Nutrient and water effects on grain production in wheat – a combined model approach

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Abstract

The aim of the project was to provide a system whereby fertiliser requirements for optimum wheat production could be estimated in advance, and also through a season, in the presence or absence of irrigation. Thus experiments were conducted with wheat cv. Domino at a total of ten sites of varying fertility in 1999/2000 and in 2000/2001. Three of the sites were eventually rejected because of disease and weed problems. There were six treatments per site, which varied the supply of N, P and K. The nutrient status of every plot was measured. Yields varied from 3 to 11 t/ha (at 15% moisture). The data were used to calibrate an empirical fertiliser response model (PARJIB) that was combined with a detailed wheat simulation model (Sirius). The combined model performed well, accounting for 80% of the observed variation in yields. The root mean square deviation of simulated compared with measured yields was 0.90 t/ha. There was no indication that the model consistently under- or overestimated yields or the response to fertiliser. The combined model also successfully simulated the effects of drought and irrigation on yields, with the model's predictions closely matching observations from independent experiments. At some sites, Sirius used without PARJIB accurately predicted response to N, but at other sites substantially overestimated both the highest attained yield and the response to N. The analysis with PARJIB showed that soil K status was the main cause of the overestimates. The combination of models proved to be very powerful.

Additional key words: *Sirius, PARJIB, simulation*

Introduction

Fertiliser is a significant cost in wheat production. It is important to be able to assess in advance the likely return on the investment in fertiliser. The aim is to maximise profit from the operation, while maintaining or hopefully improving the quality of the soils the crop is grown in. Crop & Food Research has developed two tools to assist in this process. The PARJIB fertiliser response model (Reid, 1999; Reid *et al.* 1999) can be calibrated to predict fertiliser responses for different soil test values. PARJIB is already used in conjunction with maize (Reid *et al.* 1999), tomato, carrots and bean models. It also accounts for how drought stress affects fertiliser requirements. Sirius (Jamieson *et al.*, 1998b), is a wheat simulation model developed by Crop & Food Research in conjunction with Long Ashton Research Station, BBSRC, UK, and this is able to predict the timing of development stages, how the crop grows, and the effect of shortages of water and nitrogen.

These models work in quite different ways. PARJIB is an empirical fertiliser response model that adjusts potential yield in response to soil nutrient values and fertiliser additions. It has a major requirement that it must be used in conjunction with a model of potential yield that calculates how a crop grows in response to its environment in the absence of stresses associated with shortages of water and nutrients, and protected from the effects of weeds pests and diseases. In contrast, Sirius is a simulation model that seeks to simulate the behaviour of a wheat crop, including its response to shortages of water and nitrogen (Jamieson and Semenov, 2000), on a day-to-day basis during its growth. It has been tested extensively in widely varying environments, from Canterbury (Jamieson *et* *al.*, 1998a) to the Arizona desert (Jamieson *et al.* 2000). In a sense, it pretends to be a real crop, albeit in a limited way. However, it does not calculate the effects of other nutrients. The mechanisms for response to these are more poorly understood than those for nitrogen and are certainly more poorly described in simulation models.

The combination of a simulation model that describes some processes mechanistically with another that accounts for other factors empirically is potentially very powerful, not least because it may be used to identify causes of yield variation that the 'mechanistic' model cannot account for. The objectives of the project reported here were to determine the yield responses of wheat to the availability of three major nutrients (N, P and K), from both soil reserve and fertiliser sources, plus water shortages, in a range of soil fertility conditions:

- by calibrating a combination of Sirius, run in potential mode, with a calibration of the PARJIB fertiliser model based on measurements of yield, nutrient application and soil nutrient status at a range of sites in Canterbury over two seasons
- to identify the major causes of variation in yields associated with shortages on P and K that were not simulated by the full version of Sirius.

This information is to be used to develop guidelines and, ultimately, a system for forecasting the fertiliser requirements of wheat crops using soil fertility information.

