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Grain and Protein Responses to Nitrogen Applied to Wheat Growing on a Red Earth

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Abstract

Dryland wheat was fertilized with ammonium nitrate or liquid urea–ammonium nitrate at the time of sowing or about 3 months later (generally at the terminal-spikelet stage) on a well-drained site near Harden on the south-west slopes of New South Wales. The experiments continued from the second to the fifth year (1981–1984) of the cropping phase of a crop–pasture rotation. The maximum agronomic efficiencies for yield in the four consecutive years were 19, 4, 23 and 25 kg grain per kg of applied nitrogen (N). The three large responses were obtained in wetter than average seasons and the small response was obtained during drought. In the last three years of the study the yield response to nitrogen at the terminal-spikelet stage was found to be close to but slightly less than that for N applied at sowing. In those years the agronomic efficiencies for the late-applied N were 0, 22 and 22.

The apparent recovery of fertilizer N in the above-ground parts of the crop at maturity was up to 70% of the fertilizer applied in the year of sowing, and, after the drought during which there was little uptake of fertilizer N, up to 62% by the subsequent crop. The fertilizer efficiencies in the non-drought years were higher than generally reported in south-eastern Australia, and indicate potential for profitable delayed application of N fertilizer to wheat. Grain-protein responses were variable from year to year and are discussed against a simple theoretical background of the amount of N applied and grain-yield response.

Introduction

Dryland wheat crops in south-eastern Australia, in contrast with those in many other wheat-producing regions, are usually grown with little or no N fertilizer. The practice is not due to lack of research because extensive programmes, both on research stations and farms, have sought to determine the most profitable rates, dates and methods of applying N fertilizer (Russell 1968; Osborne *et al.* 1977; Taylor *et al.* 1978; Colwell and Morton 1984). The conclusions from these programmes were that yield responses were highly variable and mostly small, and that the most profitable application of N fertilizer was either very low or none at all. The reasons generally advanced for the lack of profitable responses have been the success of biological fixation of N during the pasture phase of the rotation, the lack of highly responsive wheat varieties, the extreme variability of yield response to N in different seasons mainly due to different soil-water conditions, and the unfavourable ratio of price of grain to that of fertilizer N.

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Recent changes in the management of wheat crops may warrant a re-evaluation of the efficiency of N-fertilizer inputs. Increasing intensity of cropping presumably has led to a reduction in levels of available soil N, and the semi-dwarf wheat varieties now available are more N-responsive than their predecessors (Syme *et al.* 1976). Benefits of pastures other than N fixation can be provided in alternative ways: cereal weeds can be controlled with selective herbicides, the life cycles of soil-borne disease-organisms can be broken more effectively with alternative crops than with pastures, and the regeneration of soil structure which is normally needed after several years of conventionally cultivated crops, can be delayed when crops are direct-drilled (Burch *et al.* 1986). The problem of the variable yield response to N in different seasons is addressed in this study by testing a system of applying fertilizer N only when the responses are most likely, which in practice means in wetter than average seasons. Currently there are no means of forecasting seasonal weather in advance of sowing, so such a system has to rely on N applications at some time after sowing, but presumably not so late that the crop does not have time to respond. Such a system of conditional or tactical N fertilization was proposed by Russell (1968).

The aim of the study was to establish, at least for a favourable part of the wheat belt of south-eastern Australia, whether profitable responses are obtainable and whether a system of tactical application of N fertilizer is feasible. The field experiments reported here were conducted in association with measurements of mineralization because N derived from soil organic matter is likely to continue to exceed the fertilizer contribution (Stein *et al.* 1987).

