Uptake and distribution of nitrogen and sulphur in two Otane wheat crops

R.J. Martin

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

Abstract

Various combinations of nitrogen (N) and sulphur (S) fertiliser were applied at two growth stages to two spring sown Otane wheat crops. The dry matter yield, and concentration of N and S were measured in plant components of samples taken at anthesis and maturity. Of the N fertiliser applied 21-56% was taken up by the crop compared with only 4-25% of the S fertiliser. N application increased yield by up to 2.5 t/ha, and also increased grain N% and S%, whereas S fertiliser had no effect on either yield or grain content. Timing of application of N had different effects on yields of N and S in plant components between the two seasons. At anthesis 40% of the N and 50% of the S in the plant were in the stems. N harvest index averaged 0.8 and S harvest index 0.6. There was about 860% more N in the plant than S at both anthesis and maturity. Of the N and S in the plant at maturity 66% or more was taken up before anthesis. Uptake of N and S may have been restricted by dry conditions during growth of both crops.

Additional key words: *urea, gypsum, harvest index, fertiliser uptake*

Introduction

Increased energy requirements for bread dough mixing have occurred recently, causing problems in large automated bakeries. These increases have coincided with decreases in the sulphur content of fertilisers applied to New Zealand wheat crops, and with increases in nitrogen fertiliser applications as growers aim to combine high yields with high grain protein content.

Wooding *et al.* (1993) showed that changes in the ratio of nitrogen to sulphur in Otane wheat grains had a large effect on dough mixing properties. Increases in the level of nitrogen in the grain without a corresponding increase in sulphur led to increased work input requirements. Similar results have been obtained in Australia where Moss *et al.* (1981, 1983) found that dough extensibility decreased and resistance to extension increased as S content decreased. The decrease in the visco-elastic properties of the dough are associated with a reduction in the number of sulphur containing sulfhydryl and disulphide bonds (Frater *et al.*, 1960; Wall, 1971).

This study investigated whether combinations of N and S fertilisers would alter the uptake and redistribution of N and S in the wheat plant. Twelve combinations of rates and timings of N and S fertiliser were applied to two crops of Otane wheat grown in separate seasons in Canterbury.

Materials and Methods

Wheat, cv. Otane, was sown on 16 September 1994 and 16 August 1995 at a seeding rate of 150 kg/ha on a Templeton Silt loam (New Zealand Soil Bureau, 1968) at the Lincoln Research Farm of the New Zealand Institute for Crop & Food Research Ltd. Soil fertility details at sowing are given in Table 1.

The same 12 fertiliser treatments were used in both seasons (Table 2). The N was supplied as urea (46% N) and the S as gypsum (18% S). The fertiliser was applied

Table 1. Soil fertility status (0-15 cm) of the sites used in the 1994-95 and 1995-96 seasons, determined by AgResearch Quick Tests (Cornforth and Sinclair, 1984).

Season	pH	Ca	K	P	Mg	Na	S	NO_3-N	Total N
1994-95	6.4	12	8	22	16	7	2	5	0.23
1995-96	6.5	13	19	22	27	6	6	4	0.23

either soon after the crop had emerged or at booting. The emergence application dates were 11 October 1994 and 15 September 1995, and the booting application dates were 29 November 1994 and 14 November 1995. The fertiliser was applied by hand. It was applied either just before rain, or about 25 mm irrigation was applied within 36 hours of the fertiliser application.

Plot sizes were 10 m by 1.6 m. A randomized block design was used. In the 1994-95 season, the trial had three replicates, and in 1995-96 five replicates, but in the latter trial two replicates were on a shingle ridge and the others on deeper soil.

The crops were irrigated after the fertiliser was applied and when the soil moisture was at wilting point. Irrigation was infrequent in both seasons due to irrigator breakdowns. A total of 185 mm was applied in 1994-95, but distribution was very uneven due to windy conditions. In 1995-96 only 50 mm was applied. The crops were managed to keep them free of weeds, diseases and pests.

