kg of sulfur/ha (open bars). Error bars \pm 1 standard error.

Effects of N and S Fertilization on Mixing

WI increased in both the laboratory and industrial mixers as N fertilization increased, without S fertilization. At the laboratory scale, this increase for bromated doughs was 3.6 and 5.3 Wh/kg in SN1 (Fig. 2) and SN2 respectively, as N increased from 0N to 225N. The difference between these two trials may be attributable to the lower native soil S in SN2 (Table I). When maximum S fertilization was used, the WI of the maximum N treatment reduced by 3.3 and 3.6 Wh/kg in the SN1 and SN2 trials respectively. Bromated and nonbromated doughs produced similar results. In the industrial mixer, the differences between treatments showed the same trends, but were smaller. Fertilization with N to S in a 3:1 ratio prevented undesirable increases in WI.

FDT showed similar responses as WI to N, but not to S. In SN1, FDT was 2.3 min in the 0N/0S treatment, 4.2 min in 225N/0S. In SN2, FDT was 1 min less in 225N/75S than 225N/0S, but it showed no significant difference between 0N/0S and 0N/75S.

MDT, however, responded differently from FDT and WI. In SN1, it decreased with increasing levels of N fertilization (Fig. 3), but in SN2 there was no trend. This difference in response may be attributable partly to the formulation and partly to the mixer action. MDT was determined with a flour-water blend, whereas WI was determined with a lean baking formula, containing oxidizers such as L-ascorbic acid and $KBrO_3$. Dehydroascorbic acid, formed by ascorbic acid oxidase from L-ascorbate and oxygen, is understood to oxidize sulfhydryl groups to disulfides, strengthening the dough (Tsen 1965, Tomlinson et al 1991), and bromate also reacts during mixing (Lee et al 1958), although its main activity is during baking (Hlynka et al 1953, Cunningham and Anderson 1956). The mixograph uses a harsh pin-mixing action (Spies 1990), developing the

dough by stretching, whereas MDD mixers use a rapid, intensive kneading action (French and Fish 1981). Differences in protein composition resulting from the fertilizer treatments may alter sensitivity to mixing action or formulation.

These results showed that mixing requirements measured as WI on the 125-g MDD mixer was a better predictor of variation in the industrial-scale MDD process than either MDT or FDT. WI also was more responsive to variations in quality due to environmental or agronomic influences.

Effects of N and S Fertilization on Extension and Baking

Bromated and nonbromated doughs produced similar results. Increasing S fertilization resulted in decreased R_{max} (Fig. 4). Increasing N had no consistent effect on R_{max} in SN1 but increased it consistently in SN2 (Fig. 4). These results were similar to those of Moss et al (1983). Reduced R_{max} from S fertilization was not associated with any accompanying decrease in loaf volume (Table II), crumb grain, or bake score. Extensibility increased with increasing N and S fertilization.

Loaf volume, water absorption, and crumb grain were not significantly affected by S fertilization but increased with increasing N fertilization. Bromated loaf volumes for the extreme treatments were 775 mL (0N/0S), 850 mL (225N/0S), and 820 mL (225N/75S) (SE 15 mL). In the industrial-scale trial, nonbromated loaves averaged 3,700 mL (SE 16 mL). Crumb grain scores were 7.0–10.0; in the industrial trial, they were lowest in the 75N/0S fertilization. Increases in water absorption are desirable as less flour is required to produce a given mass of bread from each MDD mixer load. The increase in WA with nitrogen fertilization was significant in both trials when determined in the MDD mixer, significantly only in