Methods

Experiments were conducted during 1980–1984 at Harden on the south-west slopes of New South Wales. Characteristics of the soil and site are summarized in Table 1. The red earth is the major cropping soil in the Harden district and is widespread in cropping areas of south-eastern Australia. Its advantage, as far as N is concerned, is that it is not prone to waterlogging, so that denitrification losses are likely to be small. This advantage may be offset by a high potential for nitrate leaching. The experimental field was adjacent to the type site for red earths (Stace *et al.* 1968). Daily rainfall data for the site are shown in Fig. 1, with the major phenological stages and dates of field operations. Soil mineral N was determined for 10 cm layers to 30 cm at the time of sowing in each year. Ten bulked samples per plot were chilled in the field, frozen until analysis, extracted with 2N KCl and the nitrate and ammonium concentrations determined using a steam distillation procedure (Freney and Wetselaar 1967). The results are presented in Fig. 2.

Table 1. Site characteristics

Location: 34° 43′ S., 148° 20′ E., elevation 470 m slope: 4% to SW.	
Recent paddock history: 1975–1979 improved pasture	
Soil:	Red earth, Gn 2·14, rhodustalf
	Surface pH 5·6 (in water)
	Surface texture: Clay 22% silt 10%, sand 67%
	Exchange capacity: 14 cmol/kg
	Total N (0–10 cm) 0·11%

Field experiments with wheat (cv. Egret) were conducted on the same land from 1980 to 1984 following five years of pasture. The experiments were designed to test different methods of tillage and different N-fertilizer-management practices, on the growth, yield and

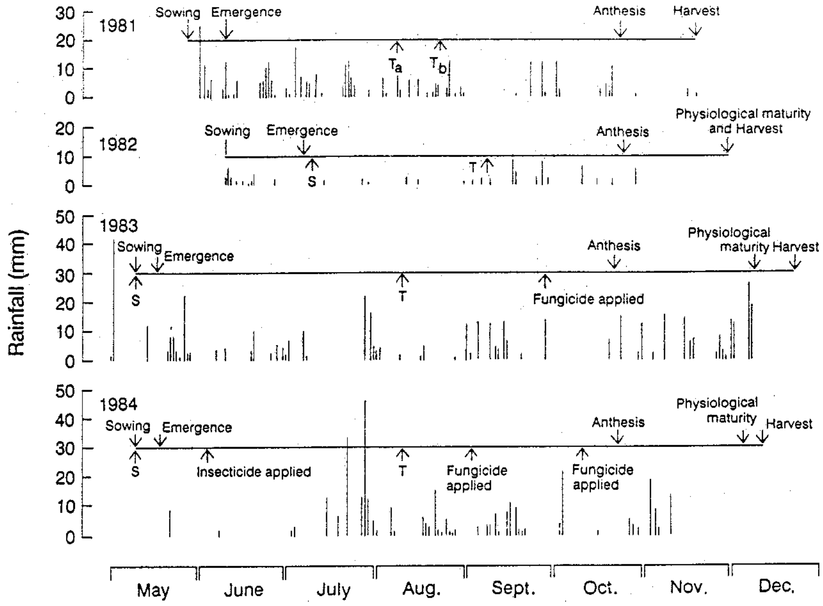

Fig. 1. Phasic development, timing of crop management and protection and daily rainfall for the four years of the experiment. The symbol S refers to N applied at sowing, and T refers to N applied at the terminal-spikelet stage (in 1981, T_a). In 1981 T_b refers to N applied at early stem elongation.

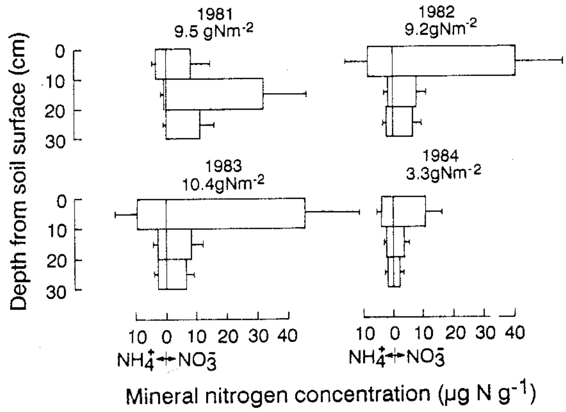

Fig. 2. Soil mineral N at the time of sowing over the four years of experiments. The histograms represent concentrations in the soil layers and the numerals represent the mass of mineral N in the top 30 cm of soil. The error bars represent half the standard errors of the means.