Materials and Methods

Ten sites were chosen for the experiment, five in each of the two years. The soil test results for these varied substantially (Table 1). There was also substantial variation in the root zone available water holding capacity (AWC), mostly affected by the depth of topsoil overlying stones. Sites were chosen to have a range of test values in N, P and K on the basis of preliminary samples, but each experimental plot was sampled ahead of the drill when the experiments were sown. Six treatments (Table 2) were applied at each site, in a randomised complete block design with three replicates. These included a zero fertiliser treatment, and N, P and K fertiliser alone and in combination. In

Table 1. Soil properties of the plots at each site. Values quoted are the means with the ranges in brackets. Note that the readily available soil N figure is the mineral N already in the soil plus the amount mineralised from soil organic matter in a standard anaerobic incubation test at 40°C (Keeney and Bremner, 1966)

	1999/2000			2000/2001			
	C&FR A3.2	Macartney	Worsfold C7	CFR A3.1	Griffiths	Mulholland	Pankhurst
Available water capacity (mm)	235	235	90	235	235	90	90
Readily available N (kg N/ha)	63 (50-72)	125 (113-139)	88 (71-104)	56 (27 - 65)	73 (57 - 104)	71 (57 - 90)	75 (65 - 115)
Olsen P (µg/ml)	14 (11-18)	21 (13-28)	25 (19-30)	11 (8 - 14)	28 (22 - 32)	11 (8 - 13)	11 (9 - 17)
Exchangeable K (meq/100g)	0.60 (0.5-0.7)	1.30 (0.9-1.7)	0.50 (0.4-0.8)	0.42 (0.3 - 0.5)	0.44 (0.4 - 0.6)	0.28 (0.2 - 0.4)	0.53 (0.4 - 0.8)
Exchangeable Ca (meq/100g)	6.7 (6.3-7.3)	8.2 (7.3-8.8)	10.5 (9.5-12.1)	7.8 (7 - 10)	14.7 (13 - 16)	8.2 (7 - 9)	8.5 (7 - 10)
Cation exchange capacity (meq/100g)	11 (10-12)	13.2 (13-14)	14.3 (14-16)	13.1 (12 - 15)	20.2 (20 - 22)	12.6 (12 - 14)	12.7 (12 - 14)

Table 2. Experimental treatments

T1	Control; no fertiliser.
T2	Blended fertiliser, 100-400 kg/ha CropMaster 15 (15:10:10), plus N in early August to match T3.
T3	Urea 1 at rates 200-400 kg/ha (92-184 kg N/ha), applied early August
T4	Urea 2, Urea 1 plus a side-dressing at the same rate (giving 184-368 kg N/ha) in late September
T5	Superphosphate to match the P applied in T2
T6	Potassium chloride to match the K applied in T2

Note: Actual fertiliser rates varied among sites as part of the PARJIB protocol

1999/2000, amounts of fertiliser in particular treatments were varied among sites, while in 2000/2001, all sites received the same fertiliser treatments. Apart from N as urea, fertiliser was applied through the drill with the seed. Urea was applied as a side dressing in early August (treatments 2 and 3), or in early August and late September (Treatment 4).

Domino was the cultivar used in all experiments. At harvest maturity, all crops were combine-harvested with a plot harvester. Yield, thousand grain weight and harvest moisture content were measured. Grain protein was also measured at three sites in 2000/2001).