At anthesis, around 7 December 1994 and 29 November 1995, two 0.1 m^2 samples of above ground plant material were taken from each plot. Leaf areas and dry weights of leaf, stem, dead and head material were determined. When the crop was mature, two 0.5 m^2 quadrats were taken from each plot, and straw, chaff and grain dry weights and thousand grain weights determined. Harvest dates were 8 February 1995 and 23 January 1996. All the yield component samples were stored and subsequently ground for analysis for N and S content using a LECO analyser.

Table 2. Applied nitrogen and sulphur fertiliser treatment details (kg/ha).

Treat.	Nitrogen		Sulpher	
no.	emergence	booting	emergence	booting
1	0	0	0	0
2	0	0	75	0
3	0	0	0	75
4	0	150	0	0
5	0	150	75	0
6	0	150	0	75
7	150	0	0	0
8	150	0	75	0
9	150	0	0	75
10	150	150	0	0
11	150	150	75	0
12	150	150	0	75

Data were analyzed using the Genstat statistical package (Genstat 5 Committee, 1993). N harvest index (NHI) and S harvest index (SHI) were calculated as the amount of N or S in the grain divided by the amount of N or S in the above ground parts at maturity.

Results

Both seasons were considerably drier than average (Table 3), and growth of both crops was severely restricted by dry soil conditions. In the 1995-96 season, many plants in the two replicates on the shingle ridge died prematurely and any grains set failed to fill. Therefore, the results from that year are for the three replicates on the deeper soil.

Yield and grain weight

Yields averaged 5 t/ha for 1994-5 and 5.7 t/ha in 1995-96 (Table 4). N fertiliser applied at emergence increased yield by 0.5 t/ha in 1994-95 and by 1.9 t/ha in 1995-96. N applied at booting had no significant effect on grain yield or size in both seasons but increased yields and grain size when no N had been applied at emergence in both seasons. S fertiliser had no effect on yield or grain size, which was around 49 mg in both seasons (Table 4).

Grain N and S content

Application of N at both emergence and booting significantly ($P<0.05$) increased grain N content in both years, but the effects were not additive (Table 4). N applied at booting significantly ($P<0.05$) increased grain S content in both years, but in 1994-95 this only occurred when N had not been applied at emergence. S

Table 3. Rainfall (mm) for the 1994-95 and 1995-96 growing seasons, and the long term (1975-1991) mean.

Month	1994-95	1995-96	Long term mean
August	5.2	56.2	68.1
September	56.4	94.0	40.1
October	19.0	39.6	54.9
November	22.7	19.8	55.7
December	24.7	15.3	61.3
January	32.3	16.0	50.3
February	25.4	32.3	51.3
Total	185.7	273.2	381.7

fertiliser had no effect on grain N or S contents. Grain S contents were generally less than one tenth the grain N contents.

N and S yields of plant components

In 1994-95, N applied at emergence significantly ($P<0.05$) increased leaf N yield and total S yield at anthesis, but N at booting had no effect on N and S yields of plant components at anthesis (Table 5). In contrast, in 1995-96, N applied at emergence had no effect apart from increasing N yield of the dead lower leaves, whereas N applied at booting significantly ($P<0.05$) increased leaf, stem and total N yield. There was no effect of N fertiliser on S yields at anthesis in either season.

Most of the N and S in the plant at anthesis was in the stems (40% N and 50% S), with less in the leaves (29% N and 16% S). The amounts of N and S in the heads were similar for both N and S treatments but were proportionately higher in 1994-95 (33%) than in 1995-96 (21%).

At maturity (Table 6) there were significant responses to N applied at both emergence and booting for grain, chaff and total N yield in both seasons, and for grain and total S yield in 1995-96. N at emergence increased straw N yield and total S yield in 1994-95, and chaff S yield in 1995-96. N fertiliser had no effect on chaff and straw S yield in 1994-95.

Nitrogen and sulphur harvest index

NHI averaged 0.8 and SHI 0.6 (Fig. 1). N applied at booting significantly ($P<0.05$) increased SHI in 1994-95, but there was no significant effect of N fertiliser on NHI. In 1995-96, N applied at emergence significantly ($P<0.05$) decreased NHI, but there was no significant effect of N fertiliser on SHI.

N:S ratio at anthesis and maturity

There was around 8.6 times more N than S in the plant at both anthesis and maturity. N fertiliser had no effect on the anthesis N:S ratio in 1994-95, but both N at emergence and N at booting significantly ($P<0.05$) increased the ratio in 1995-96 (Fig. 2).