grain protein content of wheat. The experimental design was 3 blocks of 10 main plots each comprising 3 subplots with dimensions 2·84x24 m, consisting of 16 drill rows with 17·8 cm spacings. Five tillage treatments, each represented by two main plots in each block, were unchanged over the five years of the experiment, but the N treatments which occupied all or part of the subplots were varied from year to year. The results of the tillage studies will be reported elsewhere (R. A. Fischer, unpublished).

The N-fertilizer treatments varied over the four years, depending on available plots and resources (Fig. 3). No N fertilizer was applied in 1980. Ammonium nitrate (Nitram) was applied from 1981, and liquid urea–ammonium nitrate, marketed as Easy-N, was applied from 1982. The times of N application were on the first occasion of a moist soil surface after the date of sowing (S) and, at the terminal spikelet stage (T), as shown in Fig. 1. In 1981 no N was applied at sowing, and the side subplots were allocated at random to either zero or 75 kg N ha^{-1} applied at terminal spikelet (75 T_a, while all the central subplots received 75 kg N ha^{-1} at stem elongation (75 T_b). In 1982, each subplot which had received the earlier N application during 1981 was split randomly into six subsubplots, on each of which a fertilizer treatment was imposed:

Treatment	Abbreviation
1. No applied N	0 N
2. 50 kg N ha^{-1} as Nitram applied at sowing	50 S
3. 50 kg N ha^{-1} as Nitram applied at terminal spikelet	50 T
4. 100 kg N ha^{-1} as Nitram split between sowing and terminal spikelet	50S/50T
5. 100 kg N ha^{-1} as Nitram applied at sowing	100 S
6. 80 kg N ha^{-1} as urea ammonium nitrate applied at terminal spikelet	80 UT

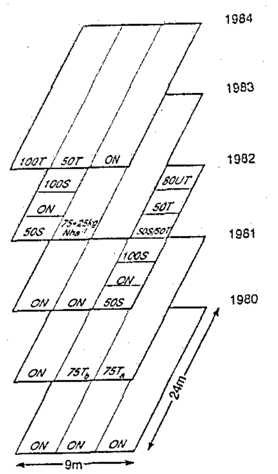

Fig. 3. Plan of a typical main plot showing the arrangements of N treatments on subplots and subsubplots during the four years of experiments. See text for symbols.

In 1983, the side subplot not used in 1982 was split into a mirror image of the subsubplots used in 1982. In addition, the central subplots (not studied in 1983) were supplied with 100 kg N ha^{-1} as urea in two supplemental splits of 75 and 25 kg N ha^{-1}. In 1984 one change was made to the fifth treatment, with the 100 S replaced by 100 T because of lodging in the 100 S treatment in 1983. Entire subplots were used for the N treatments in 1984, with the six subplots available (two identical tillage main-plots per block×three subplots) allocated at random to the treatments, with the restriction that all central subplots received 50 kg N ha^{-1} at terminal spikelet (50 T or 50 UT), i.e. those subplots which had received the 75/25 kg N ha^{-1} split in 1983. Thus, while the N treatments from 1981 to 1983 were compared, in each year, on plots with identical histories, those in 1984 had non-identical histories. The 1984 subplots were frequently inspected for stripes reflecting the N treatments in previous years, but none were observed. Since interactions between N and tillage were generally small, N responses are averaged across tillage treatments giving essentially 30 replicates (3 blocks×10 tillage mainplots) for the N effects in 1981–83 and 15 replicates (3 blocks×5 tillage main-plots) in 1984.

