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Estimation of responses of yield and grain protein concentration of malting barley to nitrogen fertiliser using plant nitrogen uptake

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Abstract. The effect of nitrogen application on the grain yield and grain protein concentration of barley was studied in 13 field trials covering a wide range of soil N conditions over 4 years at locations in south-eastern Queensland. The main objectives of the study were to quantify the response of barley to N application rate over a range of environmental conditions, and to explain the response in terms of soil mineral N, total N uptake, and N distribution in the plants.

Barley made efficient use of N (60 kg grain/kg N) until grain yield reached 90% of maximum yield. Grain protein concentration did not increase to levels unacceptable for malting purposes until grain yield exceeded 85–90% of maximum yield. Nitrogen harvest index was generally high (above 0·75), and did not decrease until the total N supply exceeded that necessary for maximum grain yield. Rates of application of N for malting barley should be determined on the basis of soil analysis (nitrate-N) to 1 m depth and 90% of expected maximum grain yield, assuming that 17 kg N is taken up per tonne of grain produced. It can further be assumed that the crop makes full use of the nitrate N to 1 m present at planting, provided the soil is moist to 1 m.

A framework relating grain yield to total N uptake, N harvest index, and grain N concentration is presented. Further, total N uptake of fertilised barley is related to N uptake without fertiliser, fertiliser application rate, and apparent N recovery. The findings reported here will be useful in the development of barley simulation models and decision support packages that can be used to aid N management.

Additional keywords: apparent nitrogen recovery, modelling, nitrate, *Hordeum vulgare*.

Introduction

Barley *Hordeum vulgare* is grown for both malting and stockfeed. To meet current standards for malting for both domestic and export markets, grain must have a protein concentration of 8·5–12·0% (on a dry weight basis) and the grain should be large (85% retained on a 2·5-mm screen). A higher price is paid for barley that meets specifications for malting quality, and the rest is sold at lower prices for manufacturing and stockfeed purposes.

Nitrogen (N) fertiliser is generally applied for barley production in Queensland and northern New South Wales, as there is little use of either legume pasture rotations or legume crops in the main barley-producing areas. There is a widely held belief that barley should be grown on less fertile sites than are used for wheat, since high grain protein concentration attracts premium payments in wheat but may not be acceptable for malting barley. Thus, barley is usually produced in areas where soil N supply is low after long-term production of non-legume crops, or as a double crop following a summer crop. In the latter case, there is limited opportunity for the accumulation of mineral N.

The extent of the decline in N concentration in the most important soils of the Darling Downs and

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surrounding areas in Queensland has been described by Dalal and Mayer (1986). Consequently, N fertiliser use has become an integral part of the production system in these areas (Birch *et al.* 1993). However, there has been limited field research on the appropriate rates or times of application of N fertiliser for barley crops. Recommendations appear to be based on the work of Littler *et al.* (1969) who found that the most economic rate of N for dryland barley was 58 kg/ha. For irrigated barley, Birch and Long (1990) found that up to 50 kg N/ha improved grain yield substantially on an N-deficient site, while lowering or maintaining grain protein concentration. This response was similar to that in wheat (Strong 1981). More recently, Cox (1994) has reported that the most economic rates of N fertiliser application to dryland barley were 35–50 kg N/ha, the rate chosen depending on crop history and fallow length. Another approach is the use of multiple regression techniques (Bole and Pitman 1980). These authors concluded that, for a N cost : barley price ratio of 7:1, the N supply could be increased by 0·3 kg N/ha for each 1 mm of soil water available to the plant. This approach, and any other that considers the effect of fertiliser N on crop yield and quality, does not include any consideration of variation in the efficiency of uptake of N and N distribution within the plants. Uptake efficiencies that varied from 10 to 60% of fertiliser N have been reported (Strong 1986; Smith and Gyles 1988).

The relationship between grain yield of barley and available N supply (nitrate N plus applied N) explained only 30% of the variation in barley in Canadian studies (Walker 1975). Later, Fowler *et al.* (1989), also working in Canada, found that the relationship between grain yield and total available N was best described by modified inverse polynomials, for both wheat and rye. The relationships between crop yield and total available N, and between grain yield and total N uptake, do not appear to have been investigated extensively in Australia. In any event, the greatest difficulty is extending the results beyond the experimental conditions in which the data were gathered. A technique of achieving this extension is the use of crop simulation models. Modelling involving the use of estimates of effective rainfall during the growing season and soil information would help farmers in making decisions on fertiliser use. The model would be a tool for the extension of experimental data beyond the domain in which experimental data were collected (Carberry and Abrecht 1991). The use of models in decision making and sensitivity analyses in relation to fertiliser use has been discussed by Angus *et al.* (1993). They argue that the use of models allows more than one limiting factor to be examined, and that the model can assess the effects of other variations, e.g. in P supply, that inevitably occur under field conditions. Further, they argue for models to contain only an appropriate level of detail for the purpose to which they are to be put. This avoids unnecessary complexity and detail of processes being modelled. However, the unavailability of data on the relationships between yield and total N availability, or between yield and N uptake, means that reliable procedures to model the effect of fertiliser use on crop yield are not available for barley production in Australia. Nevertheless, models of barley, to which such routines could be added, are available. One such model is QBAR (Goyne *et al.* 1996), and some progress has been made in adding the prediction of grain yield and protein concentration to this model (Hector *et al.* 1996). QBAR operates on the basis that nutrient supply is non-limiting, but has been modified by adding a routine to assess the effect of water stress and N economy of the plant to predict yield and protein concentration in the grain for diverse conditions of water and nitrogen supply.

In this study we aimed to quantify the grain yield and protein responses of barley to N application under diverse environmental conditions, and to explain the response using soil mineral N, total N uptake, and N distribution within the crop. The information obtained would provide guidelines on the determination of optimum rates of N fertiliser application, and provide data and equations for use in barley simulation modelling. Thus this paper is presented using the following framework:

$$\text{Grain yield (kg/ha)} = \text{total N uptake (kg/ha)} \times \text{NHI}/(\%\ \text{N in grain})$$

$$\text{Total N uptake} = \text{total N uptake without fertiliser} + \text{N fertiliser rate} \times \text{ANR}$$

where NHI is nitrogen harvest index, and ANR is apparent nitrogen recovery.