Brief soil descriptions at the sites (Table 1) are:

- Pankhurst: Chertsey shallow silt loam. This is a rapid draining soil that is quite droughty. Gravels at an average of 27.5 cm depth
- Mulholland: Lismore very stony silt loam. A shallow and very stony soil that is very free draining and droughty. Gravels at an average of 39.5 cm depth
- Griffiths and Macartney: Taitapu silt loam. This is a deep soil with good moisture retention.
- Worsfold C7: Eyre very stony sandy loam and very stony silt loam. This is a very free draining and very droughty soil. Gravels at an average of 31.5 cm depth but the topsoil above this was also quite stony.
- Crop & Food, A-block: Templeton silt loam. Deep soil with good water holding properties

Apart from fertiliser, management of the crop was identical to that in the surrounding crop, and carried out in each case by the farmer. Results from only seven of the original sites were used in the analysis. Two sites were not used because disease made the analysis invalid, and a third site was abandoned because it was overcome by a late and severe infestation of wild oats. Of the seven remaining experiments, one was dropped from the PARJIB calibration because, apparently, the farmer applied extra topdressing of N accidentally, and one further site was a substantial low outlier in the PARJIB initial calibration. The results from this site (Worsefold C7) were examined using Sirius.

Results

Yields in the experiments ranged from 3 t/ha to a little over 11 t/ha (Table 3). Response to applied fertiliser ranged from near zero to over 4 t/ha. By far the greatest and most consistent influence on yield was from applied N. Water deficit also had a substantial effect at some sites. Phosphate fertiliser had an inconsistent and generally non-significant effect on yield that seemed to be independent of the soil test P level. There were only small variations in thousand-grain weight at any site (Table 4), but it varied substantially among sites. Interestingly, the highest yielding sites in each year (Macartney and Mulholland) had the heaviest grains. The Griffiths site came a close second in 2000/2001, but had the lightest grains. Generally, the addition of N fertiliser increased grain protein (Table 5).

PARJIB Calibration

The PARJIB calibration was performed using Sirius in potential mode, i.e., with growth unrestricted by water and nutrient supply. In addition to the potential yield, the factors in the calibration were nutrient level in each plot, measured plot yield, and maximum potential soil moisture deficit at the site (Jamieson *et al.*, 1995). The calibration, subject to the restrictions

Table 3. Wheat yields (t/ha @ 15% moisture content) obtained in the two years of the experiment. Potential yields were calculated with Sirius.

	1999/2000			2000/2001			
	CFR	Macartney	Worsfold C7	CFR	Griffiths	Mulholland	Pankhurst
No fert	4.7	9.7	3.1	6.2	7.8	9.9	6.1
N P K	8.1	10.7	4.4	8.3	8.1	10.2	6.0
N only	8.6	11.0	4.7	7.6	6.9	9.4	7.5
N x 2	8.9	11.1	6.5	9.0	7.9	9.3	7.5
P only	3.8	10.5	3.2	6.0	8.5	10.2	5.5
K only	3.5	10.8	3.0	6.1	9.4	9.7	5.8
Potential yield	12.6	13.1	12.9	11.7	11.4	11.4	11.3
$LSD_{(P<0.05)}$, comparing among sites			1.05	84.8 df			
$LSD_{(P<0.05)}$, comparing treatments at the same site			0.96	79 df			

Table 4. Thousand grain weight (g) @ 15% moisture content.

	1999/2000			2000/2001			
	CFR	Macartney	Worsfold C7	CFR	Griffiths	Mulholland	Panckhurst
No fert	47	54	44	47	36	48	44
N P K	50	53	44	47	35	44	45
N only	50	53	44	48	37	46	45
N x2	51	53	45	48	34	45	44
P only	48	55	43	48	36	46	45
K only	47	55	44	47	37	48	44
$LSD_{(P<0.05)}$, among sites			2.91	93.4 df			
$LSD_{(P<0.05)}$, among treatments at the same site			2.86	78 df			

noted above, was very successful. The model has an RSME of 0.9 t/ha (15% moisture). A regression of observed on simulated yield ($r^2 = 0.80$) had a slope not significantly different from unity, and an intercept not significantly different from zero (Fig. 1). This is a strong indicator of internal consistency. We would therefore expect a model based on this calibration to be a reliable indicator of fertiliser needs at sowing time.