The experiments were sown on the first occasion after early May when the soil moisture status was judged adequate for both conventional and direct-drilled crops. The seeding rate was 90 kg ha^{-1} (120 kg ha^{-1} in 1983), and 25 kg P ha^{-1} was applied as triple superphosphate at the time of sowing. Weeds were successfully controlled with pre-emergence applications of paraquat and post-emergence applications of diclofop methyl and 2,4-D. In 1983, stripe rust was treated with triadimefon, and in 1984 with propiconazol and triadimefon. The control in 1983 was effective, but in the high-N treatments in 1984 there was obvious loss of leaf area during the grain-filling phase.

Grain yield was determined from hand-harvests of 1 m^2 on each plot. Harvest index and total dry matter were determined from a separate and smaller grab-sample. The total N content of tissue was determined by a Kjeldahl method, modified by addition of salicylic acid to include nitrate.

Results and Discussion

Crop responses to applied N are shown in Table 2. In three of the seasons there was increased yield with at least one of the treatments. The yield responses in the favourable years of 1981 and 1983 were large, but even in the drought of 1982, one of the treatments, 50 S, have a small but non-significant response. The responses were generally greater than those found previously in dryland crops in south-eastern Australia (Angus 1986). The reason for the large responses was not because the site was particularly deficient, as shown by amounts of about 10 g cm^{-2} of available topsoil N for the first three years (Fig. 2).

Table 2. Crop responses to nitrogen fertilizer

Year	Treatment	Grain yield ($t\ ha^{-1}$ at 12% moisture)	Grain protein percentage (%N×6·25)	Harvest index	Harvest index for N	Shoot N-uptake at maturity ($kg\ N\ ha^{-1}$)
1981	Control	2·85	10·5	0·43	0·79	61
	75 T_a	4·27	12·3	0·43	0·77	109
	75 T_b	4·07	12·1	0·47	0·80	99
	l.s.d.$_{0\cdot05}$	0·22	0·4	0·01	0·01	7
1982	Control	1·12	15·1	0·54	0·75	32
	50 S	1·35	14·9	0·56	0·79	36
	50 T	1·08	15·3	0·47	0·70	34
	50S/50T	1·15	15·3	0·52	0·72	35
	100 S	1·15	15·7	0·48	0·71	35
	80 UT	1·19	15·1	0·52	0·75	34
	l.s.d.$_{0\cdot05}$	n.s.	n.s.	n.s.	n.s.	n.s.
1983	Control	4·56	9·1	0·41	0·78	76
	50 S	5·70	9·4	0·38	0·75	101
	50 T	5·68	9·7	0·38	0·72	111
	50S/50T	6·31	10·3	0·39	0·70	134
	100 S	6·32	9·1	0·40	0·72	114
	80 UT	6·47	9·2	0·41	0·75	115
	l.s.d.$_{0\cdot05}$	0·58	*	0·01	0·01	16
1983 residual effects of 1982 fertilizer	Control	4·56	9·1	0·41	0·78	76
	50 S	5·99	9·6	0·42	0·77	107
	50 T	5·67	10·0	0·41	0·76	107
	50S/50T	6·17	9·9	0·40	0·75	118
	100 S	6·18	10·2	0·41	0·75	121
	l.s.d.$_{0\cdot05}$	0·58	—[A]	n.s.	0·01	10
1984	Control	2·50	8·9	0·45	0·83	38
	50 S	3·83	8·5	0·44	0·81	58
	50 T	3·55	8·3	9·45	0·78	54
	50S/50T	4·58	8·9	0·45	0·75	78
	100 T	4·24	10·2	0·43	0·67	92
	50 UT	3·44	9·1	0·43	0·78	55
	l.s.d.$_{0\cdot05}$	0·49	0·8	n.s.	0·03	10

[A] Analysis of variance unavailable because nitrogen samples were bulked.

1981

Crops became yellow during winter following prolonged rain, presumably because of N deficiency due to leaching of soil nitrate below the root zone. Nitrogen applied at the terminal-spikelet stage and during stem elongation led to increased grain yield and protein content. The earlier application led to the greater yield, N-uptake and grain protein, but the later application led to the greater harvest indices for dry matter and N.