Materials and methods

Trial sites

Trials were conducted on the eastern Darling Downs and at Gatton in south-eastern Queensland in 4 years under dryland conditions. The sites at Gatton (1989–1992), Warwick (1989 and 1990), and Acland (1990), and in 1992 also at Allora, Brookstead, Dalby, Jondaryan, and Tannymorel (2 sites, 1 on a hillside and 1 on an alluvial area), were chosen to ensure variation in mineral N supply. Soils at the experimental sites were medium to heavy cracking clay loams (vertisols), 0·6 to >1 m deep, except for the Tannymorel hillside site, which was lighter textured. The trials were located within farmers' crops, except for the Gatton trials, which were located

Table 1. Weekly rainfall (mm) from planting to harvest determined for each barley crop at the experimental sites or nearby meteorological stations in south-eastern Queensland

Week	1989		1990			1991	1992					
	Gatton 8.vi–6.xi	Warwick 8.vii–22.xi	Gatton 21.vi–29.x	Warwick 28.vi–19.xi	Acland 6.vi–30.x	Gatton 7.vi–28.x	Allora 15.v–29.x	Brookstead 1.vi–3.xi	Jondaryan 6.vi–30.x	Gatton 11.vi–10.xi	Tannymorel 6.vi–29.x	Dalby 30.v–30.x
1	0·3	8·2	7·4	5·6	2·6	8·2	30·0			12·9		
2	1·2	0·8	5·8		4·4				4·0		22·5	
3		17·2		0·4	10·0		20·0			40·6		
4	10·0	2·8		0·4	0·4		3·0	15·0	21·0	3·3	14·5	
5	4·4	0·6		30·8		10·1	8·5					4·0
6	0·3	20·0	0·2		0·4					31·6		
7	10·4	0·6	33·4	5·2	1·2	9·4		12·0	5·0		18·5	4·0
8	1·0		0·2		23·4		4·5			1·2		
9	1·0		4·6		1·8	55[A]			21·0	1·8	6·0	
10		9·0		7·6	13·2			30·0			1·5	
11	19·1				0·4					0·1		
12	0·2	0·2	17·7	7·2			29·5			24·1		
13	0·1			0·6	13·8		1·5		36·0	7·3	31·5	
14	17·4		4·0				12·0	25·0	1·0	9·1		38·5
15		2·8	2·1	2·0	5·4	60[A]			14·5		17·5	2·5
16	0·5	91·2	2·2	5·2	0·2		1·5	16·0		4·7		
17		10·6	15·0	7·6	3·4		3·5		14·0	2·8		
18	0·7	61·2			21·4	5·1				3·5		
19	31·7	23·4	5·2	33·2	0·2	9·8	5·0			0·4	6·0	9·5
20	44·9	89·4		0·4	8·2	36·5	8·5				12·5	
21	4·6					4·9		12·0		5·9	28·0	3·0
22	90·0									38·1		4·0
Total	237·8	338·0	97·8	106·2	110·4	84·0	127·5	110·0	116·5	187·4	158·5	65·5

[A] Salvage irrigation to save crop from extreme drought.

on The University of Queensland, Gatton College, and the Warwick site in 1990, which was on the Hermitage Research Station of the Queensland Department of Primary Industries.

Initial soil nitrogen status

At each site, the N status was characterised by determining the concentrations of nitrate and ammonium N in the soil in 0–10, 10–30, 30–60, and 60–100 cm depth segments prior to fertiliser application. At least 6 cores to 1 m depth were taken at each site using a Proline soil sampler, except at Acland (4 cores), and Warwick (1990) and Gatton (1990) (3 cores), where the cores were taken by hand auger because of the unavailability of the Proline. The cores were separated into the depth segments, transported at low temperature (<3°C), and stored in a freezer at <−15 °C until analysed. Duplicate subsamples for analysis were drawn from each of the depth segments and analysed according to a method identical to that described as '7C2 Mineral Nitrogen with KCl-Automated Colour' using a Technicon Auto-Analyzer II S.C. Colorimeter (Rayment and Higginson 1992). From these data and bulk density of the soil, the amount (kg/ha) of nitrate and ammonium N to a depth of 100 cm was calculated.

Fertiliser treatments

Nitrogen application rates (kg/ha) were 0, 40, 80, 160, and 320 (Gatton and Warwick 1989); 0, 45, 95, 135, and 190 (Gatton 1990); and 0, 40, 80, 120, and 160 (all other sites). The rates at Gatton in 1990 differed because of the design characteristics of the equipment used, but, as they do not differ greatly from the 0, 40, 80, 120, and 160 used at other sites, they are not discussed separately in this paper. The N fertiliser was applied as Nitram (ammonium nitrate, 34% N) and incorporated before planting.

Cultivars

The barley varieties used were Grimmett (all sites in 1989–1991 and Gatton in 1992) and Tallon (all sites in 1992).

Experimental design

The experimental design was a randomised complete block, except in 1989 and 1990 when a split-plot design was used with cultivar as the main plots and N rate as the subplots. Four replicates were used.

Cultural conditions

Land preparation was carried out by the owners of the properties on which the trials were located, and thus followed commercial practices. Basal application of phosphorus fertiliser (70 kg single superphosphate, 7 kg P/ha) was applied at all sites except Gatton, where the soil was well supplied with P. Insects and diseases were monitored at all sites. Bayleton 125 at 1·5 L/ha was applied 50 and 63 days after sowing to control powdery mildew at Gatton in 1990. No disease control was necessary at other sites. Insect infestation was minimal, and no control measures were taken. Weed control was necessary at all sites, and was achieved by the application of MCPA-amine, Buctril MA, or Banvel, at the registered application rates applied to the balance of the crop in which the trials were located, or by hand removal of weeds where weed population was inadequate to justify use of chemicals (Acland, Gatton 1990, 1991, 1992, Dalby 1992, and Jondaryan 1992). Salvage irrigation of the dryland trial (totalling 125 mm) was necessary at Gatton in 1991, because of drought conditions. In all other respects, the trials were subject to commercial crop management practices. Rainfall during the crop growth period was either recorded at the experimental sites or obtained from nearby meteorological stations (Table 1).

The trials were planted with either a small plot planter (Gatton, Warwick, Acland) or with commercial planting equipment belonging to the co-operating farmer. Row spaces varied from 17·2 to 25·4 cm. Individual plot size varied according to site. In 1992, plot size was a minimum of 10 m long by 5 m wide. Smaller plots were used in the following cases: 6 m long by 1·5 m wide (Gatton and Warwick in 1989), 13 m long by 1·6 m wide (Gatton 1990), 10 m long by 1·5 m wide (Gatton in 1991 and 1992, Warwick in 1990, and Acland). Sowing rates were generally 40–45 kg/ha in the dryland trials, except at Gatton in 1989 (60 kg/ha) and Tannymorel (50 kg/ha).

Grain yield and grain protein concentration

Grain yield at 12% water content (Y) was determined at maturity from quadrat samples 4 rows wide by 1·0 m long, except at Gatton in 1989 (3 rows by 0·7 m), Warwick in 1989 (4 rows by 0·7 m), Acland and Warwick in 1990 (5 rows by 1 m), Gatton in 1990 (2 rows by 1 m), Gatton in 1992 (4 rows by 0·5 m), and Brookstead in 1992 (3 rows by 1·0 m). Grain was separated from the residue using a small stationary thresher. Subsamples of the grain were used to determine grain N concentration, using a Kjeldahl technique identical to that described as '7B1 Water Soluble Nitrate, automated colour' (Rayment and Higginson 1992), using the same autoanalyser and colorimeter as for the soil analysis described above. Grain protein concentration was estimated assuming that 1% N = 6·25% protein.

Derived data

Three additional derived variables were calculated.

(*i*) Relative grain yield (RGY, %) for each treatment at each site was calculated as a percentage of the maximum yield that occurred at each site ($Y_{\max}$) as follows:

$$\mathrm{RGY} = Y/Y_{\max} * 100 \tag{1}$$

(*ii*) ANR for total above-ground dry matter yield for each increment in N application rate at each site was calculated as the increment in N in the above-ground dry matter expressed as a percentage of the increment in N application rate.