Some general comments can be made from the PARJIB analysis. N, K, drought and drainage had particularly strong effects on yield. Interestingly, the initial N fertiliser application at planting was of very little value at all - it was less than a quarter as effective as the later applications. There was quite a lot of winter rain, and the crop took up to 3-4 weeks to emerge. Calculated leaching losses of early-applied N were nearly equivalent to 30 kg/ha of N for 100 mm drainage. Yield responded quite strongly to soil K values, but very little to applied K. P responses were weak. The calculated threshold soil test level for response to P was 13.4 mg/kg.

The interaction of N response with other nutrients and drought was strong, so that, particularly when water was short, there was a substantially reduced N response (compare Figs. 2 and 3). A similar comparison can be made for K, but note that the response to applied fertiliser is very small, while the response to soil K is quite large (Figs. 4 and 5). The slight response to K fertiliser is consistent with previous experience for wheat in New Zealand (Greenwood *et al.*, 1984).

Table 5. Grain protein content (14% moisture content) from four sites in 2000/2001.

	CFR A3.1	Mulholland	Panckhurst
No fert	9.0	9.6	8.4
N P K	9.4	12.0	11.3
N only	9.4	11.9	9.1
2 x N	10.2	13.2	10.8
P only	9.0	10.6	8.5
K only	9.0	9.6	8.4
$LSD_{(P<0.05)}$, among sites		0.54	45.8 df
$LSD_{(P<0.05)}$, among treatments at the same site		0.51	40 df

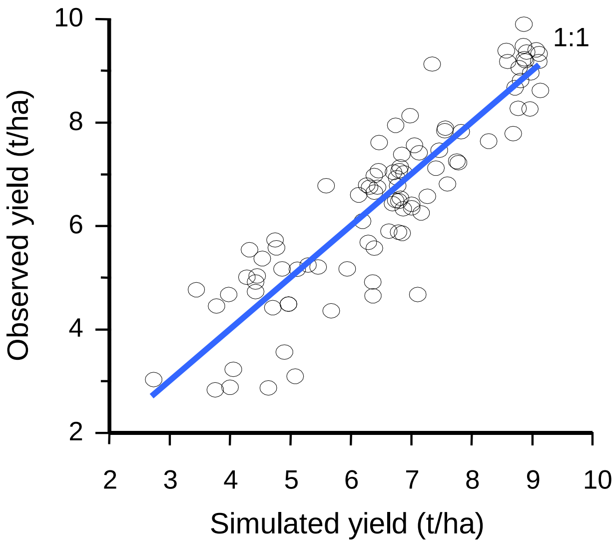

Figure 1. Comparison of wheat yield predicted from the fitted combined model and observed yields.

Analysis with Sirius

The Worsfold C7 data set was left out of the PARJIB calibration because the yield was systematically low. Simulations with Sirius were used to investigate possible reasons. Sirius contains routines to calculate the supply of N from the soil and the response of growth and grain yield to both water and N shortages (Jamieson and Semenov, 2000). So, at least as far as water and N are concerned, it can be used as both a predictive and investigative tool. A soil

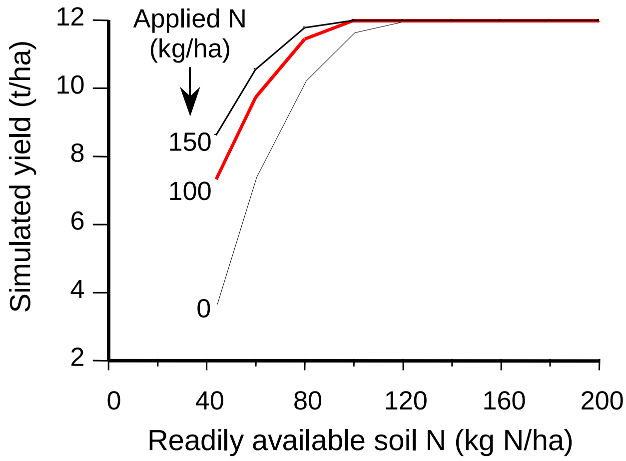

Figure 2. Simulated wheat yield response to N supply when supply of water and other nutrients is not limiting yield. The readily available soil N is measured as mineral N plus N released in an anaerobic incubation at 40°C. Potential yield was set at 12 t/ha (at 15% moisture).