1982

Seedling emergence and growth were slow due to late sowing in a cold and dry winter. Nitrogen fertilizer applications had no visible effect on crop growth, and after flowering the crops appeared increasingly stressed and had lost all green tissue before physiological maturity. None of the crop attributes measured at maturity showed significant response to applied N. Harvest indices were generally large, presumably because reserves of assimilate from stem and leaves were efficiently translocated to grain.

There was a yield interaction between cultivation method and N supply, with conventionally cultivated crops decreasing in yield with increased N fertilizer, and direct-drilled crops increasing. The yield levels for the two methods of cultivation differed greatly. Averaged over all N-treatments, the conventionally cultivated crops yielding $1 \cdot 5$ t ha^{-1} compared with $0 \cdot 7$ t ha^{-1} for the direct-drilled crops. The low yield of the direct-drilled crops was associated with poor seedling growth. The conventionally cultivated crops used most of the available water before maturity, and high N levels exacerbated the degree of water deficit—presumably an example of 'haying-off'. In contrast, the direct-drilled crops conserved soil water during the early stages of development and consequently retained more soil water with which to express a small yield response to N.

1983

The crops grew rapidly during the mild, moist winter and the overall yields were high because of the favourable water balance for the whole life of the crop. The low grain protein percentages reflected prolonged grain growth and dilution of protein with starch, while the low values for harvest index indicate continued straw growth during the grain-filling phase. The harvest index for N shows a similar range to that obtained in previous years, so although the grain was relatively deficient in N, there was no additional translocation of N from the straw.

Another reason for the high productivity in 1983 was the large uptake of soil N, shown in Fig. 4*a* and Table 2 as the above-ground N-uptake for the control treatment. The large supply of mineral N in 1983 may have been due to a carry-over from 1982, or because mineralization of organic N was stimulated by the wetting of the soil in autumn 1983, following the 1982 drought (Birch 1958; Stein *et al.* 1987).

The N uptake by the crop fertilized with 100 S peaked at 18 g N m^{-2} at a time when uptake by the control crop was 5 g N m^{-2} (Fig. 4*a*). The difference of 13 g N m^{-2} was apparently in excess of the amount of N supplied as fertilizer. The peak N-uptake by the fertilized crop was followed by a decline of 6 g N m^{-2}, while the 0 N crop continued to take up soil N. This loss of N from the shoots is in the upper range of observations reviewed by Wetselaar and Farquhar (1980).

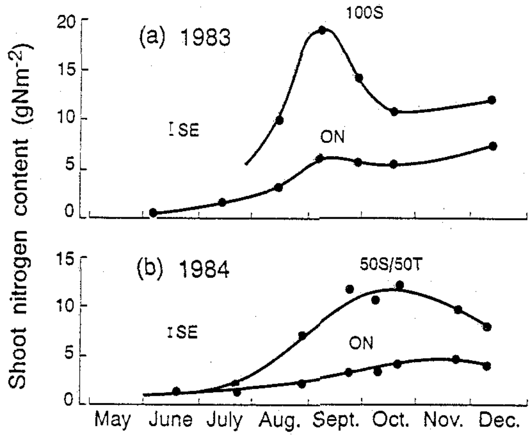

Fig. 4. Nitrogen uptake by shoots in (*a*) 1983 and (*b*) 1984. In each graph the lower line represents uptake by crops which received no added N, and the upper line by crops fertilized with 100 kg N ha^{-1}, which in 1983 was all supplied at sowing, while in 1984, half was supplied at sowing and half at the terminal spikelet stage.

The only obvious limitation to yield was lodging in some treatments. The 100 S treatment grew to a height of 1 m by late September, and was fully lodged by the time of maturity; the 50S/50T treatment partly lodged, and the lack of yield increase over the 50 T treatment may have been due to lodging (Fischer and Stapper 1987).