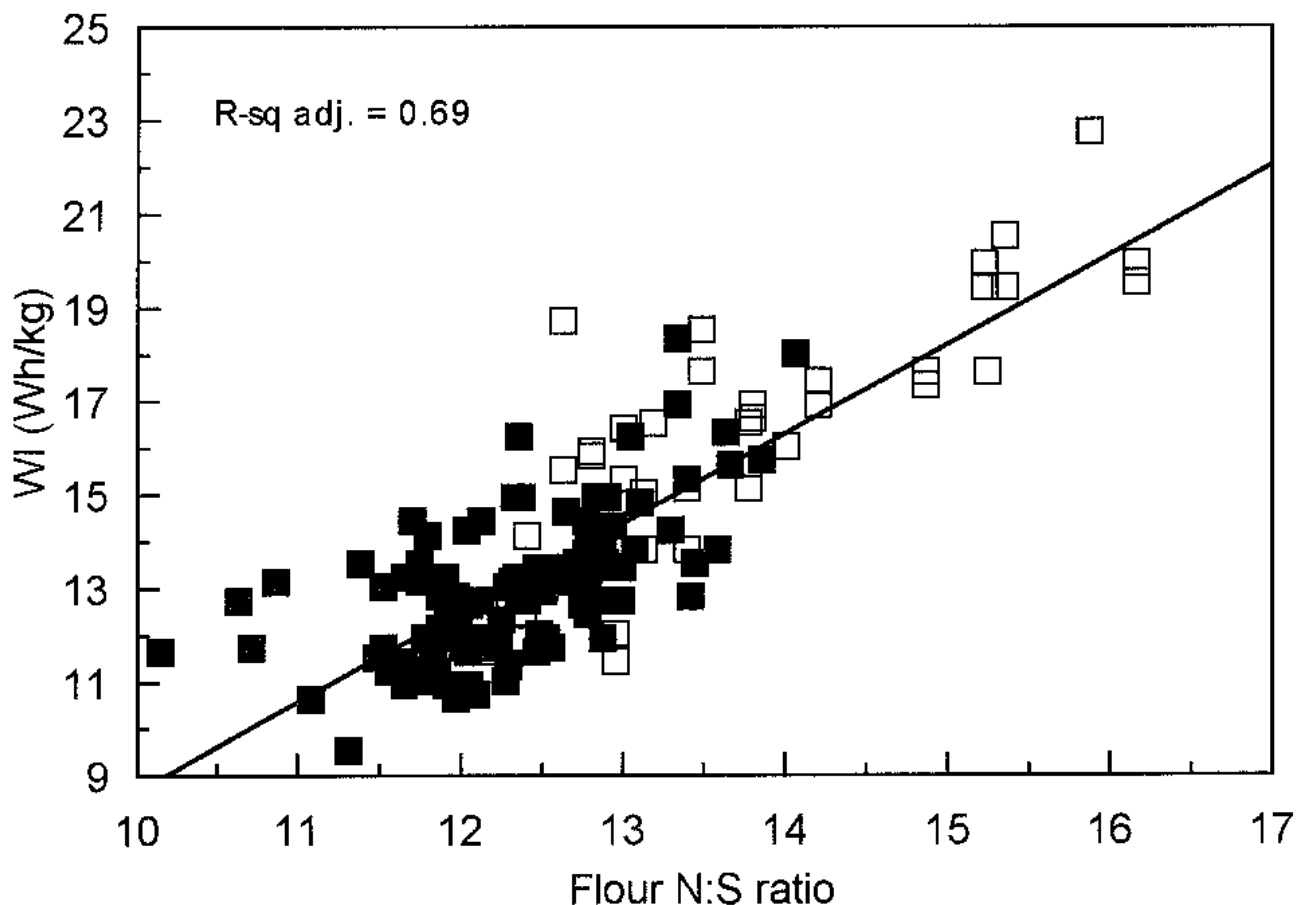


Fig. 5. Effects of nitrogen (N) and sulfur (S) fertilization on flour sulfur and nitrogen content and N-S ratio in the SN1 (a–c) and SN2 (d–f) trials; sulfur (closed symbols), nitrogen (open symbols), no fertilizer (■), 25 kg/ha (●), 50 kg/ha (▲), 75 kg/ha (◆), 150 kg/ha (⊕), 225 kg/ha (▼). Error bars \pm 1 standard error.

SN1 when determined in the mixograph, and not significant when determined in the farinograph.

Flour N and S Content

As expected, N fertilization increased flour nitrogen content, and S fertilization increased flour sulfur content. In both trials, the effect of sulfur fertilization on flour nitrogen was not significant (Fig. 5), but N fertilization had a significant and positive effect on flour sulfur content. The flour N-S ratio increased with N fertilization and decreased with S fertilization.