(*iii*) NHI was calculated as the proportion of N in the above-ground plant parts that was present in the grain.

Statistical analyses

Analyses of variance were carried out for individual experiments, and regressions on combined data, using the MGLH procedure in SYSTAT (Wilkinson 1990).

Results

Since there was little difference between the cultivars at Gatton in 1992, all results are presented as N rate means for each experiment.

Table 2 shows the site amount of antecedent nitrate-N (NO_3^--N) and ammonium-N (NH_4^+-N), control and maximum yield, and the increase in yield due to N fertiliser.

Effect of applied and soil N on grain yield

The sites reported in this paper fall into 3 discernible groups according to the responsiveness of grain yield to N application. These groups are (*i*) highly responsive sites, Warwick 1989, Acland, Gatton 1990, and Tannymorel-hillside, which had highly significant ($P < 0\cdot01$) yield responses of 1·3–2·2 t/ha; (*ii*) slightly responsive sites, Warwick 1990 and Allora, at which significant ($P < 0\cdot05$) responses of 0·5–0·7 t/ha occurred; and (*iii*) unresponsive sites, Gatton 1989, 1991, and 1992, Brookstead, Dalby, Jondaryan, and Tannymorel-alluvial.

Table 2. Amounts of antecedent nitrate-N (NO_3^--N, kg/ha) and ammonium-N (NH_4^+-N, kg/ha) in the soil, and control (C) and maximum (max.) grain yield (t/ha) (GY at 12% water content) of barley for N fertiliser trials conducted in south-eastern Queensland between 1989 and 1992

Sites are presented in order of increasing nitrate-N availability

Year	Site	NO_3^--N	NH_4^+-4	GY (C)	GY (max.)	Increase in yield (t/ha)
1990	Acland (A90)	10	64	1·8	3·6	1·8
1992	Allora (A92)	11	23	1·3	2·0	0·7
1990	Gatton (G90)	19	44	4·7	6·9	2·2
1991	Gatton (G91)	20	7	2·7	3·2	0·5
1992	Tannymorel (hillside) (TH92)	30	17	3·2	5·2	2·0
1989	Warwick (W89)	37	47	1·7	3·0	1·3
1990	Warwick (W90)	48	36	2·6	3·1	0·5
1992	Gatton (G92)	66	17	5·5	6·0	0·5
1989	Gatton (G89)	66	86	4·8	5·3	0·5
1992	Jondaryan (J92)	70	27	4·5	4·7	0·2
1992	Tannymorel (alluvial) (TA92)	71	23	3·3	3·9	0·6
1992	Brookstead	125	8	4·0	4·0	0
1992	Dalby (D92)	235	12	0·8	0·8	0

Fig. 1*a*–*m* shows widely divergent patterns of yield response to the application of N. For the 2 sites used in 1989, the data for 320 kg N/ha were excluded, as these were the only sites in which this very high rate was used, and yields were similar to the 160 kg N/ha rate (Warwick) or unreliable because of lodging (Gatton). Several sites (Gatton, Tannymorel, Jondaryan, and Brookstead in 1992, Gatton in 1989 and 1990, and Acland in 1990) had high maximum yields. These were consistent with the generally good seasonal conditions at these sites. The very low yields at Dalby in all treatments in 1992 were due to very dry conditions in the latter part of the season at this site (see Table 1) and frost damage. The intermediate maximum yields at the remaining sites were associated with moderate seasonal conditions (Table 1), which caused periodic water deficit. The response to N application was particularly strong at Gatton and Acland in 1990, and at the Tannymorel hillside site in 1992. The Acland site was the only responsive site at which there was a significant reduction in yield, to below the maximum yield, at rates of N greater than that which produced the maximum yield (Fig. 1*c*). However, in both of the slightly responsive sites (Fig. 1*e* and *f*), high rates of N reduced yield from the maximum. N application did not reduce yield below the control yield at any site.

Non-responsive sites, except Gatton, had NO_3^--N contents to 1 m of 70–128 kg/ha, NH_4^+-N of 8–86 kg/ha, and total mineral N content to 1 m depth of 94–136 kg/ha. Sites with significant grain yield

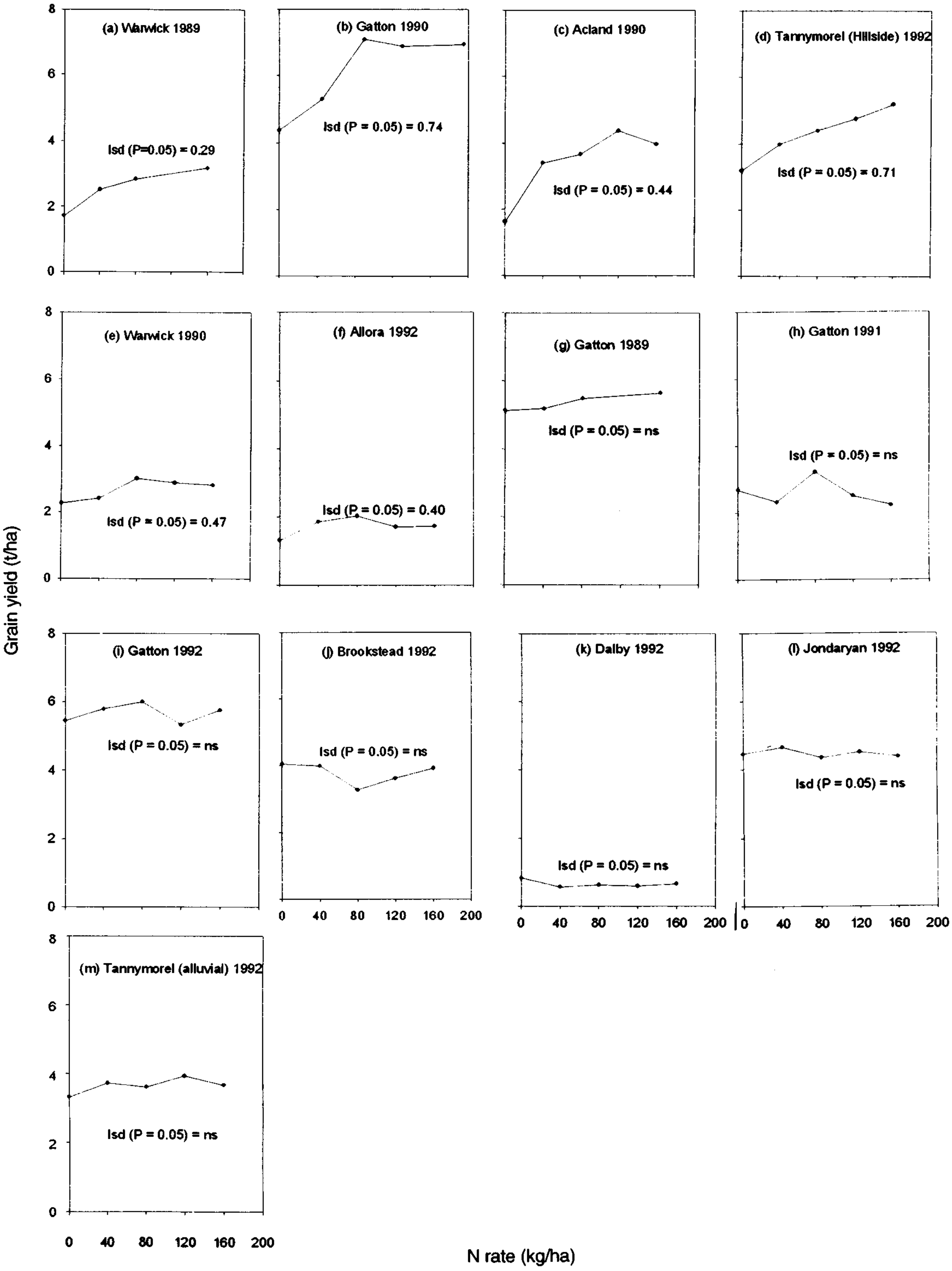

Fig. 1. Effect of N application rate on the grain yield of barley in 13 experiments from 1989 to 1992 in south-eastern Queensland. Parts (*a*)–(*d*) are for the strongly responsive sites, parts (*e*) and (*f*) for slightly responsive sites, and parts (*g*)–(*m*) for unresponsive sites.