At maturity, N fertiliser at both emergence and booting significantly ($P<0.05$) increased the N:S ratio in 1994-95, but in 1995-96 there was a significant ($P<0.05$) interaction between the applications, resulting in no overall trend.

Table 4. Interaction of nitrogen timing and rates and main effects of sulphur on grain yield (kg/ha), grain weight (mg) and grain nitrogen and sulphur concentration (expressed as a percentage) at 14% moisture from the 1994-95 and 1995-96 seasons (degrees of freedom = 30, LSDs = least significant difference of the individual means given in each section of the table).

Treatments		1994-95 Grain Yield	1994-95 Grain Weight	1994-95 Grain N %	1994-95 Grain S %	1995-96 Grain Yield	1995-96 Grain Weight	1995-96 Grain N %	1995-96 Grain S %
Nitrogen (kg/ha)									
emergence (NE)	booting (NB)								
0	0	4650	47.5	2.22	0.218	4160	45.4	1.87	0.213
	150	4809	49.8	2.92	0.246	5280	55.1	2.79	0.239
150	0	5130	49.8	2.74	0.244	6620	47.4	2.17	0.178
	150	5410	48.9	2.89	0.238	6680	49.7	2.61	0.245
	$LSD_{P<0.05}$	495	3.06	0.090	0.0178	638	3.17	0.167	0.0425
	Significant effects	NE		NE,NB, NE*NB	NB, NE*NB	NE,NB, NE*NB	NB, NE*NB	NB, NE*NB	NB
Sulphur									
0		5003	49.2	2.68	0.233	5463	49.0	2.32	0.216
75 at emergence		4886	48.7	2.70	0.241	5654	48.3	2.36	0.223
75 at booting		5112	49.1	2.68	0.233	5937	50.8	2.40	0.218
	$LSD_{P<0.05}$	428	2.64	0.078	0.0154	553	2.75	0.145	0.0368

Table 5. Interaction of nitrogen timing on nitrogen and sulphur yields of plant components (kg/ha) at anthesis in the 1994-95 and 1995-96 seasons. (degrees of freedom = 30, LSD = least significant difference of the interaction between N applied at emergence and at booting).

Applied N (kg/ha) emergence	booting	Leaf N yield	Leaf S yield	Stem N yield	Stem S yield	Head N yield	Head S yield	Dead N yield	Dead S yield	Total N yield	Total S yield
1994-95											
0	0	25.9	1.50	41.3	6.28	36.0	4.32	5.8	0.75	109.0	12.85
	150	28.7	1.82	41.2	6.70	37.1	4.33	5.1	0.67	112.1	13.52
150	0	30.5	1.87	43.0	7.05	37.9	4.68	5.4	0.70	116.8	14.30
	150	32.5	1.89	49.8	7.36	39.7	4.57	5.6	0.79	127.6	14.61
	$LSD_{P<0.05}$	4.48	0.403	6.67	0.975	4.45	0.541	2.01	0.288	13.74	1.692
1995-96											
0	0	29.4	2.51	34.0	6.49	23.5	3.16	4.7	1.41	91.6	13.57
	150	51.0	3.46	62.9	8.80	31.3	4.20	5.9	1.43	151.1	17.89
150	0	35.5	2.20	49.8	6.27	22.8	3.06	7.3	1.41	115.4	12.94
	150	54.1	2.76	61.9	7.00	28.6	3.60	7.8	1.46	152.4	14.82
	$LSD_{P<0.05}$	20.43	1.393	18.07	2.812	9.86	1.211	3.13	0.567	47.02	5.303

Table 6. Interaction of nitrogen timing on nitrogen and sulphur yields of plant components (kg/ha) at maturity in the 1994-95 and 1995-96 seasons. (degrees of freedom = 30, LSD = least significant difference of the interaction between N applied at emergence and at booting).