Flour sulfur, flour nitrogen and the N-S ratio were effective predictors of WI, MDT, FDT, and Rmax (Table III). In SN1, the optimum prediction of WI was obtained using a quadratic of the N-S ratio, whereas in SN2, it was obtained using a linear relationship of the N-S ratio and either the flour nitrogen content or flour sulfur content (both equally effective). Bromated and nonbromated doughs gave very similar coefficients (Table III), confirming the strength of the predicted relationships. For MDT, the optimum model in SN1 required flour sulfur, flour nitrogen and N-S ratio, but in SN2, the ratio was not required. For FDT, the optimum model in SN1 was achieved with flour nitrogen alone, but in SN2, flour sulfur also was required. For Rmax, the optimum model in SN1 explained only 16% of the variation using flour sulfur and flour nitrogen, but in SN2, the N-S ratio alone explained 63% of the variation.

There was considerable overlap in the N-S ratio of the two experiments (Fig. 6). The optimum model for prediction of WI using the combined data was a quadratic, similar in form to the model for SN1 alone (Table III). The similar linear model using N-S ratio as shown in Fig. 6 explained 69% of the variation within the two experiments, only 2% less than the quadratic.

These results show that determining flour sulfur content is a useful adjunct to flour nitrogen content in predicting the mixing behavior of wheat flour. Changes in protein composition due to the application of N and S fertilizer have been determined by SDS-PAGE (Wrigley et al 1984, Fullington et al 1987). At lower levels of flour sulfur, the sulfur-poor proteins (ω -gliadins and HMW-glutenins) increased relative to the sulfur-rich proteins (other gliadins and LMW-glutenins). These sulfur-rich proteins in turn were negatively correlated with Rmax and positively with Ext.

Effects of S and N on Relationship Between Mixing Requirement and Dough Strength

In an earlier report, we reviewed the nexus between mixing requirements and dough strength (Wooding et al 1999). In the present experiments, the combinations of nitrogen and sulfur treatments reduced the strength of the nexus. In SN1, for example, Rmax and MDT had a correlation (r) of 0.463 (Table II). By a simple regression, each explained only 21% of the variation in the other. Fitting separate intercepts for each N and S fertilization treatment increased the cumulative R^2 adjusted value from 21 to 72% for MDT and 44% for Rmax (Table IV). Adding sulfur fertilization treatments did not significantly increase the cumulative R^2 adjusted value. The variance due to the interaction between the covariate and the fertilization treatments was not significant; the regression lines for MDT on Rmax (or vice versa) were parallel, and only the intercepts differed with the treatments. Similarly, the cumulative R^2 adjusted value for WI with Rmax was 12%, adding the fertilizer treatments increased the cumulative R^2 adjusted to 43% for WI and 33% for Rmax, and again the regression lines were parallel (Table IV). Changes in the relationship between WI and Rmax in SN2 are shown in Fig. 7. These results show that the nexus remained strong but could be moved up or down by altering the fertilization of the crop, thus affecting flour sulfur and nitrogen content. While the optimum model of WI based on flour sulfur and nitrogen content (Table III) was not improved by including Rmax as an additional covariate, the optimum model of Rmax based on flour composition was improved by the substitution of WI for flour

nitrogen (Table V). An even better model of Rmax was achieved using MDT and flour nitrogen as the covariates (Table V). The explained variance of MDT was improved to 86% using Rmax, flour nitrogen, flour sulfur, and the $N \times S$ interaction (Table V). Changes in the relationship between MDT and Rmax in SN2 are shown in Fig. 8.