response to N application had 10–48 kg/ha of nitrate N, 17–64 kg/ha of ammonium N, and 34–84 kg/ha of total mineral N (Table 2).

Fig. 2 shows a series of plateaux of grain yield for the individual sites, as total N in the above-ground plant parts at individual sites increased to above that necessary for maximum yield. These plateaux show that the yield response to additional N uptake was small, and indicate that yield was limited by a factor other than N uptake.

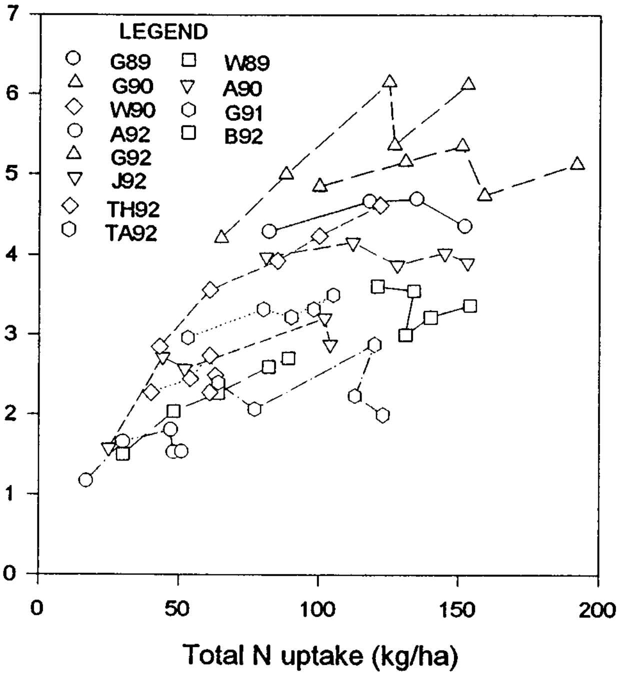

Fig. 2. Relationship between grain yield and the total amount of N in the above-ground plant parts at maturity obtained in 12 experiments in south-eastern Queensland. For site identification, see Table 2.

The relationship between the relative grain yield of the control treatment (RGY_{con}) at each site and NO_3^--N (kg/ha) to 1 m soil depth at planting was investigated, using linear and curvilinear regression models. The linear regression (Eqn 2) explained more of the variation than other regressions, and, thus, was retained:

$$RGY_{con} = 42{\cdot}3(\pm 6{\cdot}1) + 0{\cdot}685(\pm 0{\cdot}125) * NO_3\text{-N} \quad (r^2 = 0{\cdot}76,\ P < 0{\cdot}01) \tag{2}$$

Similarly, the relationship between RGY, for yields up to 90% of Y_{max}, and NO_3^--N present at planting plus N supplied as fertiliser (N_{sa}) (Fig. 3) was investigated using linear and a range of curvilinear models. The relationship was best described by a linear equation (Eqn 3), for N_{sa} <75 kg/ha, at which 90% of Y_{max} occurred:

$$RGY = 45{\cdot}0(\pm 6{\cdot}38) + 0{\cdot}60(\pm 0{\cdot}12) * N_{sa} \quad (r^2 = 0{\cdot}63,\ P < 0{\cdot}01) \tag{3}$$

Thus, each kg/ha of available N in the soil at planting contributed 0·6% to the maximum grain yield, and RGY reached 100% at about 90 kg/ha from fertiliser and soil nitrate-N reserves to 1 m depth at planting. Hence, knowledge of nitrate-N to 1 m depth can be used to predict the extent of response to fertiliser, and help to identify a site as responsive or otherwise.

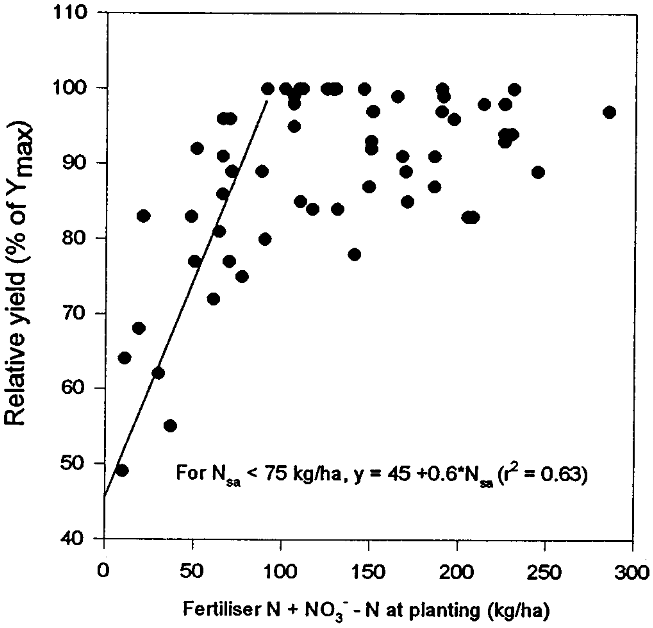

Fig. 3. Relationship between relative grain yield of barley and available N at planting (sum of nitrate N and fertiliser N) (kg/ha) obtained in experiments in south-eastern Queensland.

The coefficient of determination in the regression declined when weightings were applied to either the rate of N applied, or to NO_3^--N present at planting, to explore the possibility that differential efficiencies of uptake affected the relationship. Also, quadratic and other curvilinear relationships that were tested produced estimates of the N rate for maximum yield that were unrealistic, as they were usually outside the experimental range of N rates used in the study. No such relationships were found between RGY and either NH_4^+-N or total mineral N.