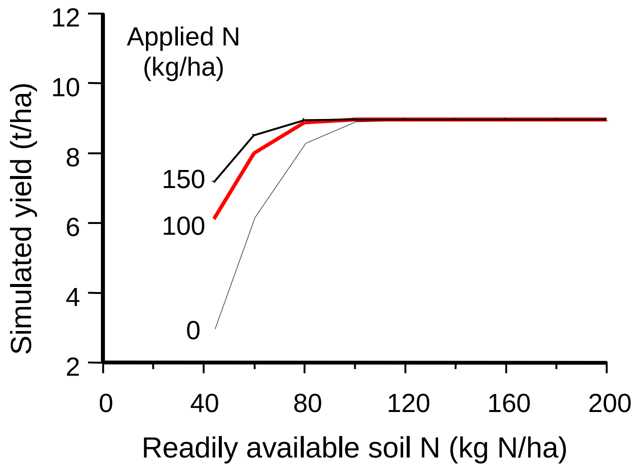

Figure 3. Simulated wheat yield response to N supply when supply of other nutrients and water are also limiting yield. The potential yield was 12 t/ha (at 15% moisture).

definition was created for the C7 soil, with as close a physical description as was possible from physical

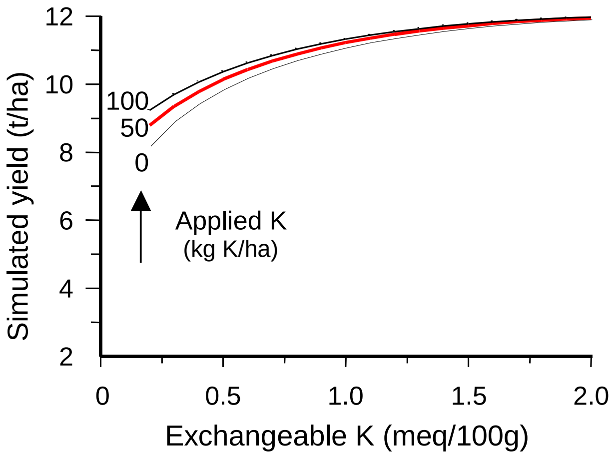

Figure 4. Simulated wheat yield response to K supply when water and other nutrients are not limiting yield. The potential yield was set to 12 t/ha at 15% moisture. Note that an exchangeable K of 1.0 is equivalent to a MAF QuickTest value of about 19.

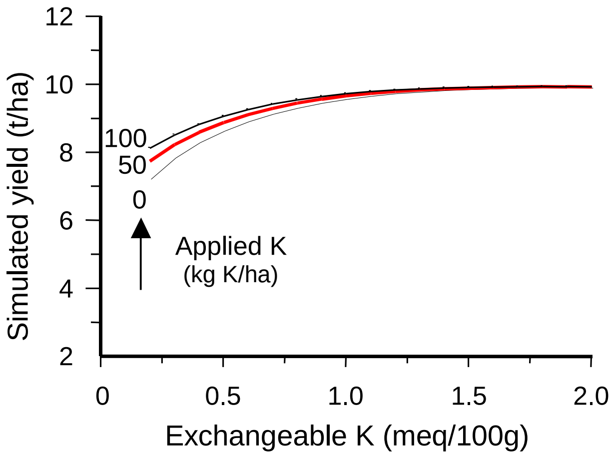

Figure 5. Simulated wheat yield response to K supply when supply of other nutrients and water are also limiting yield. The potential yield was set at 12 t/ha, and fertilizer N was supplied at 150 kg N/ha. We have assumed average soil N, P, Ca, Mg and drought conditions from our field dataset.