Applied N (kg/ha) emergence	booting	Grain N yield	Grain S yield	Chaff N yield	Chaff S yield	Straw N yield	Straw S yield	Total N yield	Total S yield
1994-95									
0	0	103.2	10.13	4.6	1.28	22.5	6.25	130.3	17.66
	150	140.4	11.83	7.8	1.29	28.7	6.16	177.0	19.28
150	0	140.6	12.52	6.8	1.21	33.4	6.78	180.8	20.51
	150	156.4	12.88	8.5	1.30	29.8	5.44	194.7	19.62
	$LSD_{P<0.05}$	16.59	1.665	2.07	0.430	8.24	1.510	16.54	2.034
1995-96									
0	0	77.8	8.86	6.7	1.99	11.7	2.55	96.2	13.40
	150	147.3	12.62	13.2	2.43	19.9	4.74	180.4	19.79
150	0	143.7	11.78	11.6	3.02	25.4	4.24	180.7	19.04
	150	174.4	16.37	16.0	3.01	30.0	6.76	220.4	26.14
	$LSD_{P<0.05}$	12.40	3.253	2.10	0.825	4.04	1.685	15.67	3.760

N and S ratio anthesis to maturity

Figure 3 compares the ratio of the N or S at anthesis to the N or S yield at maturity. Overall, there was little difference between the N and the S ratios in both seasons.

In the nil N treatment in 1995-96, both the N and S ratios for anthesis to maturity were close to 1, indicating that nearly all the N and S in the plant at maturity was taken up before anthesis. This assumes that there were no N losses to the atmosphere or that they were balanced by N uptake after anthesis. In contrast, any N applied in 1994-95 and N applied at emergence in 1995-96 resulted in about one-third of the N and S in the grain coming from post anthesis uptake.

In 1994-95 application of N fertiliser significantly ($P<0.05$) reduced the ratio of anthesis N to maturity N, but had no effect on the S ratio. In 1995-96, N applied at emergence significantly ($P<0.05$) decreased the anthesis:maturity ratio of both N and S, but N applied at booting had no significant effect.

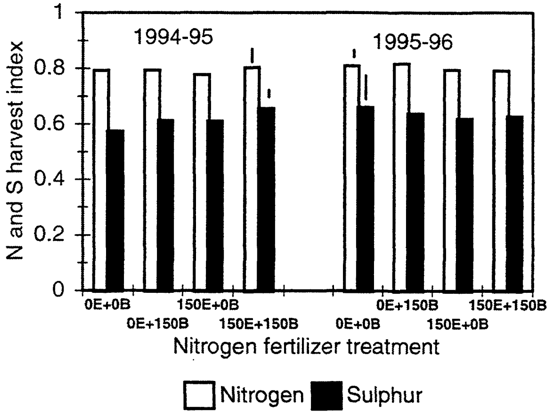

Figure 1. Nitrogen and sulphur harvest indices for Otane wheat under four nitrogen fertiliser treatments in two seasons. 0E = no fertiliser at emergence; 0B = no fertiliser at booting; 150E = 150 kg N fertiliser applied at emergence; 150B = 150 kg N fertiliser applied at booting. Vertical bars are for LSD (P<0.05).

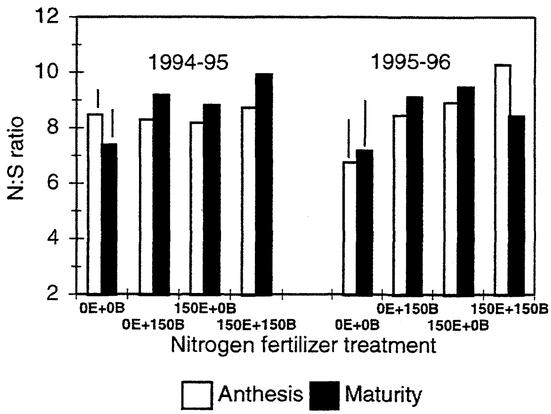

Figure 2. Nitrogen:sulphur yield ratio at anthesis and at maturity for Otane wheat under four nitrogen fertiliser treatments in two seasons. Abbreviations as in Figure 1. Vertical bars are for LSD (P<0.05).