There was also a strong relationship between grain yield in the control treatments (Y_{con}, t/ha) and the total N in the above-ground parts at maturity (N_{mat}, kg/ha) for sites other than Dalby. It was:

$$Y_{con} = 0{\cdot}059(\pm 0{\cdot}003) * N_{mat} \quad (r^2 = 0{\cdot}98,\ P < 0{\cdot}01) \tag{4}$$

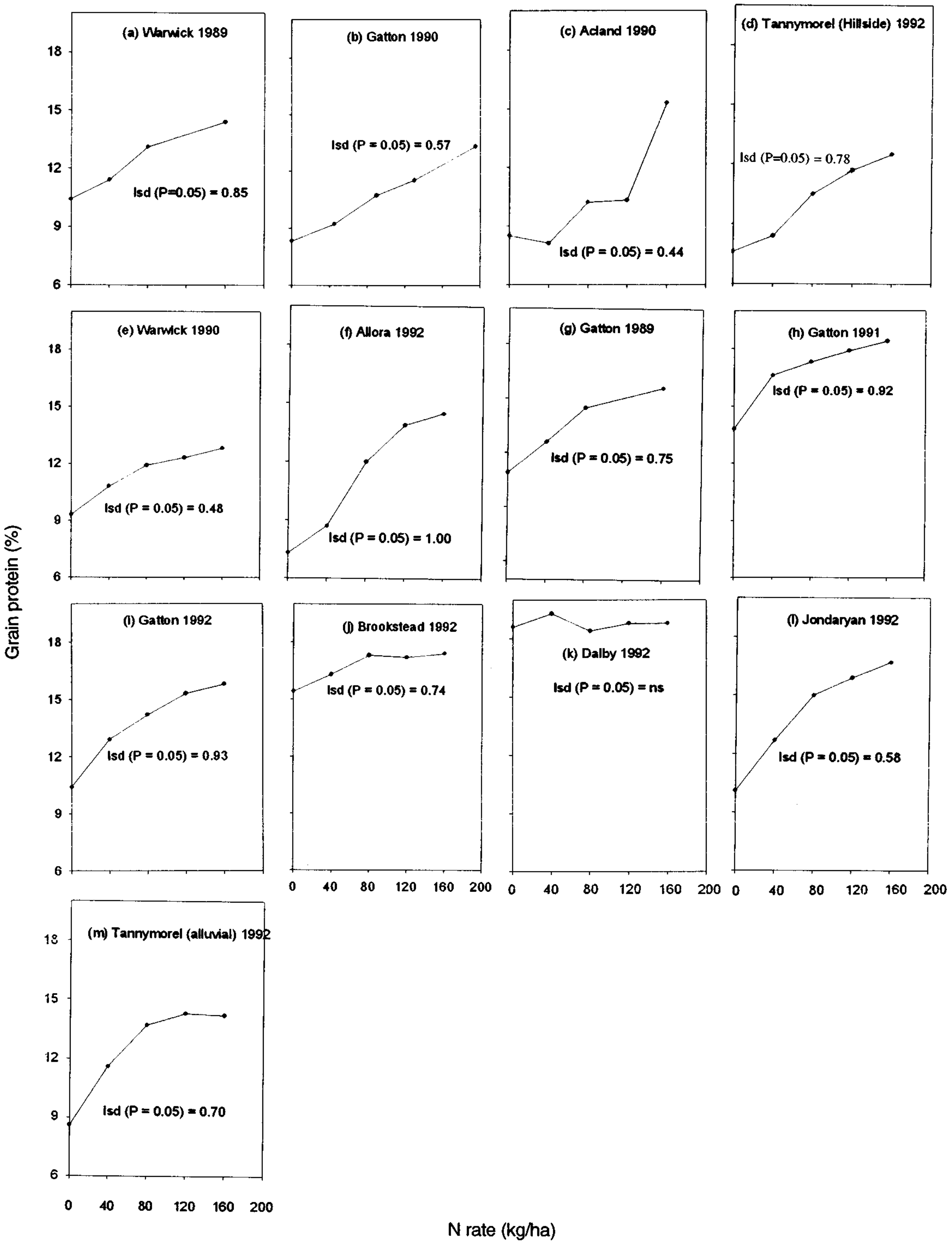

Fig. 4. Effect of N application rate on the crude protein concentration of barley in 13 experiments in south-eastern Queensland. Parts (*a*)–(*d*) are for the strongly responsive sites, parts (*e*) and (*f*) for slightly responsive sites, and parts (*g*)–(*m*) for unresponsive sites, on the basis of yield response to application of N fertiliser.

The relationship between yield and N_{mat} for N rates up to those that produced 90% of Y_{max} was:

$$Y = 0{\cdot}061(\pm 0{\cdot}002) * N_{mat}$$

$$(r^2 = 0{\cdot}99,\ P < 0{\cdot}001) \qquad (5)$$

These regressions, which have similar coefficients, show that 60 kg of grain is produced per kg of N taken up [17 kg N present in the above-ground plant parts per tonne of grain (at 12·5% moisture)].

Grain protein concentration

The effect of N application rate on grain protein concentration is shown in Fig. 4*a*–*m*. At all sites except Dalby, grain protein concentration increased in response to N application, but the nature of the response differed among sites. In the 4 sites defined as strongly responsive on the basis of the effect of N application on grain yield, and the slightly responsive sites at Warwick and Allora, low rates of N (40–45 kg/ha) increased the grain protein concentration only slightly or not at all (Fig. 4*a*–*f*). At Acland (Fig. 4*c*), which had very low antecedent NO_3^--N, the shape of the response curve differed from other responsive sites. Very little increase in protein concentration occurred until N rate exceeded 120 kg/ha. At 4 sites (Acland, Gatton 1990, Allora, Tannymorel hillside), protein concentrations in the control treatment were below 8·5%, and thus below the acceptable range for malting. At these sites, and at Warwick in 1989 and 1990, protein concentration did not exceed the maximum that is acceptable for malting (12%), even at N rates that produced 90% of maximum yield [100 kg/ha (Acland), 85 kg/ha (Gatton 1990), 40 kg/ha (Allora), 100 kg/ha (Tannymorel hillside), 120 kg/ha (Warwick 1989), and 40 kg/ha (Warwick 1990)]. For the non-responsive sites, except Gatton in 1991, Brookstead, and Dalby, which had high to very high protein concentration at all N rates, grain protein concentration in the control treatment was within the range for malting quality, but increased rapidly in response to N application (Fig. 4*g*–*m*). At Gatton in 1991, Brookstead, and Dalby, grain protein concentration reached a plateau at 18%. This concentration was not reached at any other site.

Grain protein concentration was lowest at all sites in the control treatment. It was usually in the range acceptable for malting in treatments with RGY to at least 85%, but increased sharply at higher RGY (Fig. 5). At RGY >90%, most treatments produced grain with protein concentration too high (>12%) for malting. However, Fig. 5 contains considerable scatter, and these suggested cutoffs may not be reliable.

Effect of N rate on total N in the above-ground plant parts

The relationship between total N in the above-ground plant parts at maturity and N application rate is shown in Fig. 6, for each site. N in the above-ground plant parts in the control treatments ranged from <20 kg/ha (Allora) to 120 kg/ha (Brookstead). The amount in tops exceeded the NO_3^--N in the soil to 1 m at planting except at the 2 very high N sites (Dalby and Brookstead). The amount in tops increased rapidly as N application rate increased in the responsive sites (Fig. 6*a*–*d*) and in most of the non-responsive sites (Fig. 6*g*–*m*), the exceptions being Brookstead and Dalby. These 2 locations had very high antecedent NO_3^--N, and the application of additional N had little or no effect on the amount present in the above-ground plant parts. In the slightly responsive sites (Fig. 6*e*–*f*), the increase in N in tops was less, and the maximum amount present low, even at high N rates.