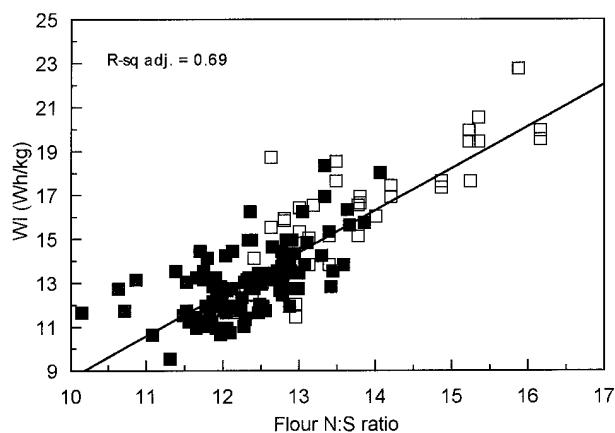


Fig. 6. Effect of the flour nitrogen (N) and sulfur (S) ratio on industrial mechanical dough development (MDD) work input (WI) requirements of Otane in SN1 (■) and SN2 (□) trials.

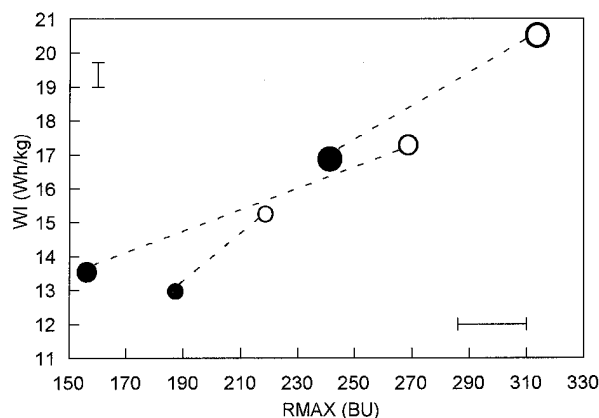


Fig. 7. Effect of nitrogen (N) and sulfur (S) fertilizer on the nexus between mechanical dough development (MDD), work input (WI), and extensigraph resistance to extension (Rmax) in SN2 trial. No sulfur (open symbols); 75 kg of sulfur/ha (closed symbols). Symbol size increases with nitrogen (0, 75, 225 kg/ha). Bars = 1 standard error for each attribute.

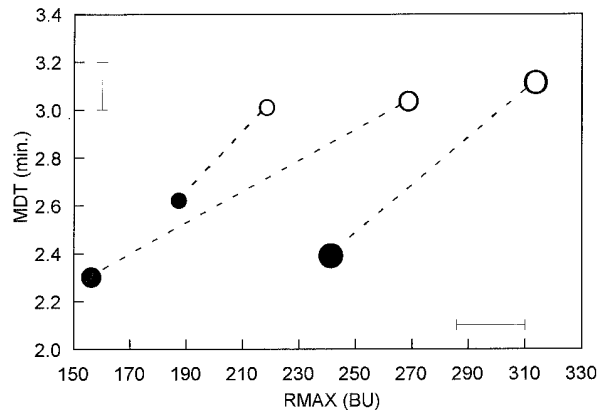


Fig. 8. Effect of nitrogen (N) and sulfur (S) fertilizer on the nexus between mixograph development time (MDT) and extensigraph resistance to extension (Rmax) in SN2 trial. No sulfur (open symbols); 75 kg of sulfur/ha (closed symbols). Symbol size increases with nitrogen (0, 75, 225 kg/ha). Bars = 1 standard error for each attribute.

TABLE III
Relationship Between Quality Attributes and Elemental Composition of Flour^{a,b}

Attribute ^c	Trial	Intercept	SE	Slope b1	SE	Slope b2	SE	Slope b3	SE	Slope b4	SE	R ² adj (%)
WI	SN1 bromated	80***	23					-12.3**	3.8	0.56***	0.16	43
WI	SN1 nonbromated	63**	20					9.7**	3.2	0.45***	0.13	47
WI	SN2 bromated	-28.1***	4.1	72***	16			2.50***	0.18			81
WI	SN2 nonbromated	-29.0***	4.4	59***	16			2.63***	0.20			81
WI	SN2 nonbromated	-21.3***	2.8			5.1***	1.2	2.04***	0.18			81
WI	SN2 bromated	-18.6***	2.6			5.3***	1.2	1.79***	0.17			81
WI	SN1 +SN2 bromated	-10.7***	1.3					1.94***				69
WI	SN1 +SN2 bromated	22*	11					-3.0	1.6	0.185**	0.060	71
MDT	SN1	34.9***	6.2	-226***	45	15.9***	3.7	-2.29***	0.50			78
MDT	SN2	4.92***	0.44	-31.5***	3.4	1.14***	0.29					81
FDT	SN1	-2.49***	0.35			3.33***	0.20					72
FDT	SN2	-0.28	1.33	-50***	10	6.27***	0.86					71
Rmax	SN1	401***	44	-2670***	570	110***	29					16
Rmax	SN2	-344**	94					42.0***	6.9			63