N and S fertiliser uptake

Figure 4 shows the increased N and S yields of the three nitrogen fertiliser treatments (averaged over the

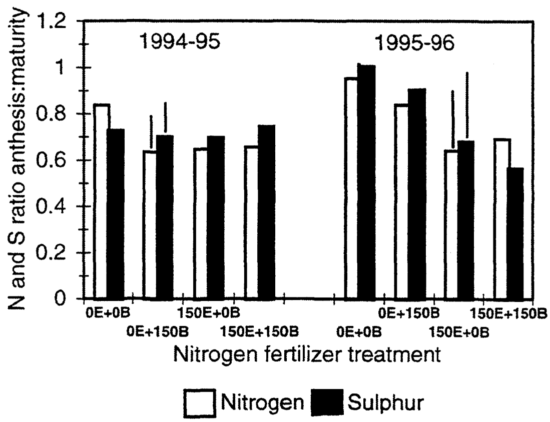

Figure 3. The anthesis:maturity ratios for nitrogen and sulphur yield for Otane wheat under four nitrogen fertiliser treatments in two seasons. Abbreviations as in Figure 1. Vertical bars are for LSD (P<0.05).

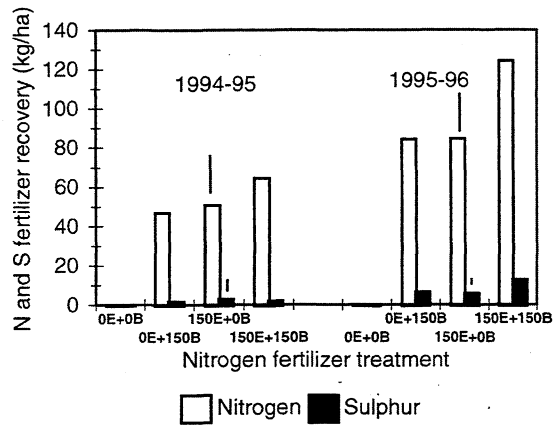

Figure 4. Nitrogen and sulphur fertiliser recoveries in Otane wheat under four nitrogen fertiliser treatments in two seasons. Abbreviations as in Figure 1. Vertical bars are for LSD (P<0.05).

three S treatments in each case) over the nil nitrogen treatment. This represents the net increase in uptake of fertiliser. N fertiliser uptake varied from 47 to 124 kg N/ha (21 to 56% of what was applied). This was considerably higher than the S fertiliser uptake, which was around 2 kg (4% of the average amount of S applied) in 1994-95 and 6 to 13 kg/ha (11 to 25%) in 1995-96.

About 80% more N fertiliser and four times as much S fertiliser were recovered in 1995-96 compared to 1994-95.

Discussion

Responses to N fertiliser

Mean yields without fertiliser were less than 5 t/ha, and were low compared to other spring fertiliser trials (Martin, 1993). Yield responses to N fertiliser differed between seasons, being less than 0.5 t/ha in 1994-95, but up to 2.5 t/ha in 1995-96. This difference in response may be a reflection of differences in the intensity and timing of the water stress experienced by the two crops. Also the yields of the 1994-95 trial were limited by take-all (*Gaeumannomyces graminis*) and *Fusarium*.

Significant yield increases occurred to N applied both at emergence and, to a lesser extent, at booting. Similar responses have been obtained in previous trials (Martin *et al.*, 1992; Martin, 1993), as was the greater increase in grain N content with N applied at booting compared to N applied at crop emergence.

N content in crop

N content and yields of plant components at anthesis and maturity in the nil N treatments were similar to those reported for a crop fertilised with 100 kg N/ha by Martin (1992). However, the N contents of the treatments receiving N fertiliser were considerably higher than those reported by Martin (1992), but were similar to levels found with added N fertiliser by Gregory *et al.* (1979) and Papakosta and Gagianis (1991).

Responses to S fertiliser

There was little or no response to the sulphur fertilisers used in this trial. Very little S was taken up compared to N, especially in the first year. However, S uptakes were similar to the 10% recovery of S from potassium sulphate applications reported by Withers and Sinclair (1994). Even in S deficient soils, optimum application rates of S for yield are only 10-20 kg/ha (Withers and Sinclair, 1994). Therefore, although gypsum is not as soluble as ammonium sulphate, which is the recommended form for sulphur application to cereals in the UK (Withers and Sinclair, 1994), this form is unlikely to have limited S availability to the crop.