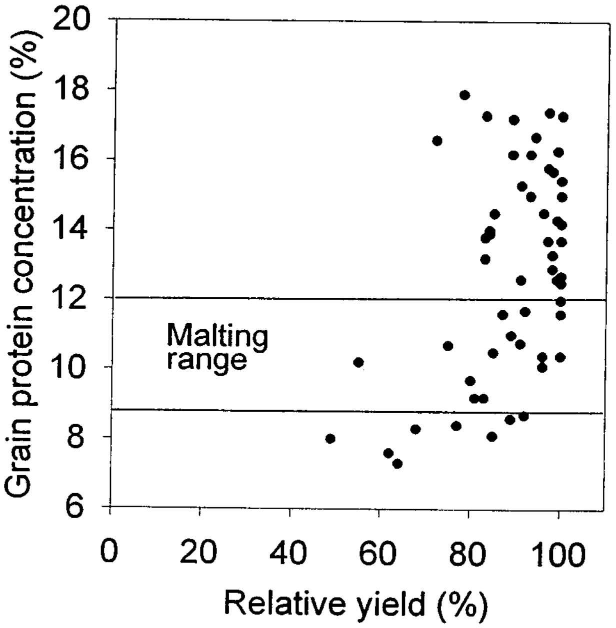

Fig. 5. Relationship between grain protein concentration and relative grain yield in barley obtained in 13 experiments in south-eastern Queensland.

For all sites except Dalby (excluded because of the frost damage), the regression between total uptake of N in the control treatment (NU_{con}, kg/ha) and nitrate N at planting (kg/ha) was:

$$NU_{con} = 22{\cdot}4(\pm 10{\cdot}5) + 0{\cdot}79(\pm 18) * NO_3^-\text{-N}$$

$$(r^2 = 0{\cdot}62,\ n = 12,\ P < 0{\cdot}01) \qquad (6)$$

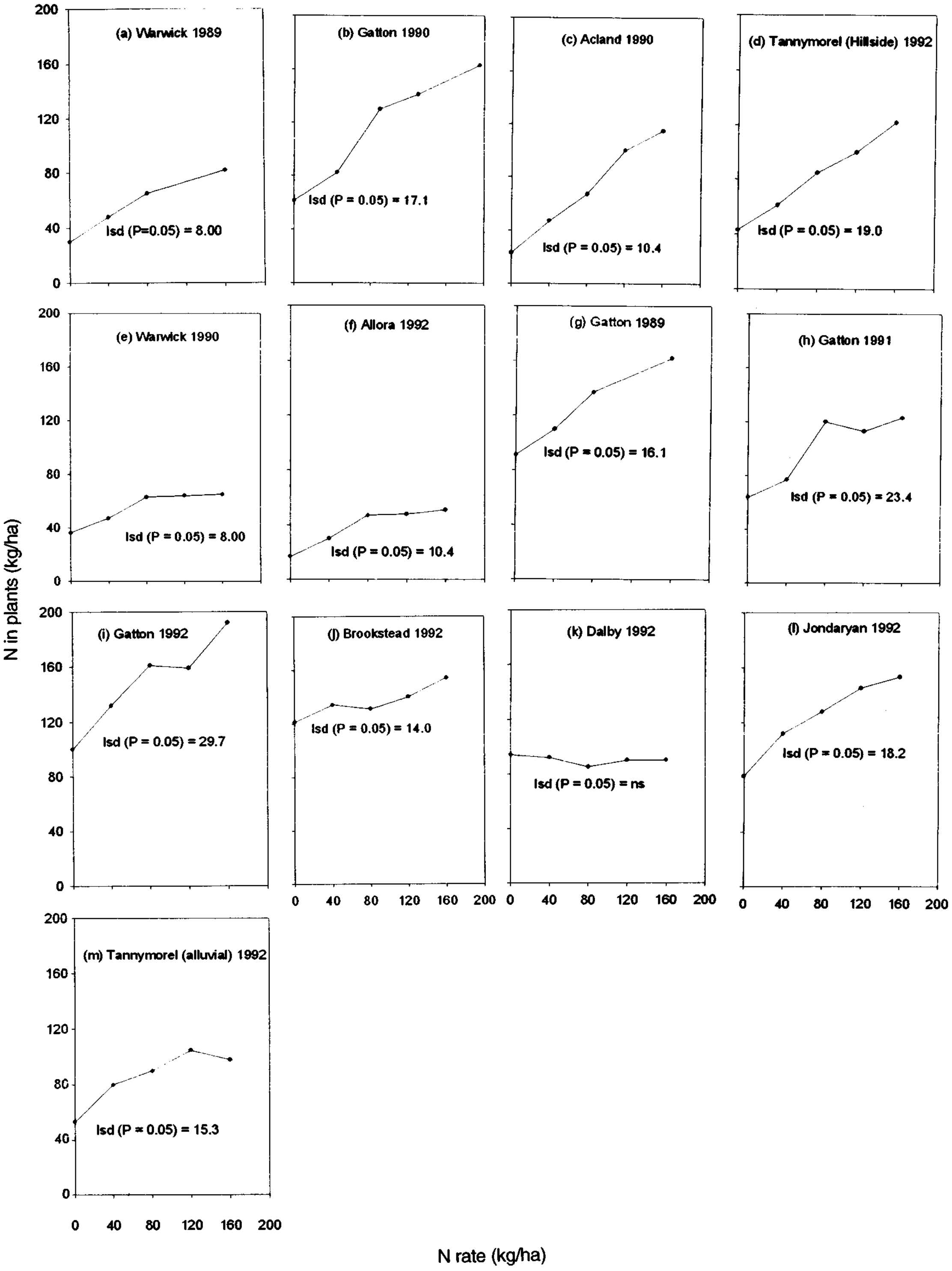

Fig. 6. Effect of N application rate on the total N uptake by barley at maturity in 13 experiments in south-eastern Queensland. Parts (*a*)–(*d*) are for the strongly responsive sites, parts (*e*) and (*f*) for slightly responsive sites, and parts (*g*)–(*m*) for unresponsive sites, on the basis of yield response to application of N fertiliser.

The regression indicates that a small, but significant, amount of N is taken up, even on sites with very low NO_3^--N at planting, and that the NO_3^--N present at planting is used efficiently (79%). The intercept in Eqn 6 represents the N that becomes available during crop life. It may be mineralised from organic matter in soil, or nitrification of NH_4^+-N present at planting, or be taken up from deeper in the soil than was sampled (1 m).

Table 3 shows the ANR averaged across sites in the 3 yield responsiveness groups for N in the total above-ground dry matter at maturity. In all 3 responsiveness groups, ANR for total dry matter was between 43 and 59% at N rates up to 80 kg/ha. At higher N rates, ANR remained higher in the responsive sites than in others.

Table 3. Mean apparent nitrogen recovery (ANR, %) of barley crops for increments in N application rate for all sites in each of the yield strongly responsive, slightly responsive and unresponsive site groups in south-eastern Queensland

ANR was calculated as the increment in N in the above-ground plant parts, expressed as a percentage of the increment in N application rate

N rate (kg/ha)	Strongly responsive (4 sites)	Slightly responsive (2 sites)	Unresponsive[A] (6 sites)
0–40	43	44	48
40–80	59	44	50
80–120	45	6	39
120–160	39	8	27

[A] Excluding Dalby.