During 1983, the plots fertilized in 1982 were sown to wheat without additional N fertilizer, and observed for evidence of residual effects. In mid-July the fertilized plots became greener and more vigorous than the controls, and by mid August were indistinguishable from the equivalent plots fertilized in May 1983. The 1982-fertilized plots did not lodge. The yield responses were similar to those of the equivalent treatments in which N was applied in 1983. However, the grain-protein responses were slightly higher for carryover N, which had probably been leached below the topsoil by rain in autumn 1983, taken up by the roots relatively late in crop development and then translocated to the grain.

1984

All treatments suffered damage from a mouse plague, red-legged earth mite and stripe rust despite some control with recommended chemicals. Throughout the season, symptoms of root disease were present, and white-heads, presumably take-all caused by *Gaeumannomyces graminis* var. *tritici*, appeared as the plants approached maturity. Visual estimates of white-head density in each plot, made 2 weeks before physiological maturity, showed a significant difference between treatments; there were 11% white heads in treatments which received 50 T, compared with a mean of 4% for all other treatments. The l.s.d.s for all attributes reported in Table 2 were relatively high, presumably because of variability caused by the biotic constraints.

As explained in Methods and shown in Fig. 3, all treatments supplied with 50 T were on central subplots which had received a split application of 75/25 kg N ha^{-1} in 1983. The second split was in July 1983 when the plants may have been too small to rapidly take up all the applied N. High levels of soil nitrate are known to favour the development of take-all (Christensen and Brett 1985), and it is possible that high transient levels of soil nitrate following urea application in 1983 promoted a build-up of the pathogen and the damage observed in 1984. The experiment was terminated because of the disease.

The pattern of N-uptake by fertilized crops in 1984 showed a similar pattern to those grown in 1983, with rapid uptake followed by a loss of shoot N (Fig. 4*b*). In 1984 there was also a small loss of shoot N from the unfertilized crops.

Timing and Form of N

Timing of N application had different effects in the three favourable seasons. In 1981 there was a trend towards a greater yield and grain-protein responses for N applied at the terminal spikelet stage than for application at stem elongation, but the difference was not statistically significant. The advantage was associated with a significantly greater N uptake from the earlier application when the water relations were more favourable. In 1983 there was no difference in yield response between the 50 S and 50 T treatments. This result is similar to previous findings in humid regions such as western Europe, where there are similar yield responses for a range of times of N application (Watson 1939; Simán 1974; Ellen and Spiertz 1980). However, there was a greater response in grain protein with the later application in 1983, associated with greater crop uptake. For the 100 kg N ha^{-1} treatments, the split application gave a similar yield to the sowing application, but a greater grain-protein response, again associated with greater N-uptake. In 1984 there were trends towards greater yield responses with earlier applications for both single and split dressings. However, there were mixed results for grain protein. The limited response to N for both times of application was apparently the result of low N-uptake, presumably due to N losses in the wet winter (see Fig. 1) and to root disease.

Comparisons of Nitram and urea ammonium nitrate (UT) applied at terminal spikelet were made in three seasons, of which the last two were favourable for expressing N-response. In 1983 rates of application were not identical, but the agronomic efficiencies presented in Table 3 suggest that UT was marginally more effective. In 1984 there was a marginal yield disadvantage from UT which was offset by a greater protein response. The difference in response between the years may have been because in 1983 all UT was sprayed on foliage, while in 1984, because of incomplete canopy cover at the time of application, much of the UT was sprayed on the soil.

Efficiency of Grain and Protein Responses

Table 3 presents three measures of the efficiency of applied N. The apparent recovery, defined as the additional N in above-ground tissue as a percentage of fertilizer-N applied, showed distinct seasonal differences and a general decline with increasing level of N. There was no consistent effect of fertilizer timing, with lower recoveries for the later application in 1981 and 1982, higher in 1983 and mixed results in 1984. It is likely that dry conditions in 1982 limited uptake, while wet conditions in winter 1984, indicated by the rainfall data in Fig. 1, led to losses through leaching or denitrification.