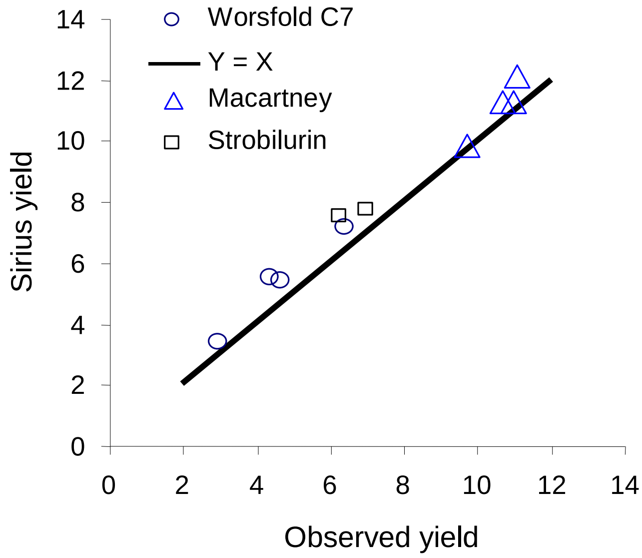

Figure 6. A comparison of simulated and observed wheat yield (t/ha) at two sites.

measurements made at the site. The ability of the soil to mineralise organic N was restricted sufficiently to match the yield of the treatment without fertiliser, but with the actual irrigation applications included in the simulations. The analysis showed that, in this experiment, water stress was a large factor in reducing yield – the crop suffered substantial water stress late in the season, although sufficiently early that reduced grain number was the major component of yield that varied. When the actual N treatments were also applied in the simulations, the simulated yield response to N was very similar to that observed (Fig. 6). In addition, the model closely predicted the yields of the Kohika wheat in an adjacent experiment (designated "strobilurin" in the figure), despite it having a substantially later sowing date and being a different cultivar. The model also predicted the yield and nitrogen response of the experiment at the Macartney site very accurately, in this case using the standard Sirius description of a Taitapu silt loam. The model predicted this restricted dataset very well.

The experimental results are very much in accord with the theory as implemented in Sirius, but the systematically low yield in the Worsfold experiment strongly suggests a very limited ability in this soil to mineralise organic N. One possible reason is that the presence of stones in the soil caused the soil test to overestimate N availability – standard soil tests are based on the soil from which stones have been removed. Also, the history of the field over the past three seasons was peas, followed by wheat, followed by potatoes. This history was probably a substantial contributor of the low capacity of the soil to mineralise N. The results suggest that more effort needs to be made to refine soil N tests to improve the accuracy of fertiliser recommendations.

A second collection of data represents cases where Sirius substantially overestimated the response to N, despite reasonably close simulation of the lowest yield in each experiment (Fig. 7). In this case factors other than shortage of N and water stress (already accounted for in the simulations) restricted yield. Those factors may have included soil K (shown here to influence yield), poor soil structure, low levels of disease, or leaching of N.

A comparison of predicted response to applied N with the observed response indicates an achievable yield under the conditions in these fields of 8-9 t/ha (Fig. 8). Under better conditions in this series of experiments the cultivar yielded in excess of 11 t/ha. Research needs to be directed toward identifying the reasons for the yield gap so that, if possible, they can be eliminated. The PARJIB model gives some clues. This analysis suggested the percentage reduction in yield associated with insufficient soil K was from 15 – 19% on the basis of the soil tests at these sites. This would be sufficient to have reduced the N response as shown. What it does indicate is that when soil K levels are low, less N should be applied. Note that these restrictions did not apply to the Macartney and Worsfold sites, in the former case because K was not limiting, and in the latter because the limitations associated with water and N shortage were much more important.