Table 4. Nitrogen harvest index (NHI) in barley at different N application rates at different sites in south-eastern Queensland

NHI was calculated as the proportion of N in the above-ground plant parts that was in the grain

Site	N application rate (kg/ha)				
	0	40	80	120	160
Acland	0·80	0·79	0·75	0·68	0·70
Allora	0·80	0·77	0·74	0·69	0·70
Gatton 1990	0·85	0·84	0·82	0·79	–
Gatton 1991	0·86	0·73	0·67	0·56	0·48
Tannymorel (hillside)	0·76	0·76	0·78	0·75	0·76
Warwick1989	0·79	0·82	0·71	–	0·75
Warwick1990	0·82	0·80	0·82	0·78	0·78
Gatton 1992	0·80	0·81	0·79	0·74	0·68
Gatton 1989	0·89	0·80	0·84	–	0·74
Jondaryan	0·78	0·74	0·72	0·70	0·67
Tannymorel (alluvial site)	0·79	0·77	0·76	0·78	0·75
Brookstead	0·73	0·68	0·63	0·63	0·62
Dalby	0·23	0·17	0·19	0·17	0·19
Mean[A]	0·81	0·78	0·75	0·71	0·69

[A]Excludes the frosted Dalby site.

Table 4 shows that, generally, NHI exceeded 0·75, except at very high N application rates, e.g. 160 kg N/ha, or on sites that were very high in mineral N at planting (Brookstead), or were frosted (Dalby).

Discussion

Effect of N application on grain yield

At the responsive sites, the grain yield response to N application rate followed the pattern reported for barley (e.g. Birch and Long 1990; Cox 1994) and other cereals (e.g. wheat; Strong 1981) in south-eastern Queensland, and for barley elsewhere (e.g. Carreck and Christian 1993). As in our study, Carreck and Christian (1993) provide clear evidence of the effects of antecedent conditions on grain yield and N uptake response by barley to N application. The production of grain per kilogram of assimilated N, referred to as physiological efficiency (Doyle and Holford 1993), in the control plots in our study was 60 kg grain/kg N taken up (Eqn 4). Based on the work of Carreck and Christian (1993) with barley, and Doyle and Holford (1993) with wheat, this value is close to the maximum. If NHI was 80% (i.e. the maximum achieved in this study, Table 4), grain protein concentration in controls would be 9·4%, which is considerably lower than the maximum acceptable for malting.

The amount of nitrate-N in the soil plus applied N (N_{sa}) that produced 90% of $Y_{\max}$ (75 kg/ha) is lower than found by Stark and Brown (1987) (118 kg/ha) for barley grown under irrigation. However, the response in terms of grain yield as a percentage of $Y_{\max}$ per kg N was similar in the 2 studies. The values were 0·62% increase in yield per kg N in the study of Stark and Brown (1987) and 0·60 in our study.

The intercept was higher in our study (45%) than in the work of Stark and Brown (1987) (23%). The relationship between yield and N uptake in the work of de Ruitter and Brooking (1994) has an intercept of approximately 1 t/ha. These findings indicate very high efficiency of N use by barley at very low levels of initial N supply, and efficient use of N that becomes available during crop growth. Investigation of very low total N supply (at planting) conditions would better elucidate the response functions and clarify the importance of sources of N other than those examined in our work.

Nevertheless, the response of the crop to N application was related to the amount of NO_3^--N present in the effective rooting zone at planting (Eqn 3). Thus, the measurement of the amount of nitrate-N present in this zone prior to planting should assist in determining the N application rate to use. This finding is similar to that for wheat for seasons in which rainfall was inadequate to leach nitrogen beyond the sampling depth used (Doyle and Holford 1993). Doyle and Holford (1993) found that, in seasons of high rainfall before planting the crop, wheat was able to take up N from deeper than 90 cm. In our study, we sampled to 1 m, but did not have much data for high-rainfall seasons. Of the years in our study, only 1989 had high rainfall (Table 1), and we only had 2 sites in that year, and at one of these (Gatton) there was some evidence of uptake of N from depths greater than the sample depth.

Uptake of N from soil reserves and fertiliser

The efficiency with which antecedent N in the soil was used by the crop can be assessed by examining the yield and N uptake in the control (Fig. 2). The regression indicates that 60 kg of grain is produced per kg N taken up in the control treatments (Eqn 4), and explains a high percentage (98%) of the variation over the diverse range of conditions encountered in our study. The relationship between 90% of $Y_{\max}$ and total N in the above-ground plant parts at maturity also showed 60 kg grain/kg N taken up (Eqn 5). Values similar to this have been reported for wheat, but only at very low rates of N (e.g. Doyle and Holford 1993). The most interesting feature of the present study is that the physiological efficiency remained high over the range of N uptake until 90% of $Y_{\max}$ was achieved. In this respect, the results differ from those of Doyle and Holford (1993), for wheat, in which physiological efficiency declined as N rate increased.

Interestingly, the findings of the present study indicate an essentially linear response to N application until 90% of $Y_{\max}$ is reached. Thus, on a similar basis as for the control treatments, the maximum grain protein concentration that can be produced is 9·4%, using an NHI of 80%. Lower or higher grain protein concentrations will be produced if NHI is lower or higher. It is evident, then, that grain yield needs to exceed 90% of $Y_{\max}$ before substantial increases in grain protein concentration can be expected.

Since the N uptake in the control ($\mathrm{NU_{con}}$) exceeded the amount of $\mathrm{NO_3^-}$-N present to 1 m depth at planting in several sites, $\mathrm{NH_4^+}$-N or mineralisation of N from organic sources during crop growth must have contributed to the N supply to the crop at most sites, substantially so at some. Alternatively, the crops may have taken up $\mathrm{NO_3^-}$-N from deeper than 1 m. This, though, does not appear to be a satisfactory explanation, as the $\mathrm{NO_3^-}$-N concentrations in the soils were generally <3 mg/kg at depths greater than 60 cm (equivalent to <15 kg N/ha for the interval 60–100 cm, if the soil had an average bulk density below 60 cm of 1·3). Further, the low rainfall during crop growth (Table 1) and in the preceding summer and autumn makes it unlikely that there was any leaching of nitrate-N to deeper than 1 m, except at Gatton in 1989. Thus, it is clear that uptake from deeper than 1 m is unlikely to have accounted for the intercept in Eqn 6, and hence, in crop mineralisation, must have contributed to the crop's N economy. However, our data do not allow further exploration of this possibility.

The apparent N recoveries (ANR) in this study were generally similar for N application rates up to 80 kg/ha (Table 3) and comparable to or slightly lower than those achieved in other studies with barley. For example, Cox (1994) reported ANR values of 54–75% for 0–75 kg N/ha in one year, and 76% averaged over 4 varieties for 0–80 kg N/ha in another year for dryland conditions. An ANR of 64% was calculated from data of Carreck and Christian (1993) for sites that were responsive to N. At N rates comparable with those of Cox (1994), the ANR values were 34 to 66%. ANR in grain in our study (data not presented, as the NHI data in Table 4 allow estimation of ANR in grain) were similar to the ANR values achieved in wheat by Doyle and Holford (1993), despite the differences in rates of N that were used in the 2 studies. Thus, barley responded to N in a manner similar to wheat. The uptake of N shown by ANR > 0 when grain yield had reached $Y_{\max}$ shows that the crop extracted N in excess of needs for dry matter and grain production. Thus, at least some N that was not needed for dry matter production was incorporated in the grain and resulted in elevated protein concentration.