Table 3. Apparent recovery of N-fertilizer, agronomic efficiency and protein response

Year	Treatment	Apparent above-ground N-recovery (%)	Agronomic efficiency (kg grain kg N^{-1})	Grain-protein response to applied N (Δprotein % kg N^{-1} $tonne^{-1}$)
1981	75 T_a	64	18·9	0·102
	75 T_b	51	16·3	0·087
1982	50 S	8	4·6	−0·005
	50 T	3	−0·8	0·004
	50S/50T	6	0·3	0·002
	100 S	8	0·3	0·007
	80 UT	2	0·9	0·000
1983	50 S	50	22·8	0·034
	50 T	70	22·4	0·068
	50S/50T	58	17·5	0·075
	100 S	38	17·6	0·000
	80 UT	49	23·9	0·008
1983	50 S	62	28·6	0·060
with	50 T	62	22·2	0·102
1982	50S/50T	42	16·1	0·049
fertilizer	100 S	45	16·2	0·068
1984	50 S	40	26·6	−0·031
	50 T	32	21·0	−0·043
	50S/50T	40	20·8	0·000
	100 T	54	17·4	0·055
	50 UT	34	18·4	0·014

Table 3 also shows the maximum agronomic efficiencies (AE) of 19, 4, 23 and 25 kg grain per kg N applied in the four years of the experiment. The highest are comparable with the upper range for spring wheat reviewed by Craswell and Godwin (1985). In economic terms the AE can be used to indicate profitability when compared with the ratio of prices of grain to fertilizer-N, which for the seasons considered was about 6. Perrin *et al.* (1976) suggest that the AE should considerably exceed the price ratio for an input to be attractive. In three of the four years of this study, the AE easily exceeded the price ratio, and in 1982, when it did not, the carryover of N to the 1983 crop also led to a profitable response.

The grain-protein responses to N are expressed in Table 3 as the increased protein percentage per kg of applied N per tonne of grain. It is important that protein response be expressed in terms of the yield over which the response is obtained rather than the conventional expression of increased protein per unit N applied. The former expression represents the basis for payment, and also implicitly contains an N-budget which enables the following step in the analysis, the combined yield/protein response, to be presented. Fig. 5 presents the trade-off between yield and protein responses for one treatment in each of the four seasons, plus the carryover response. Each data point in Fig. 5 refers to the responses to the lowest rate of N applied at the terminal-spikelet stage. These data are selected because the responses at low levels of N are likely to represent the highest efficiencies of response.

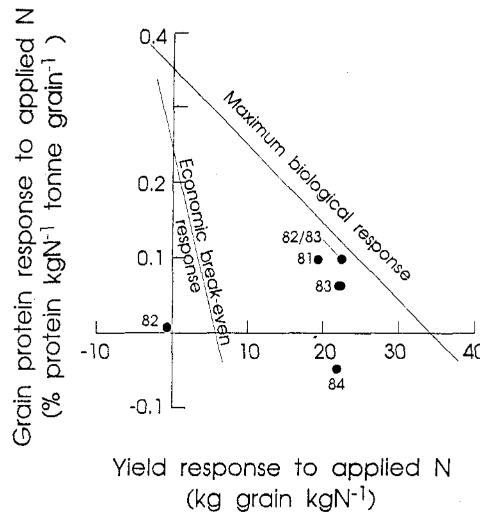

Fig. 5. Responses of yield and grain protein to applied N. The points represent observed responses for the lowest rate of N applied at the terminal-spikelet stage in the four years of the experiment and for the carryover of N applied in 1982 to crops growing in 1983. The upper line represents a biological maximum of N response, as described in the text. The economic break-even is represented by the lower line, based on grain and protein prices and N costs in the text. The portion of the graph above and to the right of the lower line represents profitable use of applied N.