^a Attribute = Intercept + b1 × flour sulfur + b2 × flour nitrogen + b3 × flour N-S ratio + b4 × (flour N-S ratio)². Slope b1 = flour sulfur; slope b2 = flour nitrogen; slope b3 = N-S ratio; slope b4 = N-S ratio².

^b *, **, *** indicate $P < 0.05, 0.01, 0.001$, respectively.

^c MDD, mechanical dough development; WI, work input; MDT, mixograph development time; FDT, farinograph development time.

TABLE IV
Relationships Between Mixing Requirements on Dough Strength and Fertilization Treatments in SN1 Trial^a

Attribute ^b	Intercept (0N, 0S)	SE	Covariate	Slope due to Covariate	SE	R ² adj. (%)	Fertilization Treatment	Change to Intercept	SE	Cumulative R ² adj. (%)
MDT	2.21***	0.20	Rmax	0.00353***	0.00075	21	75N	-0.313***	0.054	72
							150N	-0.585***	0.056	
							225N	-0.755***	0.060	
							25S	-0.054	0.054	
							50S	-0.069	0.058	
							75S	-0.181**	0.066	
							75N	-1.1	7.6	
Rmax	97.6**	35	MDT	52***	11	21	75N	-1.1	7.6	44
							150N	5.8	9.8	
							225N	34.9**	11.1	
							25S	-13.8*	6.4	
							50S	-24.3***	6.6	
							75S	-20.7**	8.0	
							75N	-19.6**	6.9	
WI	11.9***	1.3	Rmax	0.0079	0.0050	12	75N	-0.33	0.36	43
							150N	0.43	0.38	
							225N	2.03***	0.40	
							25S	-0.68	0.36	
							50S	-1.23***	0.38	
							75S	-1.74***	0.40	
							75N	-19.6**	6.9	
Rmax	216***	28	WI	3.1	2.0	12	75N	-19.6**	6.9	33
							150N	-30.5***	6.8	
							225N	-11.2	8.8	
							25S	-17.7*	7.0	
							50S	-29.4***	7.4	
							75S	-30.4***	8.8	
							75N	-19.6**	6.9	

^a *, **, *** indicate $P < 0.05, 0.01, 0.001$, respectively.

^b MDT, mixograph development time; Rmax, extensigraph resistance to extension; WI, work input.

The ratio between WI and Rmax was significantly affected only by flour nitrogen (Table V), as was the ratio between MDT and Rmax. These relationships, however, were in opposite directions, as the WI-Rmax ratio increased with increasing flour nitrogen and the MDT-Rmax ratio decreased. This shows that the dependence of WI, Rmax, and MDT on flour nitrogen content differs. This observation is relevant to the nexus between mixing requirement and dough strength, as it shows that when N fertilization has been used to improve dough strength, the increase in WI has been even greater. S fertilization can temper this response.

N and S fertilization to adjust flour nitrogen and sulfur levels can be a valid means of managing the nexus between mixing requirements and dough strength. Breaking the nexus may not be desirable, as it may be argued that mixing a flour with a low optimum mixing requirement to its optimum inherently imparts the requisite strength for the remaining steps in breadmaking. Therefore, it may

be appropriate to manage the production chain such that the flour delivered to industrial MDD bakeries requires a mixing energy of 10–14 Wh/kg, which is the estimated amount that can be imparted by current industrial mixers without causing excessive heating. Undermixing of a dough that requires too high a mixing energy is likely not to achieve the full dough strength, hence quality will be poor.

CONCLUSIONS

The present results have confirmed the need for adequate flour sulfur to lower WI requirements in industrial MDD bakeries. In addition, a strong correlation was observed between laboratory-scale and industrial-scale estimates of mixing requirements.