The relationships developed between grain yield and N uptake (Eqns 4 and 5) provide a sound framework from which to model grain yield, if N uptake is known or predicted. There seems little reason to use different equations for differing locations, presumably because of physiological requirements of the crop for N, rather than site-specific adaptation. For instance, data in Carrick and Christian (1993) show a similar relationship for barley grown in New Zealand. Also, for a geographic area similar to that in the present study, Cox (1994) reported an average of 44 kg grain/kg N (range 36–52 kg grain/kg N, across 4 cultivars) that the crop took up, in a treatment receiving 80 kg N/ha in a study in 1990. However, at 80 kg N/ha, the crop was either at or close to maximum yield, and thus the yield of grain per kg N taken up would be lower than at lower N rates. Unfortunately, many other data in the literature are not directly comparable, and usually indicate a lower ratio of grain produced per kg N applied, e.g. other data in Cox (1994) and de Ruiter and Brooking (1994). Also data may be incomplete, or apply to rates of N greater than that necessary for 90% of $Y_{\max}$.

Grain protein concentration and distribution of N in the crop

The N in the grain contributes to malting quality through its influence on grain protein concentration. The pattern of response of protein concentration to N application in the yield-responsive sites was similar to the data of Birch and Long (1990). Low rates of N did not raise protein concentration (Acland), or resulted in only small increases (other strongly yield-responsive sites). This was followed by a relatively rapid increase in protein concentration, but only in 2 of the strongly yield-responsive sites (Warwick 1989 and Tannymorel hillside) was there evidence of a plateau being reached. These effects are explained by the more rapid relative increase in grain yield than protein concentration at low rates of N application, and the reverse at higher rates. The initial lack of response to N was not present in the sites that were slightly reponsive or non-responsive in terms of yield, because N supply from the soil was sufficient to produce both moderate yields and moderate protein concentration.

The plateau in grain protein concentration as total N supply increased, where it occurred, was at 14–15% protein in the yield-responsive and slightly responsive sites, but at 17–18% in the non-responsive sites other than Tannymorel alluvial site. At the Tannymorel alluvial site, the plateau occurred at about 15% protein, and the response was similar to those at the yield-responsive sites. Thus, there may be differences in the response by the crop to applied fertiliser, and to inherently high soil mineral N supplies. This apparent anomaly may be explained by the applied N being in the dry surface soil and thus not accessible to the root system, whereas in soils that are well supplied with mineral N, the N is distributed more extensively through the profile (Strong 1981).

The grain protein concentration did not rise to levels unacceptable for malting at Acland, Gatton in 1990, Warwick 1990, Tannymorel hillside, or at Allora (a slightly responsive site) until N application exceeded 80 kg/ha. These sites had NO_3^--N of up to 30 kg/ha and total mineral N at planting of <75 kg N/ha (Table 2). All other sites had higher NO_3^--N and higher total mineral N. Thus, at sites with <30 kg/ha of NO_3^--N at planting, low protein concentrations are likely to be maintained, even when rates of nitrogen up to 80 kg/ha are applied.

In our study, grain protein concentration did not decline at low rates of N application, although such effects have been reported for irrigated wheat (Strong 1981). A similar effect might be expected in barley because the 2 crops are similar. However, Cox (1994) did not find such an effect in irrigated barley grown on a site of very low mineral N status at planting. The absence of any decline in protein concentration in the present study could be attributed to limitations imposed by low water availability during grain filling, as little rain was received at most sites during grain filling (Table 1). Since most of the carbohydrate for grain filling is assimilated after anthesis and most of the N for incorporation in grain is absorbed before anthesis (Carreck and Christian 1993), grain protein concentration will not decline at low rates of N application if water supply limits assimilate production during grain filling. The findings of Cox (1994) and this study indicate that the nature of the response of grain protein concentration in barley to N application may differ from that in wheat. Nevertheless, grain protein concentration did not increase in response to N application to levels unacceptable for malting until grain yield had reached 85–90% of $Y_{\max}$. Thus, N application rates that produce 85–90% of $Y_{\max}$ can be used with little risk of producing barley that is unsuitable for malting purposes.

The lower N harvest index (NHI) with high N application rates, and at sites with high initial N status, suggests that the ability to incorporate N in the grain had reached a limit, and the protein concentration in the grain would have been maximised at about 18%. Thus, as N supply increased further, NHI declined. Rates of N application that produced these effects would not be adopted in practice, as they would be uneconomic.

The distribution of N in the crop is important to the efficiency of use of N that is taken up by the crop. This study has provided evidence of the proportion of N that accumulates in the grain, for crops producing up to 90% of $Y_{\max}$. There is very little information on this aspect of N use by crops, and particularly barley. Hence, the information from this study will find use in crop simulation and decision support models. The distribution of N did not differ greatly in the crops grown on the highly and slightly responsive sites. Thus, there seems little reason to suggest that different algorithms would be needed to describe N distribution, except on non-responsive sites.

Application of these results

The framework developed here provides a basis of modelling the response of barley to N application. The framework fits neatly with the graphical representation of N responses proposed by van Keulen (1982), and thus the N response curve prediction model proposed by Angus *et al.* (1993). Such a model could then be added to QBAR (Goyne *et al.* 1996), to make that model more comprehensive and useful, where, as is usual, N supply limits crop yield. Although some progress has been made in adding the prediction of grain yield and protein concentration to this model (Hector *et al.* 1996), a different approach, which utilises the mechanisms of N transformation in soil and uptake and redistribution by plants, was used. This approach is more complicated than the approach of Angus *et al.* (1993). The N response curve prediction model requires, as variables, available N, N uptake by the crop, and rate of N application, supported by the parameter maximum N uptake, and data on other management factors such as cultivar, planting time, and plant protection. Grain yield can then be predicted. The model addresses most of the issues related to fertiliser use on barley at a level compatible with application in decision support systems. Thus, it should be able to be applied readily beyond the confines of the regions and crop in which the field research was carried out. The approach has been tested successfully with wheat in Western Australia (Angus *et al.* 1993), and there is no reason to expect that it would not be able to be used in other areas of Australia. The data presented here, and by Doyle and Holford (1993) (for wheat), are suitable for assessment of the approach of van Keulen (1982) and Angus *et al.* (1993) for cereals in eastern Australian environments.

Conclusions

This study provides data that can be used to improve decision making on N fertiliser use in barley. It clearly demonstrates that fertiliser can be applied to achieve 85–90% of maximum yield possible for a given set of conditions, without increasing the concentration of protein in the grain to levels unacceptable for malting purposes. Farmers have to make decisions on the rate of N application with limited information on the water availability to the crop. Uncertainty of the timing and amount of rainfall means that farmers usually take a conservative approach and apply only low to moderate rates of N, despite recommendations to the contrary for favourable water supply conditions. The data presented here and the framework used in this paper will be useful in simulation models and decision support packages, as they provide comprehensive explanations of the effect of N fertiliser on barley.

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