The data points summarize the effects of season and N-uptake on the fertilizer response. The absence of any response in 1982 indicates a lack of N-uptake. The similar yield responses in 1981, 1983 and 1984 reflect the generally favourable water balance in those seasons, with the slightly higher grain protein response in 1981 reflecting a drier spring. The higher grain protein response in 1983 for N applied in 1982, compared with that for N applied in 1983, may have been due to its delayed uptake after shallow leaching, and subsequent translocation to the grain. The low grain-protein response in 1984 was due to low N-uptake.

The biological potential yield/protein response, presented as the upper line in Fig. 5, was estimated assuming (1) a maximum of 70% applied N present in above-ground parts of the crop at maturity (Craswell and Godwin 1985) and (2) a maximum 80% of the above-ground N present in the grain (Anderson 1985). Thus a maximum of 56% of applied N is available for grain N. Assuming that grain protein is 6·25 times the N content, there is a maximum increment of 3·5 kg of grain protein per kg of applied N, or 0·35% grain protein per kg of applied N per tonne of grain. This value is shown as the intercept of the upper line on the ordinate in Fig. 5. In practical terms this intercept represents a situation in which there is no yield response to additional N, for example because of drought, or addition of N to a crop with high N-status.

The situation in which additional N leads to more grain with the same protein concentration is shown by the intercept of the solid line on the abscissa. It can be shown, with the previous assumptions about fertilizer recovery and N translocation to grain, that the maximum additional grain per unit of applied N is (with units of kg grain per kg N): 350/protein.

For example, at an unchanged 10% grain protein, the maximum yield response is 35 kg grain per kg N, as shown in the example in Fig. 5. Maintaining a higher grain protein leads to a lower potential yield response: at an unchanged 15% grain protein the potential yield response is 23 kg grain per kg N.

The trade-off between potential yield response and potential protein response is as shown by the upper line in Fig. 5. The intercepts of this line on the axes do not delimit the extreme responses because there can be greater protein response in a situation of 'haying off' in which yield is reduced, and greater yield response in a situation in which grain protein is reduced.

The relative economics of grain and protein response are shown by the lower line in Fig. 5, based on the ratios of prices of grain and additional grain protein to the cost of N fertilizer. The values used for this are for grain: \$A0.12 kg^{-1}, grain protein: \$A3 $\Delta\%^{-1}$ $tonne^{-1}$, and N fertilizer: \$A0·75 kg^{-1} N). The value of additional grain with unchanged protein concentration is calculated by the price ratio (\$0.75/\$0.12 = 6·25), which is shown as the intercept of the lower line on the abscissa. The value of additional protein at the same yield level (\$0.75/\$3 = 0.25) is shown as the intercept on the ordinate. The area of the graph above and to the right of the dashed line represents conditions for profitable use of N, while the area under or to the left represents loss. From the relative distance of the biological-potential line to the line representing profit at current prices, it is clear there is more scope for profit through yield response than through protein response.

The approach taken in this study was to establish whether, in the face of previous negative evidence, circumstances exist for profitable wheat responses to N in south-eastern Australia. The analysis therefore focused on the efficiency of responses to increments of N, rather than seeking to identify an optimum rate of application. The results of the experiments suggest that profitable responses do exist, and that if other aspects of crop management are satisfactory, the efficiency of N for grain production is close to the potential as defined in Fig. 5. There was little reduction in the efficiency of N applied at the terminal spikelet stage compared with N applied at sowing. These results indicate more potential for delayed N application than has previously been shown in south-eastern Australia. Realization of the potential may depend on a standard of crop management comparable with that used in these experiments and is conditional on high soil-water status. Because of the large between-year variations in soil-water status, a recommendation to apply N fertilizer should be based on a longer sample of seasons than the four years of these experiments. Extrapolation of the results to other seasons and regions, is to be the subject of further studies based on a simulation model and a long sequence of weather data.

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