The optimum ratio of N to S in the flour of cultivar Otane was ≈12.5:1. Higher values were associated with excessive work input requirement, >13 Wh/kg in the 125-g MDD mixer, leading to

TABLE V
Relationships Between Mixing Requirements on Dough Strength and Flour Composition in SN1 Trial^a

Attribute ^b	Intercept	SE	Covariate	Slope due to Covariate	SE	Cumulative R ² adj. (%)
MDT	15.6***	2.4	Rmax	0.00372***	0.00049	86
			Flour N	-7.2***	1.4	
			Flour S	-88***	18	
			Flour N × Flour S	43.9***	9.9	
WI	7.1***	2.7	Rmax	0.0155***	0.0044	44
			Flour N	8.8***	1.4	
			Flour S	-90***	28	
WI	-5.9***	2.1	Rmax	0.0140***	0.0041	43
			Flour N-S ratio	1.29***	0.17	
Rmax	277***	40	WI	8.2***	1.6	24
Rmax	-306***	55	Flour S	-1,200***	290	
			MDT	102***	10	
			Flour N	157***	19	
MDT-to-Rmax	0.231***	0.0011	Flour N	-0.00676***	0.00064	51
WI-to-Rmax	0.0215**	0.0080	Flour N	0.0229***	0.0046	18

^a *, **, *** indicate $P < 0.05, 0.01, 0.001$, respectively.

^b MDT, mixograph development time; Rmax, extensigraph resistance to extension; WI, work input.

excessive heat development or inadequate mixing. Maintaining the flour N-S ratio in the correct range required N-S ratios of $\approx 3:1$, although prevailing soil conditions will influence the effect of applied N and S fertilization on protein composition. The N-S ratio of the flour did not, however, allow prediction of the Rmax. Further investigation is required to establish whether these values are typical of a wide range of other cultivars and to determine the differences in protein composition that lead to acceptable Rmax values at this optimum N-S ratio.

ACKNOWLEDGMENTS

We gratefully acknowledge the New Zealand Association of Bakers, New Zealand Flour Millers Association, New Zealand Foundation for Research, Science and Technology, Australian Grains Research and Development Corporation, and CSIRO Plant Industry, Australia for funding this work. Special thanks are extended to Canterbury Flour Mills Ltd, Ashburton, New Zealand, for milling the SN2 trial wheat samples and GBH Bakeries, a division of Quality Bakers New Zealand Ltd, for the use of their bakery for the industrial-scale mixing trials. We thank the Crop Systems and Environment Team at Crop & Food Research for sowing and cultivating the trial, Andrew Wallace for advice on the statistical analysis of trial results, and referees for their constructive suggestions.

LITERATURE CITED

American Association of Cereal Chemists. 2000. Approved Methods of the AACC, 10th ed. Method 54-10, Method 54-21, Method 54-40. The Association: St. Paul, MN.

Cunningham, D. K., and Anderson, J. A. 1956. Decomposition of bromate in fermenting and nonfermenting doughs. *Cereal Chem.* 33:290-299.

French, F. D., and Fish, A. R. 1981. High speed mechanical dough development. *Baker's Dig.* 55(5):80-82.

Fullington, J. G., Miskelly, D. M., Wrigley, C. W., and Kasarda, D. D. 1987. Quality-related endosperm proteins in sulfur-deficient and normal wheat. *J. Cereal Sci.* 5:233-245.

Griffin, W. B., and Wooding, A. R. 1992. The importance of work input in breeding for improved wheat bread baking quality. Pages 235-244 in: Proc. 42nd Australian Cereal Chem. Conf. V. J. Humphrey-Taylor, ed. Cereal Chem. Div., Royal Australian Chemical Institute: Parkville, Victoria, Australia.

Hlynka, I., Templin, P. R., and Anderson, J. A. 1953. Decomposition of bromate in dough. *Cereal Chem.* 30:391-403.

ISO. 1975. Agricultural food products—General directions for the determination of nitrogen by the Kjeldahl method. 1871: International Organisation for Standardisation: Geneva.