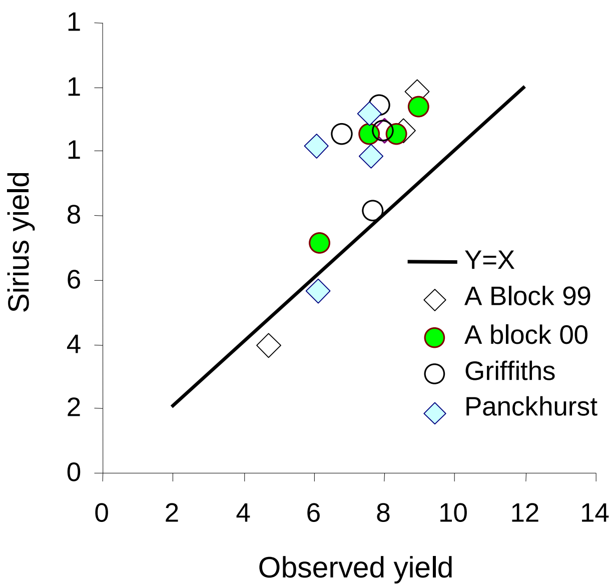

Figure 7. Comparison of simulated with observed wheat yields (t/ha) for sites where simulations overestimated yield.

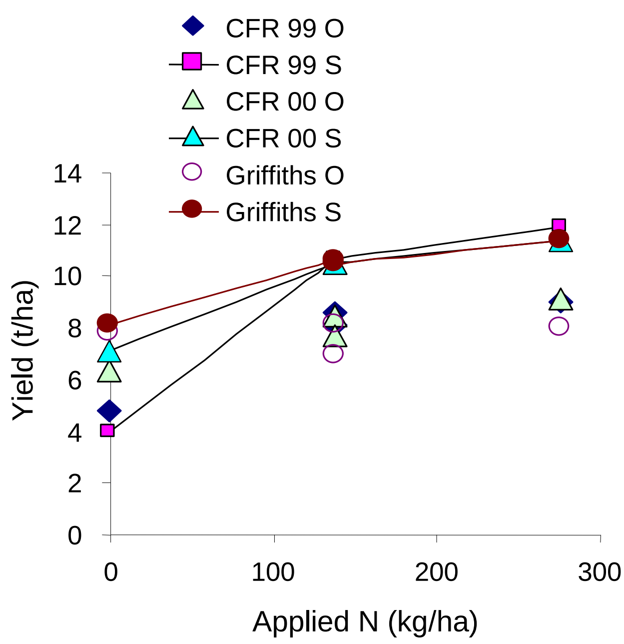

Figure 8. Predicted wheat yield response to N fertiliser (connected points) with the measured response (unconnected points) for three sites. The variation at zero applied N is associated with different initial conditions.

Conclusions

Water and N were the main factors affecting yield, with little or no response to P or K fertiliser in the set of treatments and soils under investigation. Soil tests provide a good guide to fertiliser requirements, but there are other factors, not investigated in this experiment, that also limit yield. The results from the very low yielding Worsfold site indicated that there is a need to refine soil tests to give better predictions of N release during the season. The strong response to variations in soil K is not solved by adding K in the fertiliser with the seed, at least not for the current crop. Low K levels did result in reduced response to N, and this is something that should be accounted for when assessing fertiliser needs.

What was also demonstrated in this project is the immensely powerful nature of the combination of models used. This comes about because they each fill gaps the other does not. Although Sirius has been demonstrated to handle water and N very well, it has no way presently of handling other nutrients. That deficiency is very well overcome by combining it with PARJIB. On the other hand, PARJIB, which calculates proportional yield responses to nutrient shortages, needs an estimate of potential yield to work with. For wheat, this is provided by Sirius.

Acknowledgements

We are grateful to Syd Worsefold, Jim Macartney, John Mulholland, Gary Masterton, Stuart Panckhurst, and Paul Griffiths for allowing us to undertake experiments on their farms. Myles Rea, Ross Hanson, Heather Russell, Frances McCallum, Dave Milne and Maryann Robson assisted with the sowing of experiments and processing of samples. Ruth Butler did the analysis of variance on results. Funding for this project was provided by the Foundation for Arable Research and the PGSF.

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