Previous data (Wooding and Martin, unpublished) suggest that soil S levels below 4 mg/kg would have an effect on grain protein composition. The sulphur levels in these trials of 2 and 6 mg/kg do not appear to have an effect on grain yield or grain S content. However, soil extractable S levels vary considerably over the year (Tan *et al.*, 1994) due to mineralization of sulphate from organic sulphur, a process not well understood (McLaren *et al.*, 1985; Ghani *et al.*, 1992). Therefore, a single soil test at sowing may not have been representative of soil S availability over the life of the crop.

Timing of S fertiliser had no effect on these trials. Withers and Sinclair (1994) suggest that soluble sulphate is best applied before stem extension. However, these trials were spring sown and the duration of growth is considerably shorter than for autumn sown crops. So, like N (Martin 1987), the timing of S application may be less important.

S content in crop

The amount of S in these crops at harvest varied between 13 and 26 kg/ha. This is within the range of 10 to 30 kg/ha reported overseas (Withers and Sinclair, 1994), and the distribution of S between plant components was similar to that reported by Gregory *et al.* (1979). The grain N:S ratios of around 9 to 15 and the grain sulphur contents of 0.18 to 0.25% in this study are higher than the levels of adequate S for quality (Moss *et al.*, 1981; 1983), lower than the N:S ratio of 17 and higher than the grain S concentration of 0.1% for yield (Rasmussen *et al.*, 1975; Randall *et al.*, 1981; Withers *et al.*, 1995).

In these trials, the S uptake mirrored closely the N uptake, which can be markedly affected by soil moisture content (Gregory *et al.*, 1981). Watering was erratic in this experiment because irrigation equipment was not available. Watering was also uneven due to windy conditions. Also, root N and S yields, which can be up to 20% of total plant N and S yields (Simpson *et al.*, 1983; Gregory *et al.*, 1979), were not measured in this trial.

According to Gregory *et al.* (1979) the maximum uptake of S occurs at or shortly after anthesis. There can be significant losses of N and S to the atmosphere and soil during grain filling (Gregory *et al.*, 1979, Parton *et al.*, 1988, Kanda *et al.*, 1995). In these trials, there was no net loss of S from above ground parts from anthesis to maturity, and except for the nil N and 150 kg N at booting treatment in 1995-96, where all the S was taken up by anthesis, about one-third of the net S present at harvest was taken up after anthesis. Overseas, this post anthesis uptake has been linked to low available soil S by Withers and Sinclair (1994).

Both trials were affected by inadequate and uneven irrigation, and the 1994-95 trial was also affected by soil-borne diseases. These factors may well have restricted the availability and uptake of S by the wheat plant. This complicates plant nutrition research where, ideally, factors other than the nutrients being examined should not limit the results.

Acknowledgements

I wish to thank Petrochem New Zealand Ltd for donating the urea and Winstone Wallboards Ltd for donating the gypsum. Barbara Maley and other technical staff assisted with the trials, and Charles Wright carried out the N and S analyses. The work was funded through the Public Good Science Fund of the Foundation for Research, Science and Technology.

References

Cornforth, I.S. and Sinclair, A.G. 1984. Fertiliser recommendations for pasture and crops in New Zealand. 2nd edition. New Zealand Ministry of Agriculture and Fisheries, Wellington. 76 pp.

Frater, R., Hird, F.J.R., Moss, H.J. and Yates, J.R.A. 1960. A role for thiol and disulphide groups in determining the rheological properties of dough made from wheaten flour. *Nature (London)* ***186***, 451-454.

Genstat 5 Committee 1993. Genstat 5 Release 3 Reference Manual. Oxford University Press, Oxford. 796 pp.

Ghani, A., McLaren, R.G. and Swift, R.S. 1992. Sulphur mineralization and transformations in soils as influenced by additions of carbon, nitrogen and sulphur. *Soil Biology and Biochemistry* ***24***, 331-341.

Gregory, P.J., Crawford, D.V. and McGowan, M. 1979. Nutrient relations of winter wheat. 1. Accumulation and distribution of Na, K, Ca, Mg, P, S and N. *Journal of Agricultural Science* ***93***, 485-494.