Lee, C. C., Tkachuk, R., and Finlayson, A. J. 1958. The conversion of Br⁸²-labelled bromate to bromide in nonfermenting and fermenting doughs and in baked bread. *Cereal Chem.* 35:337-349.

Martin, R. J. 1987. The effect of time of nitrogen application on the yield and quality of contrasting cultivars of autumn sown wheat. *Proc.*

Agron. Soc. NZ 17:103-108.

Martin, R. J., Saville, D. J., Daly, M. J., and Drewitt, E. G. 1989. The effects of nitrogen fertilizer on the relationship between yield and quality in wheat and barley. Pages 346-358 in: Proc. Workshop, Nitrogen in New Zealand Agriculture and Horticulture. R. E. White, and L. D. Currie, eds. Fertilizer & Lime Research Centre: Palmerston, North, NZ.

Moss, H. J., Wrigley, C. W., MacRitchie, F., and Randall, P. J. 1981. Sulfur and nitrogen fertiliser effects on wheat. II. Influence on grain quality. *Aust. J. Agric. Res.* 32:213-226.

Moss, H. J., Randall, P. J., and Wrigley, C. W. 1983. Alteration to grain, flour and dough quality in three wheat types with variation in soil sulfur supply. *J. Cereal Sci.* 1:255-264.

Ott, L. 1988. An introduction to statistical methods and data analysis. PWS-KENT: Boston.

Quail, K., Jayasena, V., Zounis, S., and Hogan, W. 1993. Optimising dough development and consistency for bread production. Pages 39-44 in: Proc. 43rd Australian Cereal Chemistry Conf. C. W. Wrigley, ed. Cereal Chem. Div., RACI: Parkville, Vic., Australia.

Randall, P. J., and Sakan, H. 1983. X-ray fluorescence spectrometry. Pages 255-269 in: Sulfur in SE Asian and South Pacific Agriculture G. J. Blair and A. R. Tik, eds. University of New England: Armidale, NSW, Australia.

Randall, P. J., and Wrigley, C. W. 1986. Effects of sulfur supply on the yield, composition, and quality of grain from cereals, oilseeds, and legumes. Pages 171-206 in: Advances in Cereal Science and Technology Vol. 8. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

Sokal, R. R., and Rohlf, F. J. 1981. Biometry: The Principles and Practice of Statistics in Biological Research. W. H. Freeman: New York.

Spies, R. 1990. Application of rheology in the bread industry. Pages 343-361 in: Dough Rheology and Baked Product Texture. H. Faridi and J. M. Faubion, eds. Van Nostrand Reinhold: New York.

Swallow, W. H., and Baruch, D. W. 1986. Loaf evaluation. Rep. WRI 86/103. Dept. Scientific and Industrial Res. Wheat Res. Institute: Christchurch, NZ.

Tomlinson, J. D., Mugford, D. C., and McGuirk, G. M. 1991. Chemicals in bread. *Chem. Aust.* 58:358-361.

Tsen, C. C. 1965. The improving mechanism of ascorbic acid. *Cereal Chem.* 42:86-97.

Wilson, A. J. 1992. Measurement of work input in industrial mixers. Pages 47-53 in: Proc. 42nd Australian Cereal Chem. Conf. V. J. Humphrey-Taylor, ed. Cereal Chem. Div., RACI: Parkville, Victoria, Australia.

Wilson, A. J., Wooding, A. R., and Morgenstern, M. P. 1997. Comparison of work input requirement on laboratory-scale and industrial-scale mechanical dough development mixers. *Cereal Chem.* 74:715-721.

Wooding, A. R., and Walker, C. E. 1992. Comparison of alternative recording mechanisms (mobile vs. fixed-bowl) for the 35- and 10-gram mixographs. *Cereal Chem.* 69:249-253.

Wooding, A. R., Kavale, S., MacRitchie, F., and Stoddard, F. L. 1999. Nexus between mixing requirements and dough strength. *Cereal Chem.* 76:800-806.

Wrigley, C. W., du Cros, D. L., Fullington, J. G., and Kasarda, D. D. 1984. Changes in polypeptide composition and grain quality due to sulfur deficiency in wheat. *J. Cereal Sci.* 2:15-24.