Gregory, P.J., Marshall, B. and Biscoe, P.V. 1981. Nutrient relations of winter wheat. 3. Nitrogen uptake, photosynthesis of flag leaves and translocation of nitrogen to grain. *Journal of Agricultural Science* ***96***, 539-547.

Kanda, K., Tsurata, H. and Minami, K. 1995. Emission of biogenic sulphur gases from maize and wheat fields. *Soil Science and Plant Nutrition* ***41***, 1-8.

Martin, R.J. 1987. The effect of time of nitrogen application on the yield and quality of contrasting cultivars of autumn and spring sown wheat. *Proceedings Agronomy Society of New Zealand* ***17***, 103-108.

Martin, R.J. 1992. Dry matter and nitrogen redistribution in autumn and spring sown wheats. *Proceedings Agronomy Society of New Zealand* ***22***, 91-96.

Martin, R.J., Sutton, K.H., Moyle, T., Hay, R.L. and Gillespie, R.N. 1992. The effect of nitrogen fertiliser on the yield and quality of six cultivars of autumn sown wheat. *New Zealand Journal of Crop and Horticultural Science* ***20***, 273-282.

Martin, R.J. 1993. Response of wheat to time of nitrogen fertiliser application in a cool temperate climate. Proceedings of the 7th Australian Agronomy Conference, 362.

McLaren, R.G., Keer, J.I. and Swift, R.S. 1985. Sulphur transformations in soils using sulphur-35 labelling. *Soil Biology and Biochemistry* ***17***, 73-79.

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. *Australian Journal of Agricultural Research* ***33***, 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. *Journal of Cereal Science* ***1***, 255-264.

New Zealand Soil Bureau 1968. General survey of the soils of the South Island. New Zealand Soil Bureau bulletin No. 27. 404 pp.

Papakosta, D.K. and Gagianis, A.A. 1991. Nitrogen and dry matter accumulation, remobilization, and losses for Mediterranean wheat during grain filling. *Agronomy Journal* ***83***, 864-870.

Parton, W.J., Morgan, J.A., Altenhofen, J.M. and Harper, L.A. 1988. Ammonia volatilization from spring wheat plants. *Agronomy Journal* ***80***, 419-425.

Randall, P.J., Spencer, K. and Freney, J.R. 1981. Sulfur and nitrogen fertiliser effects on wheat. I. Concentrations of sulfur and nitrogen and the nitrogen to sulfur ratio in grain, in relation to the yield response. *Australian Journal of Agricultural Research* ***32***, 203-212.

Rasmussen, P.E., Ramig, R.E., Allmaras, R.R. and Smith, C.M. 1975. Nitrogen-sulfur relations in soft white winter wheat. II. Initial and residual effects of sulfur on nutrient concentration, uptake and N/S ratio. *Agronomy Journal* ***67***, 224-228.

Simpson, R.J., Lambers, H. and Dalling, M.J. 1983. Nitrogen redistribution during grain growth in wheat (*Triticum aestivum* L.). IV. Development of a quantitative model of the translocation of nitrogen to the grain. *Plant Physiology* ***71***, 7-14.

Tan, Z., Mclaren, R.G. and Cameron, K.C. 1994. Seasonal variations in forms of extractable sulfur in some New Zealand soils. *Australian Journal of Soil Research* ***32***, 985-993.

Wall, J.S. 1971. Disulfide bonds: determination, location and influence on molecular properties of proteins. *Journal of Agriculture, Food and Chemistry* ***19***, 619-625.

Withers P.J.A. and Sinclair, A.H. 1994. Sulphur nutrition of cereals in the UK: Effects on yield and grain quality. Home-Grown Cereals Authority Research Review No.30, 66 pp.

Withers, P.J.A., Tytherleigh, A.R.J. and O'Donnell. F.M. 1995. Effect of sulphur fertilisers on the grain yield and sulphur content of cereals. *Journal of Agricultural Science* ***125***, 317-324.

Wooding, A.R., Martin, R.J. and MacRitchie, F. 1993. Effect of sulfur-nitrogen treatments on work input. *Proceedings of the 43rd Australian Cereal Chemistry Conference*, 45-48.